Detection of Radio Signals Reflected from the Moon*

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Summary—**This paper describes the experiments at Evans Signal Laboratory which resulted in the obtaining of radio reflections from the moon, and reviews the considerations involved in such transmissions. The character of the moon as a radar target is considered in some detail, followed by development of formulas and curves which show the attenuation between transmitting and receiving antennas in a moon radar system. An experimental radar equipment capable of producing reflections from the moon is briefly described, and results obtained with it are given. Some of the considerations with respect to communication circuits involving the moon are presented. The effects of reflection at the moon on pulse shape and pulse intensity for various transmitted pulse widths are dealt with quantitatively in the Appendix.**

I. Introduction

THE POSSIBILITY of radio signals being reflected from the moon to the earth has been frequently speculated upon by workers in the radio field. Various uses for such reflections exist, particularly in respect to measurement of the refracting and attenuating properties of the earth's atmosphere. Other conceivable uses include communication between points on the earth using the moon as a relaying reflector, and the performance of astronomical measurements.

Late in 1945, a program to determine whether such reflections could be obtained and the uses which might be made of them was undertaken by the U. S. Army Signal Corps at Evans Signal Laboratory, Belmar, N. J. The work has been continued since then, and, although for various reasons progress on it has been slow, this paper has been prepared to indicate the nature of the work and results so far obtained.

II. The Moon as a Radar Target

The moon is approximately spherical in shape, is some 2,160 miles in diameter, and moves in an orbit around the earth at a distance which varies from 221,463 miles to 252,710 miles over a period of about one month.

In considering the type of signals to be used for reflections, the manner in which the reflection occurs must be considered. If it were assumed that the moon were a perfectly smooth sphere, the reflection would be expected to occur from a single small area at the nearest surface, as would be the case with light and a mirror-surfaced sphere. However, astronomical examination of the moon reveals that, in its grosser aspects at least, its terrain consists of plains and mountains of the same magnitude as those on the earth. Further, because of the lack of water and air on the moon to produce weathering, it is probable that the details of the surface are even rougher than the earth. Thus, it is assumed that the type of reflection to be obtained from the moon will resemble the reflections obtained on earth from large land masses, or, to use radar terminology, ground clutter. An example of such a reflection obtained experimentally on earth is shown in Fig. 1. The echoes shown

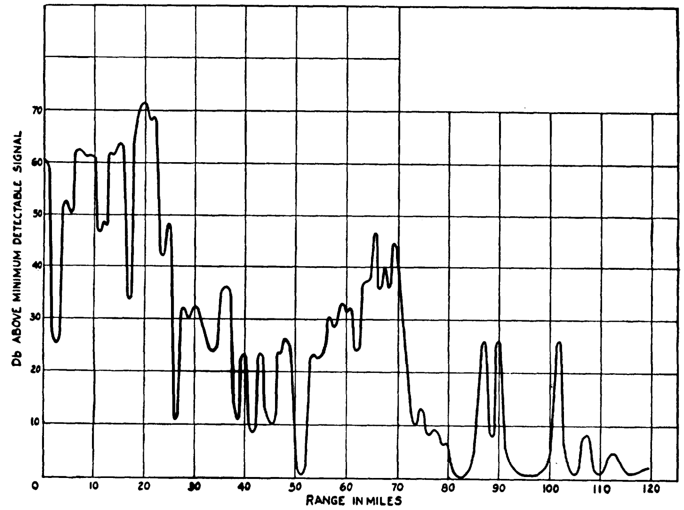

Fig. 1—Reflection obtained from a mountainous region on earth with a 25-microsecond, 106-Mc pulse.

were plotted from observations made with a 25-microsecond 106-Mc pulse transmitted into a mountainous region near Ellenville, N. Y. It will be seen that the intensity of reflection at various ranges varies in a quite random fashion, subject to a general dropping as the range increases. In this case, at 30 miles range and taking the antenna beam width as 12° and for the pulse width of 25 microseconds, or 2.7 miles, the echo at 30 miles range is the averaging of all echoes over an area of about 17 square miles. A pulse of the same width directed at the moon, using equation (35) in the Appendix, may act upon as much as 5,800 square miles. Thus, in the case of the moon, the return echo for a major portion of the time is an averaging of echoes over a very large area and could be expected to exhibit a high degree of constancy per unit projected area.

Thus the most reasonable assumption seems to be that, on the whole, the moon behaves for radio waves much as it behaves for light; that is, when illuminated from the direction of the earth, it presents a disk equal in area to the projected area of the sphere, the disk being illuminated in a generally uniform manner with any bright or dark spots distributed over the disk in a random manner. On the basis of this, it is evident that appreciable power contributions to the returning signal are received from areas on the moon which are at various ranges from the earth. Therefore, if a pulse system is used, to obtain maximum reflection the pulses should be long in time compared to the time required for a radio wave to travel in space the distance from the nearest

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point on the moon to the center and back again, if one is to be certain of the entire half surface of the moon contributing to the reflection. Since this distance is two times 2,160/2 miles and the velocity of propagation is about 186,000 miles per second, this time interval is 2,160/186,000 = 0.0116 second.

Thus, provided the pulse used for tests is appreciably greater than 0.0116 second, the moon is assumed to act as an isotropic reflector which has an area equal to the projected area of the sphere. Thus, for a wide pulse, the reflecting area of the moon is $\pi r^2 = \pi(2{,}160/2)^2 = 3.66 \times 10^6$ square miles, or 9.48×10^{12} square meters.

However, since the moon's surface is not a perfect conductor, this area must be multiplied by a reflection coefficient to account for the fact that all of the energy impinging is not reflected. With a target of this type, which assumes that the projected disk of the moon acts as a uniform reflector, the reflection coefficient for normal incidence would seem to be appropriate. A value of 17 per cent is given for the reflection coefficient of earth by Stratton.[1]

In the above discussion no attention has been given to the effect of depolarization of the wave by the reflection at the moon. This will probably cause some further reduction in effective reflection coefficient of the moon, but such further reduction is assumed to be not significantly large.

In the Appendix, the quantitative implications of this concept are considered, and it is shown that any pulse signal impinging on the moon is broadened by 0.0116 second. For pulses less than 0.0116 second duration, the maximum area effective in creating a reflection depends upon the pulse width, according to a curve given in Fig. 18 of the Appendix, so that, for a 1-microsecond pulse, the maximum effective area is only 0.00017 of the full disk area, representing a decrease in available peak signal of 37.7 db.

The previous discussion is primarily concerned with the case in which the antenna beam illuminates the entire disk of the moon in a uniform manner. If the beam is narrow enough to illuminate only a portion of the moon, the same type of considerations also apply, but spreading of pulses because of the bulk of the moon is reduced.

III. Attenuation in the Earth-Moon-Earth Path

The ratio of the signal power available at the receiver terminals to that available from the transmitter is a factor which must be known to determine the type of equipment capable of performing the experiment. This ratio may be determined in the following manner:[2,3]

At a range R from the transmitting antenna the power flow S_0 per unit area is

$$S_0 = \frac{P_t G_t}{4\pi R^2} \tag{1}$$

where

P_t = transmitter power
G_t = transmitter antenna gain over isotropic radiator
R = range.

This power impinges on the equivalent isotropic echoing area of the target A_E, is attenuated by the reflection coefficient m of the target,[4] is then re-radiated and is subject to the same spherical dispersion, so that the power flow at the receiving point S_R is given by

$$S_R = \frac{S_0 A_E m}{4\pi R^2} = \frac{P_t G_t A_E m}{16\pi^2 R^4}. \tag{2}$$

This power flow impinges on the receiving antenna of area A_R to give an available received power of

$$P_R = S_R A_R = \frac{P_t G_t A_E A_R m}{16\pi^2 R^4}. \tag{3}$$

The relation of gain to effective antenna area is given by

$$A_R = \frac{G_R \lambda^2}{4\pi} \text{ (square meters)} \tag{4a}$$

where λ is the wavelength in meters, or, since $\lambda = 300/F$, where F is the radio frequency in megacycles, and

$$A_R = \frac{7160 G_R}{F^2} \text{ (square meters).} \tag{4b}$$

Substituting (4a) or (4b) in (3) and noting that $G_T = G_R = G$ for radar-type operations, and that because of the units of (4a) and (4b) all distances must be in meters,

$$\frac{P_R}{P_t} = \frac{G^2 A_E \lambda^2 m}{1984 R^4} \tag{5a}$$

or

$$\frac{P_R}{R_t} = \frac{45.4 G^2 A_E m}{F^2 R^4}. \tag{5b}$$

It is also of interest to have the formulas in terms of the receiving and transmitting antenna area A_R. These can be obtained by combining (3) and (4a) or (4b), again taking $G_R = G_t$ to give

$$\frac{P_R}{P_t} = \frac{A_R^2 A_E m}{4\pi \lambda^2 R^4} \tag{6a}$$

or

$$\frac{P_R}{P_t} = \frac{A_R^2 A_E F^2 m}{1.13 \times 10^6 R^4}. \tag{6b}$$

[1] J. A. Stratton, "Electro-Magnetic Theory," McGraw-Hill Book Co., New York, N. Y., First Edition, p. 510; 1941.
[2] K. A. Norton and A. C. Omberg, "Maximum range of a radar set," report ORG-P-9-1 issued by the Chief Signal Officer, War Department, Washington, D. C. February, 1943; and Proc. I.R.E., vol. 35, pp. 4–24; January, 1947.
[3] The treatment is given sketchily here, as it follows generally the method of the reference.

