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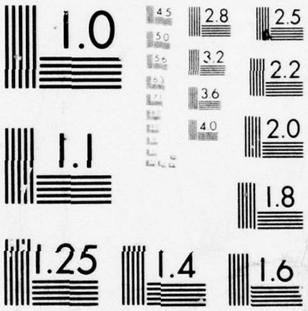
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NEW COMMUNICATION SYSTEMS

PROJECT PANGLOSS

CODE 687A · BUREAU OF SHIPS · U. S. NAVY

CONTRACT No. Nobsr 77533 (FBM)

FINAL ENGINEERING REPORT

TASK ORDER IV
SUB TASK A

MOON/PLANET RELAYS

for the period Feb. 13, 1959 to Sept. 13, 1959

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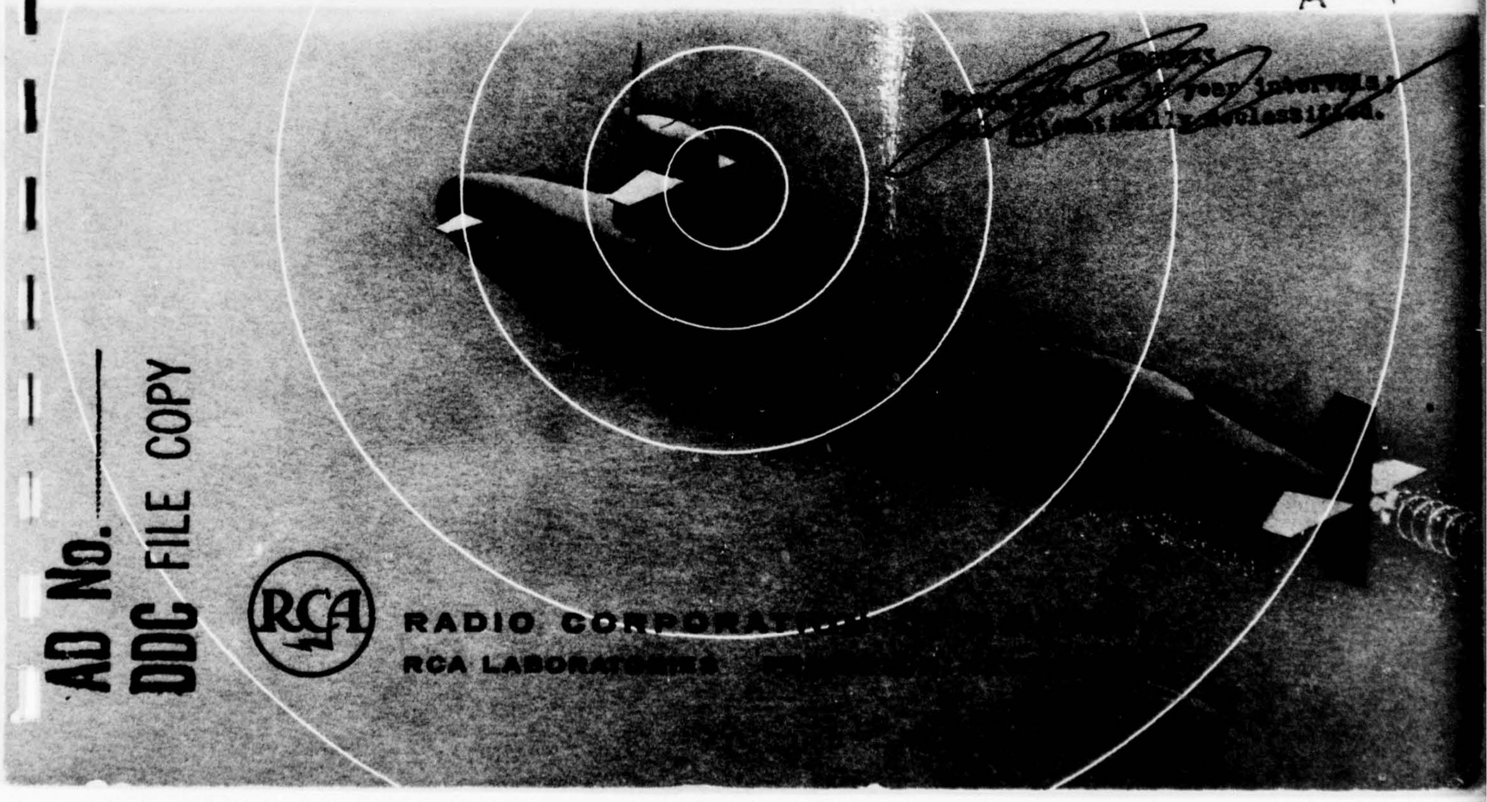

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FINAL ENGINEERING REPORT. 13 Feb-13 Sep 59.

TASK ORDER IV

SUB TASK A

⑥ New Communication Systems. Project PANGLOSS.

MOON/PLANET RELAYS.

for the period Feb. 13, 1959 to Sept. 13, 1959

Task Order IV.
Sub Task A.

⑪ 15 Sep 59

⑫ 32p.

by

RADIO CORPORATION OF AMERICA
RCA LABORATORIES
PRINCETON, NEW JERSEY

and

RCA DEFENSE ELECTRONIC PRODUCTS
DEVELOPMENT ENGINEERING
CAMDEN (2), NEW JERSEY

for

DEPARTMENT OF THE NAVY
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ABSTRACT

A communications circuit using radio reflection from the moon, planets, or sun, to link two terrestial points is investigated. Existing data on radio reflections from the moon indicate the phenomena involved, and provide some experimental comparison for calculations of signal return.

Neglecting any limitations on range, the probability of finding at least one celestial body available for use as a reflector is worked out. Because of the incommensurate motions of the planets, the probability is slow in building up; for five possible reflectors, the probability that at least one is in a useful position is 97%.

Range limitations indicate that only the moon and Venus are useful for real-time signal relaying; giving a best reliability of 57%. The sun is not useful for real-time relay communication due to absorption of incident signals, and noise radiation, by the solar atmosphere.

The constraints on useful range imposed by the physics of the problem (distances, sky noise, doppler spreading of signals, surface reflectivity, solar atmosphere), and by the hardware (transmitter power, receiver noise, antenna size, integration time) are discussed.

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I. INTRODUCTION

A. Statement of the Problem

A radio circuit using reflection from the moon, planets, or sun to link two terrestial points is investigated. The signaling rate can be slow; accuracy, rather than speed, is the important consideration in the information transmission. The problem is to find the maximum possible reliability of such a system.

B. Purpose of this Report

The purpose of this report is to examine the factors which influence the operation of a radio relay for PCCS using natural celestial bodies as reflectors, and to draw conclusions as to how effective such a system can be.

C. Scope and Plan of the Report

Results and conclusions from past moon reflection experiments are reviewed, and the maximum range at which useful return can be expected is discussed. Receiver and antenna noise, bandwidth and integration time of the receiver, transmitter power, and antenna gain considerations are examined, and are applied to the case of lunar reflection.

Extension of the system to use planets as reflectors is considered. First a statistical analysis is made to find the over-all availability of a relay system using planets, assuming they are within range. Then, the actual accessibility of the planets is calculated, and found to be slight.

