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RADAR PROPERTIES OF THE MOON

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A brief review is given of radar methods as applied to lunar studies and their interpretation. It is shown that the radar data are consistent with a porous, undulating surface strewn with rocklike objects, and argued that rayed craters are both rougher and denser than their surroundings.

INTRODUCTION

Radar observations of the moon have in the past contributed to our knowledge about the lunar surface in a number of ways. The low radar scattering cross section has led to – or confirmed – the view that the lunar surface in general consists of material which is in a rather loosely compacted state, at least to a depth of many centimeters. Variation in the amount of backscattering with angle of incidence has shown that the surface on a scale of a few centimeters is fairly smooth and gently undulating with typical average slopes of the order of 10-13°. Observations of the degree of depolarization appear to indicate that a small scale structure, probably rock-like, must be scattered over most of the surface. Finally, it has been found that young and rayed craters are much more efficient backscatterers than their surroundings.

In what follows we shall introduce the various observation techniques used in lunar radar studies, describe observational results and their interpretation. Finally, a brief discussion is given of what possible useful information can be gleaned from further radar studies of the moon, particularly in view of the spectacular photographs obtained in the Ranger, Surveyor and Luna programs.

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CROSS SECTION OBSERVATIONS

The radar cross section of the moon as a whole has been measured by a number of workers over a wavelength interval from 8 mm to 20 meters. Table 1 lists some of the results obtained. The error estimates are substantial in most cases. This is due to difficulties with absolute calibration in the data taking process. The low uncertainty at 23 cm was obtained by calibrating the radar system against a well known calibration sphere in satellite orbit around the earth. Figure 1 shows a plot of the cross section against wavelength. Due to the large experimental uncertainties it is difficult to assign a definite frequency law to the reflectivity. It does appear, however, as if the cross section increases somewhat with wavelength.

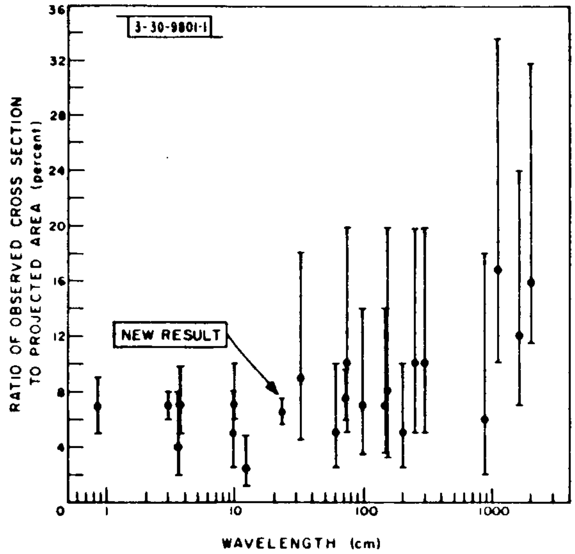

Fig. 1 Lunar Radar Cross Section Versus Wavelength.

On the basis of assuming the surface material to behave like a perfect dielectric, homogeneous with depth, one concludes that the dielectric constant must be somewhat less than three (Rea <u>et al</u>, 1965). This low value of the dielectric constant indicates that the surface cannot consist of compacted rock material, but must be porous. Radiometric observations of the thermal emission from the moon (Troitskii, 1965), however, seems to indicate an even lower value of the dielectric constant. A

Table 1

VALUES FOR THE RADAR CROSS SECTION OF THE MOON AS A FUNCTION OF WAVELENGTH REPORTED BY VARIOUS WORKERS

Author	Year	Wavelength cm	$\sigma/\pi a^2$	Estimated Error, db
Lynn _et_ _al_	1963	0.86	0.07	± 1.
Kobrin	1963*	3.0	0.07	± 1.
Morrow _et_ _al_	1963*	3.6	0.07	± 1.5
Evans and Pettengill	1963c	3.6	0.04	± 3.
Hughes	1963*	10.0	0.05	± 3.
Victor _et_ _al_	1961	12.5	0.022	± 3.
Evans and Hagfors	1966	230.	0.065	± 0.5
Blevis and Chapman	1960	61.0	0.05	± 3.
Fricker _et_ _al_	1960	73.0	0.074	± 1.
Trexler	1958	100.0	0.07	± 4.
Evans	1957	250.0	0.10	± 3.
Evans _et_ _al_	1959	300.0	0.10	± 3.
Evans and Ingalls	1962	784.0	0.06	± 5.
Davis and Rohlfs	1964	1130.0	0.19	+ 3. - 2.
Davis and Rohlfs	1964	1560.0	0.13	+ 3. - 2.
Davis and Rohlfs	1964	1920.0	0.16	+ 3.

