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COMMUNICATION MOON RELAY (CMR)

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Countermeasures Branch
Radio Division

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ABSTRACT

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Two experimental 301-Mc communication circuits utilizing the moon as a reflector were established by the Countermeasures Branch of the Naval Research Laboratory: first a transcontinental circuit from Maryland to California in November 1955, and then a transoceanic circuit from Maryland to Hawaii in January 1956. The primary purposes of these experiments were to determine the ability of the circuits to sustain teletype communications and to derive commensurable parameters for future operational circuits.

Significant findings showed that frequency diversity and circular polarization reduced the inherent fading in the circuit and enabled the successful transmission of the first official navy communication to be passed over the CMR circuit. Frequency-shift-keyed teletype signals were used in this transmission.

Evaluation of circuit parameters has resulted in the formulation of specifications and contracts for the construction of an operational circuit from Maryland to Hawaii.

PROBLEM STATUS

This is a final report on one phase of this problem; work on the problem continues.

AUTHORIZATION

NRL Problem R06-13
Projects NR 417-000, NR 417-001, and NE 071-240

Manuscript submitted April 23, 1957

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COMMUNICATION MOON RELAY (CMR)

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INTRODUCTION

Radio waves from outer space, emanating from the general direction of the Milky Way, were first detected 25 years ago and the science of radio astronomy was born (1). The following years have witnessed a phenomenal growth in this field, accelerated by the technological advances made in radio and radar during World War II. More and better radio telescopes employing receivers of increased sensitivity and a..tennas of greater resolution have been built. In the beginning, the techniques of radio astronomy were receptive, or passive, but as more powerful transmitters, capable of operating in that range of frequencies able to pass through what is known as the "radio window" in the ionosphere were constructed, interest grew in active radar techniques utilizing the moon, the nearer planets, and the sun as reflectors.

Over a decade ago, the successful reception of radar echoes from the moon was reported, nearly simultaneously, in this country (2), Russia (3), and Hungary (4). The search for new areas and methods of communication is a vigorous one and the report of radar contact with the moon coalesced and guided the interests of many experimenters to studies of the feasibility of using the moon as a reflector, or passive relay, in a communication system. The behavior of the moon as a reflector of radio-frequency energy has been discussed as a radar target (5) and has been examined for the two idealized cases of a smooth and a rough sphere respectively (6) with respect to its possible use in a communication system.

The Navy has a paramount interest in the studies of new communication systems to supplement existing ones, particularly in the development of a system which shows promise of freedom from hostile interference (jamming) and magnetic storms, which might make present systems inoperative during crucial periods. Therefore, early in 1950, a program to determine and proportion the several parameters in a moon-radar system was undertaken by the Naval Research Laboratory. These experiments began with the study of signal echoes and circuit attenuation, at a frequency of 200 Mc, by means of 10-microsecond pulse transmissions. Since existing theories (5,6) have, in general, predicted that appreciable energy would be returned from the entire illuminated hemisphere, the pulse echo should be lengthened by the round trip time from the point of initial contact to the edge of the hemisphere which is equivalent to the time required by the signal in transiting a distance equal to the diameter of the moon (approximately 0.011 second). However, echoes obtained during the 10-microsecond pulse experiments did not substantiate this prediction in that the majority of the energy in the reflected pulse occurred during the first 100 microseconds (Fig. 1). While the shape of the initial phase of the pulse indicated that the reflecting surface, if spherical and diffuse, would have to be approximately thirty kilometers in diameter, the size of the signal (received power) and realistic values for the reflection coefficient suggest that the diameter of the radiating surface would have to be about four hundred and fifty kilometers. Unfortunately, the beamwidth of the antenna used in these experiments was too broad to permit the minute examination of the reflecting surface required to explain this discrepancy. Nevertheless, the results did show that the fidelity of this circuit was higher than that suggested by the early moon-radar experimenters and implied that the circuit would be usable in moderm communication systems. Additional

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experiments utilizing cw (A1), modulated cw (A2), and audio-frequency-modulated signals (A3) supported this conclusion. The results of the radar experiments conducted under this program appear in a prior report (7). The opportunity of establishing a practical moon-relay communication system followed as a consequence of the experience gained and the availability of equipment ut[redacted]rogram. Such a circuit was established in 1955 and operational experiments were continued into the early part of 1956. This report was prepared to indicate the nature of this work and to describe the results obtained.

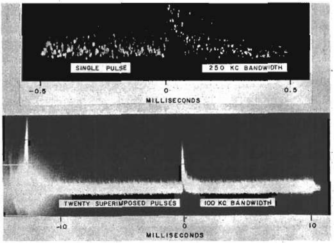

Fig. 1 - Ten-microsecond pulse experiment echo

SYSTEM DESCRIPTION

The purpose of the tests was to demonstrate the feasibility of establishing a communication system, providing hemispheric coverage, by operating an experimental communication circuit comprising two sites on the surface of the earth and the moon as a passive relay station. The frequency chosen was 301 Mc.

The transmitting site, located approximately 25 miles from Washington, D. C., was that used in the earlier moon-radar experiments. Two distant receiving sites were chosen: one at the Navy Electronics Laboratory, San Diego, California (a great-circle distance of 2000 nautical miles from the transmitting site), and the other at the Navy Radio Station, Wahiawa, Oahu, T.H. (a great-circle distance of 4350 nautical miles from the transmitter). An additional site adjacent to the Naval Research Laboratory was also employed for test purposes.

