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SUGGESTED FREQUENCY RANGES FOR SPACE MISSIONS

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ABSTRACT

The purpose of this report is to review briefly the limiting parameters affecting frequency selection for space missions in the 0.1 MHz to 100 GHz radio-frequency range. Frequency selection for capsule recovery is also considered.

SUMMARY

This study report affords a basis for space mission frequency allocation in the 0.1 MHz to 100 GHz frequency range. Limitations as afforded by the earth's troposphere and ionosphere as well as those imposed by FCC commercial broadcast frequency assignments are presented. The effects of practical and theoretical antenna design constraints are included. In brief, the following recommendations are made for communication between:

1. Earth Orbiting Vehicle – Communication Satellite.

The present space frequency assignments at VHF (nominal 136 MHz) and low UHF (nominal 400 MHz) should be employed whenever the communication satellite relay of low power signals from either aircraft or earth orbiting space vehicles is required. The primary factors involved in such a selection are the frequency independent effective receiving antenna sky noise temperature (approximately 300°K) of the earth viewing communication satellite and the increased receiving antenna effective aperture realized at the lower frequencies for a given antenna conical beamwidth. Such considerations are particularly important whenever low gain or omnidirectional antennas are employed at the space vehicle or aircraft to obviate antenna tracking.

2. Earth Terminal – Spacecraft

Earth terminal to spacecraft communication frequency selection is not critical and any available uplink frequency in the 0.1 MHz to 10 GHz range is satisfactory. Tracking of space vehicles, however, should be confined to frequencies above 2 GHz to minimize measurement errors attributable to refraction and time delay within the ionosphere. Above 10 GHz tropospheric attenuation increases rapidly and is particularly severe at low elevation angles and at the absorption resonance frequencies of 22.2 GHz (water vapor) and approximately 60 GHz (Oxygen).

3. Spacecraft – Earth Terminal

This is a very critical link for spacecraft beyond the earth's ionosphere (i.e., heights greater than 1000 km). Because of power limited spacecraft transmission, operation is required in a frequency range minimizing earth terminal sky noise in order to derive maximum benefit from low thermal noise receiver design. The effects of precipitation keep the upper bound of this frequency range below 10 GHz. It is seen that frequencies in the 1 GHz to 7 GHz range should be utilized for all deep space downlink radio communication.

4. Spacecraft - Spacecraft

For spacecraft to spacecraft communication (both vehicles above the troposphere, i.e., height above earth greater than 30 km) frequencies from 40 GHz to 100 GHz can be employed to both avoid interference from the 1 – 10 GHz portion of the microwave spectrum and to realize up to 8 dB enhancement over lower frequency operation. If omnidirectional or low gain antennas are employed to simplify antenna pointing then the use of lower frequencies (400 MHz) is required to take advantage of the increase in effective receive antenna capture area with decreasing frequency. The usefulness of VHF (nominal 136 MHz) in widely separated spacecraft to spacecraft communication is limited by high galactic background noise. While not a subject of radio frequency allocation, it is nevertheless of interest to note the possible desirability of laser vehicle to vehicle communication at 3×10^4 GHz (infrared).

SUGGESTED FREQUENCY RANGES FOR SPACE MISSIONS

1.0 INTRODUCTION

The basis for existing frequency allocations for the various commercial and government radiowave propagation requirements is to a large extent historical with the earlier assignments corresponding to the lower frequencies. Until the advent of the communication satellite, point to point radio communication between remote earth terminals was confined to frequencies below 30 MHz, the practical upper frequency limit for ionospheric skywave propagation. The first commercial television and FM broadcast assignments, which were established almost 20 years ago, began at approximately 50 MHz and have subsequently been extended to 890 MHz. In this frequency range (50-890 MHz), which includes all of the present U. S. FM Radio broadcast, VHF television broadcast and UHF television broadcast channels, there are certain gaps in the spectrum set aside for space communication and research. One purpose of this report is to point out the desirability of retaining these VHF and UHF space allocations.

Another objective of this paper is to briefly review the relative advantages and disadvantages of radiowave propagation in the 1 GHz to 10 GHz frequency range. Finally an estimate is made of the extent to which the millimeter wavelength portion of the spectrum can be utilized for future space communication and research. As of today (1966) government radiofrequency allocations for space research include frequencies up to 34.5 GHz.

Future as well as current frequency allocations for space technology in the frequency range of 0.1 MHz to 100 GHz are discussed in light of the following considerations:

1. Propagation loss.
2. Radiofrequency noise.
3. Antenna requirements.
4. Type of service required.
5. Existing frequency allocations.

2.0 ADVANTAGES AND DISADVANTAGES OF SPECIFIC PORTIONS OF THE RADIO FREQUENCY SPECTRUM FOR SPACE TECHNOLOGY

For purposes of discussion the frequency range of 0.1 MHz to 100 GHz is divided into four parts, namely:

1. 0.1 MHz to 50 MHz (skywave propagation, below 30 MHz noise primarily due to atmospherics)
2. 50 MHz to 1 GHz (commercial TV and FM broadcast, galactic noise region)
3. 1 GHz to 10 GHz (minimum sky noise)
4. 10 GHz to 100 GHz (tropospheric absorption noise).

2.1 Skywave Propagation (0.1 MHz to 50 MHz)

There are a number of reasons why the 0.1 MHz to 50 MHz frequency range is not desirable for space communication. One reason is the fact that signals traversing the ionosphere in many instances undergo a continuous refraction amounting to a virtual reflection. That is, the energy from an earth station instead of penetrating the ionosphere is returned to earth at some remote geographical location. This phenomena which is a function of frequency, geographical location, time of year, time of day, sunspot activity and so on, is sufficiently predictable to be the chief means of worldwide radio communication. These so called high frequency (HF) communications circuits generally operate between 3 MHz and 30 MHz. Between 30 MHz and 50 MHz the skywave propagation is not sufficiently consistent to be considered useful. Skywave propagation might be considered advantageous in rescue operations since the reflection loss of the ionosphere is often negligible in which case the keyed radiation from an HF transmitter of 1 to 10 watts average power can be detected up to 2000 km (1080 n.mi.) away. It should be noted that while a skywave signal transmitted via a single ionospheric reflection might be detected hundreds of kilometers away, there will always be a "dead zone" corresponding to the gap between the absence of ground-wave propagation and the appearance of skywave. Above 5 MHz a skywave skip distance of less than 200 kilometers (108 n.mi.) is rarely realized due to the near vertical incidence above the critical frequency and hence, penetration of the ionosphere by the transmitted signal.

The fact that the losses associated with ground wave propagation over sea water for vertically polarized energy decrease with decreasing frequency indicates another advantage of the lower frequencies if rescue at sea is involved. Figure 1 shows the ground wave loss relative to line-of-sight which can be expected for a number of frequencies when vertically polarized energy is transmitted over sea water. Both horizontally and vertically polarized earth terminal antennas are suitable for skywave propagation. Only vertically polarized earth terminal antennas efficiently excite a groundwave propagation mode.