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* Revised value (privately communicated to Evans and Pettengill [1963c]).

reconciliation of the radar and the radiometric determinations of the dielectric constant can be brought about by models involving a gradual transition with depth rather than an abrupt change. This change may either be in the form of a homogeneous tenuous boundary layer or in the form of a continuously changing transition layer (Hagfors, 1967). Inhomogeneity with depth can also easily explain an increase in cross section with wavelength as apparently is observed.

ANGULAR VARIATION OF THE BACKSCATTERED POWER

The capability of a radar system to resolve very finely in range can be used to measure the angular variation of the scattering. Figure 2 shows the one-to-one relation between delay and angle of incidence on the moon.

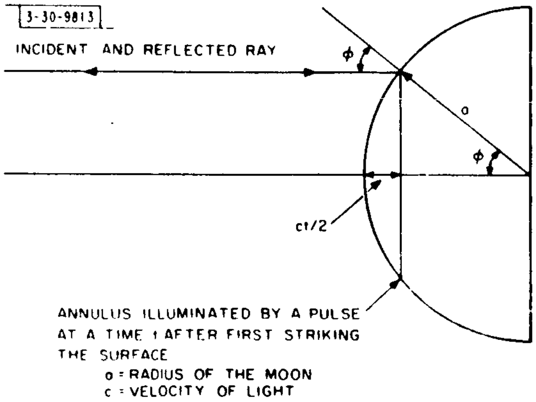

Fig. 2 Relation Between Delay and Angle of Incidence

Thus, by resolving the power returned from the moon in range it is possible to arrive at the angular scattering law. Figure 3 shows the reflected power plotted against range for several different wavelengths. A wavelength dependence is clearly seen in the data.

Before discussing what the physical significance of these results might be it should be mentioned that the angular scattering law can also be derived by a different technique. Due to relative rotation of the earth and the moon different portions of the lunar disk will scatter back with different Doppler shifts relative to the center of the moon. By frequency

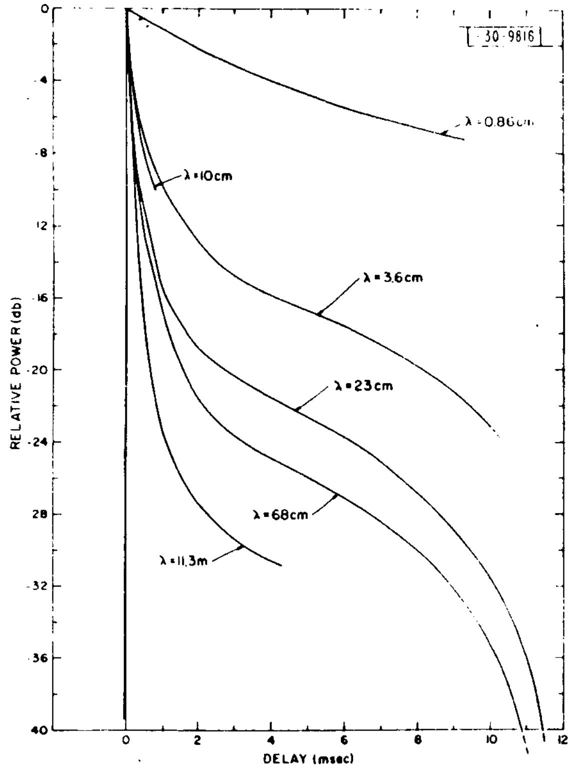

Fig. 3 Backscattered Power Versus Delay for Several Wavelengths

analysis it is possible to arrive at a strip-distribution of power across the disk. This strip distribution can be converted to a power-delay relationship and hence provides the same type of information as the direct power-delay measurements. This technique has found more frequency application in planetary observations than in lunar studies.