The high-gain transmitting antenna constructed for the moon-radar tests was used to compensate partially for the unusually large circuit loss. This antenna (Fig. 2), is a section of a paraboloid carved in the earth. Its surface was obtained by passing a plane (the earth's surface) through the vertex of a paraboloid at an angle of approximately 40 degrees from its axis. The intersection of the plane and paraboloid was an ellipse having major and minor axes of 263 feet and 220 feet, respectively. A boom, mounted in gimbals at the vertex and of sufficient length to reach the focal point, was used to support the primary feed structure. The boom movement was regulated by cables from control towers placed to permit relatively independent scanning of the celestial coordinates of right ascension and declination. Restricting the feed movement to regions of low aberration enabled steering of the antenna beam over a small portion of the sky with negligible degradation in antenna performance. However, the steering procedure was complicated by the inversion and angular amplification introduced by the reflecting surface. These factors compelled empirical determination of steering data from observations of the sun and radio stars. At the frequencies employed in this experiment, the steering range of this antenna was $\pm 7^{\circ}$ in declination and ± 30 minutes of time in right ascension. The steering data indicated that excessive pattern deterioration and loss of directive gain made the reflector virtually useless at $\pm 7^{\circ}$ from from the design center declination of N25.75°. The directive gain of this antenna at 301 Mc and N22° declination, measured by a comparison method using both the radio star, Taurus A, and the sun as sources, was 37 db above isotropic.

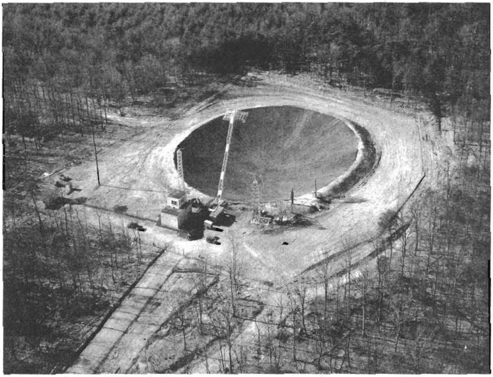

Fig. 2 - Transmitting antenna used in experimental CMR system

Experiments using both tone modulation and carrier shift, FSK, teletype transmission were scheduled. The transmitted signals in these systems were considered representative of those employed in existing communication circuits. Although conventional audio-modulation techniques were employed in the tone-modulated teletype transmission, the method used for FSK required a relay system and modulator-oscillator developed by the NRL Communications Branch. This equipment permitted the teletype keyer to control the frequency of a signal which replaced the 3.45-Mc crystal oscillator in the i-f and audio-frequency amplifier circuits of an AN/ARC-27 transmitter. Since the frequency-synthesis circuit of the ARC-27 was designed so that a change in frequency of the 3.45-Mc oscillator produced an equivalent change in the output frequency of the transmitter, the substitution described permitted the output frequency of the ARC-27 to be controlled by the teletype keyer while the operating frequency of this transmitter could be set, where desired, in its 225 to 400 Mc range. This transmitter served as the driver for the 10-kw klystron power amplifier used in these experiments. A block diagram of the transmitting system is shown in Fig. 3. Table 1 gives the transmitted power for the various modes of transmission used during these experiments.

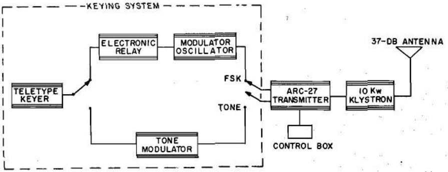

Fig. 3 - Block diagram of teletype transmitter for single-channel operation

TABLE 1
Mode of Transmitter Operations used in the Experimental CMR Circuit

Mode	Description	Conditions	Transmitter Power (kw)
IA	Single-Frequency FSK Radioteletype	200-cps FSK Shift	10
IB	Diversity FSK Radioteletype	200-cps FSK Shift, 100-kc Diversity	4
IC	Diversity FSK Radioteletype	600-cps FSK Shift, 100-kc Diversity	4
IIA	Single-Frequency Tone-Modulated Radioteletype	500- and 700-cps Tones, 25% Modulation	4*
IIB	Diversity Tone-Modulated Radioteletype	500- and 700-cps Tones, 100-kc Diversity	1.8*
IIIA	Single-Frequency CW (Low-Frequency Carrier)		10
IIIB	Single-Frequency CW (High-Frequency Carrier)		10
IIIC	Diversity CW		5
IVA	Single-Frequency Pulse (Low-Frequency Carrier)	10-cps, 50% Duty Cycle	10
IVB	Single-Frequency Pulse (High-Frequency Carrier)	10-cps, 50% Duty Cycle	10
IVC	Diversity Pulse	10-cps, 50% Duty Cycle	4
VA	Diversity Amplitude-Modulated Carrier	Music, 25% Modulation	1.8*

*Carrier Power

The principal requirements for the receiving antennas were gain and mobility. Consequently, an array of antennas was chosen. The paraboloid reflector from the SK-2 radar antenna served as the basic array element. This reflector has an aperture diameter of 17 feet and a focal length of 5 feet. The primary feed used in this experiment consisted of a combination dipole-reflector supported axially from the vertex. An aluminum frame, designed to permit rapid assembly and disassembly at the receiving sites, provided the support structure for an array of four elements. Elevation adjustments were made with jacks and changes in azimuth were accomplished by moving the array assembly. Proper adjustments of these coordinates were made prior to each operating period. Figure 4 shows one of the two similar arrays employed in these experiments.

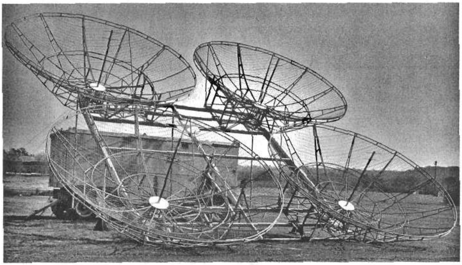

Fig. 4 - Four-element receiving array

The E-plane and H-plane patterns of a single parabola are shown in Fig. 5. These radiation patterns were obtained in a conventional manner using an elevated source at a distance of about 100 wavelengths by rotating the antenna about an axis normal to the E-plane and H-plane, respectively. Gain measurements were made by a comparison method using the sun as a source and the large horn antenna in Fig. 6 as the gain standard. The measured gain was 22 db above an isotropic radiator. Unfortunately, a sufficient number of SK-1 reflectors was not available in time to permit a similar measurement to be made on the complete array; its gain had to be obtained by determining loss values for attenuation and phase error which occurred when the four elements of this array were combined. The resulting gain of the array was 27 db.