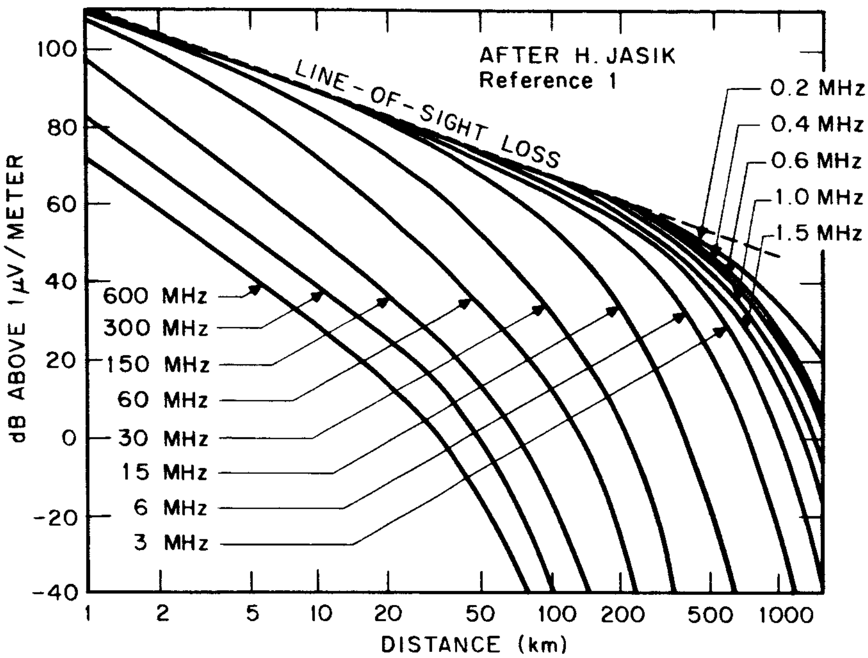
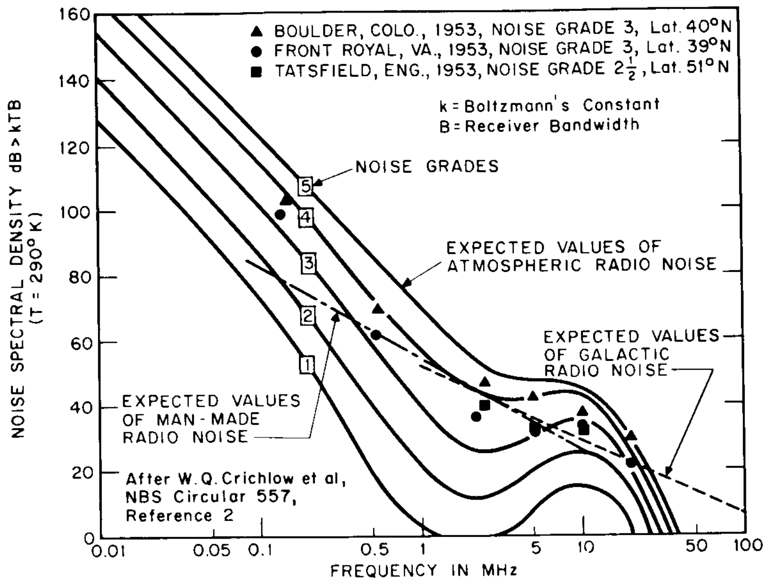


Figure 1–Field intensity for vertical polarization over sea water for 1 kw radiated power from a grounded whip antenna

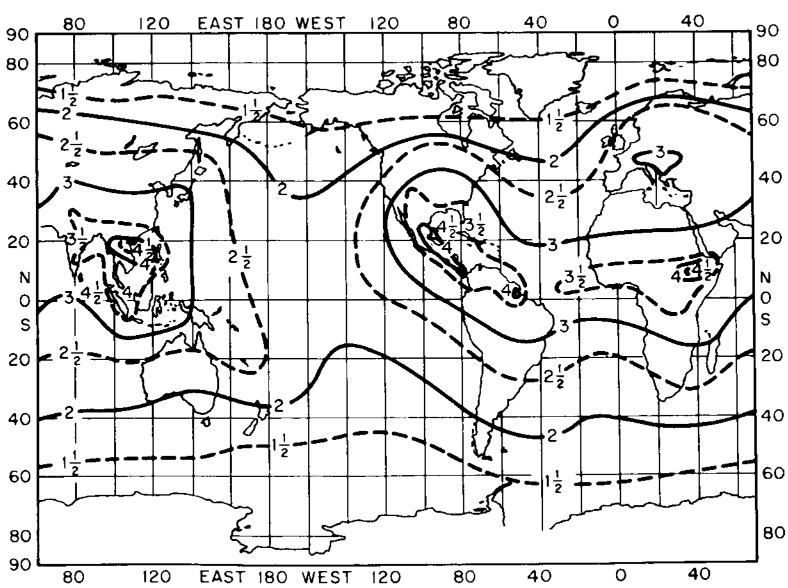
Below 30 MHz the receiver noise increases rapidly with decreasing frequency. This noise is due to atmospherics (lightning) and includes local disturbances as well as noise coupled by way of skywave from all the major storm centers of the world. Figure 2a, which is extracted from NBS Circular 557 (Reference 2) presents an estimate of the median value of atmospheric noise spectral density for a particular time block (0800 to 1200 hours local time, summer). Since the atmospheric noise level is a function of geographical location the curves are for 5 "noise grades." The NBS "noise grades" connect geographical locations having the same median atmospheric noise level for a particular time of year. The "noise grade" arbitrarily ranges from 1 to 5 with 1 corresponding to geographical locations having a minimum noise level and 5 corresponding to those with a maximum noise level. Figure 2a indicates 5 levels of noise which can be related to the estimated worldwide noise distribution for June-July-August by means of Figure 2b which was also obtained from NBS Circular 557. Since the noise level in the 0.1 MHz to 50 MHz is determined by noise external to the receiving system, low noise antenna or receiver design affords no significant improvement in received signal to noise power ratio.

Receiving antennas in this frequency range need not be efficient, only directive, to afford enhancement of the desired signal. It should be noted that below 20 MHz man-made interference (resulting from teletype, voice, loran, international telegraph, etc.) will invariably exceed the already high noise level due to atmospherics.



MEDIAN VALUES OF RADIO NOISE EXPECTED
FOR A SHORT VERTICAL ANTENNA
FOR THE TIME BLOCK, 0800-1200, SUMMER

Figure 2a



NOISE DISTRIBUTION FOR PERIOD JUNE-JULY-AUGUST

Figure 2b

Unlike the receiving antenna in this frequency range, the transmitting antenna must be efficient if transmitter power is limited. In the case of a vertical antenna over a ground plane this implies a physical length between an eighth to a quarter wavelength. The shorter length can be impedance matched to the transmitter by means of a series inductance or loading coil at the expense of reduced efficiency. At 10 MHz a quarter wavelength antenna is 7.5 meters in length. At lower frequencies (0.1 MHz), where sea-rescue communications via ground wave might be contemplated, the transmitting antenna size becomes prohibitive.