Analysis of the curves in Figure 3 shows that the scattering near normal incidence decreases markedly with wavelength whereas the scattering at more oblique angles increases somewhat with decreasing wavelength. The backscattering near normal incidence can be thought of as arising from flat facets tilted with respect to the mean lunar surface so as to be favorably oriented for reflection. On this basis the power versus angle relationship can be translated to a distribution of surface slopes. The r.m.s. slopes found in this way typically correspond to the range of angles 10-15°. At the shorter wavelengths the slopes observed tend to appear steeper. This may be understood if it is realized that the shorter wavelength observations are sensitive to structure of smaller lateral extent than the longer wavelength ones.

For the scattering at oblique incidence, i.e., at angles of incidence in excess of 25°, the returns may no longer be thought of as reflections from flat facets, but rather as scattering from a collection of relatively small individual objects. The increase in the amount of oblique angle scattering with decreasing wavelength may be understood if it is realized that the shorter wavelength experiments are sensitive to a wider range of rock sizes than the longer wavelength ones. Calculations of the strength of the backscattering expected from rocks such as the ones seen in the vicinity of Luna 9 or Surveyor I seem to show that the number of rocks per unit surface area may be adequate to account for the scattering at oblique angles of incidence.

For angles of incidence ϕ in excess of 25° the backscattering per unit surface area goes as $\cos^{3/2}\phi$. There are indications that this law changes to a $\cos \phi$ dependence near grazing incidence. In radar illumination the lunar disk therefore looks nearly uniformly bright with a brilliant spot corresponding to quasispecular return in the center.

POLARIZATION OBSERVATIONS

Radar astronomy allows the observer to control the polarization of the illumination of his target. At a wavelength of 23 cm this capability has been exploited fully in order to improve our understanding of the nature of the surface. The surface has been illuminated with circularly polarized waves and the amount of depolarization has been studied as a function of angle of incidence. Figure 4 shows the ratio of the polarized and the depolarized backscattered components as a function of angle of incidence for circular illumination. Figure 5 shows this ratio when the illumination is linearly polarized. In both of these cases the interpretation is consistent with the interpretation derived from the angular variation of the backscattered power (Hagfors, 1967).

MAPPING TECHNIQUES

Resolution in delay and in relative Doppler offset has already been mentioned as alternative techniques for obtaining information on angular power variation. Combination of the two techniques provides us with a

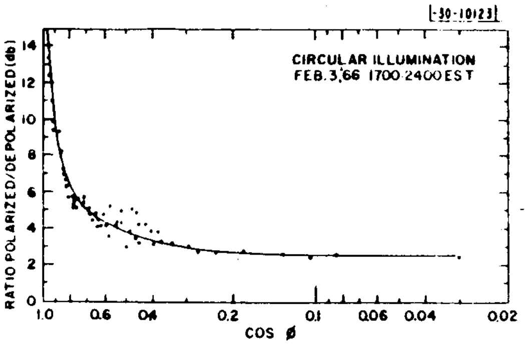

Fig. 4 Ratio of Polarized and Depolarized Backscattered Power versus cos Ø for Circularly Polarized Illumination

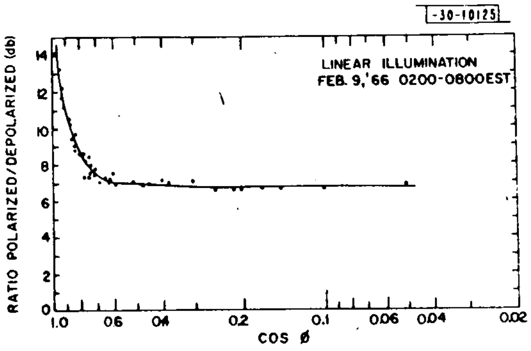

Fig. 5 Ratio of Polarized and Depolarized Backscattered Power versus cos Ø for Linearly Polarized Illumination

