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Optimum Frequencies for Outer Space Communication [1]

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Frequency dependence of radio propagation and other technical factors which influence outer space communications are examined to provide a basis for the selection of frequencies for communication between earth and a space vehicle or for communication between space vehicles.

1. Introduction

The probable future rapid advances in the use of satellites and space vehicles will intensify the requirements for adequate space communications. Since only modest transmitter power will be initially available in the space vehicle, careful engineering of the space circuits will be necessary to assure adequate communications and particular attention to the selection of radiofrequencies will be required. Optimum frequencies can be selected on the basis of the signal-to-noise ratio for a given transmitter power, a minimum distortion of phase and amplitude, the minimum likelihood of interference from other equipment, etc. This report takes signal-to-noise ratio as the sole criteria of frequency selection recognizing that diffraction and other distortions may cause problems in tracking and location.

2. Factors Affecting the Selection of Frequencies

All communication between earth and outer space must pass through the earth's atmosphere (including the troposphere and ionosphere). Communication between satellites will primarily involve radio paths outside the influence of the earth's atmosphere.

The atmosphere is frequency selective, allowing some frequencies to pass through readily while severely attenuating others. A range of frequencies in which waves readily penetrate the atmosphere is often called a "window."

Two principal ranges of frequencies pass readily through the atmosphere. They are: (1) The range between ionospheric critical frequencies and frequencies absorbed by rainfall and gases (about 10 to 10,000 Mc), and (2) the combined visual and infrared ranges (about 10^6 to 10^9 Mc).

The atmosphere is known to be partially transparent in a third range below about 300 kc. Waves are propagated through the ionosphere in this range by what is sometimes called the whistler mode. Propagation in this mode is not yet well understood.

The range 10 to 10,000 Mc is the most practical for communication purposes considering the present state of development in radiofrequency power generation. The upper limit of this range may be as low as 5,000 to 6,000 Mc during heavy rainstorms and the lower limit may be as high as 80 to 100 Mc depending upon the degree of solar activity, the location of the earth terminal, and the geometry of the signal path. On the other hand, the window may extend from as low as 2 Mc for polar locations during night-time periods to as high as 50,000 Mc at high altitude rain-free locations.

In the midportion of this window favorable propagation conditions exist, and circuit performance can be estimated on the basis of free-space propagation conditions by the following formula:

$$P'_t \propto \left(\frac{P'_r f^2 d^2}{G_t G_r}\right)$$

where: P'_t=required transmitter power, P'_r=minimum permissible receiver input power, f=frequency, d=distance between transmitter and receiver, G_t=transmitting antenna gain power, G_r=receiving antenna gain power.

Actual propagation conditions vary substantially from this free space assumption at frequencies near the edge of the radio window, and it is necessary to correct for ionospheric and tropospheric effects to obtain a true estimate of frequency dependence. This correction requires an estimate of tropospheric absorption [1] [3] at the higher frequencies and an estimate of ionospheric absorption at the lower frequencies [2]. In addition to estimating ionospheric absorption, an estimate of the probability of radio signals penetrating the ionosphere must be made [3].

To determine optimum frequencies, the variation of background radio noise within the radio window must also be considered:

(1) Cosmic noise predominates at the lower edge of the radio window and decreases with frequency until noise within the receiving equipment predominates.

(2) In most present-day facilities the receiving equipment noise tends to predominate above about 100 to 200 Mc for antennas directed toward average sky noise areas and above about 300 to 500 Mc for antennas directed toward high cosmic noise areas such as the Milky Way.

(3) If low noise receiving equipment such as the MASER amplifier is used, receiver noise may predominate above about 600 to 1,000 Mc.

[1] The basic material in this paper was unanimously adopted by the International Radio Consultative Committee at the IX Plenary Assembly in Los Angeles, April 1959, and is being issued as CCIR Report No. 115, Factors affecting the selection of frequencies for telecommunication with and between space vehicles.

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[3] Figures in brackets indicate the literature references at the end of this paper.