2.2 Galactic Noise Region (50 MHz - 1 GHz)

One obvious constraint in frequency selection in the 50 MHz to 1 GHz range is the FCC commercial assignment for U. S. FM radio broadcast and television broadcast service. These assignments are summarized in Table I. Since these assignments involve equipment designed for public use, it is extremely doubtful that they will be re-allocated for space technology in the foreseeable future. Nevertheless, as will be pointed out, it appears desirable to at least retain the current space allocations in this range (approximately 118-138 MHz, 148-162 MHz, and various assignments between 235-450 MHz, Reference 4). Figure 3 picks up the galactic noise at 100 MHz where Figure 2a left off. Figure 2a shows a galactic equivalent noise temperature 6 db above 290°K or approximately 1150°K equivalent noise temperature for a short vertical antenna at 100 MHz. Figure 3 which is for a directional antenna indicates an equivalent temperature spread from 400°K to 8000°K at 100 MHz depending on antenna pointing. It is also noted that in the 100 MHz to 1 GHz range certain noise centers within the galaxy do not emit randomly polarized radiation in which case the noise level at certain frequencies is a function of receiving antenna polarization. The noise level for zenith pointing is seen to be a minimum between 1 GHz and 10 GHz and this fact is often presented as a reason for confining space radiowave transmissions between 1 GHz and 10 GHz. However, this criterion is not appropriate for the uplink to a communication satellite employing a directive earth illuminating antenna. Such a communication satellite viewing the earth would not intercept appreciable galactic noise, but rather view the earth's effective temperature of approximately 300°K independent of frequency. This is also true of an earth orbiting spacecraft employing an antenna designed to view primarily the earth. Thus the optimum uplink frequency from an earth or near earth terminal to a communication satellite or earth orbiting spacecraft is not necessarily in the 1 GHz to 10 GHz range.

If the uplink transmitter can radiate average power at a level of tens of kilowatts, then the uplink frequency selection is not too critical. If the uplink is power limited, as in the case of transmission from an aircraft or earth orbiting spacecraft to a communication satellite, then there is an argument for using frequencies lower than 1 GHz.

Table I
Commercial Broadcast Frequency Allocations (Reference 3)

Broadcast Service	Frequency Band MHz	Channel Designation
Television	54 - 72	2 - 4
Television	76 - 88	5 - 6
FM Radio	88 - 108	201 - 300
Televison	174 - 216	7 - 13
Television	470 - 890	14 - 83

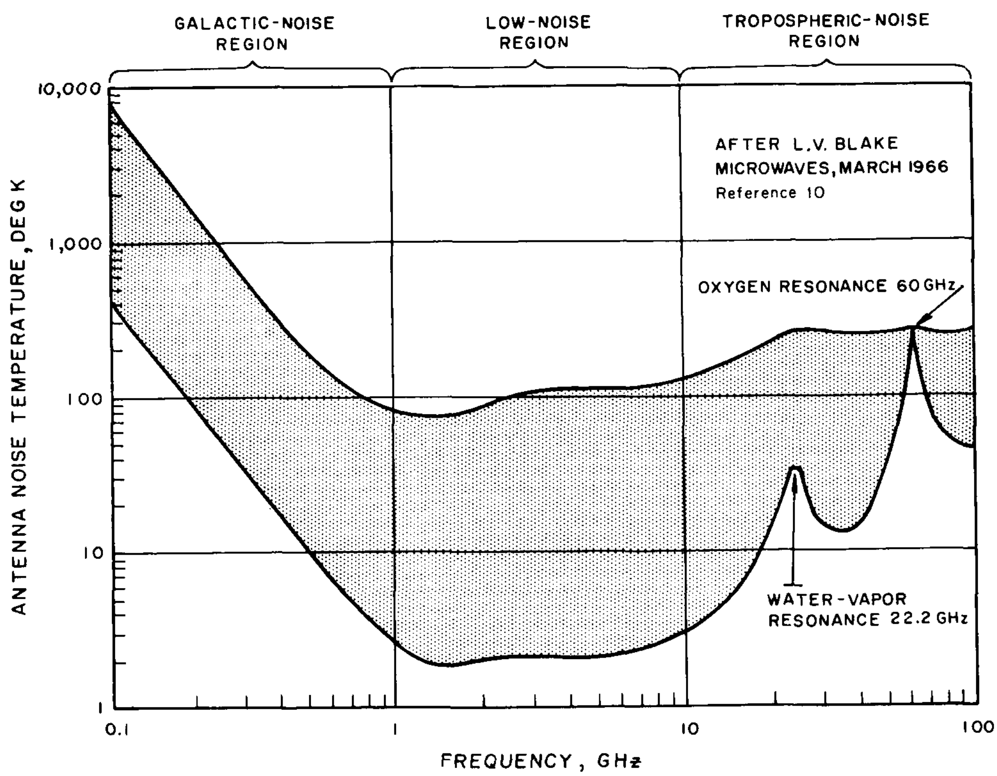


Figure 3–Irreducible noise temperatures of an ideal, ground-based antenna. The antenna is assumed to have a very narrow main beam without sidelobes or electrical losses. Below 1 GHz, the maximum values are for the beam pointed at the galactic center and the minimum values for the beam pointed at the galactic poles. At higher frequencies, the maximum values are for the beam just above the horizon and the minimum values for zenith pointing. The low-noise region between 1 and 10 GHz is most amenable to application of special, low-noise antennas.

Consider the maximum on axis power gain of a symmetric antenna array which can be expressed as being inversely proportional to the square of its conical beamwidth.

$$G = \frac{K}{\phi^2} \tag{1}$$

where: K = a constant $\doteq 27000$

ϕ = conical beamwidth (degrees).

But the antenna effective receiving aperture, A_r, (which for a given incident power density determines the received power level) is given by:

$$A_r = \frac{G\lambda^2}{4\pi} \quad \text{(Reference 5)} \tag{2}$$

where: A_r = effective receiving aperture (meters^2)

λ = wavelength (meters)

G = maximum on-axis antenna gain (dimensionless)

Combining (1) and (2)

$$A_r = \frac{K\lambda^2}{\phi^2 \, 4\pi} \tag{3}$$

Since antenna steering at the communication satellite is not desirable from a standpoint of complexity (and hence reliability), the coverage angle ϕ in equation (3) is fixed in any given application. For maximum gain, ϕ, should be as small as possible consistent with the required coverage between various earth or near earth terminals. For a synchronous satellite an optimum value of ϕ on the order of 25° is indicated. Thus for a given incident power density (watts per meter^2) at the communication satellite, the only parameter which can be altered to increase the effective receiving aperture and hence received signal level is the wavelength, λ (equation 3). Increasing λ by a factor of 10, increases the possible signal power level at the communications satellite by 20 db, assuming of course, an incident power density independent of frequency.

