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"A Lunar Theory Reasserted"—A Rebuttal

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In a recent paper Siegel and Senior [1962] have criticized the attempts of Winter [1962] to account for the scattering behavior of the moon at radio wavelengths by means of a statistical description of the surface. Instead they contend that their original theory [Senior and Siegel, 1959] when written was "in accordance with all the experimental data available at that time (and, incidentally since that time also) . . ." Experimental evidence is presented in this paper which is not in accord with Senior and Siegel's theory and which therefore invalidates the above statement.

1. Introduction

In 1957 the author published the results of a series of experiments which showed that the moon scatters radio waves principally from a small region at the center of the visible disk having a radius of the order of one third the lunar radius [Evans, 1957]. These results were obtained at a wavelength of 2.5 m, and their publication was closely followed by that of the work performed several years earlier at the U.S. Naval Research Laboratory [Trexler, 1958; Yaplee et al., 1958]. Trexler's results were obtained at a wavelength of 1.5 m and Yaplee's at 10 cm; yet both experiments indicated this same form of scattering behavior.

Since these early experiments, more detailed investigations have been carried out (notably by Pettengill and Henry, 1962; Hughes, 1961; and Evans, 1962a, b). These have provided quantitative results for the power scattered by the moon as a function of range delay measured from the nearest point on the surface at different radio wavelengths. Some of these results are presented in this paper.

On the theoretical side, several workers have attempted a description of the lunar surface features from which the scattering properties can be calculated and compared with the observed behavior. Most authors [Hargreaves, 1959; Brown, 1960; Hagfors, 1961; Daniels, 1961; Hayre and Moore, 1961; and Winter, 1962] have employed some form of statistical description of the surface. With the exception of Brown [1960] these authors have all assumed that the true height of the lunar surface is normally distributed about the mean. Hughes [1962] has criticized Daniels [1961] for making this assumption, but Daniels [1961, 1962] has presented convincing arguments which show that radio reflections cannot be used to determine the scale of structure which is many times larger than the radio wavelength. Hence, although the assumption of a Gaussian distribution of heights may be incorrect, one would not be able to ascertain this from radar studies alone. The horizontal scale of the structure can then be defined by an autocorrelation function, $\rho(\epsilon)$, where ϵ is the distance between any two points on the surface with heights h_1 and h_2, and specifies the correlation of these heights. Hargreaves [1959] and Hagfors [1961] have assumed a Gaussian function for $\rho(\epsilon)$ whereas Daniels [1961] and Hayre and Moore [1961] have investigated the case of an exponential function. Finally Winter [1962] has examined the case where $\rho(\epsilon)$ has the form of $1-\text{const}\ \epsilon^2$. The best agreement with the experimental results seems to be provided by the exponential law [Daniels, 1961; Hayre, 1961; Evans, 1962–b].

2. Senior and Siegel's Theory

Senior and Siegel [1959] presented a theory for the moon's scattering in which they reached the conclusion that the "principal" reflection came from the first few Fresnel zones at the leading edge of the moon. A further five (later increased to 20 to 30 in Senior and Siegel, 1960) scattering regions were invoked to account for the power reflected at delays beyond the leading edge of the moon. The arguments which lead to this result may be summarized as follows. If there were a single prominent scatterer at the leading edge of the moon, its character could be inferred from a study of the power returned by it as a function of wavelength. Thus a suitably oriented flat surface would scatter back more favorably as the wavelength λ is reduced in proportion to λ^{-2}. Only a smooth convex region would show no wavelength dependence. Senior and Siegel *assumed* that for the moon one such scatterer existed and further *assumed* that radar observations with pulses of 2 to 5 μsec duration were capable of resolving this scatterer. They next scaled down the published values for the lunar cross section obtained using long pulses or cw measurements according to a law communicated to them by Youmans. This law states the value for the peak cross section as a function of pulse length and at that time had been determined only at one wavelength. Senior and Siegel next *assumed* that this law applied to all wavelengths, and proceeded to correct the val-

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ues for the cross section of the whole moon by the same large factor (>100) to obtain the peak cross section that might have been obtained had 2 to 5 μsec pulses been employed instead. (See tables 1 and 2, Senior and Siegel, 1962.) The cross sections observed for the whole moon had been measured by most workers to an accuracy of $^{+100}_{-50}$ percent, and to this order of accuracy showed no wavelength dependence. When scaled down by the same factor they again showed no wavelength dependence (as might be expected) and from this Senior and Siegel concluded that the single scatterer which they had *assumed* to exist was a convex region, which they then *assumed* to have the same radius of curvature as the moon, i.e., the principal reflection was from a Fresnel zone.