[4] The effect of area of the target and its reflection coefficient m are kept separate in this treatment to avoid later confusion.

The formulas (5) and (6) are based on the tacit assumption that the beam width of the antenna is sufficiently large that the moon is illuminated over its entire surface by the transmitted beam. If the beam width is so narrow that the entire beam falls on the moon, then the moon can be considered as an isotropic source radiating the transmitter power reduced by the reflection coefficient m, and the power received back at the earth is simply

$$P_R = \frac{P_t A_R m}{4\pi R^2}, \tag{7a}$$

whence

$$\frac{P_R}{P_t} = \frac{A_R m}{4\pi R^2}, \tag{7b}$$

and substituting the values of (4a) and (4b) in (7b) gives

$$\frac{P_R}{P_t} = \frac{G_R \lambda^2 m}{16\pi^2 R^2} \tag{8a}$$

or

$$\frac{P_R}{P_t} = \frac{570 G_R m}{F^2 R^2}. \tag{8b}$$

Equations (5) and (6) hold for relatively wide beam widths, while (7) and (8) hold for very narrow beam widths. Since antennas do not have sharply defined beams of uniform density, the transition from the region where (5) and (6) are valid to the region where (7) and (8) are valid is not a sudden one, and neither one is precise in the region of transition. However, the region in which the transition occurs can be determined by assuming that the values of P_R/P_T obtained from each equation are equal and calculating the relations which must exist for their equality. Equating (6a) and (7b) gives

$$\frac{A_R^2 A_E m}{4\pi\lambda^2 R^4} = \frac{A_R m}{4\pi R^2},$$

and writing the area of the moon's disk at πr^2 where r is the radius of the moon, and the area of the antenna A_R as $\pi D'^2/4$ where D' is the diameter of the antenna aperture in meters, gives

$$\frac{r}{R} = \frac{\lambda}{D'} \cdot \frac{2}{\pi}. \tag{9}$$

Now, if α = the angle subtended by the moon, and since α is a very small angle, $\alpha/2 = r/R$, substituting in (9) and solving for α gives

$$\alpha = 1.28 \frac{\lambda}{D'} \tag{10}$$

where α is expressed in radians.

From the earth, the moon subtends an angle of almost exactly 1/2° or 0.0087 radians, the precise amount depending upon the exact position of the moon in its orbit. At its most distant point (apogee), this angle is 2,160/252,710 = 0.00855 radian. If such value be placed in (10), then $\lambda/D' = 0.00855/1.28$ gives the value of λ/D' at which the transition of validity from (5) and (6) to (7) and (8) occurs. Converting to a more useful form, the substitution of $\lambda = 300/F$ where F is the frequency in megacycles, and $D' = D/3.28$ where D is in feet (D' in meters), is made. Using these, it may then be said that (7) and (8) should be used for

$$FD > 1.46 \times 10^5, \quad \text{or} \quad F > \frac{146 \times 10^3}{D} \tag{11}$$

where F is in megacycles and D is in feet.

In the case of a square-aperture antenna, the same general considerations approximately apply, if D is taken as the length of one side.

In order to determine the actual attenuation involved, it is necessary to insert in (6b) the values for R and A_E. R will be taken as the maximum range, 252,710 miles or 4.07×10^8 meters. The area has previously been given as 9.48×10^{12} square meters, and the reflection coefficient m as 0.17. The area in square meters of a round-aperture antenna is $\pi D^2/4 \times 10.75$ where D is in feet. Substituting these values in (6b) gives

$$\frac{P_R}{P_t} = 2.77 \times 10^{-31} D^4 F^2 \tag{12}$$

where D is the effective antenna diameter in feet and F is in megacycles. Performing a similar substitution in (7b), one obtains

$$\frac{P_R}{P_t} = 5.97 \times 10^{-21} D^2 \tag{13}$$

where D is the effective antenna diameter in feet.

In practical antennas it is usually not possible to obtain the gain given by (4) because the aperture is usually not uniformly illuminated, either because of practical difficulties or to reduce side lobes in the pattern. The effective diameter of a round-aperture antenna should be taken as about 85 per cent of its physical diameter in applying (11), (12), and (13), so that, for practical antennas, (12), (11), and (13), respectively, become

$$\frac{P_R}{P_t} = 1.448 \times 10^{-31} D^4 F^2. \tag{14}$$

The above is true for low frequencies. If

$$F > \frac{172 \times 10^3}{D}, \tag{15}$$

then

$$\frac{P_R}{P_t} = 4.31 \times 10^{-21} D^2 \tag{16}$$

where, in each case, D is the actual antenna-aperture diameter in feet and F is the radio frequency in megacycles.

The results of these equations are shown in Fig. 2. The solid curves give the attenuation for various sizes of antenna apertures, as indicated. The dashed line indicates the transition between a beam wider than the moon and one narrower. As indicated previously, this transition does not occur abruptly as in these idealized curves, but the curves do give a basis for close estimation of the system requirement.

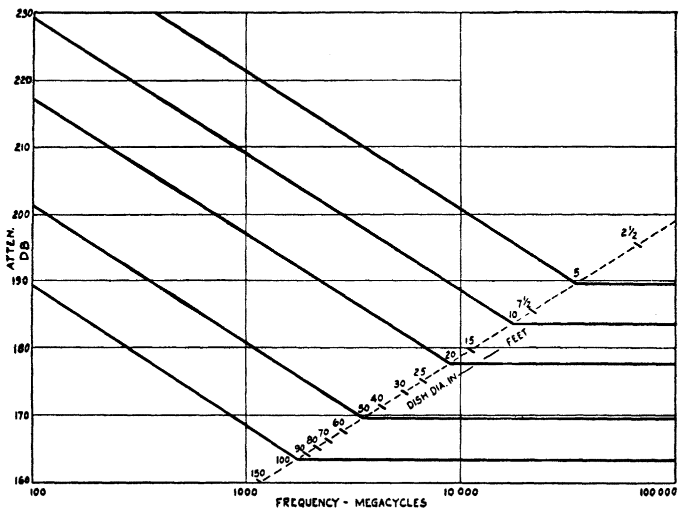

Fig. 2—Attenuation of the earth-moon-earth radar path for various frequencies and antenna apertures.

In all of the above, no effects of attenuation due to losses in the atmosphere or space, nor to the effect of refraction in the atmosphere, have been considered. However, at frequencies in the range from 100 to perhaps a few thousand megacycles, it is probable that for a considerable portion of the time these effects will not materially affect the attenuation figures given in the curve, since shorter-range radar operation in this frequency range gives results which are consistent with the assumption of negligible losses in the atmosphere and, with some exceptions, no refraction effects.

At frequencies much below 100 Mc, ionospheric refraction or reflection effects become much more pronounced, and it is probable that signals could not be sent to the moon and back at these lower frequencies.

It should also be noted that, in the above discussion, no attention has been given to ground reflections. If the antenna beam width is wide enough and the angle at which the antenna is aimed is low enough so that the ground is heavily illuminated by the beam, the ground-reflected wave will, at certain elevation angles, reinforce the direct wave, so that, under ideal conditions, the antenna gain will be increased by 6 db, and the over-all attenuation of Fig. 2 may be reduced under these conditions by as much as 12 db.

Equipment Requirements

The attenuations shown in Fig. 2 for ordinarily used antenna sizes are considerably in excess of the spread between transmitter power and minimum detectable signal for the receiver in a usual radar system. Further, as shown in the Appendix, to obtain attenuation even as small as shown in Fig. 2, a pulse width in excess of 12,000 microseconds is necessary, so that consideration of ordinary radar systems is ruled out on this ground, in addition to the long travel time to the moon and back which makes desirable the use of a low pulse-repetition rate.

Fig. 3 gives a basis on which the performance of a radar system may be approximately estimated. The input noise power with which a signal must compete is given by $P_{\text{noise}} = KTB$ where K = Boltzmann's constant $= 1.37 \times 10^{-23}$ joules/degree, T is the effective input (antenna) resistance temperature in °K, and B is the bandwidth in cps. This figure must in increased by the noise factor of the receiver.[2,5–7]

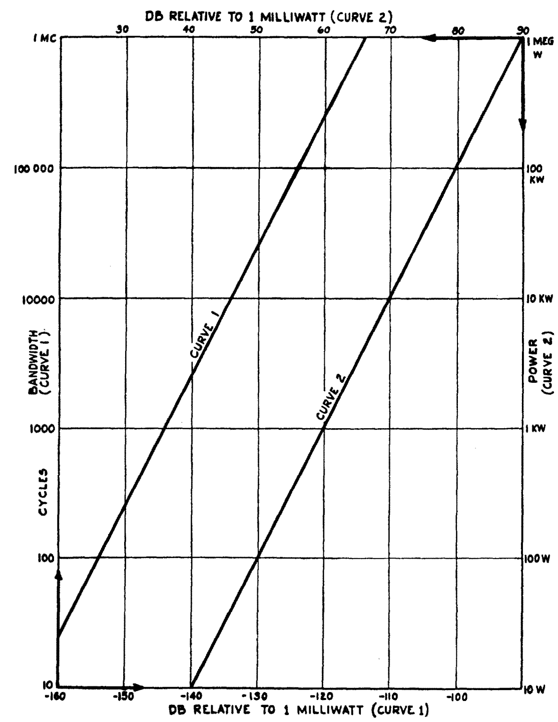

Fig. 3—Johnson noise and transmitter power levels in decibels with respect to 1 milliwatt.

