RADIO COMMUNICATION VIA THE MOON

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ABSTRACT

Radio reflections from the moon were first detected (in the United States and Hungary) in 1946 using VHF radars constructed from military radar equipment. These and subsequent observations at HF (in Australia) and VHF (in England) revealed that the echoes were subject to both rapid and slower fading. By 1954 it had been established, by means of experiments at Jodrell Bank, that the slower fading was caused by the rotation of the plane of polarization of the radio waves in the earth's ionosphere—the so-called Faraday effect. The rapid fading was believed to be caused by interference between the many scattering centers on the surface of the moon, whose relative distance from the earth is constantly changing owing to its libration. Studies of this fading at Jodrell Bank in 1956 confirmed this theory and revealed that most of the power in the reflected signals arose from scatterers lying near the center of the visible disk. The range extent of these returns was less than 1 ms, that is, much less than the full radar depth of the moon (approximately 10 ms). Accordingly, it was recognized that radio waves modulated by speech (or music) could be reflected from the moon and remain reasonably intelligible. Subsequent experiments, supported by the Pye Company, explored this form of communication as a possible alternative to overseas HF broadcasting.

In 1957 it was disclosed that the U.S. Navy had independently reached the same conclusions through experiments in which short pulses reflected from the moon were examined for their range spread. The Navy had initially classified these findings. Subsequently, the Navy began construction of a 600-ft-diameter, fully steerable radio telescope to observe the moon and thereby eavesdrop on Soviet military radio nets by monitoring any reflected signals. This project was never completed; the cost was grossly underestimated, and the advent of satellites gave the U.S. a more reliable way of eavesdropping on the Soviets. For similar reasons, the use of the moon as a passive reflector for overseas broadcasting never developed. Geostationary communication satellites provided a far better means of delivering this service.

INTRODUCTION

From the vantage point of 1994 it seems incredible, but for a brief period around the late 1950s there was some serious consideration of using the moon as a passive reflector of radio waves for transoceanic communications. We now live in a "global village" created primarily through the advent of TV, and its worldwide distribution via communication satellites. It is easy to forget, however, that this came into being only recently. Prior to 1926, there were no voice circuits across the Atlantic—only telegraph cables. During World War II, Churchill and Roosevelt conversed over radiotelephone circuits, which were not at all secure. Coaxial cables capable of supporting voice communication were laid across the Atlantic after the war, but as late as 1965, when the first INTELSAT communications satellite was launched, there were only 300 such circuits. It is not surprising, therefore, that before that time, there was interest in other ways of spanning the oceans. These included reflecting signals off large balloons placed in orbit about the earth, or copper wires and, for a brief while, the moon.

My involvement in these matters arose as a consequence of going to the University of Manchester's radio astronomy research station at Jodrell Bank in 1954 for graduate work. There I was assigned the task of studying the moon by radar to ascertain its scattering properties, and using the moon to reflect radio waves back to earth to try to determine how many electrons were in the earth's ionosphere. Herein, only the first of these efforts is reviewed.

PRIOR WORK

The exploitation of radar during World War II led immediately thereafter to two attempts to reflect radio waves off the moon using an apparatus largely constructed from surplus wartime radar equipment. Z. Bay in Hungary succeeded in detecting echoes, but was obliged integrate many echoes (by applying the receiver output voltages to a set of electrolytic cells which released gas) to establish their presence. DeWitt and Stodola (1) in the United States employed a more powerful radar which allowed them to see individual pulse returns on the display. They found considerable variation in the amplitudes from pulse to pulse, and on some occasions the echoes were absent altogether, though the radar appeared to be operating properly.