The assumption of incident power density at the communication satellite independent of frequency is consistent with the use of omni or near omni-directional antennas at the near earth terminal to obviate antenna tracking. This is exactly the situation considered recently (1965) with the relay of aircraft transmission at 136 MHz via Syncom III (Reference 6). In this series of experiments an omni antenna at the aircraft did in fact permit recording of telemetry via Syncom III although the signals were marginal.

Syncom III radiated less than 1 watt at 136 MHz. This aircraft to satellite experiment will be pursued further in late 1966 with the launching of the first NASA Applications Technology Satellite, (ATS), which employs an 8 element 136 MHz phased array capable of continuously illuminating the earth (Reference 7). The ATS satellite will radiate 40 watts at 136 MHz.

The lower frequency limit for such communication satellite antenna design is determined by the physical antenna size required to achieve the desired beam-width and hence gain.

The foregoing has indicated the relative advantages which can in certain instances be offered by frequencies in the 50 MHz to 1 GHz frequency range if voice or telemetry are to be relayed. If tracking of an aircraft or earth orbiting spacecraft is to be accomplished in this frequency range then the effect of the ionosphere on range, range rate and angle measurement must be carefully considered.

The effective index of refraction at any point within the ionosphere decreases with increasing frequency and for frequencies above 100 MHz is given approximately by: (Reference 8)

$$n \approx 1 - \left(\frac{40.3\,N_e}{f^2}\right) \tag{4}$$

where: n = index of refraction

N_e = electron density (electrons/meter^3)

f = frequency in Hz

Signal delay and signal refraction are both functions of the index of refraction, the lower frequencies sustaining the greatest distortion. A survey report covering the effects of the ionosphere as well as the troposphere upon range, range rate and elevation angle tracking data is given in Reference 9.

Another advantage of the lower frequencies which is currently employed at all tracking sites is the possibility of receiving a strong off-axis signal at VHF during initial acquisition and then effecting a subsequent transfer to high resolution track at S or C-band.

One final favorable feature of the lower frequencies if voice communication is relayed by communication satellite is the fact that the Doppler shift of the signal decreases with decreasing frequency. That is:

$$|\Delta f| \doteq \pm \frac{|V_r|}{c} (f_0) \tag{5}$$

where: $|V_r|$ = absolute value of radial velocity of vehicle relative to communication satellite

c = velocity of light = 3×10^8 (meters/second)

f_0 = nominal carrier frequency (Hz)

Δf = Doppler shift (Hz)

Thus if no Doppler tracking is employed at the communication satellite receiver, the lower frequencies require less receiver bandwidth to continuously receive a given carrier. If the required bandwidth to receive a given modulated signal is less than that required to accommodate the Doppler shift, then the lower carrier frequencies result in less received noise. The noise power spectral density at the communication satellite viewing the earth with a directive array is:

$$\Phi = T_e k \tag{6}$$

Φ = spectral density while viewing earth (watts/Hz)

T_e = effective noise temperature $\doteq$ 300°K

k = Boltzmann's constant = 1.38×10^{-23} Joules/°K.

If Doppler tracking is employed at the communication satellite then the range of the frequency excursion of the local oscillator is less at the lower frequencies thus presenting a less severe lock-up and subsequent automatic frequency tracking problem.

2.3 Low Sky Noise Region (1 GHz - 10 GHz)

The "low noise region" indicated in Figure 3 is strictly applicable to an earth or near earth antenna which is not illuminating, either partially or totally, specific radiating bodies such as the sun, moon or earth. Figure 3 is important when considering earth terminal reception of signals from a spacecraft. It is noted that the upper limit of tropospheric absorption noise (in the absence of precipitation) above 10 GHz increases rather gradually to approximately 300°K. It might be thought that under certain conditions frequencies between 10 GHz and 100 GHz could be useful for earth terminal reception. However, with the exception of ionospheric absorption (which as shown by Figure 4 is negligible above 1 GHz) all the noise and attenuation effects attributable to the atmosphere tend to increase with increasing frequency.

Figure 5 indicates the rather severe attenuation low elevation angle signals above 10 GHz undergo in traversing the entire atmosphere. The absorption resonance lines at 22.2 GHz and 60 GHz present particularly high attenuations. Figure 6 indicates the frequency dependence of attenuation in db per km of rain thickness which can be expected for a number of different rates of rainfall. Finally Figure 7 presents an estimate of the increase in effective sky temperature (i.e. noise temperature) as a function of rain-rate and frequency. The foregoing considerations keep the optimum earth terminal receiving frequency in the 1 GHz to 10 GHz range. The present Unified S-Band downlink frequencies at a nominal 2.3 GHz and the AN/FPS-16 or AN/FPQ-6 pulse radar systems at a nominal 5.4 GHz fall within this range. However, as is pointed out in the next section of this report, certain frequencies above 10 GHz appear well suited for communication between spacecraft which are above the earth's troposphere (h > 30 km) in which case the tropospheric absorption noise indicated in Figure 3, the attenuation indicated in Figure 5 and the precipitation effects indicated in Figures 6 and 7 are of no consequence.