If the pulse width of a radar transmitter is approximately (by a factor of from 1/2 to 2) equal in seconds to the reciprocal of receiver intermediate-frequency-amplifier bandwidth in cps, the minimum detectable signal will be of the order of the effective input noise (that is, KTB increased by the noise factor). It can be assumed that the effective antenna resistance is at a temperature of 300°K and, even if this assumption is not precise, when the noise factor referred to this temperature is not too close to 1, the error introduced by a lower effective antenna temperature will not be serious. The minimum detectable signal is also affected by pulse-repetition rate and other factors, but the above consideration gives a useful initial approximation.

[5] The references given are relevant to this and later discussion.
[6] A. V. Haeff, "Minimum detectable radar signal and its dependence upon the parameters of radar systems," Proc. I.R.E., vol. 34, pp. 857–861; November, 1946.
[7] H. T. Friis, "Noise figures of radio receivers," Proc. I.R.E., vol. 32, pp. 419–422; July, 1944.

In Fig. 3, curve 1 gives decibels relative to 1 milliwatt corresponding to Johnson noise (KTB) for various bandwidths at a temperature of 300°K, while curve 2 gives decibels relative to 1 milliwatt for various transmitter powers. As an example of the use of these curves, a typical 3,000-Mc radar set might have a receiver noise figure of 12 db, a receiver bandwidth of 1 Mc, a pulse width which is the reciprocal of this, 1 microsecond, and a transmitter peak power of 100 kw. The spread between transmitter and receiver would in this case be determined by:

(1) Receiver minimum signal is -114 db from the point on curve 1 for 1 Mc, increased by the noise factor of 12 db, or -102 db.

(2) Transmitter power from the point on curve 2 corresponding to 100 kw is $+80$ db.

The spread in this case is 182 db. In Fig. 2 it will be seen that, even with a 20-foot dish and assuming that full reflection could be obtained with the 1-microsecond pulse, the attenuation in the earth-moon-earth path would be 185 db. Actually, the use of the short (1-microsecond) pulse would make the attenuation 37.7 db greater, as discussed in the Appendix. Thus, on the basis of the assumptions used here, such a system falls about 40 db short of being capable of producing reflections from the moon.

All of this suggests that the type of radar system needed is one with a very wide pulse and correspondingly narrow receiver bandwidth. As previously pointed out, a pulse width substantially greater than 0.012 second is desirable, and, if a pulse width of 0.05 second be considered, using the criterion that the bandwidth should be the reciprocal of the pulse width, a bandwidth of about 20 cps is indicated.

To use such a narrow bandwidth requires a degree of frequency stability far beyond usual radar requirements, and so, in undertaking the moon-reflection experiment, the use of a rather elaborate crystal control was contemplated. The narrow bandwidth in the receiver makes it necessary to consider doppler shift between the frequencies of received and transmitted signal due to the relative velocity between the moon and the equipment on the earth. The relative velocity between a point on earth and the moon depends upon two components, one due to the rotation of the earth about its axis, and the second due to the motion of the moon in its orbit about the center of the earth. At the latitude of Evans Signal Laboratory, 40° 10′ North, the velocity component due to earth's rotation depends upon the angle at which the moon is viewed, and may be as much as 795 miles per hour at moonrise or moonset. Added algebraically to this is the velocity relative to the center of the earth of the moon in its orbit. This varies between plus 185 miles per hour and minus 185 miles per hour, so that the relative velocity may reach 795 plus 185 equals 980 miles per hour or 0.273 mile per second at this latitude. Since the velocity of light is 186,000 miles per second, and since the velocity with which the path length changes is twice the figure given above because of the two-way path, the frequency may be shifted by as much as a maximum amount ΔF which is related to the operating frequency by

$$\Delta F = F \times \frac{0.273 \times 2}{186{,}000} = 2.96F \times 10^{-6}. \qquad (17)$$

It was found that the Signal Corps was in possession of some experimental transmitting and receiving equipment, obtained from E. H. Armstrong, which was designed for 111.5-Mc operation, and which could be modified to approximate the requirements above. The system finally used overcame the frequency-stability problem by using a single crystal for obtaining the frequency control of the transmitter and all of the local-oscillator injections in the receiver except the final one. A multiplicity of mixers based on this single crystal is used to heterodyne the signal down to 1.55 Mc, where an independent adjustable-frequency crystal provides the final local-oscillator injection to heterodyne the signal down to the final intermediate frequency of 180 cps with a bandwidth of about 50 cps. Thus, the problem of frequency stability becomes one of maintaining a stability of about ± 20 cps at 1,500 kc, which does not require unusual techniques. Variation of the frequency of this crystal allows tuning of the receiver to the precise frequency required. The frequency to which the receiver is tuned, or, more precisely, the frequency by which its tuning must differ from the transmitter, depends upon the magnitude of the doppler effect, which must be calculated for the particular circumstances under which the operation is conducted. At the 40° 10′ North latitude, considered here, the maximum shift for a 111.5-Mc signal, using (17), will be $\Delta F = 111.5 \times 10^6 \times 2.96 \times 10^{-6} = 327$ cps, which, although small, is an appreciable shift when bandwidths of 50 cps are being considered. A simplified block diagram of the equipment is shown in Fig. 4. The apparatus has been described in detail elsewhere.[8]

The transmitter used initially had a peak power of about 3 kw. The noise factor of the receiver was 5 db and its bandwidth about 50 cps. However, because the amplifiers preceding the 180-cps narrow-bandwidth amplifier had a bandwidth wide compared to the 180-cps intermediate frequency, the receiver had an image response equal to the main response and separated from it by 360 cps. This image in effect doubles the bandwidth of the receiver, so that the incoming signal must compete with the noise in 100 cps of bandwidth rather than 50. Referring to Fig. 3, the equivalent receiver noise level is -154 db for 100 cps plus 5 db for noise factor, or -149 db. The transmitter level is plus 65 db for 3 kw, so that the total spread is 149 plus 65, or 214 db.

Reference to Fig. 2 shows, at 111.5 Mc and with an

[8] Jack Mofenson, "Radar echoes from the moon," *Electronics*, vol. 19, pp. 92–98; April, 1946.