Use of the sun as a radio reflector is examined, and found to give an inadequate return signal.

Finally, the maximum availability of the system is calculated, and possible avenues for improvement are suggested.

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II. RADIO REFLECTION FROM THE MOON

Reference to the extensive literature on reflection of radio waves from the moon shows the following important points:[1-8]

A. Echoing Area

The effective echoing area of the moon, which is a product of scattering area, reflectivity, and directivity, is a slowly decreasing function of frequency. As shown in Figure 1, the ratio of echoing area to projected area of the moon falls off from 0.1 at 100 Mc/s toward 0.05 at 10,000 mc/s.

B. Fading

Two types of fading are observed:

1. Slow fading, over a period of minutes or hours, is due to Faraday rotation effects in the earth's ionosphere. This effect is negligible at frequencies above 1000 mc/s, and is easily avoided at the lower frequencies by use of circular polarization.

2. Fast fading, with a period of seconds or minutes, is due to interference effects which are caused by librations (apparent rotation) of the moon. These librations produce a frequency spreading. Fast fading can be eliminated by use of frequency diversity; use of two transmissions 10-20 kc/s apart is adequate for this purpose.[9] Although there has been no experimental evaluation as yet, it would appear that space diversity with separations of several hundred wave lengths probably would be equally effective.

C. Pulse Stretching

Most of the energy of reflected pulses is received with a time interval several orders of magnitude smaller than the 11.6 millisecond transit time from the front to the center of the moon and back. Figure 2 shows the distribution of energy in the reflection of a 12 μsec pulse of a 200 mc/s carrier; half of the returned energy arrives in a 50 μsec interval, and 90% arrives within 200 μsec.[6] Similar results at other frequencies from 30 to 3000 mc/s lead to the conclusion that the return signal is that reflected from the first Fresnel zone. This is the familiar result for optical backscattering from a smooth sphere; the effective scattering area for a perfectly reflecting sphere is π , providing that the radius is appreciably greater than a wave length.[10]

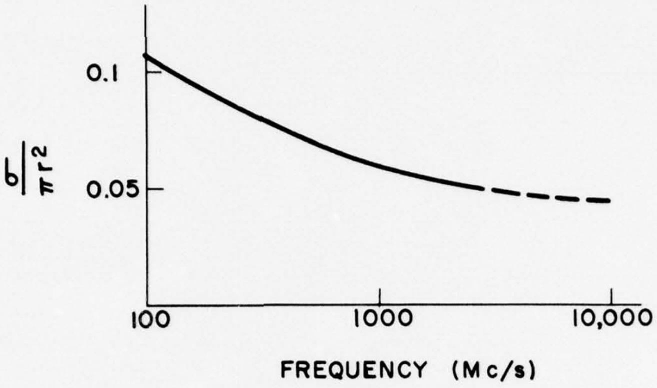

Figure 1. The Empirical Ratio of Effective Echoing Area of Moon (σ), to Projected Area of Moon (πr^2), as a Function of Frequency

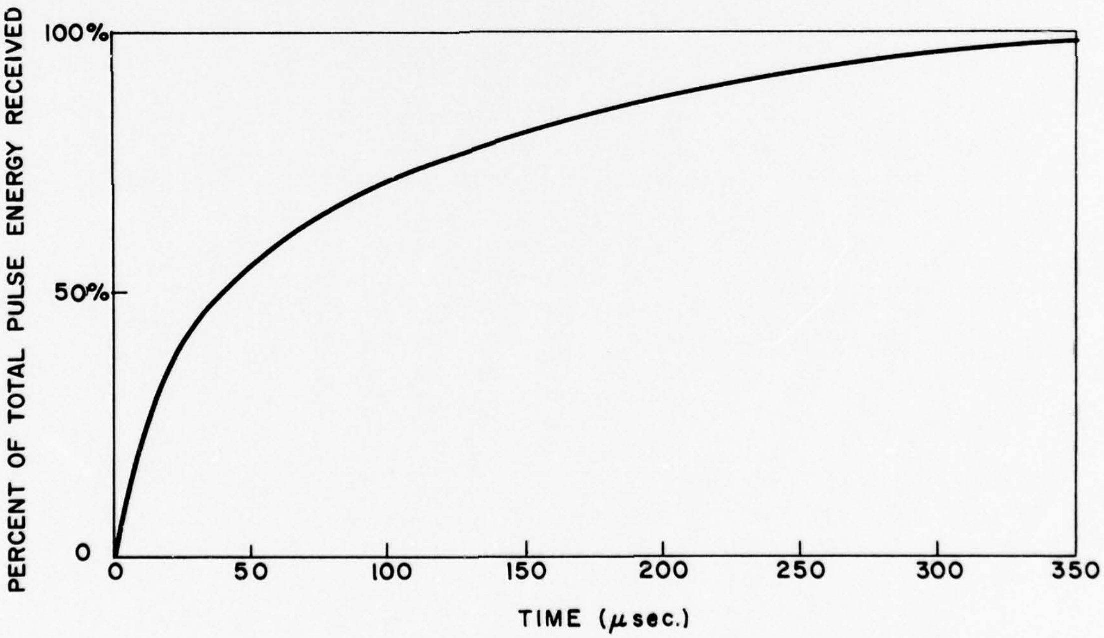

Figure 2. Distribution of Energy in Time for a Received Pulse Reflected from the Moon. The Transmitted Pulse was 12 μsec. Long with a Carrier Frequency of 200 Mc/s

III. RANGE AND DETECTABILITY LIMITATIONS OF MOON/PLANET RADIO RELAY

A. Radio Receiver Sensitivity

Radio reception range is limited by noise. Communication cannot be maintained if the received signal cannot be distinguished from the internal and external noise at the receiver. This noise is usefully represented in terms of effective noise temperatures. If T_a (the antenna noise temperature) represents the external noise coming into the receiver, and T_r (the receiver noise temperature) indicates the internal noise generated in the receiver, the effective noise power input to the receiver is:

$$N = k(T_a + T_r)B \tag{1}$$

where

k = Boltzman's Constant = $1.38 \times 10^{-23} \ \frac{\text{watt-sec}}{^{\circ}K}$

B = the effective bandwidth of the receiver.

To make the noise power small, and thus maximize signal-to-noise ratio, two possibilities suggest themselves; either keep T_a and T_r low, or use smallest possible receiver bandwidth, B.

1. Noise Temperatures

Figure 3 is a graph showing antenna temperature as a function of frequency.[11, 12] If the antenna is not pointed at the sun, the antenna temperature has a minimum value below $100^{o}K$ in the frequency range 1-10 kmc/s. This frequency interval is called the "space window" and is centered at C-band. When the antenna is directed at the sun, frequencies above 10,000 mc/s give the lowest noise, but the quiet sun temperature in this frequency range is still about $10^4\ ^{o}K$.

