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THE FEASIBILITY OF A DIRECT RELAY OF APOLLO SPACECRAFT DATA VIA A COMMUNICATION SATELLITE

by P. E. Schmid

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ABSTRACT

The purpose of this paper is to provide an estimate of the extent to which communication satellites can be utilized in the 1970's for relaying data directly from an Apollo-type spacecraft to a fixed earth station. Both 24-hour synchronous altitude (36,000 km above the earth's surface) and 6-hour orbits (10,400 km above the earth's surface) for the communication satellite are considered. A Unified S-Band type of data transfer is assumed. The relative merit of using frequencies below S-Band for voice communication is also briefly discussed.

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INTRODUCTION

The technical feasibility of a communication satellite system to supplement the Manned Space Flight Network (MSFN) during the forthcoming Apollo missions will, of course, depend on the specific requirements placed on such a system. The primary reasons for considering the use of communication satellites during Apollo-type missions are:

1. Increased reliability in the areas of communication, telemetry recording and spacecraft tracking, which in turn reflects a higher probability of mission success.
2. Eventual cost reduction in world-wide network operations.
3. Possibility of centralized mission control.

The latter consideration would reduce, if not obviate, the need for dispersing high level technical personnel around the globe. The question of feasibility can be examined in light of the state-of-the-art or in terms of anticipated technological progress. Many papers, reports, and memorandums concerning the use of communication satellites during various phases of the Apollo program have been generated. Most of the analyses are based upon a projected state-of-the-art.

Within the next decade it is not reasonable to expect a communication satellite system which could completely parallel or supplant the Manned Space Flight Network. Although the reasons for such a statement are fairly obvious, they are summarized in a later section of this report. Also, reasons are presented for the desirability of 24-hour synchronous orbit over random subsynchronous orbit communication satellites. The number of tasks an Apollo support communication satellite could perform during any given mission is quite large. For example, consider Figure 1 where the Command Service Module (CSM), a tracking ship, a Manned Space Flight Network (MSFN) ground station, a communication satellite (Comsat), an Apollo aircraft, Mission Control Center—Houston (MCCH), and the NASA Communications (NASCOM) Network are all indicated. Simple voice communication from the Apollo Spacecraft to Houston might be sent via at least five different signal paths, each taking advantage of the relay capability of the communication satellite.

Examples are:

1. CSM-Ship-Comsat-MCCH
2. CSM-MSFN-Comsat-MCCH
3. CSM-Comsat-MCCH

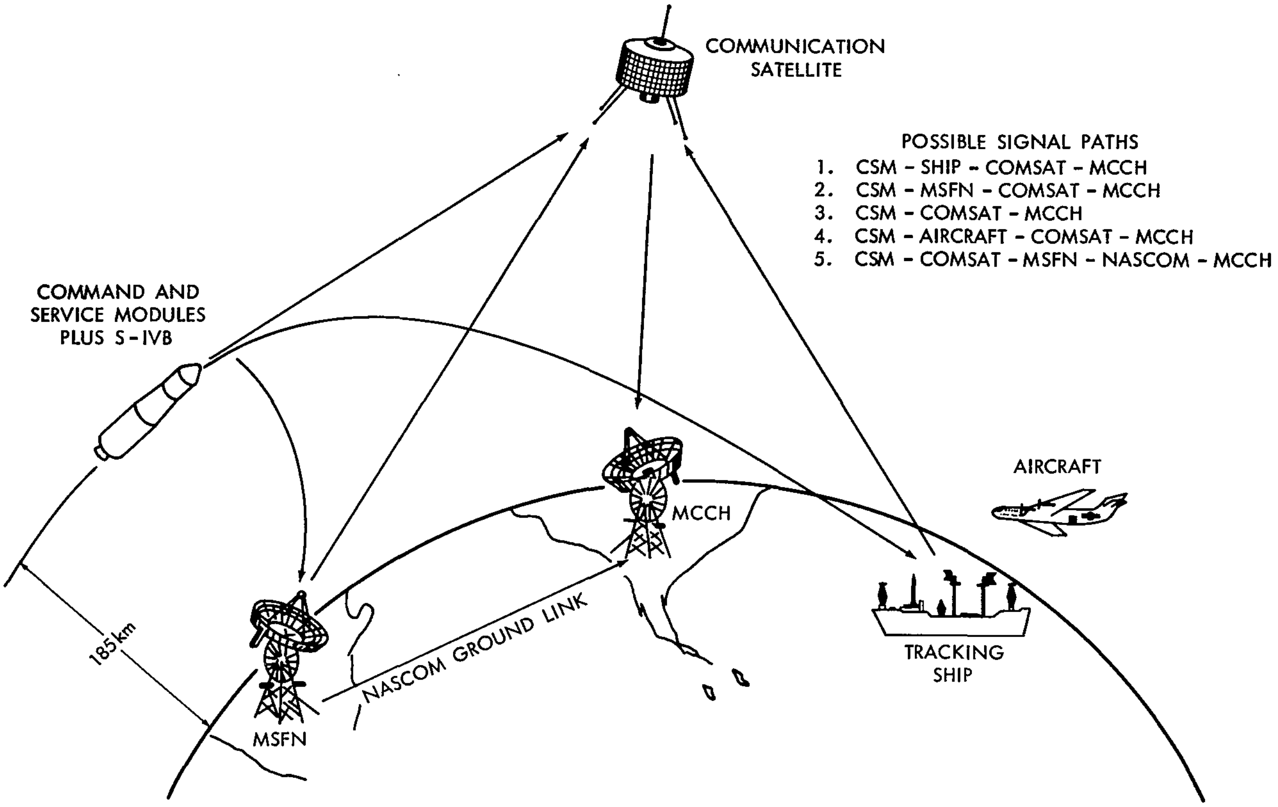

Figure 1—Possible communication links between an earth orbiting Apollo spacecraft and mission control.

4. CSM-Aircraft-Comsat-MCCH
5. CSM-Comsat-MSFN-NASCOM-MCCH

If one now adds all the possible signal paths and various frequencies for up-and down-link telemetry, voice, tracking, and TV data transmission, as well as communication and data transmission between the various ground tracking stations required during full mission operation, it is apparent that any analysis of Apollo Comsat support must be confined to one specific configuration at a time, hopefully one which is meaningful in terms of actual future implementation. A few of the specific signal paths via synchronous communication satellite which have been considered in other studies are:

1. Communication between MCCH and MSFN land and ship stations via communication satellite (Reference 1).
2. MCCH to aircraft communications via satellite during the injection phase of Apollo missions via communication satellite (Reference 1).
3. Communications and data transfer between two "earth stations" and the continental United States via communication satellite (Reference 2).
4. Transmission of data from up to seven data collecting stations to a central processing station via communication satellite with limited multiple access capability (Reference 3).
5. The re-transmission via communication satellite of television data such as might be received from an Apollo Spacecraft at a remote tracking site (Reference 4).

It is noted that each of the five applications just mentioned permit a relatively high power radio-frequency link from the earth or near-earth terminal to a communication satellite. This, of course, is not the case if signals are to be sent directly from an Apollo Spacecraft to MCCH via communication satellite. The next section summarizes the limitations on a spacecraft to Comsat transmission link based upon a best guess of the projected state-of-the-art. Then is discussed the feasibility of establishing continuous voice communication to MCCH from the Apollo Spacecraft during all phases of the Apollo Mission. This type of coverage is not now possible even during earth orbit, since during this phase the spacecraft to MSFN ground tracking station radio horizon is limited to approximately 1800 km and communication gaps will occur outside of the coverage circles shown in Figure 2. This is appropriate for a minimum tracking station elevation angle of 5 degrees. Finally the last section presents the conclusions of this report in summary form.

LIMITING FACTORS IN THE RELAY OF SPACECRAFT INFORMATION VIA A COMMUNICATION SATELLITE

The weakest link in Apollo spacecraft-to-earth terminal radiowave propagation via a communication satellite is the link between the spacecraft and the communication satellite. The reason for this is primarily due to:

1. The limited radio frequency output power.
2. The antenna gain constraint at the communication satellite (Comsat) if the complexity of automatic track between two scanning antennas is to be avoided.
3. The antenna gain limit at the Apollo spacecraft dictated by physical size considerations and spacecraft attitude stability.
4. The fact that the communication satellite is unmanned.
5. The inability to employ ultra low noise receivers (20°K effective noise temperature) in conjunction with correlation and integration techniques which require equipment not compatible with spacecraft hardware.

As will be shown, limitations associated with this spacecraft-Comsat link are such that even with the state-of-the-art projected to 1976a wideband (4 MHz) radio-frequency, direct link from Apollo CSM to MCCH via communication satellite does not appear feasible. The parameters which impose these limitations will be elaborated upon. They are applicable to both the Apollo vehicle and communication satellite, and include:

1. Spacecraft antenna gain, beamwidth, and effective aperture.
2. Spacecraft transmitter carrier frequency, power level, and modulation techniques.
3. Spacecraft receiver effective noise temperature, equivalent noise bandwidth requirements, and bandwidth limitations.
4. Effects of orbit perturbations and station keeping requirements.