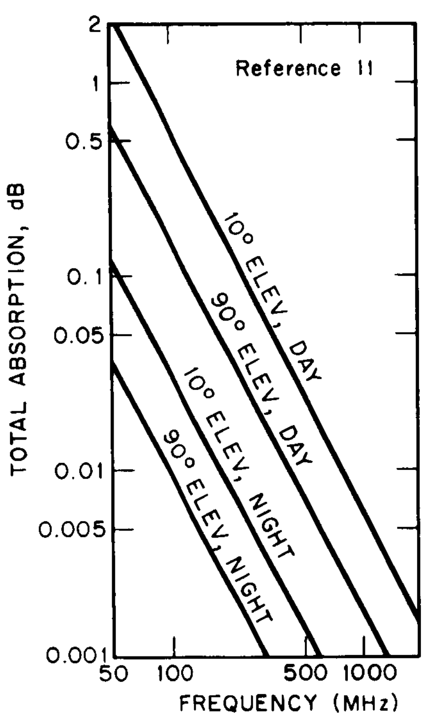


Figure 4–Ionospheric attenuation for a source at 1000 km height

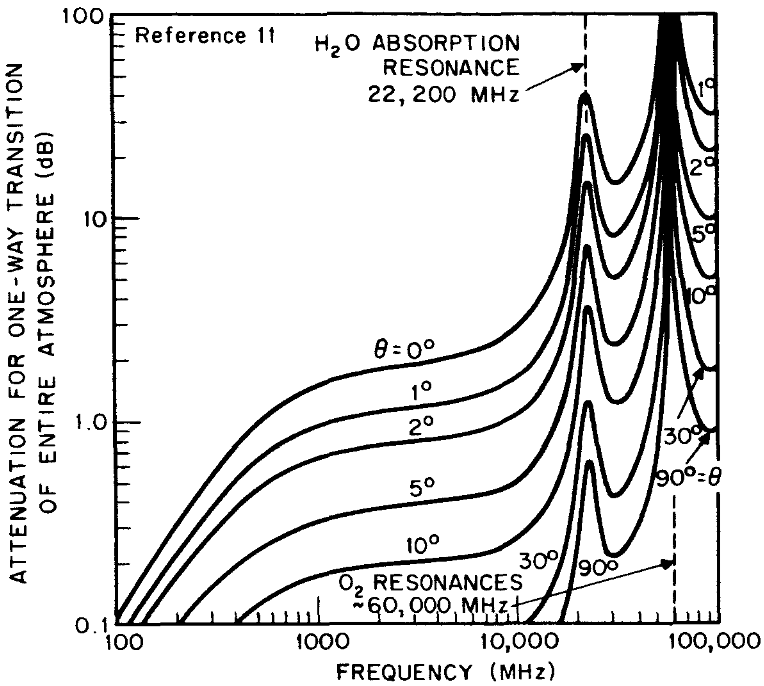


Figure 5—One way attenuation through the standard summer atmosphere due to oxygen and water vapor.

2.4 Tropospheric Attenuation and Noise Region (10 GHz - 100 GHz)

The radio spectrum from 10 GHz - 100 GHz represents a frequency range of relatively high attenuation if transmission through the earth's atmosphere is required. The atmospheric noise and attenuation associated with this portion of the spectrum is indicated in Figures 3 and 5 respectively. It has also been suggested that whenever the atmospheres of Mars, Venus, or Jupiter are traversed by radio signals that 3 GHz be used for optimum communication efficiency (Reference 14).

However, there are at least two situations where millimeter wavelength transmissions might be used to advantage. The first is during spacecraft reentry where the attenuation due to plasma formation (i.e., ionization due to reentry heating whenever temperatures exceed 3000°K) can often exceed that due to atmospheric attenuation. Since this phenomenon is an inverse function of frequency, communication blackout due to plasma formation under certain conditions might be minimized by using higher frequencies (100–400 GHz). In any particular case the degree to which reentry communications can be free from blackout will depend on many spacecraft parameters including: operating frequency, reentry velocity, altitude, orientation, physical structure and antenna design. Figure 8 suggests the severe attenuation associated with reentry velocities on the order of 9 km/sec at an altitude of 61 km.