Different types of receiver are characterized by quite different noise temperatures, as shown in Figure 4.[12] At "space window" frequencies conventional tubes such as triodes have low gain and high noise. Crystal-input superhetrodyne receivers operate with high ($1000^{o}K$) noise. Traveling wave tubes can be somewhat better ($400^{o}K$). Best of all for use with low antenna temperatures are maser and/or variable reactance (parametric) amplifiers. Both of these devices have noise temperatures below $100^{o}K$. The parametric amplifier is the simpler to use, since it is a solid state device requiring no cooling.

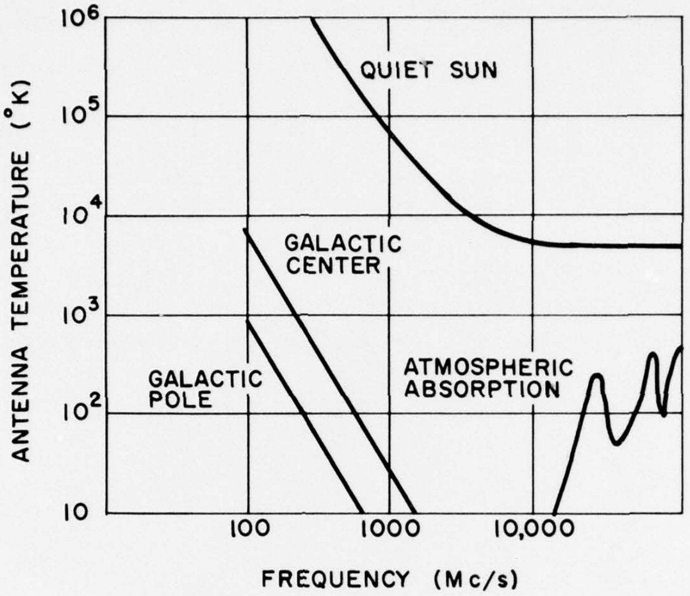

Figure 3. Antenna Temperature as a Function of Frequency

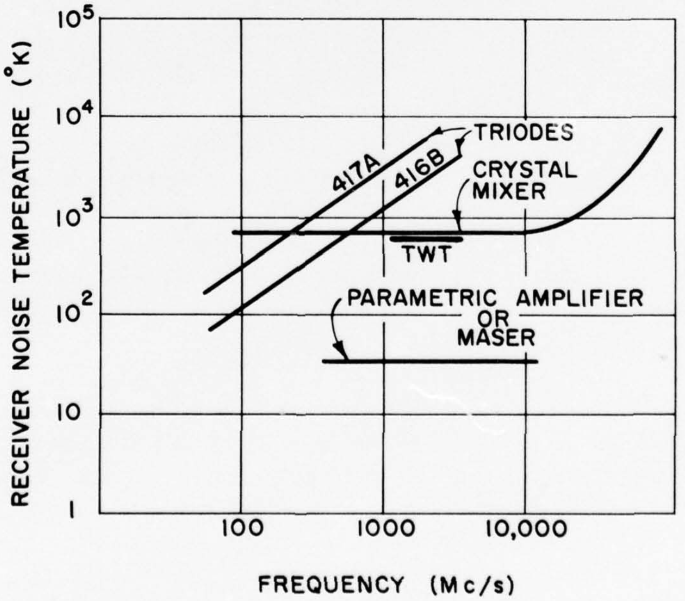

Figure 4. Effective Noise Temperatures of Various Receiver Inputs

In calculating the noise power with which the received signal must compete in the moon/planet relay, a receiver temperature of $100^{\circ}K$ and an antenna temperature of $100^{\circ}K$ (except when looking at the sun) will be used.

2. Receiver Bandwidth

The effective receiver bandwidth required for this project is set not by signaling rate, since an extremely low rate is acceptable, but by oscillator stability, doppler smearing, and tuning accuracy. An I.F. bandwidth of 1000 c/s is considered a reasonable value. To further cancel noise, post-detection integration is used.[13] For reliable detection of a received signal which is down in the noise, the received power must be approximately:

$$P_r \geqq 12.5\, kT \sqrt{\frac{B}{\tau}} \qquad (2)$$

where

τ = post-detection integration time;

τ will be taken as 10 seconds for purposes of calculation.

B. Transmitter Power

The transmitter power rating for this communication system is in terms of cw power. Pulsed operation is not feasible because the need for range requires small bandwidth, which means long pulses or, effectively, cw transmitter operation. At the present state of development of UHF and microwave transmitting tubes, cw power rating of a single tube, as a function of frequency, is given by the equation:[14]

$$P\,(kilowatts) = \frac{160}{f^2} \qquad (3)$$

where the frequency, f, is expressed in kMc/s.

If higher transmitter power is required, several tubes can be paralleled through hybrid tees. The impedance matching must be done with care to prevent reflections which could damage the tubes. Narrow bandwidths simplify the matching problem.

The successful performance of high peak-power systems suggests that there should be no great problems with breakdown in the waveguide (using a pressurized system), or at the output pressure window, for cw powers which are achievable. Cooling of the waveguide will probably be required in cw operation.

C. Antenna Size and Gain, Beam Width

Antenna gain depends on the size of the antenna, and the frequency or wave length being radiated. The relationship for parabolic reflectors is

$$Gain = 2\pi \left(\frac{D}{\lambda}\right)^2$$

$$= \frac{2\pi}{c^2} D^2 f^2 \qquad (4)$$

where

D = diameter of (parabolic) antenna dish

f = frequency of radiated signal

λ = wave length of radiated signal

c = velocity of light = 3×10^8 meter/sec.

Equation No. 4 promises unlimited gain, at whatever frequency, as antenna size is increased. This gain is achieved by reducing the angle into which power is radiated. The antenna beam width is

$$\theta = 1.2 \left(\frac{\lambda}{D}\right)$$

$$= \frac{1.2c}{Df} \qquad (5)$$

The angle subtended by the moon is about $1/2^{\circ}$. The planets subtend smaller angles, of course; but a narrow antenna beam imposes stern requirements on the construction tolerances of the antenna as well as on the aligning and tracking mechanism for steering the antenna. To avoid too-severe directing problems, a minimum beam width of $1/2^{\circ}$ will be assumed for the moon/planet relay. This beam width corresponds to an antenna gain of 50 db; the corresponding parabolic antenna diameter is shown as a function of frequency in Figure 5. The antenna is sizable at the lower frequencies - about 40 meters in diameter at 1 kmc/s - but not so large as to present structural difficulties or tolerance problems.