A low loss transmission line was used between the antennas and the low noise preamplifier in the receiving system. The gain of this amplifier was sufficient to make the noise figure of the receiving system essentially equal to the noise figure of the preamplifier. An R-278B/GR, a crystal-controlled multi-channel receiver, followed this preamplifier. The 100-kc bandwidth of this receiver obviated tuning of this receiver during the operational period. The rf stages of this receiver were modified so that their operation would be independent of the local gain control. Additional modifications of this receiver permitted the use of this gain control without avc action and provided a 2-Mc output for the final receiver, the Collins 51J-4. The i-f (255 kc) of this communications receiver was displayed on an oscilloscope. In addition to providing the signal for the teletype equipment, the audio output of this receiver was recorded on magnetic tape to supplement evaluation of the received signal. A dual channel oscillograph was also employed to record special pulse signals used in determining the performance of this circuit. A block diagram of the receiving system is shown in Fig. 7.

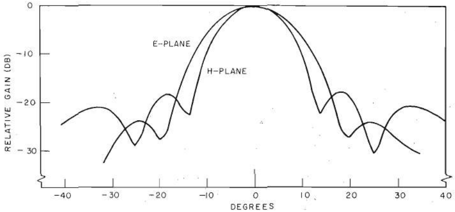

Fig. 5 - E-plane and H-plane radiation patterns of the SK-2 paraboloid

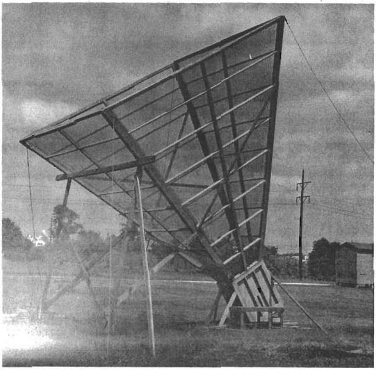

Fig. 6 - Horn antenna used as gain standard

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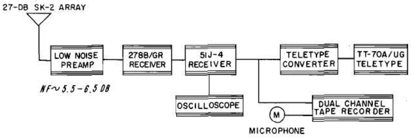

Fig. 7 - Block diagram of teletype receiving system for single-channel operation

Supporting equipment at the receiving sites included:

(a) A noise source to measure the noise figure of the receiver immediately before and after an operation.

(b) A signal generator to check the sensitivity of the receiver before a test.

(c) An electronic frequency counter to measure the incoming frequency as soon as the signal was discernible above the noise.

(d) A radiometer to verify the accuracy of the aim of the antenna array by observation of radio stars and to evaluate the overall performance of the antenna system.

(e) A monitoring receiver to check interference in the operating band.

(f) A theodolite for tracking the moon and plotting its position in altitude-azimuth coordinates.

(g) Impedance measuring equipment to determine the input impedance of the antenna.

PRELIMINARY EXPERIMENTS

In October 1955, a preliminary test circuit was established between the transmitting site at the Stump Neck Annex of the Naval Powder Factory, Indian Head, Maryland and the receiving site adjacent to the Naval Research Laboratory (a distance of approximately 25 miles). The transmitting and receiving equipment described in the preceding section were employed. Although the direct (ground wave) signal prevented teletype operation, the performance of the circuit was evaluated using both frequency-shift keying and audio-tone modulation.

The declination of the moon during these operations ranged from N18° to N23° . The signal-to-noise ratio as a function of operating time for a declination of N22° is shown in Fig. 8.

MARYLAND-TO-CALIFORNIA CMR

The arrival of the experimental team at the Navy Electronics Laboratory, San Diego, California, was timed to precede that of the equipment to permit the surveying required to

[redacted]

establish the orientation of the antenna system, and to complete other field assignments which would permit the installation of the receiving equipment as it arrived. The installation is shown in Figs. 9 and 10 and the operating conditions are given in Table 2. A final check of the equipment was made using a signal generator modulated by the proper audio tones for teletype operation; the orientation and performance of the receiving antenna were evaluated using the radio source, Taurus A.

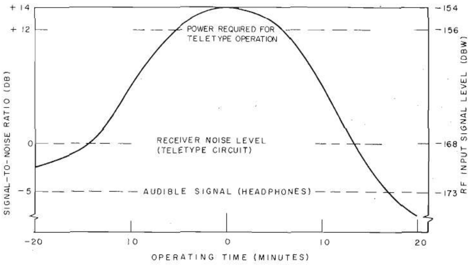

Fig. 8 - Predicted received signal and signal-to-noise ratio for the preliminary experimental CMR circuit

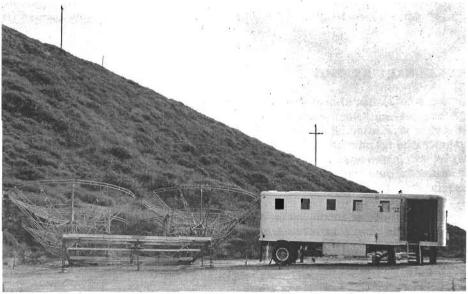

Fig. 9 - NEL receiving installation

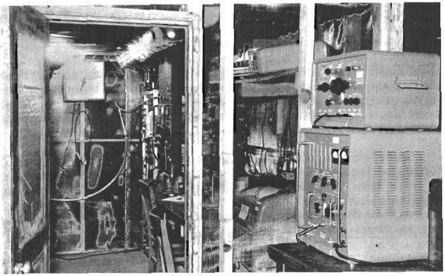

Fig. 10 - Receiving equipment at the NEL site

TABLE 2
Calculated Signal-to-Noise Ratios for Maryland-to-California Experiments

Mode	Description	Conditions	Max S/N (db)
IA	Single-Frequency FSK Radioteletype	200-cps FSK shift	14
IIA	Single-Frequency Tone-Modulated Teletype	500- and 700-cps Tones	4
IIIA	Single-Frequency CW (Low-Frequency Carrier)		14