(4) Noise within conventional receivers normally increases slowly as the operating frequency is increased, but may tend to decrease at the higher frequencies if MASER amplifiers are employed.

For antennas of fixed physical size, high frequencies have the advantage of greater gain but the disadvantage of narrow beamwidths and associated tracking problems.

High speed vehicles traveling so that the distance between transmitter and receiver is rapidly changing have apparent frequencies differing from the actual transmitter frequencies by the Doppler frequency shift component in the direction of reception.

Within the solar system there is evidence of appreciable densities of electrons out to great distances from the sun.

Transmission time delay will become substantial in outer space communications, e.g., 2.6 sec are required for a round trip radio signal to the moon. This time delay is essentially independent of operating frequency.

3. Discussion

Although great distances are involved, the propagation medium in space beyond the first 500 miles of the earth's atmosphere is believed to be essentially transparent to radio waves. Thus we may estimate performance on the basis of free-space propagation. Frequency dependence of receiver input power under free-space propagation conditions depends upon the type of antenna at the transmitter and receiver. This frequency dependence is shown by the following free-space propagation formula:

$$P_r \propto \left(\frac{P_t G_t G_r}{f^2 d^2} \right)$$

where: P_r is receiver input power, P_t is transmitter power, and other symbols have the same meaning as before.

Frequency dependence of receiver input power for free space propagation conditions can be summarized as follows:

(1) If both the transmitting and receiving terminals of a free-space communication link use nondirective antenna (e.g., two vehicles in space) or if beamwidths at both terminals are fixed, the receiver input signal power increases as the frequency is decreased:

$$P_r \propto \left(\frac{P_t}{f^2 d^2} \right).$$

(2) If one terminal of a free-space communication link uses a directive antenna of fixed physical size and can operate with narrower and narrower beamwidths as frequency increases and the other terminal uses a nondirective antenna or a fixed beamwidth antenna, e.g., a directive antenna on the earth's surface ($G_t \propto f^2$) and a nondirective antenna on a space vehicle, the receiver input signal power is independent of frequency [$P_r \propto (P_t/d^2)$].

(3) If both terminals of a free-space communication link use directive antennas of fixed physical size and can operate with narrower and narrower beamwidths as frequency increases, e.g., a directive antenna on the earth's surface and a directive antenna on a more elaborate space vehicle ($G_t \propto f^2$ and $G_r \propto f^2$), the receiver input signal power increases as the frequency is increased [$P_r \propto (P_t f^2/d^2)$].

Frequency dependence for practical space-communication circuits requires that atmospheric effects be included. Receiver input signal power and receiver input noise power for a directive receiving antenna and nondirective transmitting antenna are shown in figure 1. The receiver input power includes ionospheric and tropospheric effects for a 1,000-mile propagation path tangential to the earth's surface for summer midday operation during periods of high solar activity and for moderate rain conditions such as experienced 1 percent of the time in the Washington, D.C., area. This is typical of the most adverse propagation conditions normally encountered in the absence of sudden ionospheric disturbances, instances of intense sporadic *E*, areas of auroral activity, or rain conditions of cloudburst proportions. During more favorable propagation conditions, such as a propagation path normal to the earth's surface during the night at the lower frequencies or in a high altitude rain-free location for the higher frequencies, the receiver input power can be expected to be essentially independent of frequency over a wider range of frequencies. The receiver input power as shown between 100 and 500 Mc in figure 1 will be typical over a much wider frequency range during these favorable propagation periods.