D. Echoing Area of Planets

The effective echoing area for the planets is an important unknown in the moon/planet relay problem. There is some experimental evidence for the

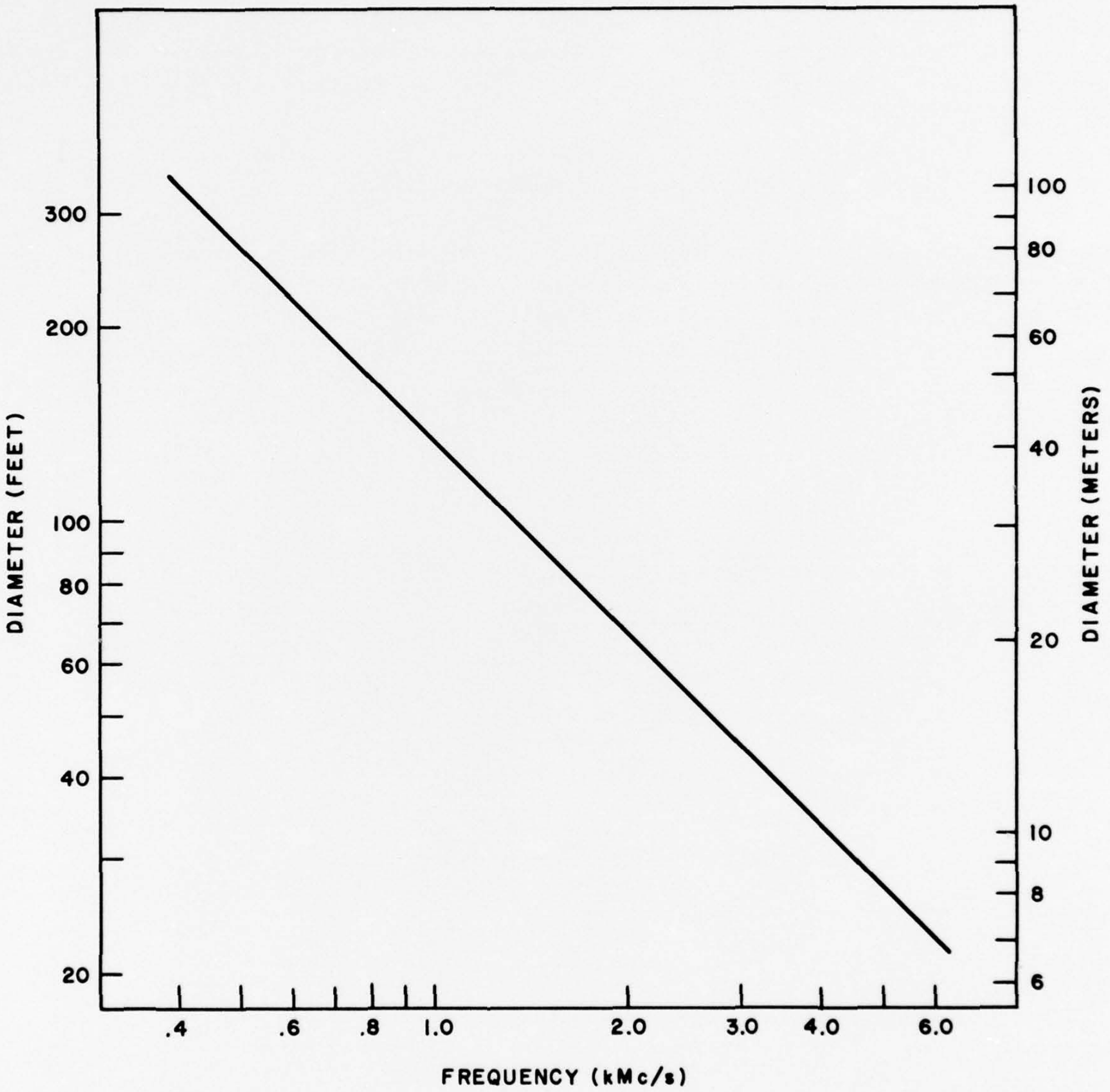

Figure 5. Diameter of Parabolic Reflector for 50 db Gain and 1/2° Beam Width, as a Function of Frequency

moon, and one radar experiment has been made with Venus.[15] Results of moon reflection experiments are shown in Figure 1. The echoing area, σ, is seen to be about 1/10 of the area of the projected disc, πr^2, where r is the radius of the moon. The one Venus experiment suggested that Venus is a perfect reflector, i. e., $\sigma = \pi r^2$. If this result is correct, it may be because the reflection took place in the ionized atmosphere of Venus. Or, if the reflection took place from its surface, the roughness may have introduced a directivity to compensate for a reflection coefficient less than unity. Reflection might occur at the surface of other planets rather than in their atmospheres. To be realistic, a value of $\sigma = 1/10\ \pi r^2$ is taken as the basis for the calculations below.

E. Achievable Signal-to-Noise Ratio for Earth-Moon-Earth Relay

The results of the foregoing sections will be applied here to find the signal-to-noise ratio which can be achieved in a low-signal-rate relay system using the moon as a reflector. The ratio of received signal power to mean noise power is:

$$\frac{P_r}{P_n} = \frac{\dfrac{P_t G_t}{4\pi d^2} \times \dfrac{\sigma}{4\pi d^2} \times A_r}{k(T_a + T_r)\sqrt{\dfrac{B}{\tau}}} \qquad (6)$$

Take P_t = transmitter power = 10^6 watts.

(This figure is reasonable for UHF.)

G_t = 10^5 (corresponding to 1/2° beam width, regardless of frequency)

σ = echo area of moon = $1/10\ \pi r^2$ when r = moon radius = 1.74×10^3 km.

d = moon-earth distance = 3.85×10^5 km

A_r = area of receiving antenna. Solutions will be found for 3-meter and 30-meter antenna diameters

T_r = receiver noise temperature = 100° K

T_a = antenna noise temperature = 100° K

k = Boltzman's constant = 1.38×10^{-23} watt-sec/°K

B = predetection bandwidth = 10^3 cps

τ = postdetection integration time = 10 sec.

These figures yield:

$\frac{P_r}{P_n}$ = 88 db for a 30 meter receiving antenna

= 68 db for a 3 meter receiving antenna

IV. RADIO RELAYING VIA PLANETS

Radio reflection from the moon is a well-established fact; a substantial body of scientific literature discusses it, and the daily papers tell of its application for voice communication purposes. The only shortcoming to radio communication via lunar reflection is the fact that the moon is simultaneously in view to two points differing in longitude by ΔL_h hours for only about $(12 - \Delta L_h)$ hours a day.* The logical thought is to fill in the blank periods by use of some neighboring planets as reflectors.

A. Compound Probabilities of Planet Availability

The motions of the bodies in the solar system are incommensurate, so the probabilities of their being within useful range of the earth are independent of one another.** If we neglect for the moment the longitude factor, and if we assume that the heavenly bodies are always within range, then any one of them is available half of the time; ie, the rotation of the earth puts the body out of sight half of the time.

Under these assumptions, the probability that the body is available for radio reflection is 1/2. Considering two such bodies, each independently available half the time, the net probability that one or both are available is 3/4; the probability is not unity because of the lack of proper synchronism of their orbits. Extending the reasoning to larger numbers of bodies, each assumed to have an independent probability of accessibility of 1/2, the net probabilities of having at least one celestial reflector available are shown in Table 1:

---

*This expression is a first-order approximation, neglecting the angle between the plane of the equator and the ecliptic.

**Except that, as indicated in Figure 6, Venus and Mercury are both seen (in a radio sense) during approximately the same hours that the sun is visible to an observer on the earth.