These results spurred Grieg et al. (2) to examine the possibility that the moon could be used as a passive reflector in a radio relay circuit between continents. Two concerns arise in such a scheme. First, the radio system must be capable of overcoming the large loss of intensity in traversing the approximately 384,400 km to the moon and back. Owing to the spherical expansion of the waves from any antenna, the flux density falls with the square of the distance R from the source. Thus, in the two-way journey to the moon and back there is a reduction of a factor $\sigma/(4\pi R^2)^2$, where σ is the scattering cross section of the moon. Even if the moon were a perfect reflector, this loss would be 2.78×10^{-24} m^2 or -235.6 dB. In actuality, the moon reflects only about 7 percent of any incident meter-length radio waves, so the overall loss is closer to -247 dB. Therefore, a fairly powerful transmitting station is required with a directive antenna capable of beaming the energy toward the moon, and the receiving station must have a similar antenna. Waves shorter than about 5 m are required to reliably penetrate the earth's ionosphere, and at the time Grieg *et al.* (2) wrote their paper, transmitters suitable for the kind of service they contemplated could be built at high power only for wavelengths longer than several centimeters. Accordingly, these considerations bounded the region of the radio wave spectrum in which such a relay service might be contemplated.

The second issue that Grieg *et al.* (2) considered is the way in which the moon might scatter the incident wave. They speculated that some of the fading observed by DeWitt and Stodola may have been caused by the presence of multiple scatterers on the lunar surface. These would contribute reflections which were sometimes constructive and at other times destructive. The critical issue was the extent in range of these scatterers.

When viewed optically from the earth at full moon, the lunar surface is approximately uniformly bright. That is, the limbs are about equally bright as the center despite the fact that sunlight is there incident at a grazing angle. Were the moon to scatter radio waves in the same fashion, the echoes would be returned with a spread in delay of 11.6 ms. This would cause any modulation on radio waves with a frequency of greater than about 100 Hz to be destroyed. There the matter was left until further (secret) work was undertaken in the U. S. and my work began at Jodrell Bank in 1954.

Progress was made, however, on understanding the nature of the deep echo fading. Kerr and Shain (3) in Australia performed experiments using a shortwave broadcast transmitter and were able to distinguish between a short period fading of the echoes (presumed to be of lunar origin) and slower overall large changes in the strength of the echoes, which they suggested was of terrestrial ionospheric origin. This was confirmed later at Jodrell Bank by Murray and Hargreaves (4), who recognized that plane-polarized radio waves traversing the ionosphere have their plane of polarization rotated depending upon the number of electrons lying along the path. This is known as the Faraday effect. The amount of rotation is doubled on the return path. Thus, in the course of the day as the ionosphere builds up or decays, there will be periods when there is 90° difference between the polarization of the waves and the receiving antenna (see also Browne *et al.* [5]); the echoes will then be unobservable.

THE JODRELL BANK EXPERIMENTS

Radar reflections from the moon were successfully obtained at Jodrell Bank by Murray and Hargreaves (4) using a radar they constructed which operated at 120 MHz at a power of about 3 kW for pulse lengths of 30 ms. The antenna was an array of dipoles (Figure 1) that could be phased to alter the elevation of the beam. The array consisted of 10 elements, each of which comprised a reflecting screen tilted back at 45° and placed in line behind the previous one. Each screen was one wavelength wide and four wavelengths long and was illuminated by two rows of full-wave dipoles. The physical aperture was 250 m^2, and the overall efficiency was between 60 and 70 percent. The antenna allowed the moon to be seen at transit (i.e., due south) for about an hour each day for about 2 weeks each month (when the moon is highest).

The echoes obtained with this equipment were photographed from an A-scope display. In Figure 2, which illustrates both the slow- and long-period fading, the transmitter was pulsed every 1.8 s. Measurements of the correlation between the echoes (through the calculation of the noise-corrected autocorrelation coefficient) gave values in the range 0.2 and 0.4, indicating a fading period of the order of 1 s or less. The amplitude distribution was found to match the Rayleigh law (see Figure 3), indicating that a large number of scatterers contributed to the returns (i.e., the lunar surface did not offer one dominant reflecting region).