The CMR circuit was established on November 27, 1956. The operation of this circuit was marginal because of the low declination of the moon (N18.75°), which greatly reduced the gain of the transmitting antenna. Although the signal level was insufficient for teletype copy, it was audible throughout the entire operating period and recorded on magnetic tape. On the following evening, adjustment of the polarization of the receiving-antenna feeds to obtain maximum signal resulted in the increase of a low-amplitude interfering signal whose frequency was within the bandpass of the receiver. The interfering signal caused the teletype equipment to fail in spite of the apparent high amplitude of the desired signal.

At 2351 PST, November 29, 1955, a teletype message from Dr. R. M. Page, Associate Director of Research at NRL, to Dr. Franz N. D. Kurie, Technical Director of the Navy Electronics Laboratory was transmitted over the circuit. The message read

"Lift up your eyes and behold a new horizon"

During the remaining three days of the tests, the circuit was operated with a reasonable degree of success with the exception of a period on December 1, when a tone-modulated teletype signal replaced the frequency-shift carrier transmission. However, teletype operation was not expected during this phase of the experiment because of the reduction in transmitted power during tone-modulated teletype operation.

Additional experiments included an attempt to measure possible rotations in the plane of polarization of the signal. This phenomenon has been reported by other experimenters and is normally attributed to the Faraday effect. The Maryland-to-California experiments, although inconclusive because of the off-axis, cross-polarization characteristics of the paraboloid antenna, showed evidence of polarization rotation.

Although teletype copy was obtained during the expected intervals of the operating period, signal fading, present at all times, introduced errors in the message. Examination of the audio recordings revealed the presence of two apparently independent fading rates. Although this observation directly correlated with results reported by other investigators (8), it was not evident from the 10-microsecond pulse experiments. Undoubtedly, the frequency spectrum of this pulse provided, in effect, frequency diversity transmission.

Immediate attention was focused on a method to overcome fading in this circuit. Consequently, the receiving equipment, except for the antennas which were shipped to Hawaii, was returned to the NRL experimental receiving site. Frequency diversity was employed to take advantage of possible frequency selectivity in the propagation medium or reflecting surface; circular polarization was used to minimize the effect of possible changes in the plane of polarization.

DIVERSITY EXPERIMENTS

Frequency diversity experiments were carried on at NRL during the operating periods in December. Diagrams of the transmitting and receiving equipment employed in this series of tests are given in Figs. 11 and 12. Circular-polarized primary feeds were constructed for the transmitting antenna (Fig. 13), and the Wurzburg antenna (Fig. 14) which was used at the receiving site adjacent to the Naval Research Laboratory. Experiments were conducted by filling the earth-moon-earth space with energy, then turning off the transmitter and examining the echo. Keying the transmitter in this manner avoided the masking of the echo by the ground wave. Beat-frequency-oscillator operation of the two R-390/URR receivers provided audio signals with amplitude and phase related to the received echoes. The R-390/URR, a military communications receiver similar to the 51J-4, is designed for diversity operation. The signals were recorded for both single-channel and frequency-diversity reception. Samples of these recordings are shown in Fig. 15. While not conclusive, the recordings indicate that frequency diversity operation and the use of circular polarization reduced the occurrence of deep signal fading. Additional experiments were scheduled for the Hawaiian circuit where, in the absence of the ground wave, the signal could be recorded under more realistic conditions.

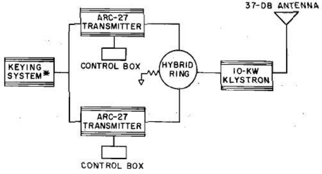

Fig. 11 - Block diagram of teletype transmitter for diversity operation

*KEYING SYSTEM ILLUSTRATED IN FIG. 3

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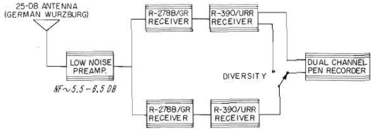

Fig. 12 - Block diagram of receiving system for diversity operation

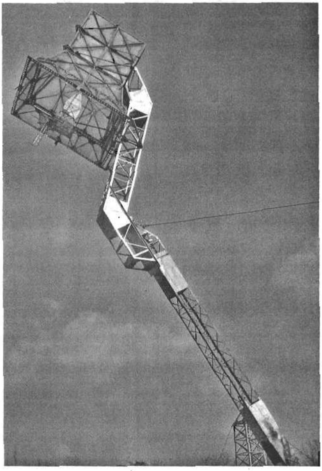

Fig. 13 - Circular-polarized primary feed for the 263-foot transmitting antenna

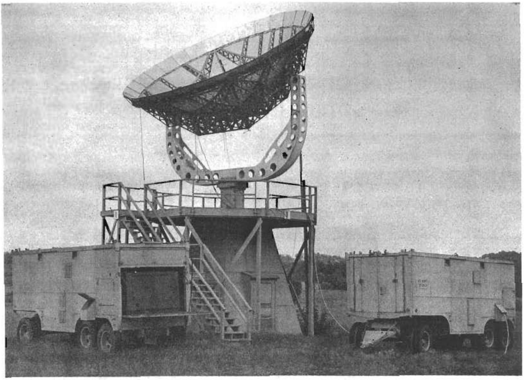

Fig. 14 - German Wurzburg antenna at the NRL receiving site

MARYLAND-TO-HAWAII CMR

The communication experiments from Maryland to Hawaii began on January 21, 1956 and were concluded on January 25, 1956. They included five one-hour operational periods and a similar number of preparatory runs which, as nearly as possible, duplicated all conditions of the "live" experiment. The mock runs established operational procedures and familiarized the personnel with their assignments.