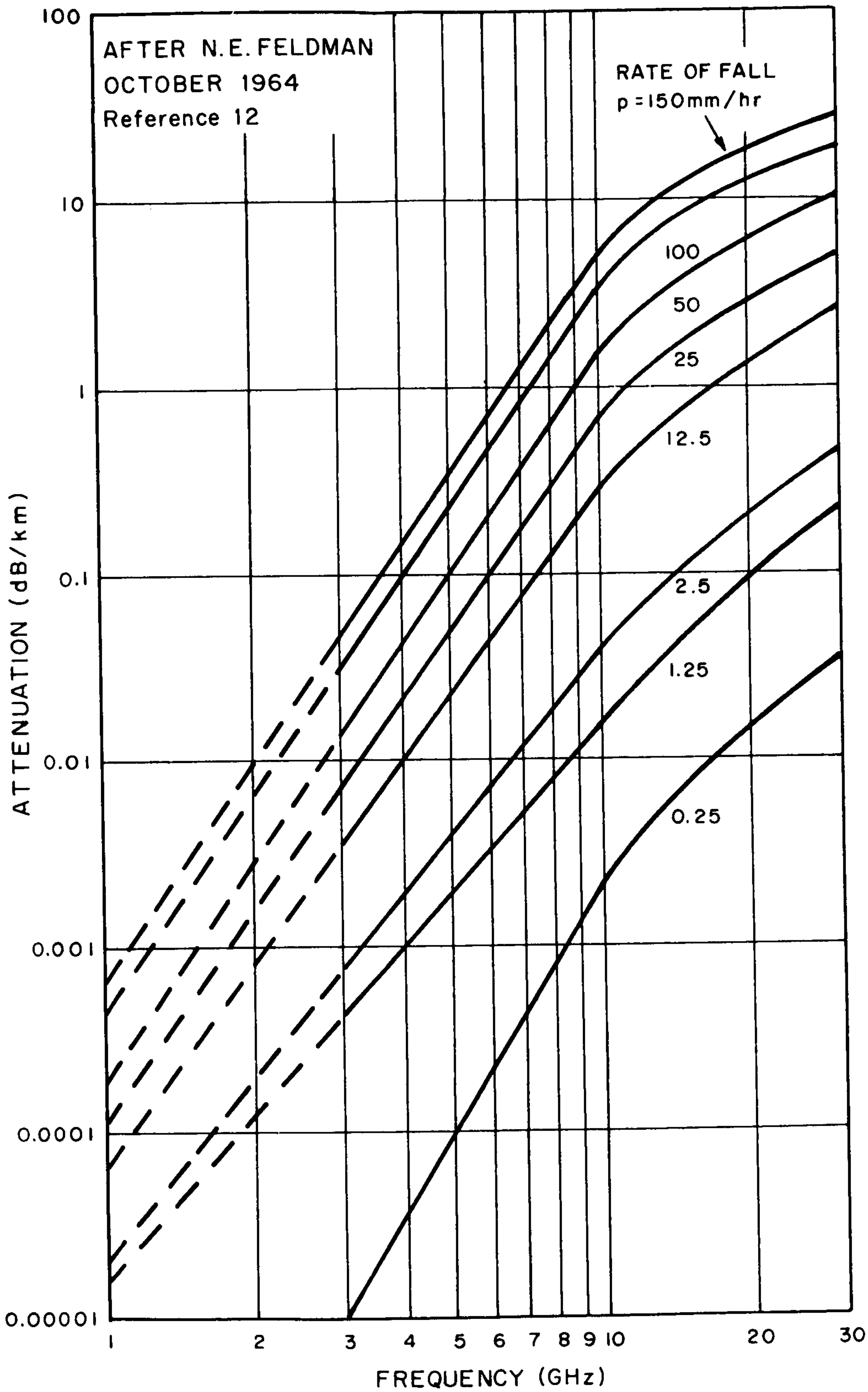


Figure 6—Attenuation at 18° C for a number of rains

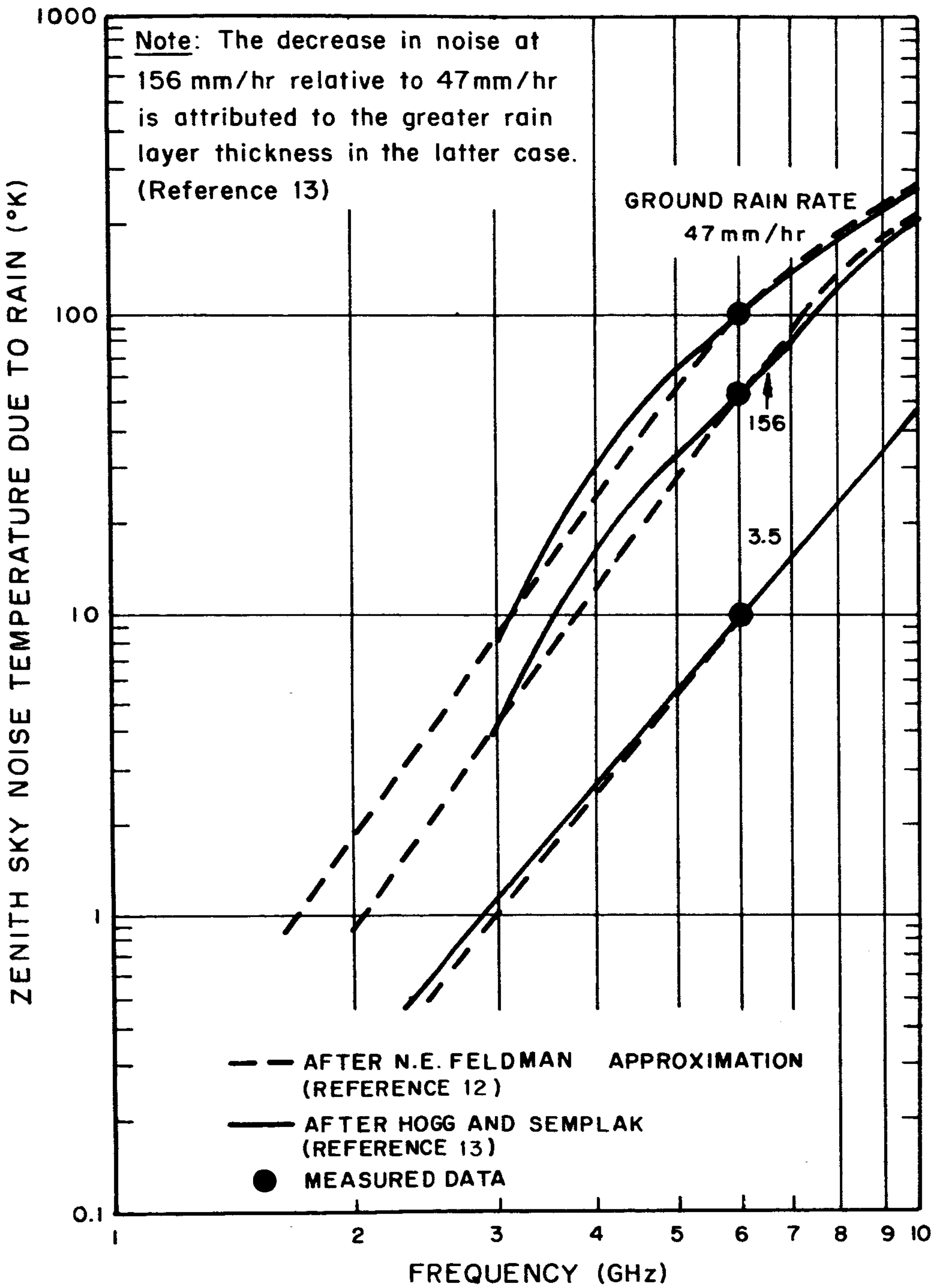


Figure 7–Estimated sky temperature due to rain

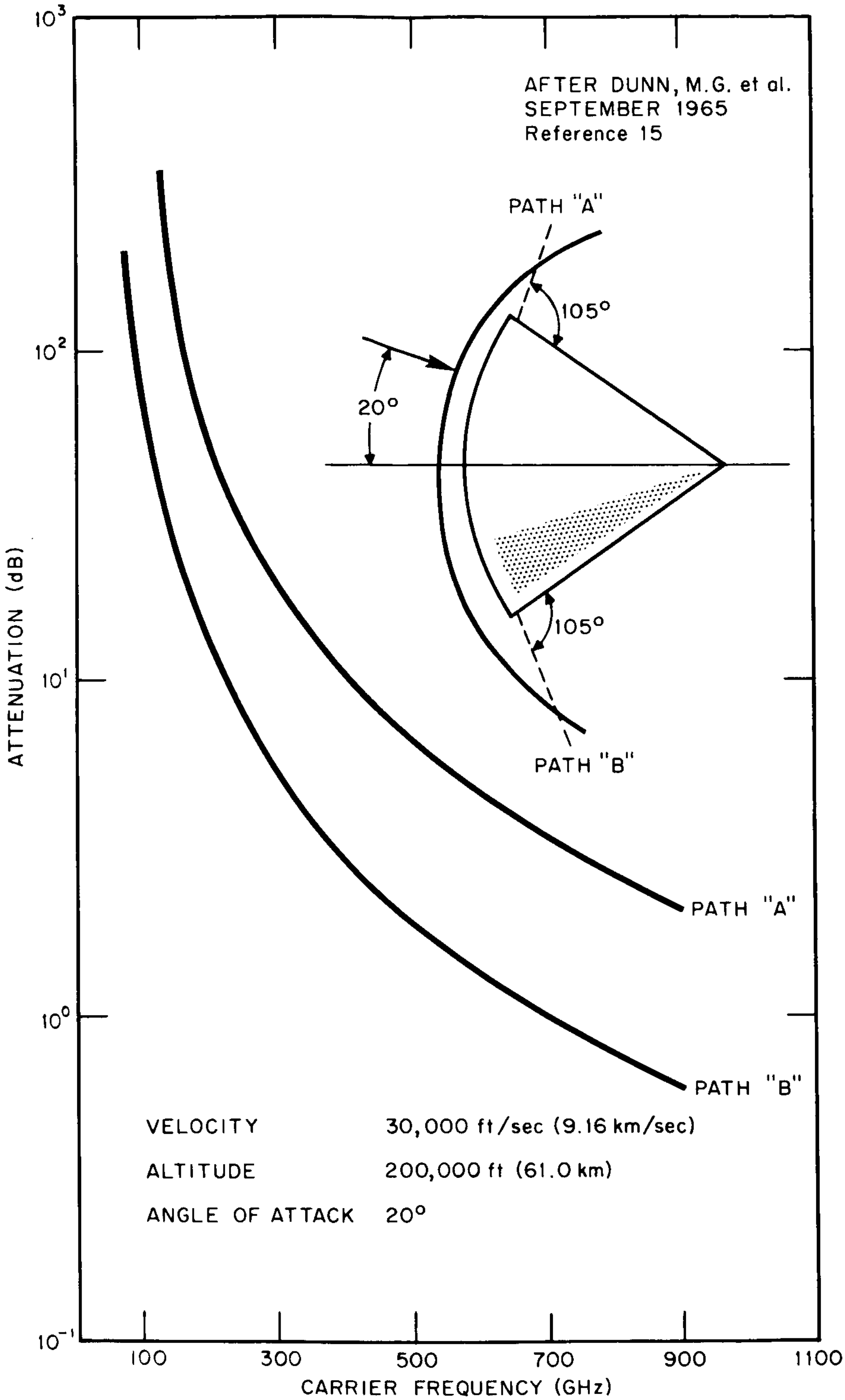


Figure 8–Estimate of attenuation due to Apollo Re-entry Plasma Formation

A second possible application of millimeter wavelength propagation is spacecraft to spacecraft communication outside of the earth's atmosphere. It will be recalled that section 2.3 of this report presented limits imposed on radiowave propagation in the 1 to 10 GHz range. Practical limits upon antenna size, antenna pointing accuracy, transmitter power, and receiver noise do not appear to alter the conclusion that 1 to 10 GHz transmission is desirable for spacecraft to earth communication. This is brought out by Figure 9 which is based upon preliminary results of a current study (Reference 16) which includes practical hardware as well as atmospheric limitations. Figure 9 suggests that if precipitation is included, a selection of frequencies between 1 GHz and 7 GHz is optimum for spacecraft to earth communications. It also indicates that for spacecraft to spacecraft communications three apparent peaks occur – namely, 3 GHz, 100 GHz, and 3×10^4 GHz (infrared). The spacecraft to spacecraft "figure-of-merit" (as will be shown, a number proportional to received signal to noise power ratio, S/N) in the radio-region is less than for the earth terminal case since the spacecraft antennas are necessarily size limited. At optical wavelengths the situation reverses because of improved coherence in the absence of the atmosphere.