The correlation between the echoes exhibited small night-to-night variations, which appeared to depend upon the apparent spin rate (called libration) of the moon as seen from earth. Figure 4 illustrates the causes of this. Diurnal libration (having a value at transit of approximately $12 \cos \phi \times 10^{-7}$ rad/s, where ϕ is the latitude of the terrestrial observer) is the largest of these, but at different times in the lunar month, the libration in longitude (having a maximum value of 4×10^{-7} rad/s) can add or subtract.

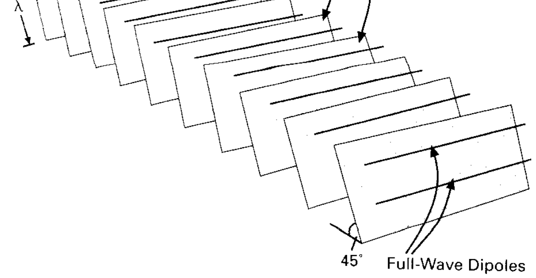


Figure 1: The antenna system employed at Jodrell Bank during 1953–57 to study the moon at 120 MHz.

This apparent spin of the moon can be thought of as giving rise to a Doppler broadening of the echoes. A strip of the lunar surface along the apparent instantaneous spin axis reflects signals without imparting any Doppler shift (see Figure 5), but strips on the approaching hemisphere are Doppler-shifted to higher frequency, while the reverse is true for the receding hemisphere. The maximum Doppler shift f_0 for reflection from the limbs in the Jodrell Bank experiments was given by $1.4 \times 10^6 L_T$ Hz, where L_T is the libration rate, and is on the order of ± 2 Hz. Nowadays, one could measure this Doppler broadening by performing a phase-coherent analysis of the returns in a digital computer, but in 1955 we had no digital computer and had to approach the problem by measuring the echo autocorrelation function—recognizing that this is the Fourier transform of the echo power spectrum. [Strictly, this is true for power-law detectors and is modified in the case of linear detectors; see Lawson and Uhlenbeck (6)].

To explore the correlation of the echoes over intervals shorter than the normal 1.8-s repetition interval, the radar was modified to transmit pairs of 20-ms pulses at intervals of 1/4, 1/2, 3/4, 1, 1-1/4, and 1-1/2 s every 4 s. Figure 6 shows the autocorrelation function measured using these pulse-pairs plotted against the product of the maximum Doppler shift f_0 and the pulse separation t. A sensible single curve is obtained showing that the fading varies with the libration rate L_T and is therefore of lunar origin.

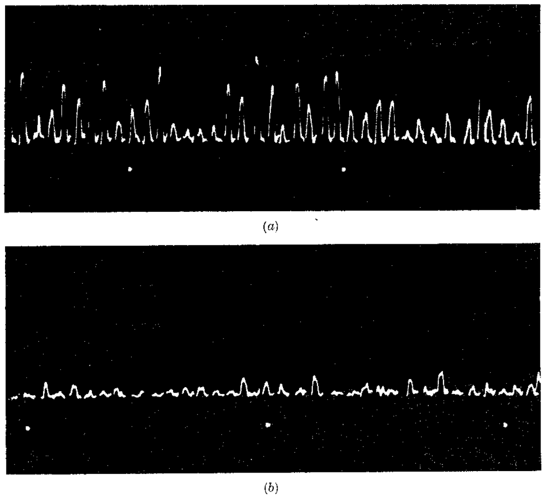


Figure 2: Examples of echoes from the moon observed at Jodrell Bank. Pulses were sent at intervals of 1.8 s, and the pulse-to-pulse variability is caused by multiple reflections from the lunar surface. The overall level difference between the upper and lower panels is caused by the Faraday effect in the earth's ionosphere.