The circuit included the transmitter to drive the large moon-radar antenna at the Maryland site, the space from earth-moon-earth, and the receiving equipment (Fig. 16) with its array of eight SK-2 paraboloids (Fig. 17) at Wahiawa, Oahu, T.H. The additional four-element array was employed to offset partially the loss of transmitter power incurred during dual-frequency (diversity) operation. Both the transmitting and receiving antennas were circular polarized: one was right circular, the other left circular. The change of polarization is necessary to overcome the reversal of polarization which occurs when the signal is reflected from the surface of the moon.

The received signal was passed through low-loss, Styraflex cable to a four-stage, low-noise preamplifier. The output of the preamplifier was connected to a pretuned, single-channel, crystal-controlled receiver, the AN/URR-13B, of which only the rf and mixer stages were used. The mixer output (nominally 18.6 Mc) was fed to two R-390/URR communication receivers which separated the diverse frequencies. Arrangements were made so that the outputs of these two receivers could be combined for frequency diversity reception or kept separate for frequency-selective fading determinations. A block diagram of the receiving equipment is shown in Fig. 18.

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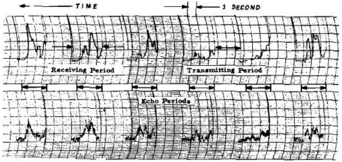
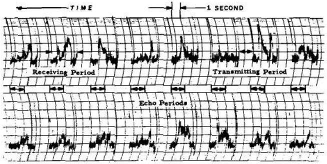
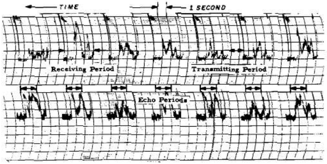


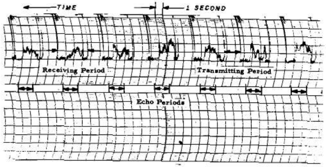
(a) Single frequency recordings from two orthogonal, linear-polarized antennas



(b) Dual-channel recordings of two circular-polarized signals with 12-kc separation



(c) Dual-channel recordings of two circular-polarized signals with 100-kc separation



(d) Recording of two circular-polarized signals combined for diversity reception

Fig. 15 - Diversity experiment recordings at NRL

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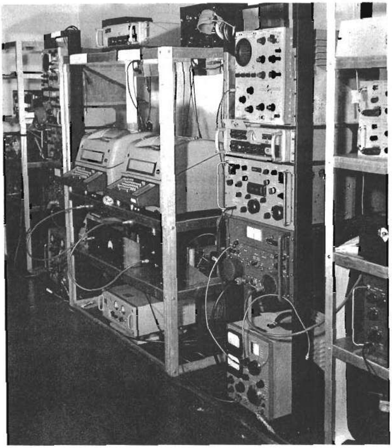


Fig. 16 - Receiving equipment installation at the Naval Receiving Station, Wahiawa, T.H.

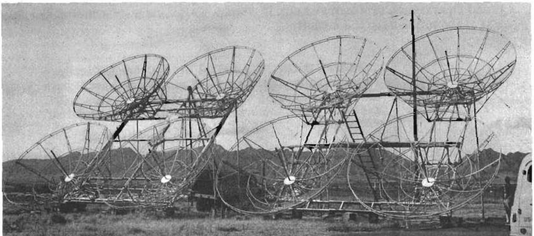
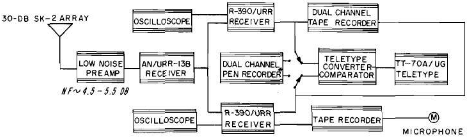


Fig. 17 - Eight-element SK-2 receiving array at the Naval Receiving Station, Wahiawa, T.H.



*PEN RECORDER USED DURING PULSE EXPERIMENTS ONLY

Fig. 18 - Block diagram of teletype receiving system for diversity operation

The modes of operation utilized in these tests, the transmitted power, and the maximum signal-to-noise ratios are given in Table 3. The signal-to-noise ratio for diversity FSK is shown in Fig. 19 as a function of operating time for a declination of N22°.

The first official naval communication to be passed over the CMR circuit was a teletype message received at 1649 HST, January 22, 1956 from Rear Admiral H. C. Bruton, Director of Naval Communications, to Captain Dingfelder, U.S. Naval Radio Station, Wahiawa, T.H. which read

> "With the transmission of this first official message, another marker along the road toward jamproof communications is being passed. I consider the successful conclusion of this project of tremendous importance to naval communications."

At 1739 HST, January 23, 1956, the following message from Admiral Burke, Chief of Naval Operations, to Admiral Felix B. Stump, Commander-in-Chief of the Pacific Fleet, was transmitted over the circuit:

> "Admiral Burke to Admiral Stump. On the inauguration of this new experimental system, naval communication is again exhibiting its forward look. NRL and Naval Communications are to be congratulated."

In addition to the teletype transmissions, audio-frequency modulation in the form of music was transmitted during one experiment. Unfortunately, the reduction in transmitted power required in Mode VA resulted in a very low signal-to-noise ratio and the melodies were barely identifiable. The pulsed transmissions (mode III) were recorded to study fading rates, of which there were two: one slightly greater than 1 cps, the other approximately 0.1 cps. These fading rates agree with those observed during the earlier experiments.