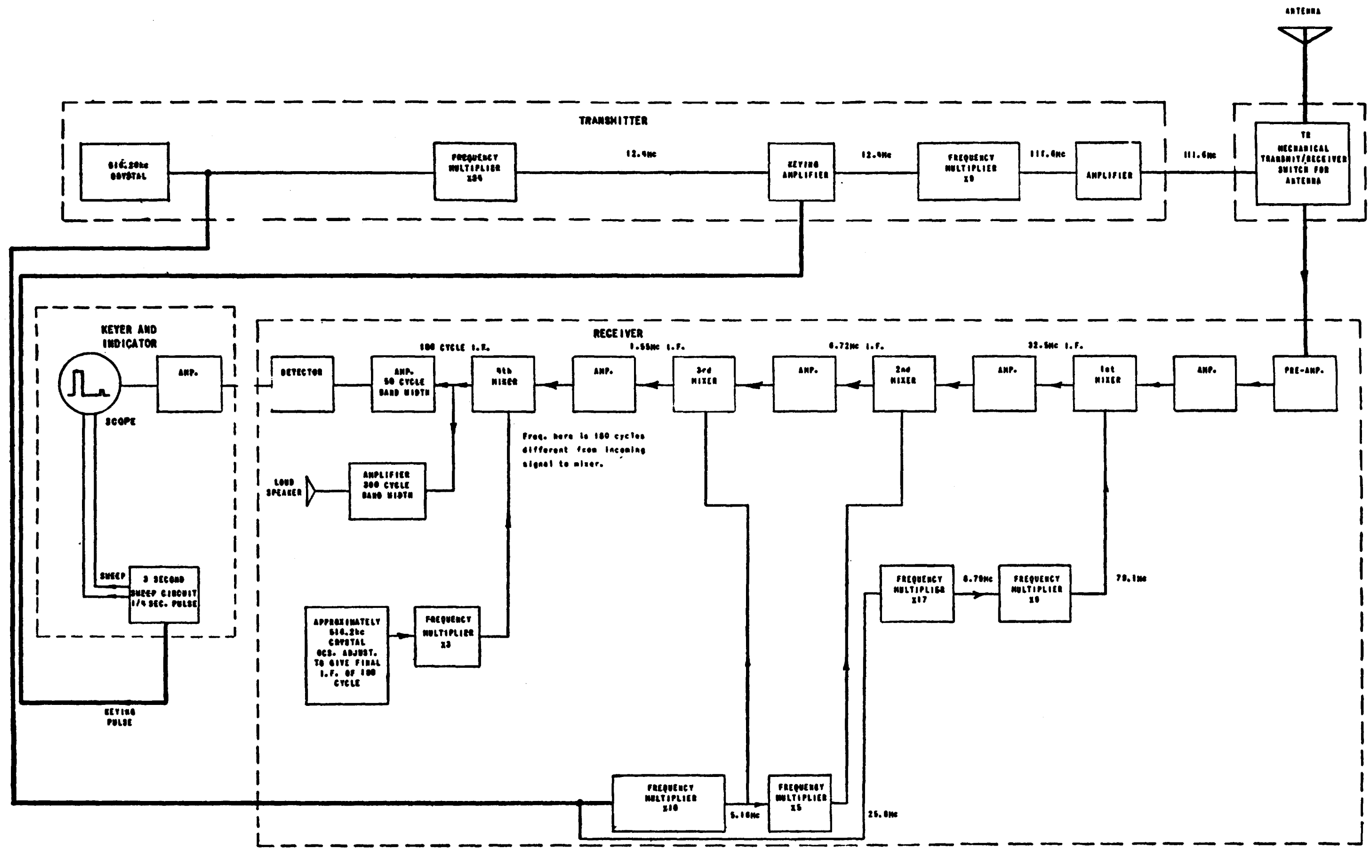

Fig. 4—Simplified block diagram of the 111.5-Mc moon radar system.

antenna diameter of 50 feet, an attenuation of slightly under 200 db. For 111.5-Mc operation, an antenna having gain equivalent to that of a 50-foot circular antenna is not too difficult to construct. (Large antennas for higher frequencies become difficult because of the accuracy of construction required.) It was decided that two antennas of the type used on the Army SCR-270-271 radar series could be assembled together to provide an array of dipoles about 40 feet square to give a gain (with the current distribution used) of about 250 over that of an isotropic radiator. Substituting this value in (5b) for $F=111.5$ Mc and the other values as used in deriving (12), it is found that $P_r/P_t=1.34\times 10^{-21}$, corresponding to 198.7 db attenuation. Thus the equipment previously described, with its 214-db capability, should be capable of showing a reflection from the moon, even with allowance for moderate transmission-line losses not considered previously, some atmospheric attenuation, and a loss due to depolarization by the reflection at the moon.

The antenna described above was mounted on a reinforced standard mount for the SCR-271 radar system, which is capable of rotating the antenna in azimuth only. Because of this search limitation, observations were restricted to a relatively short time near moonset and moonrise. (The antenna beam width is about 12 degrees.) The fact that the beam necessarily is directed horizontally implies that substantial ground reflections occur which break the antenna beam into a lobed structure, with the round-trip attenuation in the center of these lobes being, under ideal conditions, as much as 12 db less than if no ground reflections were present. The extent to which this 12 db is realized depends upon ground conditions at the "bounce point," and in this case an arbitrary estimate is made of an 8-db gain from this source. Using the previous figures, which show an approximate 15-db margin, and adding the above 8 db gives a 23-db excess performance, neglecting transmission line, polarization, and propagation losses.

The power output of the transmitter was later increased to about 15 kw by use of an SCR-270-271 trans-

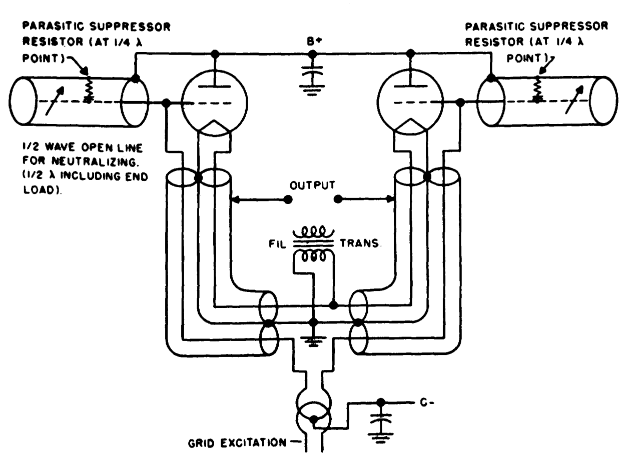

Fig. 5—Schematic diagram of the triode radar transmitter converted to a neutralized 15-kw amplifier.

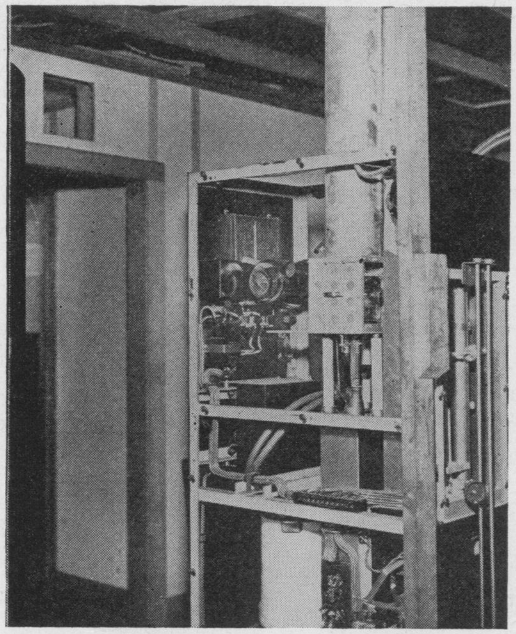

Fig. 6—Photograph of the radar transmitter converted to an amplifier. The ½-wavelength open lines for neutralizing are visible projecting out the top.

mitter modified to operate as a neutralized triode amplifier. The neutralizing was accomplished by open 1/2-wavelength lines connected between the plate and grid of the WL 530 tubes originally used as oscillators, and the grid excitation is supplied "bazooka" fashion by lengths of coaxial line attached to the cathode output lines. A schematic diagram of the rather unusual arrangement is shown in Fig. 5. Fig. 6 is a photograph of this amplifier, and Figs. 7 and 8 show other apparatus used in the experiments, and an aerial view of the station.

Measurement of System Performance

Measurements of the performance of such a system are necessary in order to evaluate the results obtained.

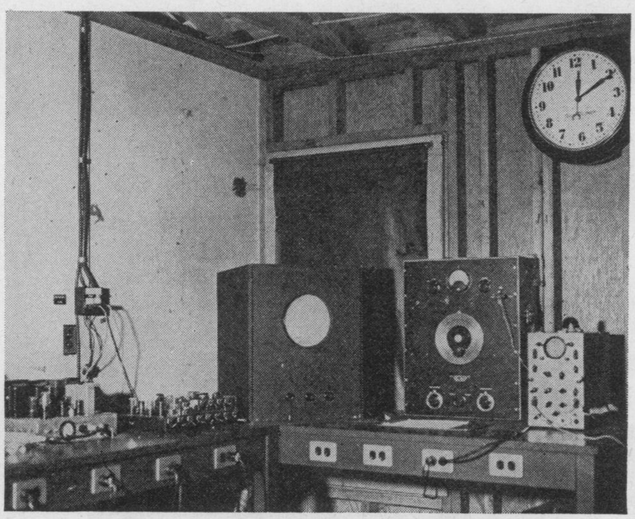

Fig. 7—Keying oscillator and sweep circuits, viewing oscilloscope, audio oscillator and oscilloscope for tuning the receiver to proper doppler shift, and miscellaneous controls.

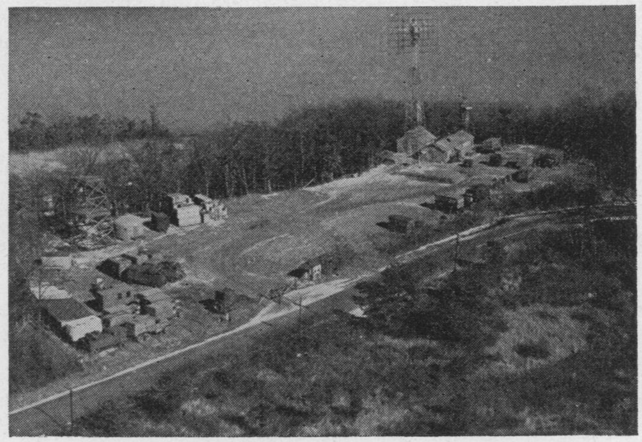

Fig. 8—Aerial view of the moon-radar installation looking in the general direction of moonrise.

Some of the measurements and adjustments are performed in a somewhat unusual way and will be described here.