In this report, a Unified S-Band type of transponder is assumed aboard the Apollo spacecraft, and hence, to this extent, the Apollo spacecraft electrical characteristics are defined (Table 1). The Unified S-Band System characteristics described in this report are based upon the current (June 1966)

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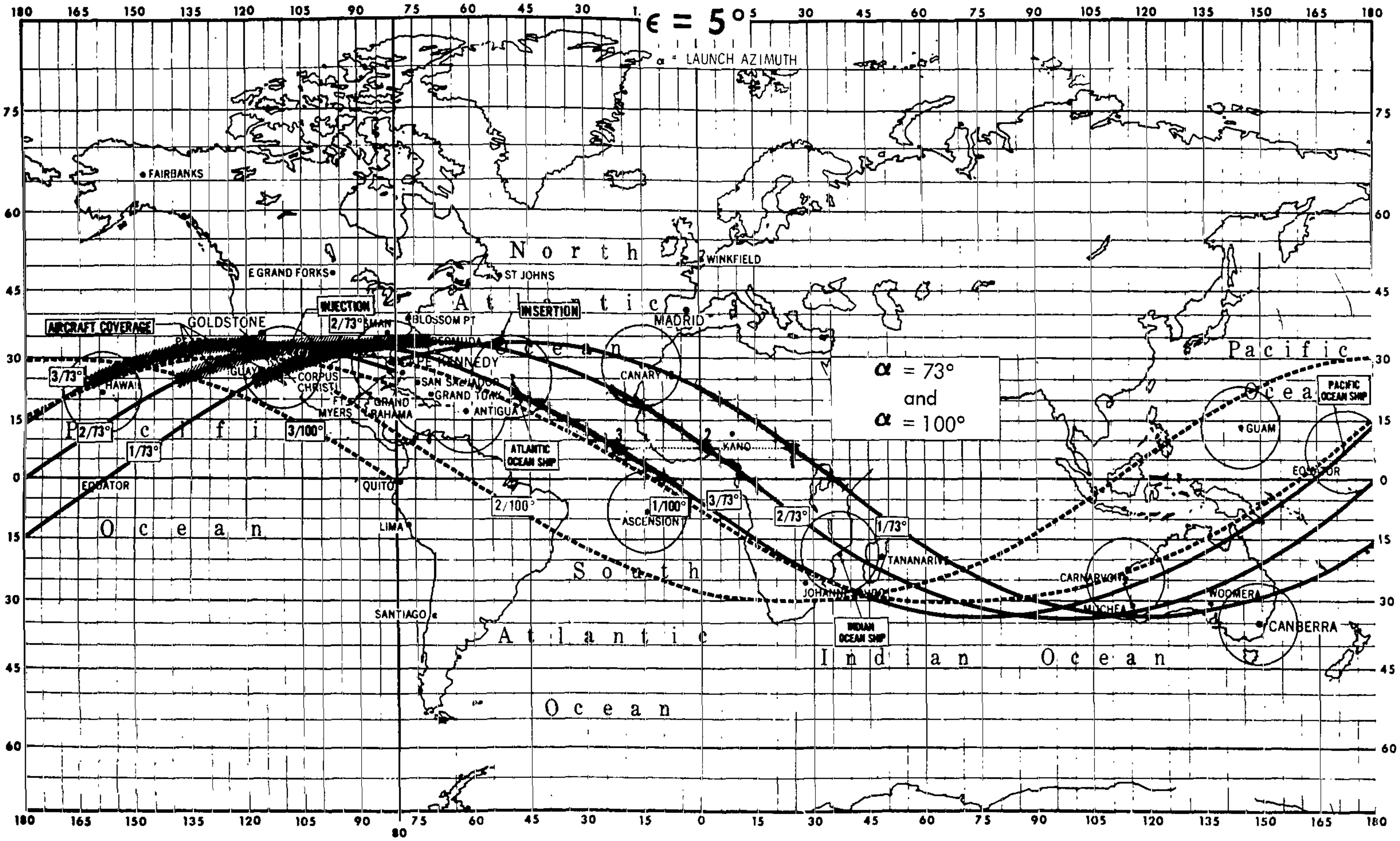


Figure 2–Apollo parking orbits 1 through 3 (station coverage).

Table 1

Unified S-Band Command and Service Module (CSM) Transponder and Antenna Characteristics—Block II.