TABLE 3
Calculated Signal-to-Noise Ratios for Maryland-to-Hawaii Experiments

Mode	Description	Conditions	Max S/N* (db)
IA	Single-Frequency FSK Radioteletype	200-cps FSK Shift	18
IB	Diversity FSK Radioteletype	200-cps FSK Shift, 100-kc Diversity	14
IC	Diversity FSK Radioteletype	600-cps FSK Shift, 100-kc Diversity	14
IIA	Single-Frequency Tone-Modulated Radioteletype	500- and 700-cps Tones	7
IIB	Diversity Tone-Modulated Radioteletype	500- and 700-cps, 100-kc Diversity	4
IIIA	Single-Frequency CW (Low-Frequency Carrier)		18
IIIB	Single-Frequency CW (High-Frequency Carrier)		18
IIIC	Diversity CW		14
IVA	Single-Frequency Pulse (Low-Frequency Carrier)	10-cps, 50% Duty Cycle	18
IVB	Single-Frequency Pulse (High-Frequency Carrier)	10-cps, 50% Duty Cycle	18
IVC	Diversity Pulse	10-cps, 50% Duty Cycle	14
VA	Diversity Amplitude-Modulated Carriers	Music	<1**

*1-kc bandwidth

**S/N dependent upon bandwidth-2 kc assumed

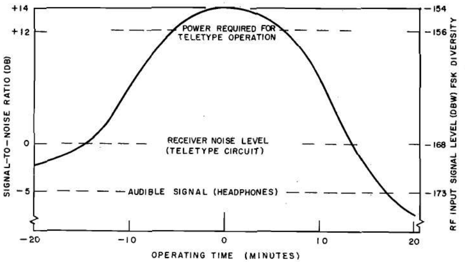


Fig. 19 - Predicted received signal and signal-to-noise ratio for the Maryland-to-Hawaii CMR diversity experiment

PROPOSED SYSTEM

As a result of the tests, a communication system was proposed and its specifications derived. Of course, in a practical application, continuous tracking antennas must be employed at both the transmitting and receiving sites. Since communication will not be available throughout the entire day, the primary function of this circuit will be to supplement normal communication facilities. Its potential antijam characteristics and relative freedom from ionospheric disturbances make this system usable under conditions where conventional communications fail. For example, excessive power requirements make wide-band jamming impractical; therefore, hostile transmitters may be expected to employ narrow-band jamming techniques, which may be avoided by random carrier-frequency shift combined with a priori frequency-shift information at the receiving site. Conventional long-range communication is obtained by utilizing the ionosphere as a reflector. When the ionosphere is turbulent, these long-range circuits may be seriously impaired. Since the ionosphere is relatively transparent at the frequencies employed in the CMR system, the only effects anticipated are those of polarization rotation and dispersion, which are minimized by the use of circular polarization and frequency diversity.

The daily operating time of such a system would be dependent upon the interval of time during which the moon would be visible at both sites. This time is a function of longitude and latitude of the sites, the declination, right ascension, and, to a lesser extent, the horizontal parallax, and it can be determined from the tables of moonrise and moonset given in The American Ephemeris and Nautical Almanac (or equivalent tables).

For a system operating between Washington, D.C., and Pearl Harbor, the operating times are determined by moonrise at Pearl Harbor and moonset at Washington, D.C. The duration of the operational period for this circuit as a function of the declination of the moon is given in Fig. 20. The Eastern Standard Time of operation and the duration of these periods for December 1956 are depicted in Figs. 21 and 22.

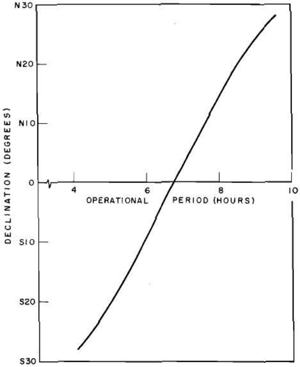


Fig. 20 - Relationship of the maximum length of the operational period to the declination of the moon for a Washington-to-Hawaii CMR operational circuit

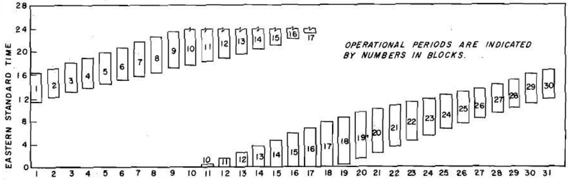


Fig. 21 - Operational periods of the proposed CMR circuit between Washington, D. C. and Hawaii during December 1956

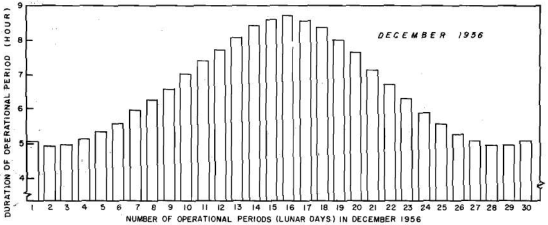


Fig. 22 - Length of operating periods for the proposed CMR circuit between Washington, D.C. and Hawaii in December 1956

Consideration of economic factors, availability, and simplicity of operation led to the following choice of proposed system parameters:

PARAMETER	DESCRIPTION	REMARKS
Transmitting Antenna	84-ft diameter	Equatorial mount
Receiving Antenna	84-ft diameter	Equatorial mount
Frequency Range	400 to 450 Mc	100-kc freq. diversity
Transmitted Power	35 kw	Klystron amplifier
Receiver Noise Figure	6 db	1-Mc bandwidth
Receiver Bandwidth	3 kc	Final i-f bandwidth
Recorder	Teletype and Facsimile	Standard U.S. Navy Equipment

Under these conditions, a 22-db signal-to-noise ratio is expected which should be adequate for teletype communications.