The following is a brief explanation of the derivation of Figure 9. When considering power transfer between two remote points by means of electromagnetic propagation the received signal to noise power ratio can be expressed as:

$$\frac{S}{N} = \frac{G_T G_R P_T \lambda^2 L}{R^2 (4\pi)^2 \Phi_n B} \qquad (7)$$

where: S = signal power (watts)

N = noise power (watts)

G_T = transmit antenna gain

G_R = receive antenna gain

λ = operating wavelength (meters)

L = total system loss factor ($L \leq 1.0$)

Φ_n = noise spectral density due to all sources (watts/Hz)

B = receiver equivalent noise bandwidth (Hz)

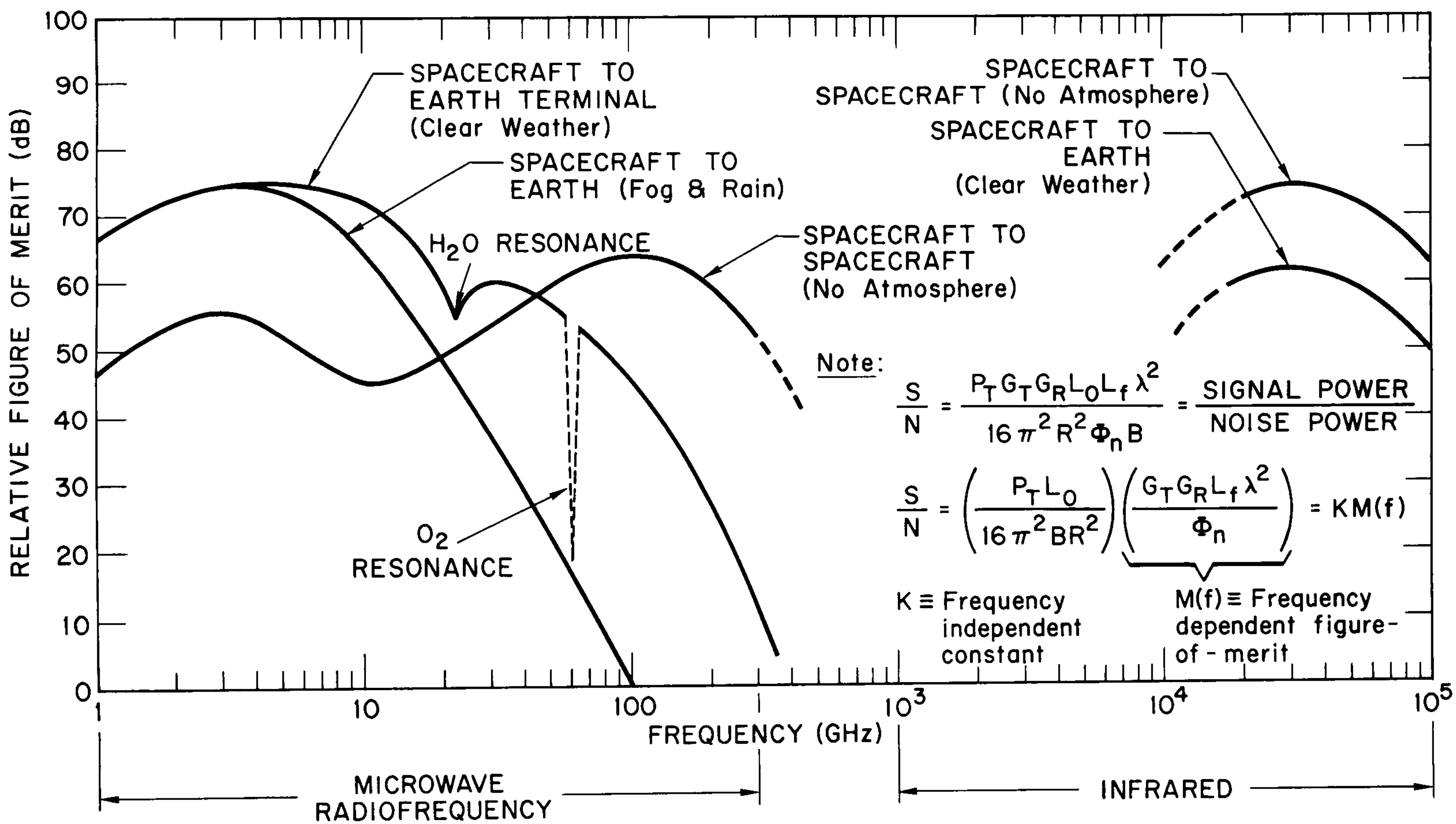


Figure 9–Relative figure of merit vs. frequency

A frequency dependent "figure-of-merit" can be defined by separating the frequency dependent and frequency independent parameters in Equation (7). Thus Equation (7) can be re-written as:

$$\frac{S}{N} = \left(\frac{P_T L_0}{16\pi^2 BR^2}\right)\left(\frac{G_T G_R L_f \lambda^2}{\Phi_n}\right) = KM(f) \qquad (8)$$

where: L_0 = frequency independent losses

L_f = frequency dependent losses

P_T = constant (a spacecraft transmitter power level of one watt is feasible in both the radio and infrared regions)

K = a constant for any given range, R, and receiver bandwidth, B

M(f) = a frequency dependent "figure-of-merit" since with the above assumptions S/N is directly proportional to M(f)

The relative figure-of-merit plotted in Figure 9 is simply M(f) as presented in Reference 16 normalized such that 0 db corresponds to the lowest calculated value of M(f). The frequency dependent antenna, noise and loss parameters account for the relative peaks indicated in Figure 9.