The receiver has a pass band of about 50 cps at 111.5 Mc. It was found that ordinary signal generators are not capable of maintaining such stability even for a fraction of a second. A signal generator was converted to crystal-control operation with a vernier frequency control in the form of a variable capacitor across the crystal. With this it was found possible to maintain the frequency for very short intervals, but the problem of leakage due to inadequate shielding and filtering remained. This problem can be appreciated by considering the fact that, as indicated previously, the equivalent receiver input noise level is -149 db with respect to 1 milliwatt, or 1.25×10^{-18} watt, which in terms of voltage across a 50-ohm transmission line is 0.008 microvolts. In view of these difficulties, use of the signal generator was abandoned in favor of noise-factor measurement by a diode noise generator. The use of such a diode will be briefly described, since its use for this purpose has not been widely publicized.

In a diode operated so that the plate current is adjusted by the filament temperature with plate voltage fixed and high enough so that increasing plate voltage causes no increase in plate current (that is to say, a temperature-limited diode), a noise current is present in the plate circuit whose value is given by

$$I_{\text{noise}}^2 = 2eI_dB \qquad (18)$$

where

e = the charge on an electron, 1.59×10^{-19} coulombs
I_d = the diode plate current in amperes
B = the bandwidth in cps
I_{noise} = the rms noise current.

If this current is made to flow in a resistor of R ohms, the voltage developed across the resistor is

$$E_{\text{noise}} = R\sqrt{2eI_dB}. \qquad (19)$$

Thus the resistor may now be considered as a constant-voltage noise source E in series with a resistor R, from which the available power[4] is

$$P_{\text{noise}} = \frac{E_{\text{noise}}^2}{4R} = \frac{eI_dBR}{2}. \tag{20}$$

The noise available at the receiver output in the absence of any added diode noise is

$$P_{0_1} = NKTBG \tag{21}$$

where

G = the available power gain of the receiver

N = the noise factor of the receiver (N here is a power ratio. It may be converted to decibels if desired)

P_{0_1} = the receiver noise power with the diode noise source connected but no diode plate current; that is, no noise contribution from the diode.

If the diode noise is now added to the receiver input and increased until the receiver noise output is doubled, that is, increased to $2P_{0_1}$, then the contribution due to the added diode noise P_{noise} is P_{0_1}. For this condition, the added noise-output contribution of the diode is

$$P_{0_2} = P_{0_1} = \frac{eI_dBR}{2}G \tag{22}$$

where P_{0_2} is the added output noise power due to the diode plate current. Equating (21) and (22),

$$N = \frac{e}{2KT} I_dR \tag{23}$$

and substituting the previously given value of $e = 1.59 \times 10^{-19}$, $K = 1.37 \times 10^{-23}$, and $T = 300$, gives

$$N = 19.4 I_dR. \tag{24}$$

Fig. 9 shows a schematic diagram of the diode noise source for use on the 250-ohm line feeding the antenna system. The one-fourth-wave tubing supports for the diode assembly serve as isolating elements to feed filament and plate voltages to a special tungsten-filament diode. The whole assembly is placed on the transmission

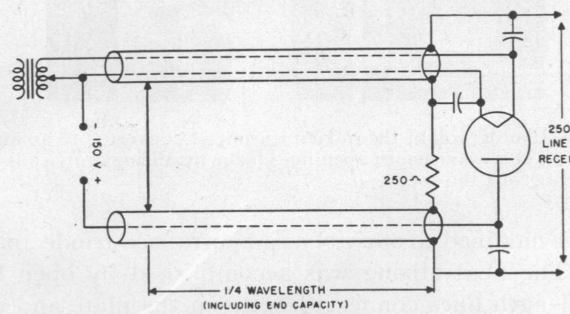

Fig. 9—Schematic diagram of diode noise generator for noise-factor tests.

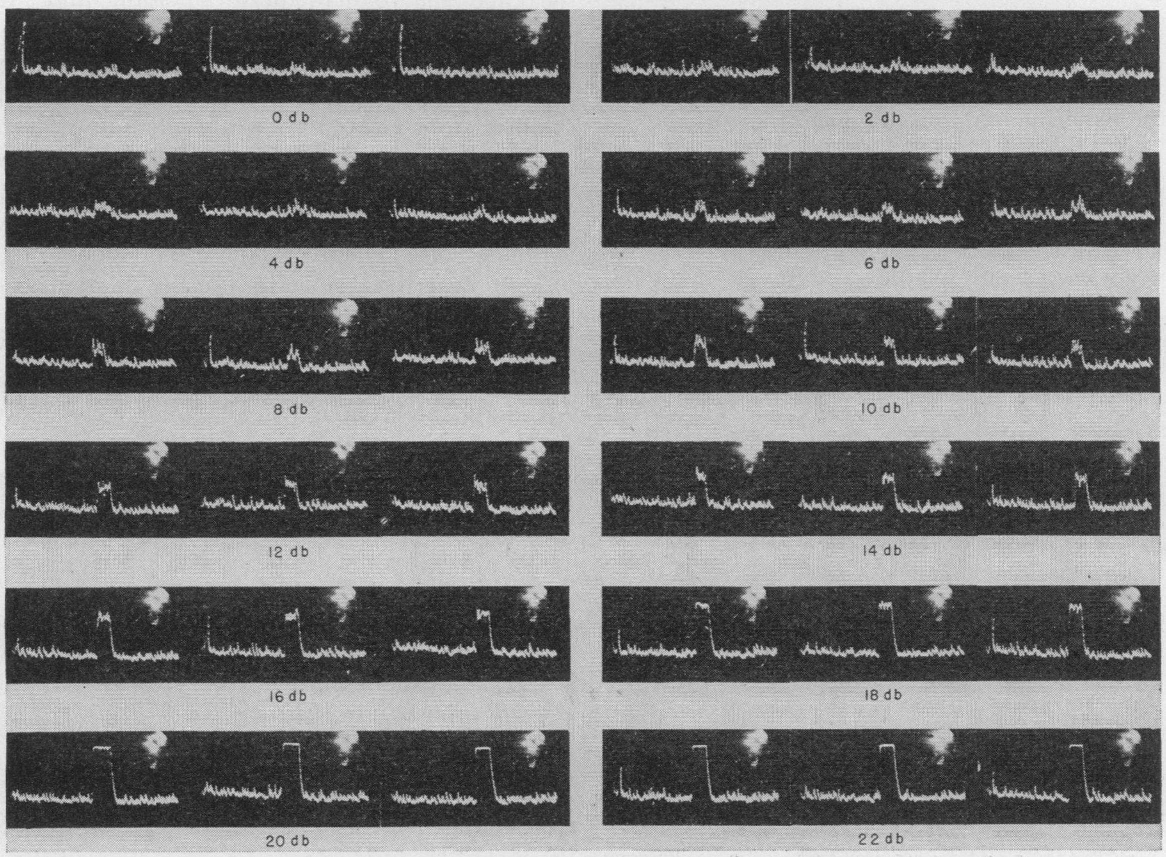

Fig. 10—Test calibrating signals in the moon-radar receiver. Levels given are db with respect to receiver equivalent-input-noise level.

line, and a short circuit placed on the line to the antenna at a distance of one-fourth-wavelength from the diode, so that the 250-ohm diode load replaces the antenna impedance. The diode current is then raised until the receiver noise power output, as indicated by a thermocouple connected *before* the final detector, is twice the output for no diode current. Substituting $R=250$ in (24), the noise factor is

$$N = 4.85I_{\text{ma}} \tag{25}$$

where I_{ma} is the diode plate current in milliamperes.

The effect of a pulsed signal of any given intensity may be simulated by injecting a signal at one of the intermediate frequencies, and by means of a thermocouple at the receiver output, referring the level to the receiver input. This injection can be most conveniently done at the 180-cps intermediate frequency. A series of test signals of this kind is shown in the oscilloscope photographs of Fig. 10. These photographs show the test pulses on the 4-second sweep of the oscillosope, and the decibel levels shown are with respect to the noise output of the receiver. Referred to the receiver input, if the noise factor is 3.2, that is, 5 db, then the 0-db signal in the photo corresponds to an input signal of -149 db with respect to 1 milliwatt, the 2-db signal to -147 db, etc. These photographs facilitate estimation of the intensity of returns from the moon.

The receiver frequency can be easily adjusted by connecting the vertical deflection plates of an oscilloscope to the receiver output and a standard audio oscillator to the horizontal deflection plates. (See Fig. 7.) The small leakage from the transmitter produces a frequency in the output circuit which is the difference between the transmitter and receiver frequencies, $\pm$ the 180-cps final intermediate frequency. Thus, for example, if it is desired to receive on a frequency 200 cps higher than the transmitter frequency, the audio oscillator is set to 180 plus 200 or 380 cps, and the final receiver crystal oscillator is adjusted until a stationary circular pattern is obtained on the oscilloscope (care must, of course, be taken that the upper or lower heterodyne as required be chosen).

The transmitter output power is measured by a crystal detector used with a directional coupler.[9] This detector operates in conjunction with a calibrated amplifier and oscilloscope arrangement to give an oscilloscope deflection which is a measure of the transmitter power on each pulse. The directional coupler used is also capable of measuring power reflected back down the transmission line from the antenna, and so may also be used to determine the SWR of the transmission line.