Specifications for such a system have been proposed by the Bureau of Ships with the exception that the transmitter was increased to 70-kw for diversity operation. This system is presently under development (BuShips Work Order No. 833-66110) and is scheduled for operation in 1957.

RECEIVER NOISE FIGURE

The noise figure of the receiver in the proposed 400 to 450 Mc CMR circuit is of prime importance. This arises because the ambient antenna temperature, except when the antenna is pointed at the sun, the galactic equator, or one of the intense radio sources, will be approximately 100°K. Consequently, a receiver with a noise figure greater than 4 (a realistic value at these frequencies) would become the primary source of noise and a further increase in the noise figure will materially affect the signal-to-noise ratio in this circuit. Furthermore, any attempt to increase the transmitted power or the antenna gains to offset the effects of a higher noise figure is impractical because of the relatively large values presently assigned to these parameters. Thus, the most effective means of providing sufficient signal-to-noise ratio for the operation of this circuit is to maintain a relatively low noise figure in the receiving system.

Two low noise preamplifiers were constructed for the communication experiments described in this report. One employed the Western Electric 416B coaxially mounted in a single-stage, grounded grid amplifier; the other used the General Electric 6299 in a similar stage followed by a two-stage conventional amplifier which employed this same tube. Unfortunately, the single-stage preamplifier did not have sufficient gain to reduce the noise figure of the receiving equipment to the desired value and the three-stage amplifier was employed in all of the experiments. However, the single-stage preamplifier was used ahead of the multistage preamplifier during the Hawaiian tests and resulted in approximately 1-db improvement in the noise figure.

Although lower noise figures are theoretically obtainable, the 4.5 to 6.5 db range is representative of field equipment operating at 300 Mc and can be obtained and maintained with relative ease.

CMR DOPPLER

Although the locations of the transmitting and receiving sites are fixed, the rotation of the earth, the revolution of the moon about the earth, and the ellipticity of the moon's orbit introduce a Doppler frequency shift in a CMR circuit. Analysis of this Doppler effect is made difficult by the complex motions of the earth-moon system (9). However, a solution can be derived using the coordinates of the moon, which are published in standard references for celo-navigation, and the longitudes and latitudes of the sites.

The Doppler equation is given by

$$F_{Rx} = F_{Tx} \sqrt{\frac{(c + v_{Rx})\ (c + v_{Tx})}{(c - v_{Rx})\ (c - v_{Tx})}}$$

where

F_{Rx} is the received frequency

F_{Tx} is the transmitted frequency

c is the velocity of propagation

v_{Rx} is the velocity of the receiving site along the earth-moon-earth signal path and is defined as positive if the distance between the receiving site and the moon is decreasing.

v_{Tx} is the velocity of the transmitting site along the earth-moon-earth signal path and is defined as positive if the distance between the transmitting site and the moon is decreasing.

If this equation is expanded and higher powers of v/c are neglected, then

$$F_{Rx} = F_{Tx} \left(1 + \frac{v_{Rx} + v_{Tx}}{c}\right)$$

which results in a Doppler shift of

$$F_{Rx} - F_{Tx} = F_{Tx} (v_{Rx} + v_{Tx})/c .$$

The velocities, v_{Rx} and v_{Tx}, can be obtained from the time rate of change of distance in the earth-moon-earth circuit. Representing the distance, D, from a point on the surface of a spherical earth to the center of the moon by

$$D = R\,(1 + \csc^2 H_p - 2 \csc H_p \cos \theta)^{1/2}$$

where

R is the radius of the earth

H_p is the horizontal parallax of the moon

θ is the angle between the radii to the sublunar point and the site,

gives a velocity, v, between this point and the moon of

$$v = \frac{R^2 \csc H_p}{D} \left[(\cot H_p \cos \theta - \csc H_p \cot H_p) \frac{dH_p}{dt} + \sin \theta \frac{d\theta}{dt}\right].$$

The velocities v_{Rx} and v_{Tx} may be calculated from available parameters if $\cos \theta$ and $\sin \theta (d\theta/dt)$ are expressed as

$$\cos \theta = \sin L \sin \delta_m + \cos L \cos \delta_m \cos LHA$$

$$\sin \theta \frac{d\theta}{dt} = (\cos L \cos \delta_m \sin LHA) \frac{dLHA}{dt} - (\cos L \sin \delta_m \cos LHA - \sin L \cos \delta_m) \frac{d\delta_m}{dt}$$

where

L is the latitude of the site

δ_m is the declination of the moon

LHA is the local hour angle of the moon

dLHA/dt and $d\delta_m/dt$ are the time rates of change of the moon's LHA and declination.

The local hour angle may be replaced by the equivalent Greenwich hour angle modified by the longitude of the site or

$$LHA = GHA - W \text{ Longitude}$$

$$LHA = GHA + E \text{ Longitude}$$

to facilitate the use of standard tables. This implies that

$$dLHA/dt = dGHA/dt .$$

Examination of the velocity equation reveals that three approximations can be made which, in general, will introduce only a small change in the calculation of the received frequency. These are

$$\csc H_p = \cot H_p = 1/H_p$$

$$(\cos L \sin \delta_m \cos LHA - \sin L \cos \delta_m) \frac{d\delta_m}{dt} = 0$$

$$(\cot H_p \cos \theta) \frac{dH_p}{dt} = 0 .$$

These components would introduce less than a 10-cps error in the calculated Doppler shift in the proposed circuit.