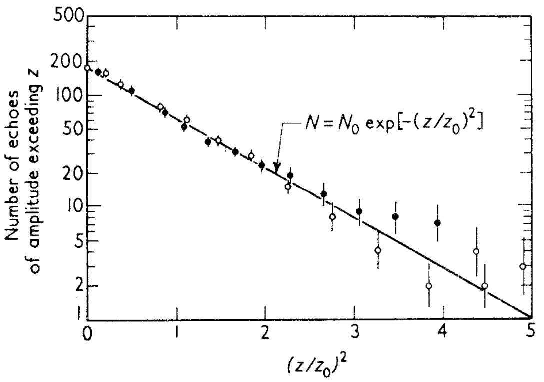
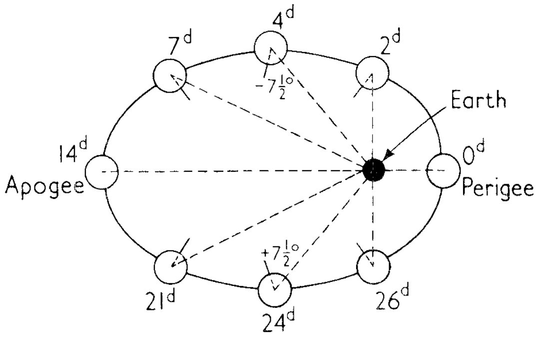
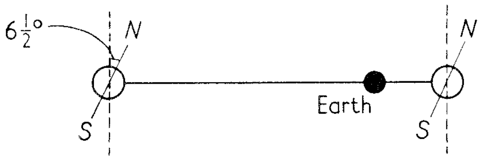


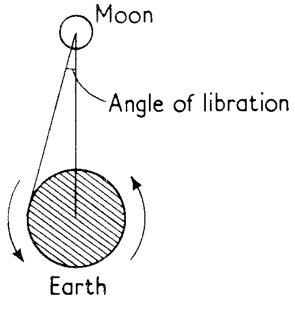
Figure 3: Plot of the number of echoes having an amplitude greater or less than the mean z_0 showing that the distribution fits the Rayleigh law.



(a) Libration in longitude (plan)



(b) Libration in latitude (elevation)



(c) Diurnal libration

Figure 4: Causes of lunar libration: a) Libration in longitude is caused by the elliptical orbit of the moon, which prevents the moon from presenting exactly the same face to the earth, b) libration in latitude caused by the tilt of the lunar spin axis with respect to the plane of its orbit, and c) diurnal libration caused by the motion of a terrestrial observer.

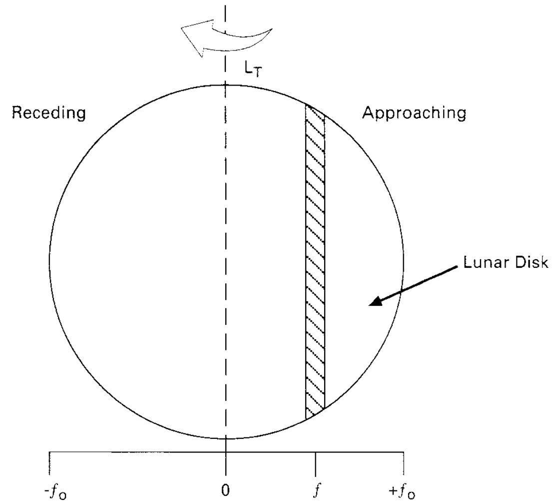


Figure 5 : Doppler broadening of lunar reflections caused by the instantaneous apparent spin (at rate L_T). Strips on the lunar disk parallel to the spin axis contribute the same Doppler shift f.

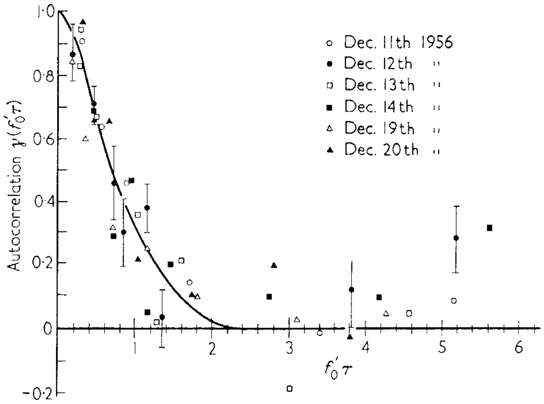


Figure 6: Correlation between pairs of echoes observed at Jodrell Bank as a function of their spacing τ and the maximum Doppler shift f_o (see Figure 5). The solid curve is a fitted Gaussian function.