As an example of the interpretation of Figure 9 consider a one watt spacecraft transmitter at 3 GHz. If spacecraft to earth terminal transmission is desired, the relative value of M(f) is seen to be 74 dB. The corresponding value of M(f) at 3 GHz for spacecraft to spacecraft transmission is 56 dB. Thus if spacecraft to spacecraft 3 GHz transmission is conducted at the same range separation, R, and with the same receiver bandwidth, B, as the spacecraft to earth link, a loss of 74 minus 56 or 18 dB in S/N can be anticipated. Another interpretation is that for the above conditions and a given required minimum S/N the data rate for the spacecraft to earth circuit can be made $10^{1.8}$ or 63 times that permissible in the spacecraft to spacecraft circuit.

In the region between the upper microwave (300 GHz) and infrared (3×10^4 GHz) a gap exists due to the effect of stringent fabrication tolerances upon hardware feasibility. Although the results indicated in Figure 9 are preliminary, it is of interest to note the possibility of improvement in spacecraft to spacecraft radio communication by operating in the millimeter wavelength range. For this reason frequency allocations in the 10 to 300 GHz range may acquire more signigicance as the communication parameters become more clearly defined.

3.0 CONCLUSIONS

Section 2.0 has shown that for space communication there is a strong correlation between the type of service desired and the optimum radio frequency for that service. Therefore the concluding comments regarding radio frequency allocations will be in terms of the following specific services:

1. Air-sea rescue.
2. Aircraft (or equivalent) relay via communication satellite.
3. Spacecraft to earth communication.
4. Spacecraft to spacecraft communication.
5. Earth to spacecraft transmission.

3.1 Air-Sea Rescue

During recovery of a space capsule which is down in a body of water the recovery may be effected by means of aircraft or ships. If the capsule communicates to an aircraft and line-of-sight transmission is assumed any frequency in the 100 MHz to 1 GHz range might be employed although the lower frequencies are desirable from the standpoint of ease of acquisition. No particular advantage would be gained by going to HF (3 to 30 MHz) during aircraft recovery unless skywave communication is desired (distances greater than 200 km). The radio horizon distance is given by: (Reference 17)

$$d = 130\sqrt{h} \tag{9}$$

where: d = distance to radio horizon (kilometers)

h = aircraft height (kilometers)

If for example, the aircraft is flying at an altitude of 1.22 km (4000 ft) the maximum radio range to a capsule on the earth's surface is on the order of 143 km (77 n.mi.).

If capsule to ship communication is required then surface wave propagation is desirable in which case vertically polarized signals between 5 and 10 MHz are indicated. Higher frequencies will result in severe surface wave attenuation while lower frequencies present space capsule antenna problems. A "fringe benefit" is the skywave mode which at approximately 6 MHz is invariably present (i.e., day or night). It should be noted that with low power, ground wave propagation is only of value for vertically polarized signals over sea water. Thus for any dry land recovery area only the skywave remains as an incentive to use HF in which case a frequency near 6 MHz should be employed.

3.2 Aircraft Relay Via Communication Satellite

Frequencies between 100 and 400 MHz are desirable in the situation where an aircraft or earth orbiting spacecraft utilizes an omni or broadbeam antenna to obviate tracking problems while relaying signals via a communication satellite. The forthcoming NASA ATS synchronous communication satellite experiments (late 1966) at 136 MHz are intended to further demonstrate the feasibility of such aircraft to earth terminal radio communications. As indicated in Section 2.2, the beamwidth (and hence gain) of a communication satellite is fixed while the effective noise temperature seen is approximately 300°K independent of frequency. Hence for a given incoming power density (watts/meter^2) the lower frequencies permit the use of a larger comsat receiving antenna aperture with a corresponding increase in received signal strength. It is felt that this specific application warrants the retention of current allocations for space in the 100 to 500 MHz frequency range.

3.3 Spacecraft to Earth Communication

All the evidence points toward the restriction of deep space to earth radio transmissions to frequencies between 1 and 10 GHz. If the effects of precipitation are included then the use of frequencies from approximately 1 to 7 GHz is indicated.

Near-earth orbiting spacecraft to earth transmission is generally radio horizon limited and hence the range separation is never much more than approximately 1500 km. For the near-earth case line-of-sight voice or telemetry transmission can be achieved anywhere in the 0.1 GHz to 10 GHz range. However, all downlink ranging signals should be above 2 GHz to minimize ionospheric refraction effects. An interesting feature of the early Soviet Vostok manned earth orbital flights (Vostok II, August 5, 1961) was the HF, 9 MHz to 20 MHz, voice communication scheme between pilot and Soviet ground stations (Reference 14). This experimental communication system was necessary since the Soviet Union had not built a worldwide communication network and apparently voice communication was obtained by means of multiple skip skywave transmission (i.e., multiple reflections between the earth's surface and ionosphere). With such a scheme, as suggested in section 2.1, many coverage gaps will exist between spacecraft and any given ground station. However, this problem can be alleviated to some extent if many widely separated HF reception points are interconnected by "hard-line communication" (i.e., cable).

3.4 Spacecraft to Spacecraft Communication

If omnidirectional or low gain spacecraft antennas are considered then

400 MHz is a reasonable frequency choice in view of receiving antenna cross-section considerations coupled with the moderate galactic sky noise levels at UHF.

The eventual use of 10 to 100 GHz frequencies for spacecraft to spacecraft radio communication is of course a matter of speculation. However the possibility of realizing up to 10 dB improvement over the "conventional" microwave frequencies suggests a careful monitoring of future frequency allocations in the 10 to 100 GHz range. Above 100 GHz there is also the possibility of overcoming radio blackout associated with high velocity ($v > 8$ km/sec) earth re-entry. Utilization of millimeter and sub-millimeter wavelengths for space application is a subject of continuing study.

3.5 Earth to Spacecraft Transmission

The transmitter power level and antenna gain at the earth terminal can in practice greatly exceed that utilized at any spacecraft. For example, the Unified S-Band Systems employs up to 20 kw of transmitter power and 50 dB of antenna gain (26 m dish). Thus any available frequency in the 100 MHz to 10 GHz range might be considered for purposes of uplink communication barring any radio frequency interference problem.

Uplink range and angle track signals, however, should be restricted to frequencies above 2 GHz to eliminate measurement errors associated with refraction and time delay as the signal traverses the earth's ionosphere. Above 10 GHz uplink signals would incur increased tropospheric attenuation especially at low elevation angles and near the absorbtion frequencies of 22.2 GHz and 60 GHz.

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