Further simplification of the Doppler equation can be made with an additional sacrifice in the precision of the calculation; thus,

$$F_{Rx} = F_{Tx} \left\{ 1 - \frac{R}{c} \left[\frac{2 \frac{dH_p}{dt}}{H_p^2} - \cos \delta_m \frac{dGHA}{dt} (\cos L_{Rx} \sin LHA_{Rx} + \cos L_{Tx} \sin LHA_{Tx}) \right] \right\}$$

The approximation, $R \csc H_p = D$, which was used in deriving this equation can introduce an error of approximately four percent in the Doppler shift, $F_{Rx} - F_{Tx}$. However, this error is a function of the location of the transmitting and receiving sites and in the proposed circuit, should result in less than a 12-cps error. Use of this simplified Doppler equation enables automatic correction of the change in frequency introduced by the rotation

[redacted]

of the earth-moon system from the position of the antennas and their rotational rates. The required correction is given by

$$-\frac{F_{Tx}R}{c} \cos \delta_m \frac{dGHA}{dt} (\cos L_{Rx} \sin LHA_{Rx} + \cos L_{Tx} \sin LHA_{Tx}).$$

Although this correction could be made at either location in the proposed circuit, it is impractical to make the entire correction at the transmitter in a system employing multiple receiving sites.

An alternative method exists in which each site, either transmitting or receiving, corrects for its contribution to the Doppler shift. In this case, the change in frequency which would be required would be

$$\frac{FR}{c} \frac{1}{H_p^2} \frac{dH}{dt} - \frac{dGHA}{dt} \cos L \sin LHA \cos \delta_m$$

where F is a constant frequency and could be interpreted as the assigned frequency of the CMR circuit. In the proposed circuit, the change in frequency required to compensate for this effect would be less than 600 cycles at either site.

The additional assumption that

$$\frac{1}{H_p^2} \frac{dH_p}{dt}$$

is constant during the operating period permits the use of a constant frequency correction for this component in the Doppler equation. Of course, this introduces an additional error in the calculation. However, its magnitude is similar to that introduced by the previous approximation, $R \csc H_p = D$, and in many systems this magnitude of error may be permissible.

The circuit Doppler shift and the contribution to it by the velocity of each site relative to the moon for February 19, 1957 are shown in Fig. 23. This date was chosen because of the large value of the component introduced by the change in distance between the earth and the moon. The Doppler shift introduced by this changing distance and the operating periods for December 1956 are given in Fig. 24.

CONCLUSIONS

Although the experiments described in this report were limited because of the restricted operational periods and the low signal-to-noise ratio, they confirmed the ability of the moon relay to sustain communication signals. They also illustrated the need for additional work including

a. examination of the circuit's performance for longer operating periods with horizon-to-horizon coverage,

b. examination of the characteristics of this circuit throughout the range of radio frequencies which can be transmitted through the atmosphere especially at the higher frequencies where essentially no work of this nature has been undertaken,

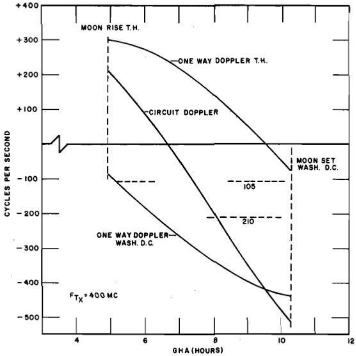


Fig. 23 - Doppler frequency shift for a CMR circuit between Washington, D.C. and Hawaii for February 19, 1957

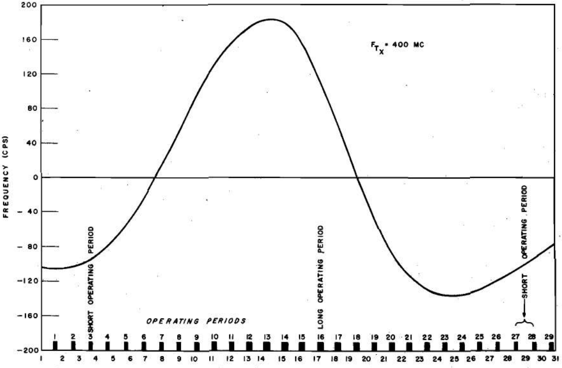


Fig. 24 - Doppler shift, introduced by earth-moon distance variation, for a CMR circuit between Washington, D. C. and Hawaii

[redacted]

c. further examination of the polarization and fading effects,

d. a detailed examination of the reflecting surface,

e. additional measurements of the Doppler frequency shift and the Doppler frequency spread which may be introduced by librations and nutations in the earth-moon system (10).

The proposed Communication-Moon-Relay operations will permit study of this circuit over an extended period and experiments using a 60-foot antenna have been planned by the Communications Branch of NRL to examine the circuit at higher frequencies. However, this work will probably not yield the information required to determine the specific nature of the reflection surface. Experiments using a narrow-beam antenna coupled with a study of the Doppler frequency spread could provide this information. Certainly, such knowledge will be required before full use can be made of the moon as a passive reflector.

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REFERENCES

1. Jansky, K., Proc. I.R.E. 21:1387 (1933)

2. Mofenson, J., "Radar Echoes from the Moon," Electronics, 19:92-98 (1946)

3. "Russian Moon Radar," Daily Press, January 1946 (from Ref. 4 — no scientific report known)

4. Bay, Z., "Reflection of Microwaves from the Moon," Hungarica Acta Physica, 1:1-22 (1946)

5. DeWitt, John H., Jr., and Stodola, E. K., "Detection of Radio Signals Reflected from the Moon," Proc. I.R.E., 37:229-242 (1949)

6. Grieg, D. D., Metzger, S., and Waer, R., "Considerations of Moon-Relay-Communication," Proc I.R.E., 36:652-663 (1948)

7. NRL Report, TS - 5430 - 14A/55

8. Little, C. G., Rayton, W. M., and Roof, R. B., "Review of Ionospheric Effects at VHF and UHF," Proc. I.R.E. 44:992-1018 (1956)

9. Trotter, B. E., "Moon Doppler Navigation," (NRL report in preparation)

10. Pawsey, J. L., and Bracewell, R. N., "Radio Astronomy," Oxford: Claredon Press, 1955

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