Figure 7 shows the resulting power spectrum for the echoes obtained by fitting a Gaussian function (exp. $[-1.3\,(f_0t)^2]$) to the observed autocorrelation function. Figure 7 also shows the expected Doppler spectra were the moon to scatter uniformly brightly (Lommel-Seeliger) or according to the Lambert Law (reflected power varies as the cosine of the angle of incidence). It is evident that the bulk of the returns are from a region of the lunar disk having a diameter of the order of one-fifth that of the moon. Evidently, the regions most nearly normal to the ray path return most of the echo; hence, it can be concluded that on the scale of the wavelength employed (2.5 m), the moon appears relatively "smooth." Subsequent, more precise experiments and improved theory permitted the mean surface slope to be determined from radar reflection studies.

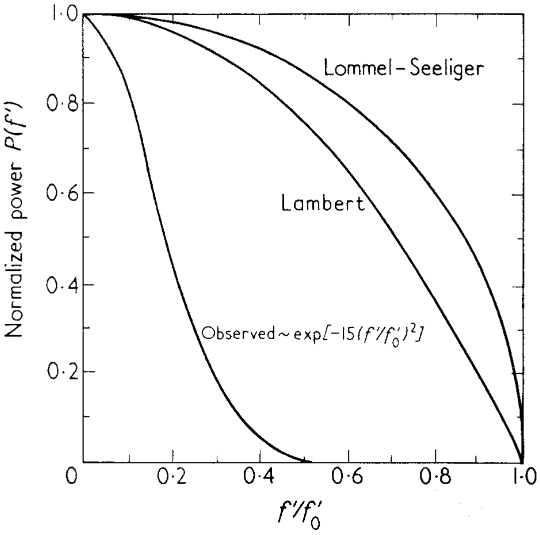


Figure 7: The Doppler broadening of lunar echoes derived from the results shown in Figure 6 compared with a uniformly bright lunar surface (Lommel-Seeliger) and one obeying the Lambert scattering law.

For intervals of the order of 10 times the wavelength λ, this is about 5° for $\lambda = 2.5$ m (7).

To confirm the conclusion that most of the echo was from the center of the lunar disk, experiments were performed with pulses only 2 ms in length (i.e., shorter than the 11.6-ms range depth of the moon). The echoes showed no measurable range delay broadening when contrasted with photographs of the same transmitter pulses leaked into the receiver (8).

The results described herein were presented at an international conference (URSI General Assembly, Boulder, Colorado) in 1957, and provoked the release of then classified results obtained by the U.S. Navy (9). In this work, a very powerful (1-MW) radar operating at 198 MHz was employed, together with a large parabolic reflector. Employing pulses of only 12 µs in length, Trexler (9) reached the same conclusion as I did, namely, that the bulk of the observable return was from the center of the lunar disk and had a limited range extent (of the order of 100–200 µs [see Figure 8]). The implications of this were that amplitude-modulated radio waves reflected by the moon would not be so distorted that all of the intelligence would be removed.

SEQUEL

At Jodrell Bank, we conducted further experiments to examine the bandwidth of a moon-relay circuit using the newly completed 250-ft-diameter radio telescope. These experiments were performed at 162.4 MHz using equipment kindly loaned by the Pye Company of Cambridge.