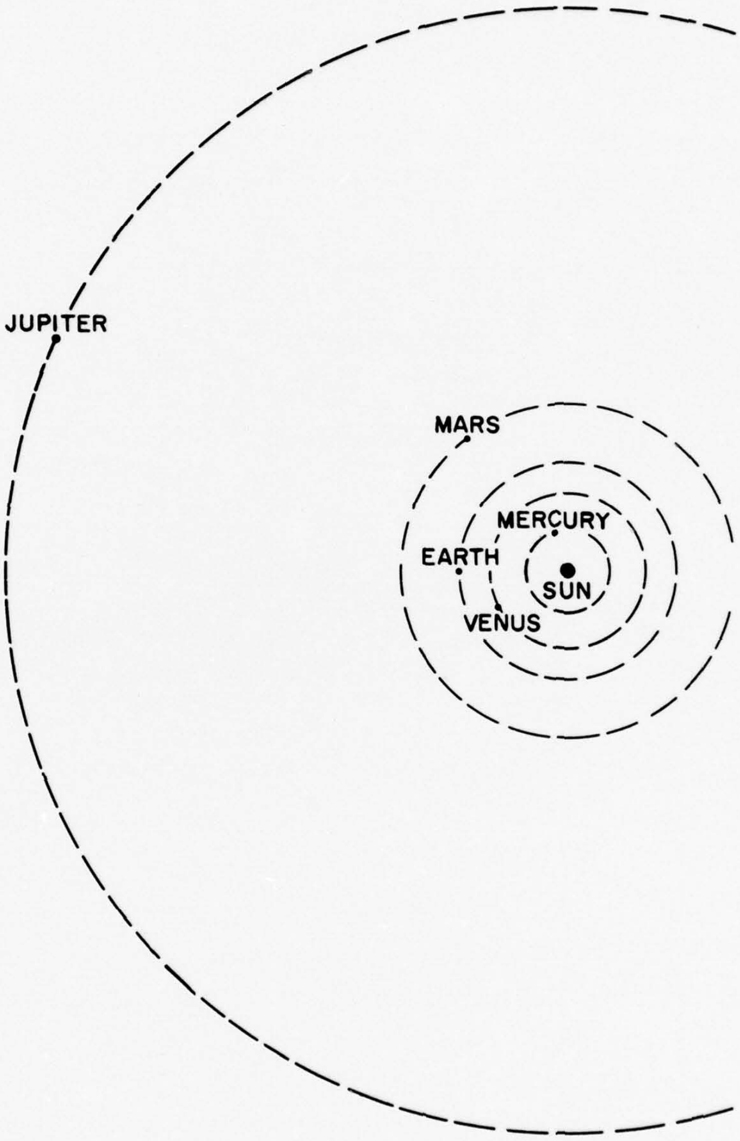

Figure 6. The Nearer Planets of the Solar System

TABLE 1

Number of Reflectors (N)	Probability $P(N)$
1	.500
2	.750
3	.875
4	.9375
5	.970

Table 1. Probability of finding at least one reflector available if all are independent and have probability of availability = 1/2.

The conclusion to be drawn from Table 1 is that over the long term average there will be a reflector available only $P(N)$ of the time. Of course, there can be long periods of 100% availability, but there must surely come some times when there is zero availability. For a system which must be extremely reliable, this situation is not wholly satisfactory. However, there remains the possibility of using moon/planet relaying as an extra backup system; so investigation of just how useful it can be, is in order.

The net probabilities in Table 1 are actually too high, for several reasons: (1) two different points on earth would be used, so that the probability per planet should be somewhat less than half; (2) the inferior planets (and the sun, if it is considered as one of the reflectors,) would be visible during approximately the same periods; hence their joint contribution to the net probability of a reflector being accessible would be reduced; (3) most important of all, the planets are not within effective range of the earth over their full orbits.

B. Echo Strengths and Useful Ranges of Planets

For slow signaling rates, which permit integration of received signals, and with the aid of large transmitting and receiving antennae, strong signals can be obtained by lunar reflection. The strength of the received signal reflected back from the planets can be estimated, compared to that from the moon, by comparing the ratio of (A/d^4) where A is the projected area of a planet, and d is its distance from earth. (The return signal strength is proportional to transmitted power, antenna gains, and the (A/d^4) ratio. Therefore, for other parameters fixed, this ratio gives a comparison of received signal strengths.) The results of such a comparison are shown in Table 2, in which return power is compared to that from the moon:

TABLE 2

Reflector	Position in Orbit	Signal Return (relative to moon)
Moon	Any	0 db
Sun	---	-51 db*
Venus	Closest to earth	-70 db
Mars	Closest to earth	-86
Mercury	Closest to earth	-91
Jupiter	Closest to earth	-95
Venus	Farthest from earth	-101
Jupiter	Farthest from earth	-102
Mercury	Farthest from earth	-105
Mars	Farthest from earth	-114

Table 2. Comparison of signal return from the nearer planets with that from the moon.

Using the moon as a reflector, the signal-noise ratio of the echo signal was found to be 88db for a receiving antenna with a 30 meter diameter, and 68db for a receiving antenna with a 3 meter diameter. Since 14 db is the minimum signal-to-noise ratio required, there are 74 db in excess for the 30-meter antenna. Table 2 indicates that Venus should just about be available when at its closest approach to earth,** while Mars and the other planets are out of reach. Useful reflection from the sun is also seen to be a possibility, with several large "ifs" such as: if the solar noise is not too great; and if there is not too much absorption of the incident electro-magnetic wave in the solar atmosphere.

For example, to find just how much of the time Venus is within range such that

$$P_r = 12.5\, kT \sqrt{\frac{B}{\tau}}$$

take:

$$P_t = 10^6 \text{ watts}$$

$$\dot{G}_t = 10^5$$

---

* A signal reflected from the sun will be received against a noise background stronger by the order 20 db than that for the other reflectors, and will suffer attenuation in the solar atmosphere.

** As demonstrated in the Lincoln Lab experiments.[15] Those experiments used an 84 ft. antenna, a freq of 440 mc, and about 3 x 10^5 watts transmitter power. The received signal was down 19 db from the estimate here. To recover the signal, a 5 minute integration was used.

echo area of Venus $= \pi R_V^2$

$D_r = 30$ meter

$B_{i.f.} = 1000$ c/s

$\tau = 10$ sec

$T = T_a + T_r = 200^\circ$ K

For these numbers, the radar equation and signal-to-noise criterion yield $d = 69.4 \times 10^6$ miles.

The orbit of Venus lies within 69.4 million miles of the earth 26% of the time; so (on account of the rotation of the earth), Venus is available only 13% of the time, again neglecting longitude separation of transmitter and receiver.

C. Conclusions

The conclusions drawn from the investigations in this section are:

1. Of all the planets, only Venus ever comes within useful range of the earth, and even Venus is both in sight and in useful range only 13% of the time. The reader should realize that the meaning of "useful range" here - capable of returning a signal sufficiently strong for real time processing - may not apply in situations where much longer post-detection integration periods are possible.

2. Even if as many as 5 of the celestial bodies were always within range, because of the independence of their motions a radio reflection communication system could be not more than 97% reliable. The frequency and duration of outages would be functions of date, and transmitting and receiving sites.

3. Even at the price of much larger antennas and much higher power, one cannot achieve higher reliability with celestial body relaying than with that old standby, ionospheric propagation using HF waves.