Figure 2 shows essentially the same information as figure 1, except that the distance is increased to 300,000 miles, the receiving antenna diameter is increased to 120 ft, the use of cooled amplifiers such as the MASER is anticipated, quasi-maximum

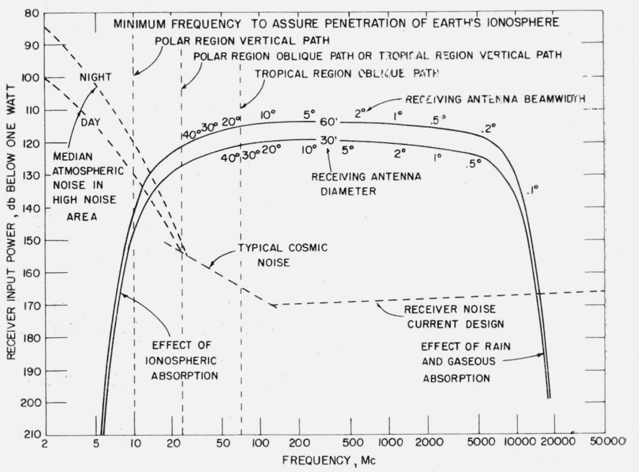

FIGURE 1. *Technical considerations in selecting frequencies for radio communication to earth from a space vehicle based on 1,000 miles (typical satellite distance).*

Omnidirectional vehicle antenna—30- and 60-ft diam parabolic receiving antenna. One watt transmitter—one kilocycle bandwidth.

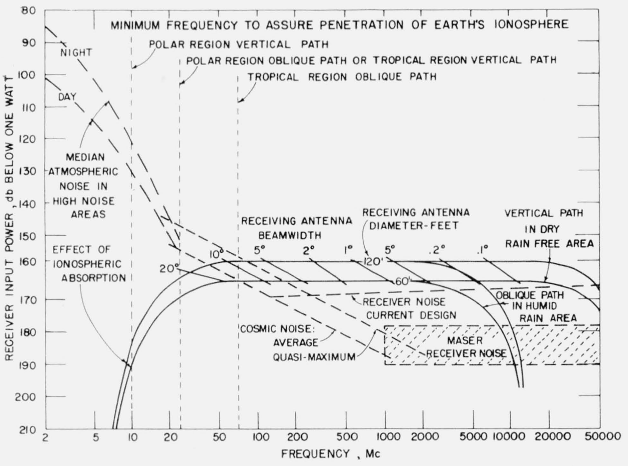

FIGURE 2. *Technical considerations in selecting frequencies for radio communication to earth from a space vehicle based on 300,000 miles (distance to circle moon).*

Omnidirectional vehicle antenna—60- and 120-ft diam parabolic receiving antenna. One watt transmitter—one kilocycle bandwidth.

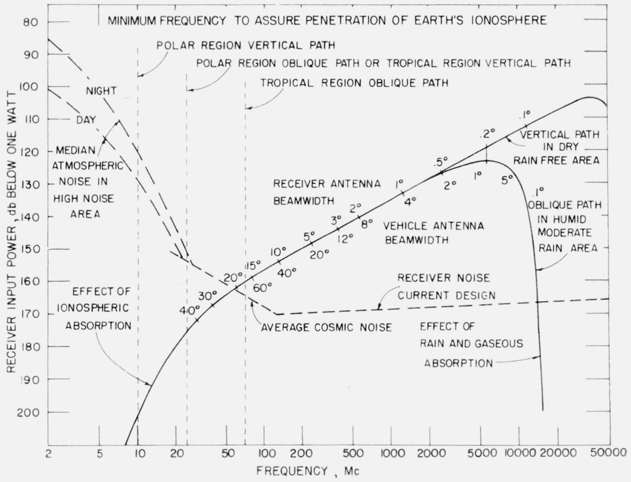

FIGURE 3. *Technical considerations in selecting frequencies for radio communication to earth from a space vehicle based on 300,000 miles (distance to circle moon).*

Fifteen foot diameter parabolic vehicle antenna—60-ft diam parabolic receiving antenna. One watt transmitter—one kilocycle bandwidth.

values of cosmic noise for high gain antennas are given, and receiver input power is shown for a vertical path in a dry rain-free location.