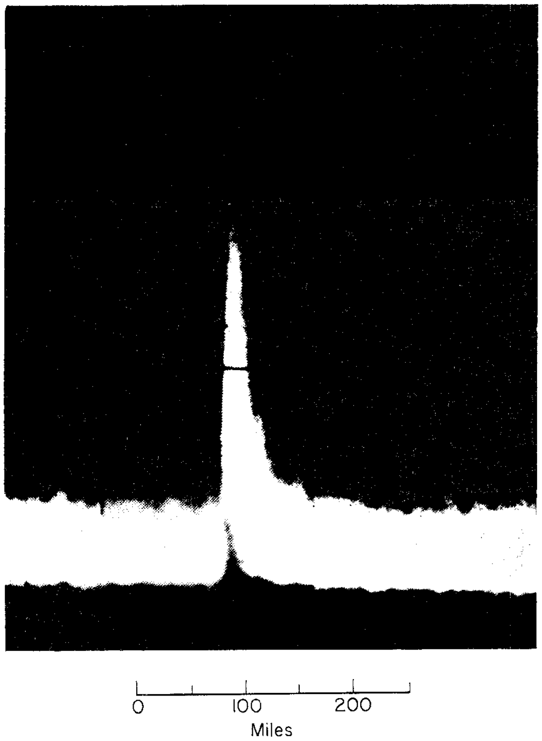


Figure 8: Reflections observed from the moon by Trexler (9) employing a powerful radar using 12-μs pulses. The short range extent confirms that the reflections are largely from the center of the visible disk.

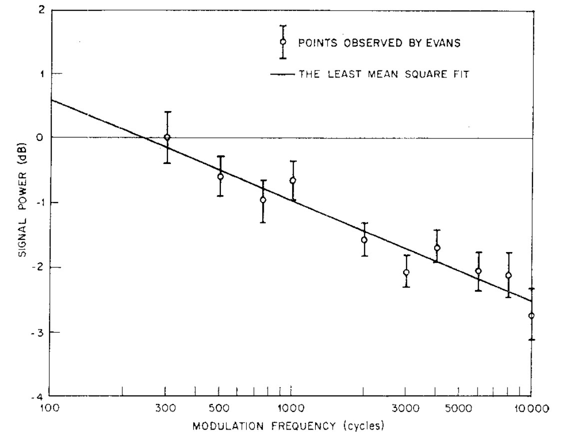


Figure 9: Results obtained at Jodrell Bank showing the average intensity of an amplitude-modulated signal reflected from the moon as a function of the modulation frequency. These results demonstrated that the bandwidth of a moon-relay circuit is adequate for speech.

The idea was to see if the moon could be used for broadcasting overseas more reliably than at HF. Figure 9 shows how average intensity of a single audio tone fell off as the modulating tone frequency was increased (10). These experiments were performed using amplitude-modulated (i.e., double sideband) signals, and no simple theory is available to relate the results to the impulse function for the moon. Had single sideband been employed instead, the correlation between the carrier and the tone sideband would be expected to fall off as the Fourier transform of the impulse response (10). The average intensity should then have fallen off less rapidly than shown in Figure 9, because only one sideband would have been recovered at the receiver and the possibility of the two sidebands interfering (i.e., having different amplitudes and phases) is removed.

These experiments showed that speech-modulated signals were recognizable after reflection from the moon, but that the fading distorted music and made it objectionable. Evidently, a feasible relay system could be constructed if: circularly polarized waves were employed (to overcome the Faraday rotation); suppressed-carrier single sideband were used with modulation frequencies limited to < 3–4 kHz; and a large signal-to-noise ratio, S/N, were provided so that the effects of the rapid fading could be minimized using automatic gain control (AGC). The advent of communication satellites, however, obviated the need for any such scheme. Radio amateurs around the world still use the moon to make contact with one another (using Morse code). They call this mode "earth-moon-earth" (EME), and operate at frequencies between 50 MHz and 12 GHz.

In the U.S., a different idea was conceived for exploiting the radio reflection properties of the moon. Since it was evident that intelligible signals could be received after lunar reflection, it was recognized one could "eavesdrop" on radio transmissions in other countries if a large enough antenna were built and pointed continuously at the moon. Given that considerable military traffic in the USSR was then being passed over radio circuits, the U.S. Navy decided to build a 600-ft-diameter radio telescope to monitor this traffic by lunar reflection. Construction of this telescope was begun at Sugar Grove, West Virginia, in about 1958, but was abandoned in 1963. It fell victim to rising costs and the recognition that satellites could be used to collect this information more reliably.

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