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V. RADIO RELAYING VIA THE SUN

The sun differs from the planets in being a mass of gas with a turbulent ionized atmosphere instead of a hard sphere, and also in being an active source of r.f. energy. Therefore, it is necessary to investigate not only the reflecting properties of the sun but also the interfering noise radiated by it.

A. Reflecting Properties of the Sun [16,17]

1. Effective Radius

The sun which the eye sees is the photosphere, which appears as a disc with sharp edges. Above the opaque photosphere lies the atmosphere of the sun, consisting of luminous but nearly transparent gases. There are two principal regions in the solar atmosphere. Extending several thousand miles above the photosphere is the chromosphere, made up of ionized hydrogen and helium. Above the chromosphere is an extensive layer of diffuse but highly ionized gases called the corona. The gases in the corona are at a temperature of 10^6 degrees Kelvin, considerably hotter than the 3×10^4 degree temperature of the chromosphere. The photosphere temperature is a mere 6000 degrees Kelvin. Figure 7 shows the relative sizes of the three regions of the sun. Both the chromosphere and the corona contain free electrons, and their densities decrease with increasing height above the surface of the sun. The number of free electrons per unit volume, N, is most conveniently expressed as a plasma frequency through the relation:

$$f_p = \frac{1}{2\pi} \sqrt{\frac{e^2 N}{\epsilon_o m_e}} = 9 \sqrt{N} \text{ cycle/sec} \tag{7}$$

e = electron charge

m_e = electron mass

ϵ_o = permitivity of free space

N = electron density

All units are in the MKS system. The variation of plasma frequency with height above the surface of the photosphere is shown in Figure 8. The plasma frequency, f_p, decreases sharply with increasing height in the upper chromosphere, then levels off in the corona.

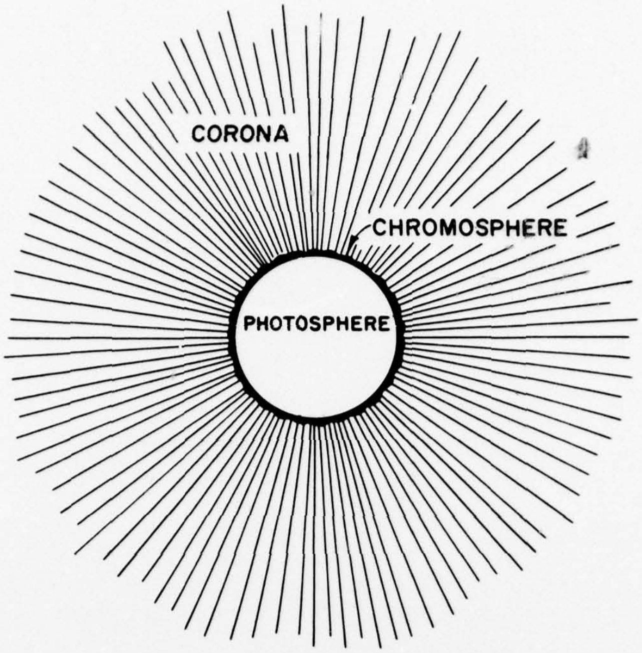

Figure 7. The Sun and Its Atmosphere, Showing Relative Sizes of Photosphere, Chromosphere and Corona

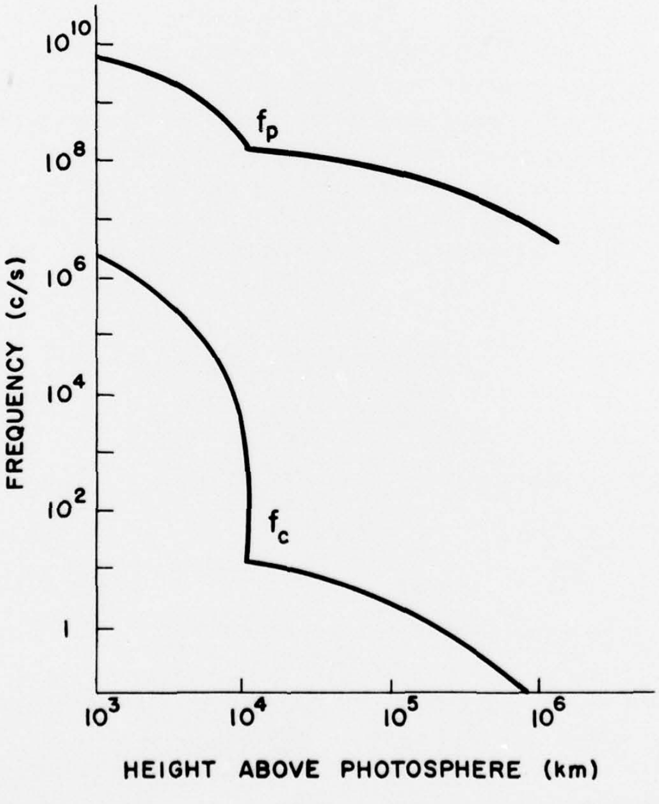

Figure 8. Plasma Frequency and Collision Frequency in the Solar Atmosphere

The frequency of electron-atom collisions varies with altitude through both temperature and electron density, according to the expression:

$$f_c = 2.7 \times 10^{-6} NT^{-1/2} \ln(2.4 \times 10^{-3} NT^{-1/3}) \text{ cycles/sec} \tag{8}$$

N is, again, the electron density per cubic meter.

T is temperature in degrees Kelvin.

Equation (8) is plotted in Figure 8. Collision frequencies are seen to be appreciable only in the chromosphere, and lower corona.

There is associated with the sun a general magnetic field having a surface value of the order of 50 gauss. Considerably stronger magnetic fields are associated with sun spots; the field above a large sun spot is typically 3500 gauss. The magnetic field intensity is conveniently represented by the electron gyro frequency (or cyclotron frequency):

$$f_h = \frac{eB}{2\pi m} \quad (MKS\ units)$$

or (9)

$$f_h = 2.8 \times 10^6\ H \text{ cycles/sec}$$

H = magnetic field intensity in gauss

The variation of cyclotron frequency as a function of height above the surface of the sun is shown in Figure 9.

In the absence of magnetic field, the ionized solar atmosphere presents to a radio wave a relative dielective constant given by:

$$\epsilon_r = 1 - \left(\frac{f_p}{f}\right)^2 \tag{10}$$

When $f = f_p$, $\epsilon_r = 0$ and propagation ceases; i.e. the radio wave is reflected.