Figure 3 shows the theoretical improvement at the higher frequencies if a directive antenna is used on the space vehicle. Although receiver input power is shown only for a 15-ft diam parabolic antenna on the space vehicle, this improvement with increased frequency applies for all directive antennas of fixed physical size. Since the increase in antenna gains at the higher frequencies more than offsets the slightly increased power requirement due to increased receiver noise at these frequencies, the first impression is that the higher the frequency the better the expected circuit performance as long as the frequency is below the upper limit of the radio window. (About 6,000 Mc for oblique paths during moderate rainfall and up to 50,000 Mc for high altitude rain-free location.) The physical problem of antenna design and tracking, however, establishes minimum permissible antenna beamwidths and is believed to place practical limits on this upper frequency at much lower values.

Theoretical effective power requirements for greater distances are shown in figure 4 as a function of frequency. Power requirements shown are the minimum detectable radiated power (6 db S/N ratio) from a space vehicle to a 60 ft diam earth-based antenna under the most adverse propagation conditions normally encountered. Allowances for fading and antenna beamwidth limitations are not shown by the chart. Approximate distances from earth to the moon, the sun, certain planets, and to typical manmade satellites are shown.

For systems with minimum permissible beamwidths, any increase in antenna size reduces this practical upper frequency since antenna beamwidth decreases with increase in antenna size. The relationship between antenna size, operating frequency, and antenna beamwidth for parabolic antennas is shown in figure 5. If either the ground terminal or

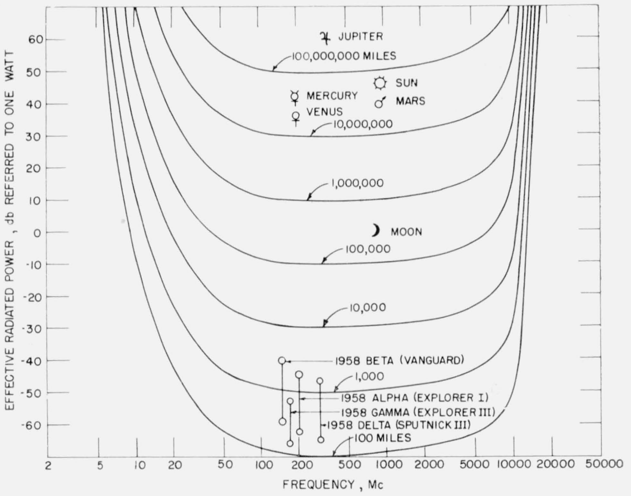

FIGURE 4. *Theoretical effective radiated power required from space vehicle to permit detection on earth.*

One kilocycle bandwidth—6 db signal-to-noise ratio—receiving antenna—60-ft parabola—daytime operation—high solar activity—rain and gaseous absorption based on 1 percent of time (Washington, D.C.). Radio path approximately horizontal to earth—receivers of current design.

space vehicle maximum antenna physical size and minimum antenna beamwidth is fixed, the optimum frequency can be estimated from figure 5.

Figure 6 is a nomogram to estimate the bandwidth allowance required to accommodate the Doppler frequency shift for radio transmissions from high speed vehicles.

For communication between vehicles in outer space, free-space propagation conditions apply over a wide frequency range. Frequencies above or below the earth's radio window can be expected to minimize interference problems with operations on earth. These frequencies will be below about 10 Mc or above about 10,000 Mc. Selection of an optimum frequency can be based on free-space