Directional couplers for open lines and at this relatively low frequency are rather unusual, and the one used here will be briefly described. A photograph of the coupler is shown in Fig. 11. It consists of two one-fourth-wave shorted sections A and B which are tapped onto the main open 250-ohm transmission line at two points C and D which are separated by one-fourth wavelength.

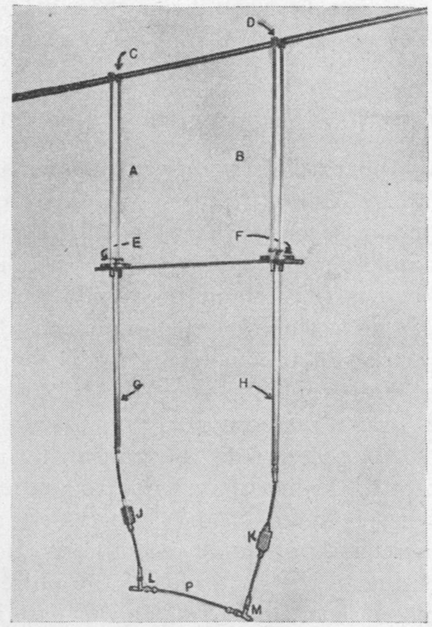

Fig. 11—Photograph of the directional coupler used for power measurement on the moon-radar system open transmission line.

On each of these a 50-ohm unbalanced line is tapped at a point (E and F) near the shorted end, so that approximately 1/30 of the voltages on the 250-ohm line at points C and D are applied to the respective 50-ohm lines. The 50-ohm lines are provided with "bazooka" one-fourth-wave skirts (G and H) to provide a balanced to unbalanced connection. The 20-db 50-ohm pads (J and K) are provided to furnish additional attenuation and assure proper termination of the 50-ohm lines. L and M are the two output points which are connected by the auxiliary one-fourth-wave line P (which is shorter physically than the open line one-fourth-wave section CD because of the dielectric material used in the 50-ohm line). It will be seen that energy extracted from the line at C travels to point L through a path of the same length as the energy extracted at point D which travels to point M.

Now, considering the functioning of the coupler, it will be seen that, of the energy traveling along the main transmission line, say in the direction C to D, small and (very nearly) equal fractions are extracted by lines A and B. These two fractions of the energy reach point M by equal path lengths and so are in phase at this point, and reach point L by path lengths which differ by one-half wavelength and so cancel (except for a small residue which exists because the energy available at D is less than that at C by the amount which has been extracted at C). Similar reasoning for the energy traveling along the main line in the direction from D to C will reveal that the extracted fractions add at L and cancel

[9] W. W. Mumford, "Directional couplers," Proc. I.R.E., vol. 35, pp. 160–165; February, 1948.

at M. Thus, very closely, a measurement at M is a measure of the power being transmitted along the main line in the direction CD, and a measurement at L is a measure of the power being transmitted along the main line in the opposite direction. From these measurements the net power and the SWR may be determined.

Reflections Obtained from the Moon

With the apparatus in somewhat cruder state than described above, echoes from the moon were first obtained at moonrise on January 10, 1946. Oscilloscope deflections and an audible tone pulse in the loudspeaker connected across the 180-cps if amplifier were easily perceptible. One of the earliest photographs, that of an echo at moonrise on January 22, 1946, is shown in Fig. 12. In this photograph the sweep is that of a conventional type-A radar oscilloscope; that is, the sweep starts at the left of the screen with the transmitter pulse (not visible except for a disturbance due to the mechanical transmit/receive switch) and progresses uniformly across the screen. At about $2\frac{1}{2}$ seconds a vertical deflection occurs due to the reception of the pulse returned from the moon. The total sweep in this case is slightly in excess of 3 seconds.

Unfortunately, the project has been beset by numerous apparatus difficulties and the fact that, because of other work, it has been difficult to concentrate effort on it. As a result, the data which can now be reported are still fragmentary, but some useful qualitative conclusions can be drawn.

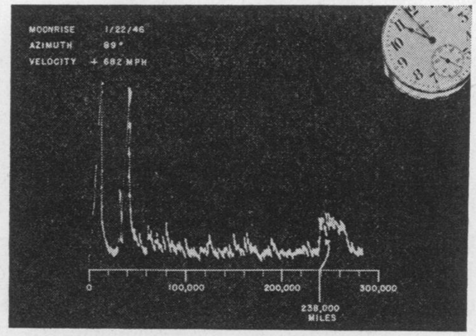

Fig. 12—Oscilloscope traces of moon radar echo observed during rising of the moon, January 22, 1946.

As previously indicated, observations have so far been limited to moonset and moonrise because of the limitations of the antenna structure. In general, results have been poorer at moonset than at moonrise, presumably

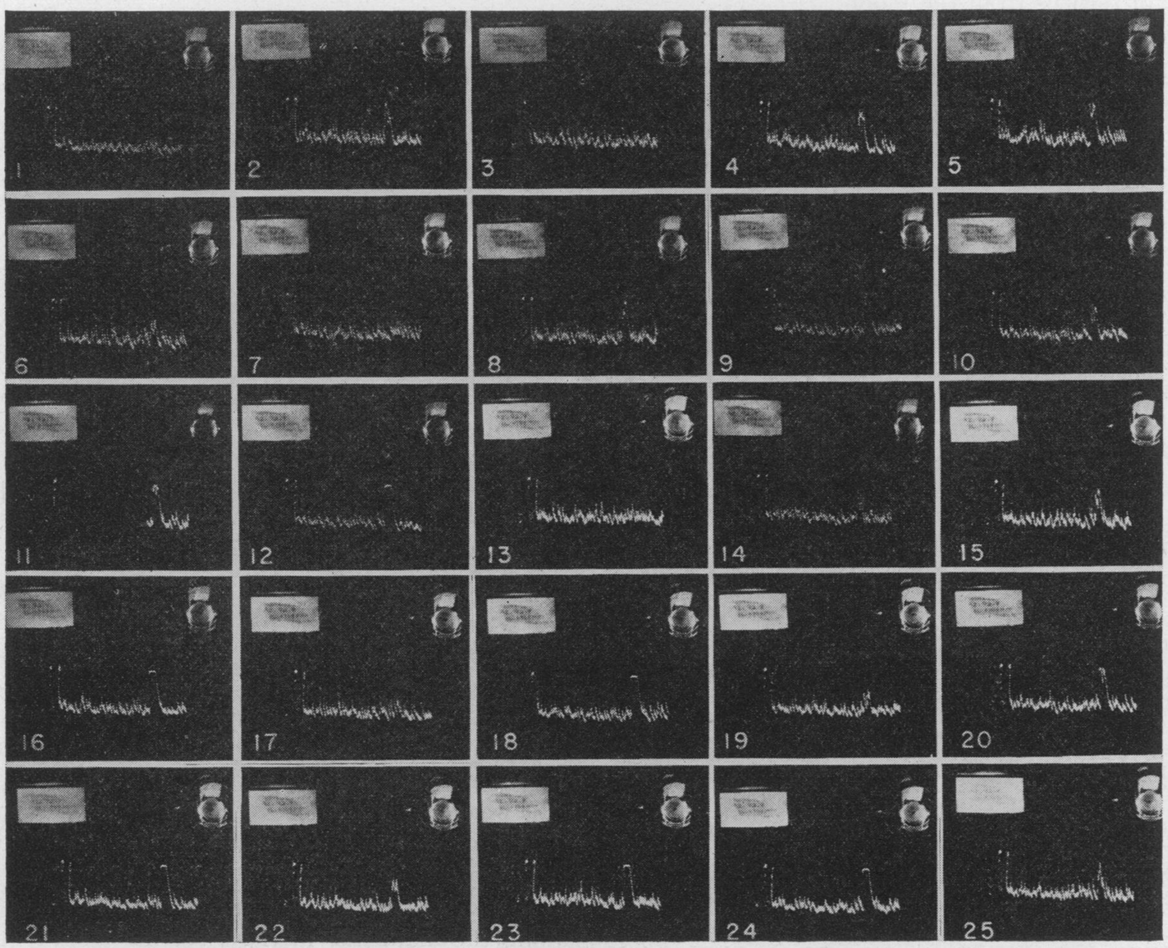

Fig. 13—Twenty-five successive moon echoes. The time interval between photographs is approximately 4 seconds.

because the antenna looks over land at moonset, under which condition the effect of ground reflection is probably less effective than when, as at moonrise, the antenna looks over the sea. So far, no significant correlation has been observed between echo effects and the time of day at which observations must be made, weather conditions, and the azimuth position of the moon. Undoubtedly, however, there are relations involving at least some of these factors, and it is hoped that eventually some precise information of this kind may be obtained. For example, it has been noted that the relation between the time on a particular day at which the first echoes were received differs from the time of optical moonrise by an amount which varies by several minutes from day to day. Frequently echoes are received before optical moonrise. This is undoubtedly due in part to changes in atmospheric refraction and attenuation from day to day, and in part to changes in the radiation pattern in different directions. Frequently, even with the equipment to all appearances in satisfactory working order, no echoes are observed.