coordinate system of circles centered on the sub-radar point and straight parallel equidistant lines across the disk of the moon. This gives a two-fold ambiguous coordinate system for mapping purposes. If the antenna beam of the radar is narrow enought the two-fold ambiguity can be resolved and maps may be produced. This technique was used by Pettengill and Henry (1962) in the first identification of the crater Tycho as an anomalously bright radar scatterer. This technique has now been perfected by Drs. Pettengill and Thompson to the extent where high-resolution radar maps can be constructed. An example of such a map is shown in Figure 6. The resolution in the map is approximately 2 km which comes very close to the best available optical resolution by ground-based means. Figure 7 shows an optical photograph of the same crater (Plinius). A number of rayed or new craters have been shown to be anomalously strong scatterers of radio waves. The enhanced scattering from these craters is generally believed to arise from a combination of rougher terrain as well as denser material (Thompson and Dyce, 1966). Detailed maps of radar reflectivity are currently being constructed of the equatorial regions of the moon by the MIT Lincoln Laboratory at a wavelength of 3.8 cm and by Cornell University at 70 cm.

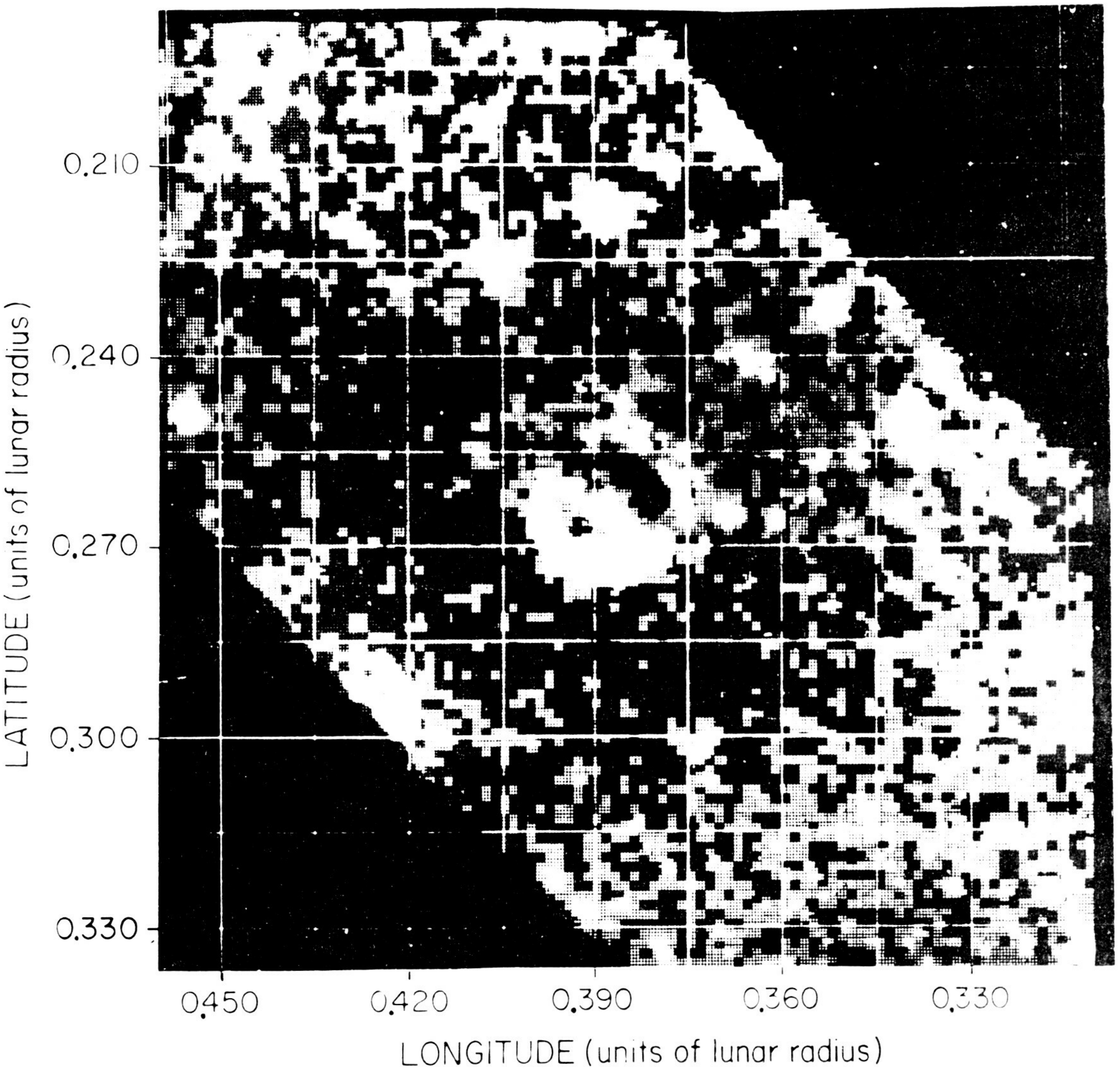

Fig. 6 Example of Radar Map of the Crater Plinius. (Courtesy of Dr. G. H. Pettengill)

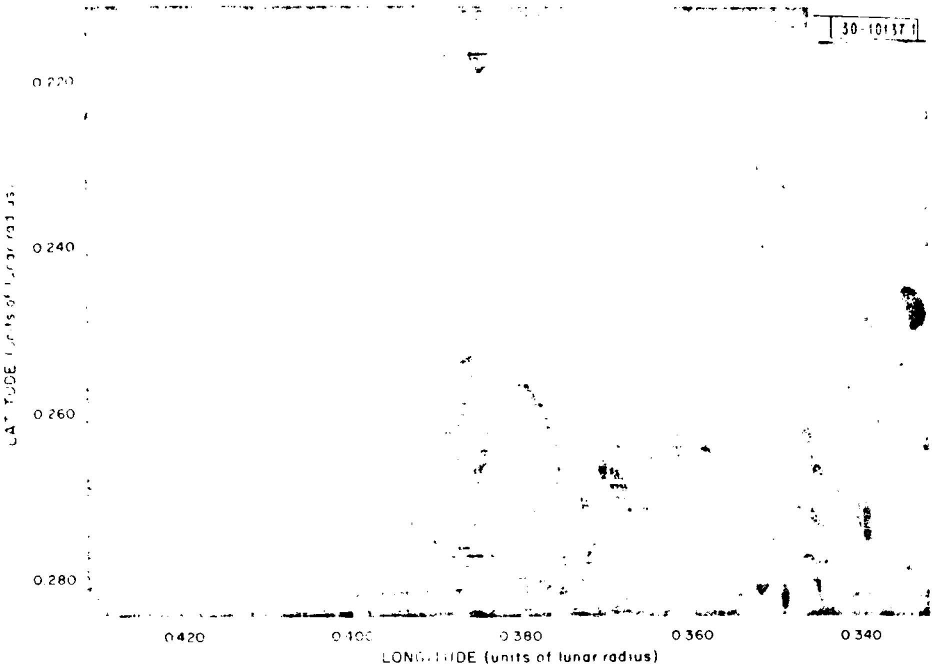

Fig. 7. Optical Photograph of the Crater Plinius

DISCUSSION

What purpose can further radar studies of the lunar surface serve after extremely detailed photographic information has been obtained from missions such as Surveyor or Orbiter? In order to answer this question one might point to the disagreement about the physical nature of the lunar surface which still persists. It would seem that detailed radar observations of the landing areas of the Surveyors might contribute to resolving the remaining points of disagreement among proponents of various types of surface models. Radar mapping methods can be applied relatively inexpensively to the whole visible portion of the lunar surface. Direct exploration of the whole of the lunar surface by photographic techniques, by the landing of instrument packages or by manned exploration might on the other hand prove to be extremely costly.

The interpretation of the radar data at the present time in many respects remains somewhat ambiguous. Some of these ambiguities may be completely removed after a few representative areas on the moon have been explored in situ and by radar methods. The physical nature of unexplored areas may then be determined by radar through simple extrapolation. Finally, it should be pointed out that most of the observational methods employed in radar studies of the moon can be directly applied to planetary radar explorations. Hence we may foresee that the moon will continue to be explored by radar in the future – if for no other reason – as a test target for planetary investigations.

ACKNOWLEDGMENT

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