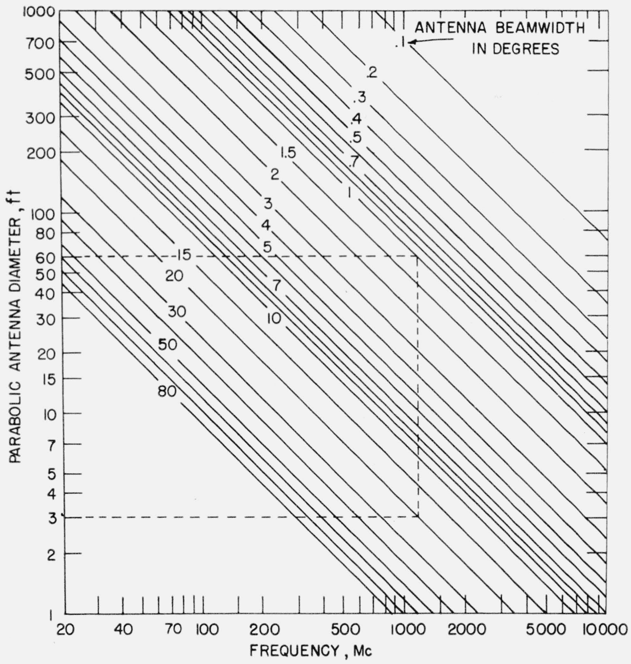

FIGURE 5. *Chart to estimate optimum frequencies for outer space communication when directive antennas are used at both terminals, and physical antenna size and minimum permissible antenna beamwidth are fixed factors.*

Example: Based on a 1 deg minimum beamwidth for the earth terminal, the optimum frequency for a 60-ft diam parabolic is about 1,200 Mc and the optimum vehicle antenna size is a 3-ft diam parabolic based on a 20-deg minimum beamwidth criteria for the space vehicle antenna.

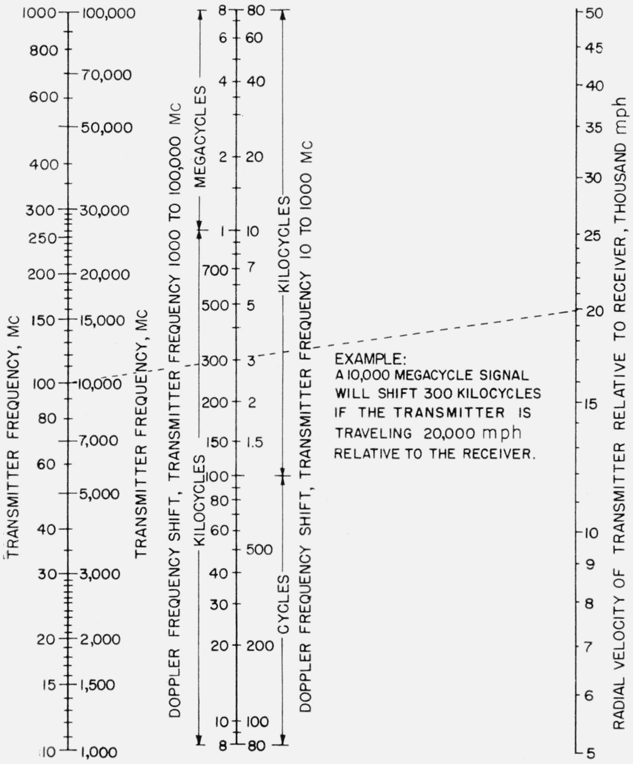

FIGURE 6. *Chart to estimate Doppler frequency shifts.*

propagation but requires an estimate of noise powers in outer space, particularly as to the radio noise at frequencies between 2 and 10 Mc. Frequencies below 2 Mc are considered impractical because of antenna sizes required and the substantial plasma frequencies probably occurring in outer space during periods of severe magnetic storms. If radio noise is excessive below 10 Mc and if antenna orientation problems limit the use of high gain antennas, the optimum frequency for communication between space vehicles may fall within the 10 to 10,000 Mc radio window.

4. Conclusions

Communications between earth and outer space are theoretically possible within two broad frequency bands; about 10 to 10,000 Mc and in the infrared and optical regions. At the current state of the equipment art the lower band is definitely favored.

The upper limit of the lower band is dependent upon tropospheric conditions, and the lower limit depends upon ionospheric conditions. The band, therefore, is not sharply defined but is dependent upon geographic location and time of operation. For reliable communication to any earth terminal location, this lower band narrows to about 70 to 6,000 Mc.