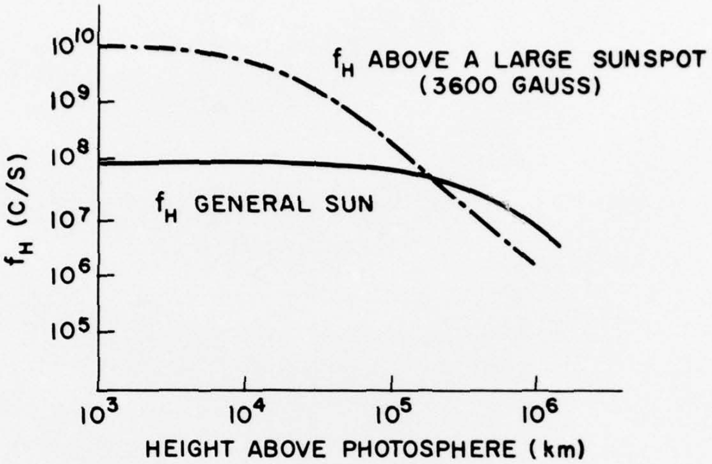

Figure 9. The Magnetic Field in the Solar Atmosphere, Represented in Terms of Electron Gyro-Frequency

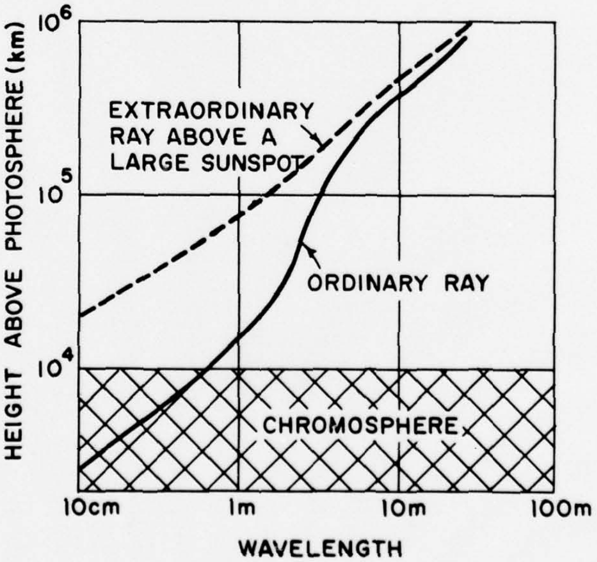

Figure 10. Levels of Zero Dielectric Constant in the Solar Atmosphere

In the presence of a magnetic field, there are two modes of propagation for an electromagnetic wave in the ionized atmosphere of the sun. The two modes are called the ordinary and the extraordinary rays, and their velocities depend on both the magnitude of the magnetic field and its direction relative to the direction of propagation. Rays in directions about that of the magnetic field conform to a set of conditions known as quasi-longitudinal, while rays in directions about the perpendicular to the magnetic field conform to conditions known as quasi-transverse. The magnetic field of the sun is essentially perpendicular to its direction from the earth, so for almost all ray directions except those very close to the direction of the magnetic field the quasi-transverse conditions apply. These conditions give the reflection levels which, occur when:

$$\begin{aligned} f_p &= f \qquad \text{(ordinary ray)} \\ f_p &= f\sqrt{1 - \frac{f_h}{f}} \qquad \text{(extraordinary ray)} \end{aligned} \tag{11}$$

Heights at which these levels occur for different frequencies are shown in Figure 10. Except in the vicinity of large sun spots, microwave and higher UHF frequencies penetrate to the chromosphere (and likewise are emitted from it). For these frequencies, then, the effective radius of the sun is very close to its optical value. The condition of zero dielectric constant gives the lowest level for penetration or escape only for radially directed rays. For oblique incidence or emergence the rays are continuously bent away from the sun so that the innermost level is raised. This effect is similar to the 4/3 effective earth radius effect in terrestial shortwave radio propagation.

2. Directivity of Scattering

The directivity of reflection might well be a function of turbulence in the sun's atmosphere. If the sun acts as a rough reflector, its back scattering cross-section will be 8/3 the area of the projected disc[2], and pulses reflected from it will have rise and decay times of the order of five seconds. If the sun acts as a smooth, perfect reflector, its backscattering cross-section will equal the projected disc area, but the energy will be largely that from the first Fresnel zone so the rise and decay time for a pulse will be only about one-half a period, i. e. $1/2f$. Experiments have shown that the moon reflects as a smooth sphere with very little pulse spreading-far less than would be observed if it were a rough reflector in depth, but a good deal more than $1/2f$. The Venus returns were so far down in the noise that no information on pulse spreading was discernable, nor was it clear whether the reflection occured at the planet surface or in its atmosphere.

3. Absorption of Electromagnetic Energy in the Solar Atmosphere

The ionized atmosphere of the sun constitutes an absorbing dielectric medium which will attenuate and refract an incident radio wave in the layers above the reflection level. The absorption along a ray trajectory, in the absence of magnetic fields, can be expressed in terms of the integral of absorption coefficient measured back from the reflection point. This integral, called the "optical depth", varies with frequency and also with angle of incidence of the ray in the solar atmosphere. Numerical values for central solar rays over a range of frequencies have been worked out.[18]

However, the magnitude and frequency-dependence of the absorption can be easily visualized with the aid of Figure 8 and the following formula for attenuation of the radio wave:[19]

$$Loss = 4.33 \frac{f_c f_p^2}{f^3} \; db/wavelength \qquad (12)$$

f_c = collision frequency

f_p = plasma frequency

f = signal frequency

Since the electromagnetic wave penetrates the solar atmosphere to the level where $f = f_p$, the higher frequencies penetrate deeper, encountering higher collision frequencies as well as higher plasma frequencies. Moreover, at the shorter wave lengths a given depth of penetration corresponds to more wave lengths, so the attenuation accelerates with increasing frequency. Attenuation for the central ray estimated in this manner is shown in Table 3:

TABLE 3

Frequency	Attenuation
100 mc/s	10db
1,000	20
10,000	>30

Table 3. Attenuation of a radially directed ray reflected from the sun, as a function of frequency.

The figures in Table 3 are conservative estimates; actual loss will be somewhat less for two reasons:

a. In the presence of the magnetic field of the sun, the incident electromagnetic wave will split into two rays, the ordinary and extraordinary, as described above. The extraordinary ray will not penetrate as deeply into the solar atmosphere, and hence will not be attenuated as heavily as the ordinary ray.

b. Non-central rays will be reflected at a higher elevation in the solar atmosphere than the central ray, and so will be less attenuated.

B Solar Radio Emission[17]

The radio spectrum from the sun consists of a basic "quiet level" of radiation plus super-imposed disturbance which vary in both intensity and duration as functions of wave length.

1. Radiation from the Quiet Sun

The quiet-sun radio emission is due to thermal emission from the highly ionized gases in the chromosphere and corona. The noise intensity of a given frequency can be calculated from the temperature at the depth of origin and also can be measured experimentally. The two results are in good agreement as shown in Figure 11 (also in Figure 3). The apparent temperature increases linearly with wave length from 10^4 degrees K at $\lambda = 1$ cm, to 10^6 degrees K at $\lambda = 1$ meter.

2. Slow Variation of Quiet Sun Emission

There is a slow periodic variation of solar radiation intensity in the range of wavelengths from 10,000 mc/s (3 cm) to 500 mc/s (60 cm). This slow variation is shown in Figure 12. The intensity varies by 30% or 40% as the sun spot area in the disc of the sun goes through its monthly cycle.