3. Arguments Against Senior and Siegel's Model

Most critics of this model [Smith, 1959; Hughes, 1960; Evans, 1962c] have concerned themselves with the first two of Senior and Siegel's assumptions. Radio reflections from the moon are seen to fade. This arises because scattering centers located at the same range move relative to one another as a result of the moon's libration, and the reflections from these scatterers are therefore subject to destructive and constructive interference. As Smith [1959] pointed out, this fading can be seen at all range delays up to and *including* the leading edge of the moon even when short (2 to 5 μsec) pulses are used. This suggests that more than one scatterer is present. The rate of fading is of course lowest at the leading edge of the moon for the relative line-of-sight velocity of the scatterers is there a minimum. As a special check on this point Hughes [1960] repeated the experiments performed by Yaplee [1958] and found the signal showed "no steady component but fluctuates in a random fashion . . ." This result is hardly surprising in view of the fact that a 5μsec pulse illuminates a region at the center of the moon of the order of 8000 km^2, in which innumerable reflecting centers may be located. Purcell (see Senior and Siegel [1960]) has questioned the last made assumption, i.e., that the convex region (assuming it exists) has the same radius of curvature as the moon. Other authors [Hughes, 1960; Hayre, 1961; and Winter, 1962] have argued that the smooth monotonic decrease in the average echo power as a function at delay cannot be explained on the basis of one "principal" reflector and a limited additional number of greater ranges. Instead they argue the scattering centers must be so numerous that they can be described only in statistical terms. In addition no variations of the echo characteristics have been reported while the selenographic coordinates of the moon's mean center change due to libration, though the motion is quite large (±7°). It would seem difficult to arrange that a smooth Fresnel zone always be present at the leading edge of the moon for this wide range of aspect angles. Thus the *simplicity* claimed by Senior and Siegel [1962] for their model is achieved only by ignoring these experimental facts, and cannot therefore be regarded as a virtue.

Despite these apparently overwhelming objections Senior and Siegel [1961] [Siegel and Senior, 1962; also Siegel, 1961] have continued to defend their model. In their most recent paper [1962] they have asserted that the model "was in accordance with all the experimental data available at that time (and incidentally, since that time also) . . ." New experimental evidence which is contrary to the model is presented below.

4. New Experimental Results

A detailed study of the average reflecting properties of the moon at wavelengths of 68 and 3.6 cm has been carried out by Lincoln Laboratory M.I.T. [Evans, 1962 a, b]. The measurements were conducted by transmitting 30-μsec pulses and by averaging the echo power as a function of delay measured from the leading edge of the moon. For this latter task a 48-channel integrator device was constructed which had a resolution in delay (i.e., between channels) of 20 μsec. The results of this work are presented in figure 1. It can be seen that at both wavelengths there is a smooth monotonic decrease in the echo power with delay. However the *shape* of the two profiles is not the same. Thus the third

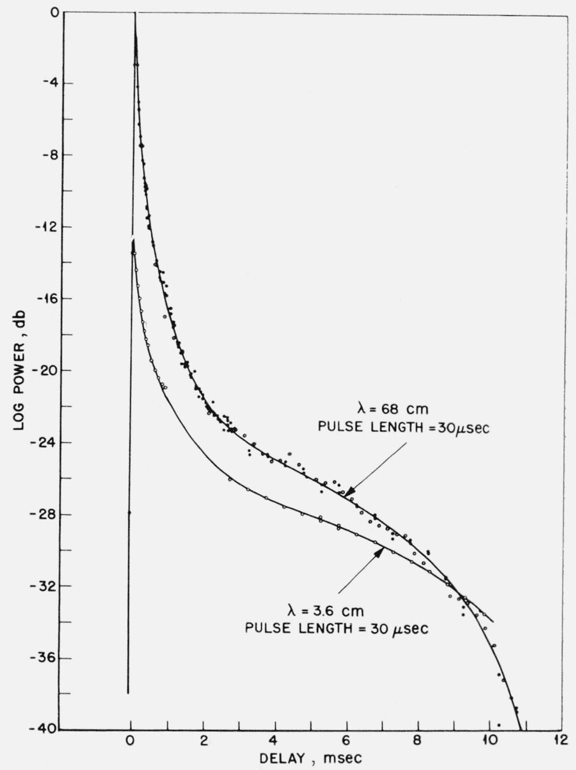

FIGURE 1. *Log power versus delay at 3.6 cm and 68 cm wavelengths.*

The results obtained by Evans [1962–a, b] for the distribution of average echo power as a function of range delay observed at 68- and 3.6-cm wavelength. The difference in the echo intensity at the leading edge is significant and indicates that the reflection in this region cannot be caused by a Fresnel zone.

assumption made by Senior and Siegel—that the law communicated to them by Youmans can be applied to all wavelengths—is incorrect. This law has been termed the "modulation loss law" [Trexler, 1958], and it is obtained from the impulse response curves shown in figure 1 from

$$\text{peak cross section} \propto \int_0^{\tau} P(t)\, dt,$$

where τ=pulse length,

$P(t)$=impulse response (fig. 1).