Within the 70- to 6,000-Mc band the optimum frequency will depend upon the specific communication service required and will be a compromise between the maximum practical antenna size, the minimum beamwidth which will permit acquisition or tracking, and the radio noise levels.

For space vehicles using essentially omnidirectional antennas communicating with earth terminals using directive antennas, the receiver input power will be constant with frequency over much of the 70- to 6,000-Mc band, and the background noise level and beamwidth requirements to assure tracking determines the optimum frequency. Background noise from sources within the antenna beam (cosmic noise) predominates at the lower edge of the band and noise generated within the first stages of the receiver predominates at the upper edge of the band. The crossover point between these noise sources determines the frequency with the maximum signal-to-noise ratio and, therefore, the optimum frequency for communication if antenna beamwidths are satisfactory at these frequencies. These optimum frequencies are about as follows:

(1) 100 to 200 Mc for conventional receivers with antennas directed toward average cosmic noise sources;

(2) 300 to 500 Mc for conventional receivers with high gain antennas directed toward high cosmic noise sources such as the Milky Way;

(3) 1,000 to 3,000 Mc if the receiver is equipped with cooled amplifiers such as the MASER.

Antenna beamwidths must always be considered and compromises made between beamwidth and optimum signal-to-noise ratios. Since receiver noise increases only slowly with frequency and receiver input power is constant up to about 6,000 Mc, higher frequencies may be used with only slight decrease in S/N ratio but at the expense of increased tracking difficulty.

As more elaborate space vehicles capable of maintaining attitude and employing directive antennas are developed, the receiver input power will increase with frequency and the background noise level will no longer determine the optimum frequency. The optimum frequency will be governed by a compromise between maximum practical physical antenna size and the minimum antenna beamwidth consistent with acquisition and tracking techniques. If attitude control of the space vehicle and acquisition and tracking limitations of the ground stations establish minimum antenna beamwidths at both terminals, the fixing of the maximum practical antenna size at either terminal will establish the optimum frequency and antenna size for the other terminal. As attitude control and tracking techniques improve the optimum frequency increases. As larger antennas become practical the optimum frequency decreases. The optimum frequency is therefore closely associated with particular applications and can be selected once the physical antenna size and minimum beamwidths are established. For a 1-deg minimum beamwidth for the earth antenna and a 20-deg minimum beamwidth for the space vehicle antenna, optimum combinations of frequencies and antenna sizes are shown in table 1.

TABLE 1

Earth antenna diam	Optimum frequency	Space vehicle optimum antenna diam
ft	*Mc*	*ft*
30	2400	1½
60	1200	3
120	600	6

The optimum frequency for communication between outer space vehicles is unknown. It will depend upon radio noise in outer space and upon the ability of the vehicles to maintain attitudes and thereby use directional antennas. For omnidirectional antennas or for any fixed antenna beamwidth the optimum frequency will be the lowest frequency consistent with the practical antenna size and outer space radio noise levels. Since operation at frequencies outside the radio window will tend to minimize the radio interference problem between the space vehicles and earth, space vehicles with omnidirectional or broad beamwidth antennas should be assigned trial frequencies below 10 Mc if antennas at these frequencies are practical. For more elaborate space vehicles with the ability to properly orient antennas with very narrow beamwidths, operation at frequencies above or near the upper edge of the radio window is recommended (above 10,000 Mc). If physical antenna size limits the use of frequencies below 10 Mc and if the inability to orient antennas limits the use of frequencies above 10,000 Mc, antenna size and antenna beamwidth compromises will determine optimum frequencies. Frequencies may then be selected by the use of figure 5 in the same manner as for communication between space vehicles and earth, when both terminals use directive antennas except that the earth's ionospheric and tropospheric limitations will no longer apply.

5. References

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The following paper has just been brought to the author's attention:

S. Perlman, L. C. Kelley, W. T. Russell, Jr., and W. D. Stuart, Concerning optimum frequencies for space communication, IRE Trans. on Communs. Systems, **CS-7,** 167 (Sept. 1959).

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