3. Disturbed Radiation from the Sun

Disturbed radiation phenomena fall into three classifications. These are: a) outbursts associated with solar flares; b) noise storms associated with large sun spots; c) other isolated bursts.

a. Outbursts

In an outburst the radiation intensity leaps up by many orders of magnitude within a few seconds, remains high with large fluctuations for a period of several minutes, and then decays within the course of an hour to the original

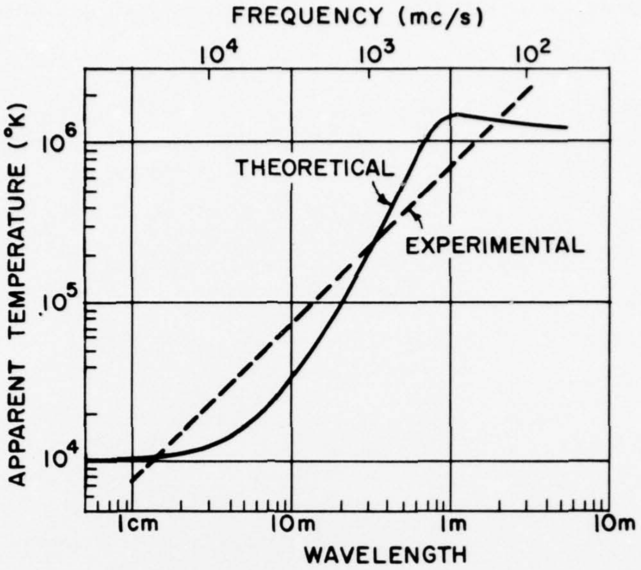

Figure 11. Experimental and Theoretical Values of Black-Body Temperature of the Quiet Sun as a Function of Wavelength

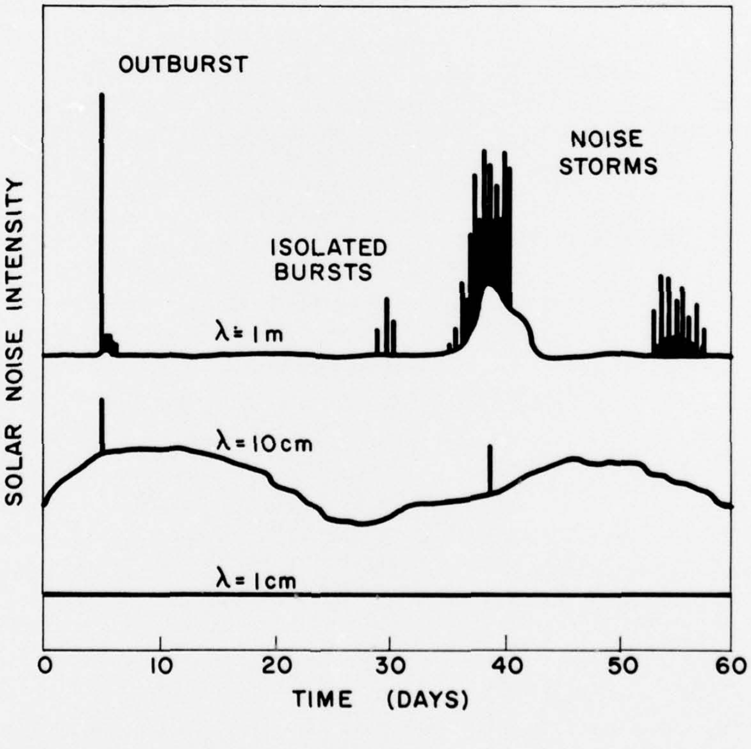

Figure 12. The Nature of the Enhanced Emission from the Sun at Various Wavelengths

level. The outburst may extend over the entire frequency range from 1 cm to 15 meters, though its intensity is greater in the lower frequencies. The initial increase in intensity is not simultaneous at all frequencies; the outburst appears first at the lower frequencies, indicating that it is associated with a disturbance rising from the inner levels of the sun to the outer ones. This disturbance is visible as a solar flare.

b. Noise Storms

Noise storms are generally less intense but of longer duration than outbursts. The intensity typically is 20 db above the quiet level for hours or even days. The enhanced radiation is circularly polarized, arising from the atmosphere above a sun spot. Noise storms do not extend across the spectrum but are generally limited to the metric wave lengths.

C. Conclusions: Calculation of Signal-to-Noise Ratio for Sun-reflected Radio Wave

In the absence of any experimental data, calculations of radio reflection from the sun will be based on a smooth sphere with radius equal to the optical value of 7 x 10^5 km, and losses in the atmosphere which increase with frequency as shown in Table 3. Since the quiet sun noise and also the disturbed radiation increase at lower frequencies, a compromise on operating frequency must be made. At a frequency of about 1400 mc/s, the quiet-sun radiation temperature is down to 2 x 10^4 degrees K and the disturbances are fairly well settled down to infrequent brief outbursts. The reflected signal can be calculated using:

$P_t = 10^6$ watts (a generous transmitter power)

$G_t = 50$ db $= 10^5$ (corresponds to 30-meter dish)

$R_{Sun} = 7 \times 10^5$ km

$d = 1.5 \times 10^8$ km

These figures yield:

$P_r = 1.4 \times 10^{-15}$ watts from a 30-meter receiving antenna

$= 1.4 \times 10^{-17}$ watts from a 3-meter receiving antenna

Attenuation in the solar atmosphere will reduce these results by 20 db, yielding:

$P_r = 1.4 \times 10^{-17}$ watts (30-meter antenna diameter)

$P_r = 1.4 \times 10^{-19}$ watts (3-meter antenna diameter)

As indicated above, for satisfactory reception this received signal must be about 14 db greater than the noise signal.

$$P_n = k(T_a + T_r)\sqrt{\frac{B}{\tau}}$$

where

T_a = antenna temperature, = 2×10^4 °K

T_r = receiver temperature, assumed negligible compared to T_a

B = predetector bandwidth = 1000 c/s

τ = postdetection integration time = 10 seconds

Using these figures,

$$P_n = 2.8 \times 10^{-18} \text{ watts}$$

so the S/N ratio is 5, or S/N = 7 db, with the 30-meter receiving antenna.

This ratio is too low for useful reception; the S/N should be about 15, or 10 db higher. Transmitter power used in this calculation is already overly generous, but some extra sensitivity might be picked up by reduction of predetection bandwidth, and/or by longer integration time. However, the possible improvement is quite limited; decrease of bandwidth would complicate the frequency tracking problem, and integration time for real-time data processing is limited to a maximum of about 30 seconds, due to leakage resistance in the large condensers used.[9] Even if sensitivity were raised to the tolerable minimum in this way, any increases in noise level would put out the system again.

The conclusion drawn is that the sun is not a useful reflector for reliable, real-time radio relaying, even at low data rates.

VI. CONCLUSIONS

The above studies and calculations indicate that a radio relay system for real time communication, even at very slow signaling rates, can usefuliy employ only the moon and Venus as reflectors. No other celestial body gives a strong enough return signal.

For two terrestial points (ΔL_h) hours apart in longitude, the moon is available approximately $\frac{12 - \Delta L_h}{24}$ of the time, and Venus $0.26 \times \frac{12 - \Delta L_h}{24}$ of the time.

Then the net probability of an available path is

$$(.57 - .05 \, \Delta L_h)$$

To attain greater reliability by increasing the useful range of such a system, transmitter power increases by several orders of ten are required. Such transmitter improvement is not likely to occur within the next several years.

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