The use of log scales in figure 1 tends to mask the large difference in the behavior at the two wavelengths. In figure 2 the results presented in figure 1 have been plotted together with those obtained by Hughes [1961] after normalizing the intensities at the origin. A clear wavelength dependence in $P(t)$ can be seen to exist and will be discussed in a later paper [Evans and Pettengill, 1963]. Hence it is evident that a single correction factor connot be applied to data obtained at different wavelengths to scale the values for the cross section of the whole surface down to a peak cross section for a pulse length τ=2 to 5 μsec. Thus whatever else may be said of the model presented by Senior and Siegel, the analysis which was employed in its derivation is invalid.

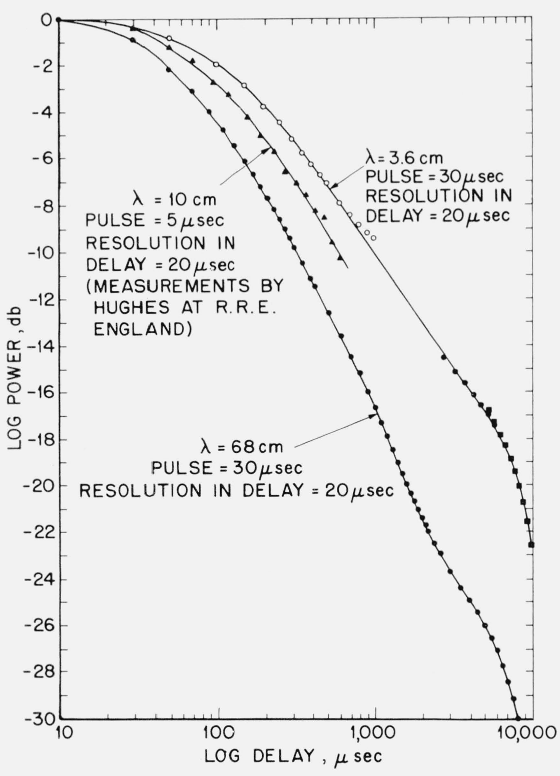

FIGURE 2. *Log power versus log delay.*

The results shown in figure 1 are here reproduced together with those obtained by Hughes [1961]. The intensities have been normalized at the origin to demonstrate the wavelength dependence of the scattering behavior of the moon.

The principal experimental evidence against the model is contained in figure 1. In this figure the relative intensity of the two curves has been obtained after allowance for the parameters of the two radar equipments [Evans, 1962a]. The uncertainty in the relative levels of the two curves is at most ± 3 db. Thus the cross section of the moon at 5 msec delay differs by 2 ± 3 db, and at the leading edge there is a difference of 10 ± 3 db. Hence though the absolute intensity of the echoes from the diffuse regions may be the same, those from the leading edge differ by at least a factor of 5. It follows therefore that the "principal" reflector cannot be a Fresnel zone. Instead it seems likely that there are no "principal" reflectors. We conclude that many reflected signals are present at any given delay and the change in the intensity at the leading edge of the moon is merely a consequence of the fact that the shorter wavelength is sensitive to fine-scale structure on the surface to which the longer wave is not. (To a first approximation structure with a vertical scale $\ll \lambda/4$ has little effect on the reflected wave.) Thus the "bright" spot seen at 3.6 cm is not so "bright" as at 68 cm and covers a larger region. Most people are familiar with this kind of behavior in the light reflected from ball bearings of varying roughness.

5. Discussion

It would seem hardly necessary that different authors should have gone to such lengths to refute the model proposed by Senior and Siegel. The reason perhaps lies in the fact that Senior and Siegel use the existence of a hypothetical Fresnel zone at the leading edge to provide a scatterer of known theoretical cross section. By comparing the "modified" cross sections with this theoretical one they are able to derive a value for the dielectric constant of the lunar surface $k=1.1$. This value is so close to that of air that it implies very peculiar properties for the lunar surface. Attempts by Senior and Siegel's colleagues [Brunschwig et al., 1960] to manufacture a material having this low a value of the dielectric constant failed, despite the use of a variety of particle sizes and vacuum conditions. Senior and Siegel [1962] have argued that the low value for the dielectric constant ($k=1.5$) obtained by Salomonovich [1962] from a study of the radiometric brightness of the moon near the limb supports their model. In addition Troitski [1962] obtained a value of $k=1.5\pm 0.3$ from the variation of lunar temperature at different radio wavelengths. However in neither of these papers were the effects of surface roughness fully allowed for, and it seems therefore that the values reported represent lower limits. In a recent review of the radio emission results, Mayer [1961] arrived at a value $k=3$. Thus these data cannot yet be said to yield an unambiguous result. In any event, even if reliable independent evidence did exist for a low value of the dielectric constant, Senior and Siegel's model for the radio wave reflection properties of the moon must still be rejected for the reasons stated above.

6. References

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