One of the most striking effects noted has been a large, rapid variation in the signal strength observed. These changes occur much too rapidly to be accounted for by the coarse lobe structure of the antenna. In Fig. 13 is a sequence of 25 successive sweeps with the echoes in successive pictures separated by about 4 seconds. It will be seen by comparison between the test signals of Fig. 10 and the actual echo signals of Fig. 13 that, in the fourth line of echo signals, pictures 16 to 20, the decibel levels are about as follows:

Picture No. (Fig. 13)	*Decibel Level*
16	20
17	2
18	20
19	6
20	14

These are separated in time by only about 4 seconds, which corresponds to a change in elevation of the moon of about 0.016 degree, which is a very small amount in terms of the beam width, or even the width of the lobes into which the beam is broken by the ground reflections. This rapid variation in signal level conceivably could be due to rapid bending or absorption of the path through the atmosphere, and this seems reasonable and probable in view of the fact that on numerous occasions, when the equipment appeared to be working in a completely satisfactory manner, no echoes were obtained. Another possibility is that libration of the moon (rotation of the moon with respect to the point on earth from which it is viewed), might account for such variations. At moonrise or moonset this rotation reaches a maximum rate of 3 degrees per day. This corresponds to a (differential) velocity at the outer edge of the moon of about 1 meter per second. That is, in 4 seconds, one edge of the moon moves 4 meters closer to and the other edge 4 meters away from the observer. If large contributions to the particular reflection happen to come from large areas near the edge of the moon, this movement might easily cause large variations in signal strength. This view, however, is not consistent with the concept of random roughness of the moon, and is one of the questions which it is hoped future work will answer. An effort was made particularly to observe variations in signal strength on a day when it was calculated that the rate of libration in both latitude and longitude would be at a minimum, but no conclusive result was obtained.

It should be noted that the photographs of Fig. 13 were obtained with a transmitter peak power output of about 15 kw. According to the calculations given previously, this corresponds to a calculated excess system performance of about 30 db. Neglecting transmission-line losses, depolarization, and atmospheric attenuation, the signals received should have a peak power of 30 db above rms receiver noise. From comparison of Figs. 10 and 13 it is seen that moon echoes in excess of 20 db above receiver noise were obtained.

The effects of extraneous noise, both local and cosmic, have been very bothersome, and the effects are difficult to separate. Interference from ignition systems of passing automobiles, neon signs, harmonics, or other interference from other radio operations, and interference from other laboratory operations are among the local sources which have been identified, together with many unidentified disturbances. A 111.5-Mc narrow-band amplifier (about 100 kc wide using cavity resonant circuits) is included in the rf amplifier system to reject strong near-by signals which might cause cross-modulation difficulties in later stages, but does not aid in eliminating the interference from disturbances within the finally used pass band.

Noise from the sun has been observed in the form of a considerable increase in output noise level, superimposed on which are large bursts of noise of shorter duration. A comparison device in which the antenna connection of the receiver is periodically switched between the antenna and a resistor, with the output of the receiver being synchronously switched from one side to the other of a balance device, has been used as an extremely sensitive means to measure such noise. The resistor is so arranged that the known noise current from a temperature-limited diode may be passed through it to permit calibration of the system.

The noise from the sun has been observed as the sun rises and sets, and the maxima and minima of the antenna lobe structure are discernible as the sun passes through the beam. Observation of the echoes from the moon is usually impossible when the sun is in the same direction as the moon at the time observations must be made. It is outside the scope of this paper to discuss this noise question in more detail, but it is mentioned as one of the difficulties encountered.

From the time when the first moon-radar experiments were performed there appears to have been a progressive increase in the external noise level to an extent that it is frequently difficult or impossible to discern radar echoes from the moon because of the high noise level. Whether the increase has been local or cosmic is difficult to determine, because of the wide antenna beam width and the fact that the present antenna cannot be raised in elevation.

Use of the Moon in Communication Circuits

One of the reasons for initiating the moon-radar study was the possibility that the moon might be used to reflect communication signals from one point on earth to another. It is outside the scope of this paper to consider this matter in extended detail, but it will be briefly discussed in the light of the moon radar experiments.

Analytical consideration of the question indicates that communication in this manner is subject to limitations and difficulties which rather discourage its consideration except in extreme situations. Some of these considerations are:

(a) Unless a very narrow-beam-width transmitting antenna is used, the probable multiplicity of reflections from the moon would make necessary complicated apparatus to obtain a wide-bandwidth communication channel.

(b) Unless narrow-beam-width antennas are used, the power requirements are very large.

(c) If narrow-beam antennas are used, the construction of them is difficult, and a tracking problem arises.

(d) A moon-communication circuit is only usable at such times as the moon is simultaneously visible from both receiving and transmitting points.

(e) The long transmission travel time would be objectionable in some cases.

The experiments reported above indicate that some of these considerations are very important, and that there are additional considerations that should also be mentioned.

(f) Examination of Fig. 13 indicates that the attenuation of the earth-moon-earth path is subject to rapid and large variations.

(g) If the attenuation variation mentioned in (f) is due to rapid bending of the path, the problem of using narrow-beam antennas becomes even more difficult.

(h) During periods when the sun and moon both fall in the beam width of the receiving antenna, the noise contribution of the sun will be very high. At other times there may be some contribution of noise from the sun by reflection from the moon, but this will probably be negligible. (It was not identifiable in the moon-radar experiments.)

Thus, while the moon-radar experiments are in themselves a demonstration of the fact that a communication link using the moon as a passive reflector is definitely possible, such a system is subject to difficulties and limitations which make its extensive and general use unlikely, as viewed at present.

In connection with the subject of communication circuits involving the moon, it is interesting to consider the possibility of a one-way radio circuit to the moon. Equation (1) gives the power flow per unit area at the moon at a range R. If a receiving antenna of area A_R' were placed on the moon, it would intercept a power P_R' given by

$$P_R' = S_0 A_R'. \tag{26}$$

If G_R' is the gain of this receiving antenna, the relation of G_R' and A_R' is given in (4b). Combining (1), (4b), and (26) gives the gain from the transmitter antenna terminals on earth to the receiver antenna terminals on the moon as

$$\frac{P_R'}{P_t} = \frac{571 G_t G_R'}{R^2 F^2}. \tag{27}$$

It should be remembered that the antenna gains are with respect to an isotropic antenna, R is in meters, and F is in megacyles.

To evaluate the above figures, consider a nondirectional transmitting antenna (gain of 1) and a simple receiving antenna with a gain of 10, at a frequency of 100 Mc. For this case and the range of 4.07×10^8 meters, $P_R/P_T = 3.45 \times 10^{-17}$, or an attenuation of 164.6 db.

Now consider a standard FM broadcast station of 50 kw operating on 100 Mc and an FM receiver operating with a bandwidth of 200 kc. From curve 1 of Fig. 3 the thermal input noise to such a receiver is -121 db with reference to 1 milliwatt and, allowing a receiver noise factor of 5 db, the equivalent input noise is $-121+5 = -116$ db. If it be assumed that a signal 10 db greater than this might give usable FM reception, a -106-db signal would be sufficient for operation of the receiver. The 50-kw transmitter output corresponds, from curve 2 of Fig. 3, to $+77$ db with respect to 1 milliwatt, so the spread between transmitter and receiver is 183 db against the path attenuation of 164.6 db. Thus it is evident that, even without an extraordinary antenna system, an FM broadcast station on earth could be readily received on the moon. In fact, this calculation shows that even a 1-kw FM station could probably be detected. If antennas similar to those used in the moon-radar experiment were used at each end of the circuit, the 164.6-db path attenuation would be reduced to about 127 db. If the path length were then increased to 50,000,000 miles, the attenuation would only be increased by 46 to 173 db, a figure still within the 183-db spread of the 50-kw 200-kc bandwidth FM system. Thus, using only presently developed radio equipment, Mars and Venus also are at times within reach of a 50-kw FM station on the earth, and vice versa.

These speculations, of course, omit consideration of the fading and attenuation observed in the radar experiments and which might make reception difficult. However, in the one-way path considered here, this should be less serious than in the two-way radar path, and if it ever becomes practical to place a nonpassive relay station on the moon, possibly with means for regenerating the signal shapes, earth-point to earth-point-communication via the moon might look much less discouraging.

General Conclusions

The work so far has indicated that, under some conditions, a radio signal can be transmitted from the earth to the moon, be reflected, and again be detected on the earth, and that the character of this path changes materially from time to time, both rapidly and on a long-time basis. The most important observations concern the interesting questions which are raised and which it is hoped future research and experiment will answer.

More detailed information concerning the precise nature of the reflection at the moon should be obtained by use of a pulse narrower than the 0.0116 second required for travel across the moon and back. Fig. 18 shows that with a pulse of 1,000 microseconds the peak return would only be down about 8 db, and the increased bandwidth required for a 0.001-second pulse over the 50-cps bandwidth used in the experiments reported here would increase the receiver noise contribution by 13 db, representing a degradation in system performance of 21 db. Fig. 13 shows just about this excess in system performance for the present equipment arrangement. Thus, with some increase in transmitter power and a compromise pulse width of perhaps 2,000 microseconds, under the best conditions it should be possible to get some indication of return pulse shape with equipment generally similar to that described in this paper, except with wider intermediate-frequency and video bandwidth in the receiver.

It would be desirable to obtain observations of moon echoes over extended periods, not only with a horizontally directed antenna as described, but also with an antenna capable of movement in all directions. The work should also be extended to other frequencies.

Fig. 13 shows the need for an arrangement for transmitting pulses in more rapid sequence so that the effects which occur during the 4-second intervals between the pulses in Fig. 13 can be observed. The effects of noise from the sun and other cosmic sources, and its effect on these operations, should be further investigated.

It is hoped that the plans which have been made for investigating these and other questions can be carried to completion and the results published in a later paper.

Acknowledgments

The authors particularly acknowledge the help of H. D. Webb and J. Mofenson for their extended work in the conduct of this experiment and in the review of this paper, and the contribution of Walter McAfee in discussions of echoing-area problems and review of this paper. Some of the other individuals who made substantial contributions to the work were J. Ruze, O. C.Woodyard, A. Kampinsky, J. Corwin, C. G. McMullen, W. S. Pike, F. Blackwell, H. Kaufman, R. Guthrie, H. Lisman, J. Snyder, G. Cantor, and A. Davis.

APPENDIX

Effect of Reflection from Moon on Shapes and Amplitude of Radio-Frequency Pulses

The shapes and intensity of echo pulses from the moon can be derived on the basis of the assumption that the moon looks, for radio waves in the frequency range considered, like a uniformly illuminated disk. Consider first the situation for a pulse of duration ΔT, which is small compared to the time required for a wave to travel twice the distance equal to the radius of the moon (that is, the time for a round trip over a path length equal to the radius of the moon). If ΔT is the pulse length, the range interval in miles over which the reflection is obtained is $\Delta X = \Delta T/2 \times 186{,}000$.

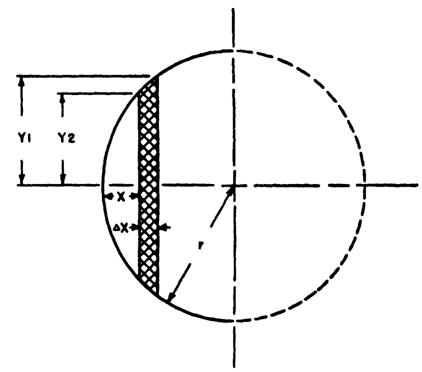

Fig. 14—Short radar pulse passing across the moon.

Referring to Fig. 14, the projected area active in producing a reflection for a pulse of width ΔX is the difference in the circles having radius of y_1 and y_2. That is,

$$\Delta A = \pi Y_1^2 - \pi Y_2^2. \tag{28}$$

By the geometry of Fig. 14,

$$Y_1^2 = r^2 - (r - X - \Delta X)^2 \tag{29}$$

and

$$Y_2^2 = r^2 - (r - X)^2. \tag{30}$$

Combining (28), (29), and (30)

$$\Delta A = 2\pi\Delta X\left(r - X - \frac{\Delta X}{2}\right) \tag{31}$$

and, for the condition stated, that ΔX is small compared to $r - X$ except for the very end of travel, where $r \approx X$, the $\Delta X/2$ may be ignored, leaving

$$\Delta A \approx 2\pi\Delta X(r - X). \tag{32a}$$

In Fig. 15 this is plotted and shows the shape (in terms of *power*) of the returned pulse (observed from a great distance) as the radiated pulse (measured from its trailing edge) passes over the moon. The manner of rise to the peak value $2\pi r\Delta X$ has not yet been considered, but obviously it rises to this value in the time ΔT in some such fashion as shown in the dotted portion of Fig. 15.

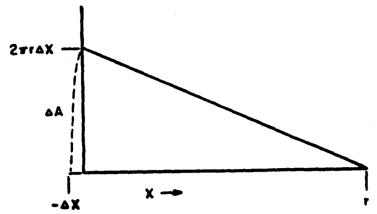

Fig. 15—Shape of return pulse from the moon for very short transmitted pulse. (Curve is on a power basis.)

The manner of rise will be considered in more detail in the analysis of the effect on a pulse wide compared to the moon.

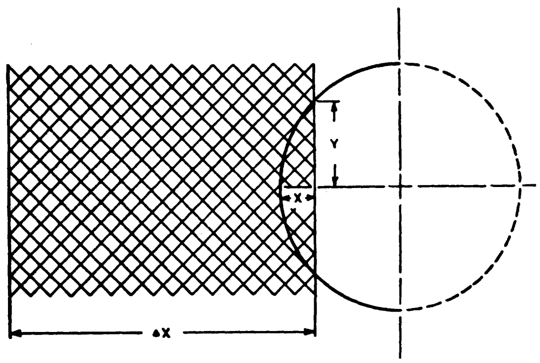

Fig. 16—Long radar pulse passing across the moon.

Consider a pulse such that ΔX is larger than r (see Fig. 16). Now, as the leading edge of pulse starts across the moon, the power returned varies in proportion to the area illuminated—that is, the area illuminated when the leading edge is at point X is

$$A_X = \pi(2rX - X^2). \tag{33}$$

This will continue until X reaches the value r when the pulse levels off to its peak value, corresponding to $A = \pi r^2$, at which level it continues until the trailing edge of the pulse reaches the edge of the moon at which time the power level starts to decrease. The power returned at the time the trailing edge is at position X' measured in the same co-ordinate as X is proportional to the total disk area less the portion left unilluminated, or, now using (33) for the unilluminated area

$$A_{X'} = \pi(r^2 - 2rX + X^2). \tag{34}$$

A plot of the effective area in terms of time which is the power shape of the returned pulse is given in Fig. 17, based on (33) and (34) and the above considerations. In this figure, distances have been converted to a time basis to show the extent of pulse broadening.

For values of pulse width $\Delta T'$ intermediate between ΔT very short and ΔT larger than 0.0116 second, the pulse will rise along the initial rise curve of Fig. 17 to a value given by analogy to (33) as

$$A_{\max}' = \pi(2r\Delta X - \Delta X^2) \tag{35}$$

and then drop linearly for a period of (0.0116 second $-\Delta T$) as shown in Fig. 15. At this point the leading edge of the pulse has reached the center of the moon, and the trailing edge is at $r - \Delta X$ so that the power contributing area has reached an intermediate value given by substituting $r - \Delta X$ for X in (34) or,

$$A_{\text{int}}' = \pi(\Delta X)^2 \tag{36}$$

after which the value then drops to zero as along the main decay curve of Fig. 17. This action has been dotted in on Fig. 17.

Fig. 18 facilitates estimation of the maximum value of area effective for a particular value of pulse width in terms of the area which would be effective if the pulse were wide enough to utilize the full moon. The rising portion of the curve of Fig. 4 has been replotted in Fig. 18 to show area (or echo power) in terms of db relative to power from full area and microseconds transmitted pulse length.

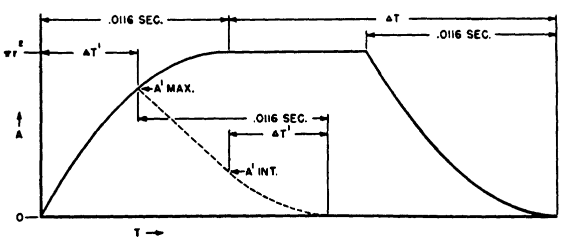

Fig. 17—Shape of return pulse from the moon for very long or fairly long (dotted curve) transmitted pulse. (Curves are on a power basis.)

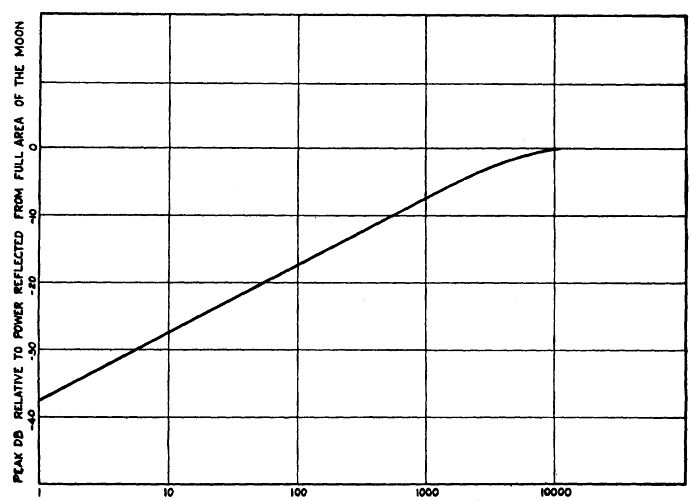

Fig. 18—Peak power reflected from moon as a function of pulse width, in terms of peak power reflected for a very long pulse.

Thus, for example, the peak power level of echo from a 1-microsecond transmitted pulse of a given peak power would be expected to be about 38 db below that of the echo from a 0.05-second transmitted pulse of the same peak power.

In all of the above, the effect of the back side of the moon is ignored, since, at the "line-of-sight" frequencies considered here, it is in a "shadow" region.