Transmitter		Receiver	
Parameters	Characteristics	Parameters	Characteristics
Maximum power Amplifier RF output	11.2 watts	IF 3 db Bandwidth	4 MHz
Microwave circuit loss	6.7 db (Omni antenna) 7.2 db (High gain antenna)	Microwave circuit loss	7.0 db (Omni antenna) 7.0 db (High gain antenna)
Down-link carrier frequency	Phase modulation: 2287.5 MHz Frequency modulation: 2272.5 MHz	Up-link carrier frequency	2106.4 MHz
		Noise figure	11 db maximum
High gain antenna	Maximum on axis Gain: 27.4 db Beamwidth ≈ 5°	High gain antenna (Same antenna structure as transmit antenna with monopulse receive capability)	Maximum on axis Gain: 23.7 db Beamwidth ≈ 5°
Omni antenna	-3 db over 80% of spherical coverage	Omni antenna	-3 db over 80% of spherical coverage
		Dynamic range	-52.5 to -132.5 dbm
		Carrier tracking loop noise bandwidth	320 Hz to 1800 Hz
Antenna polarization	Right-hand circular (RCP)	Antenna polarization	Right-hand circular (RCP)

NOTE:

1. These characteristics are for the CSM. The LEM has a similar transponder except that the receive and transmit carrier frequencies are approximately 5 MHz below the corresponding CSM PM carrier frequencies. The LEM transmits at only one carrier frequency, which is normally PM modulated, but can be FM modulated for purposes of TV transmission.
2. There are two separate transmitters associated with each CSM transponder. One is associated with the phase modulated signal (Table 5), the other with the frequency modulated signal (Table 6).
3. Block I systems do not employ a high gain antenna.
4. Table 1 is based upon information available as of June, 1966. This includes material from Reference 5.

system performance specifications. The more recent references cited have been referred to for those parameters which have undergone the usual evolutionary change experienced in the development of any type of new electronic equipment. Field testing of the Unified S-Band System is now underway.

Antenna Considerations

As is well known in the field of radio communication, the maximum rate of data transfer between two points can be increased by either increasing the signal power or decreasing the noise power at the receiving terminal. Since high data rates (10^6 bits per second or greater) require RF transmission bandwidths on the order of MHz, and since mean-square noise voltage increases with increasing bandwidth, a theoretical upper bound on data rate transmission is quickly established for any particular point to point radiowave transmission problem.

When it is necessary to investigate the possibilities for signal to noise power ratio (S/N) improvement at the receiver, the so called "one-way range equation" (first introduced by H. T. Friis of Bell Telephone Laboratories in 1946, Reference 6) is invariably employed. This expression permits an estimate of received signal power which can then be compared to the noise power calculable from an effective noise temperature and an equivalent noise bandwidth. Even though the fundamental concepts involved in such one-way calculations are quite straightforward, the interrelation of such parameters as received signal power density, antenna effective aperture, antenna gain, and antenna beamwidth are sometimes misinterpreted, and therefore a review of some elementary considerations seems appropriate. Although the following elementary development is quite general, it will be paralleled with a discussion of the specific parameters associated with the earth-orbiting Apollo spacecraft-to-communication satellite link indicated by Figure 3. In this manner the one-way range equation will be developed in light of the specific antenna coverage problem, which must be considered whenever Apollo CSM or LEM spacecraft-to-communication satellite radiowave propagation is to be analyzed.

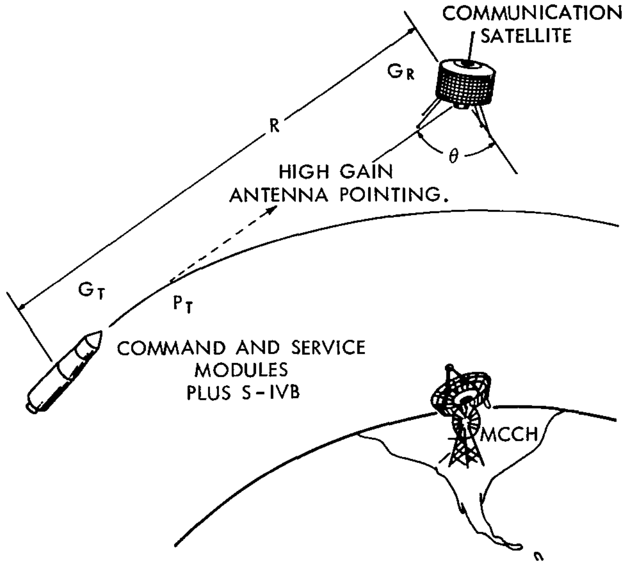


Figure 3—Apollo spacecraft-to-communication satellite geometry.

Gain and Beamwidth

Consider the situation depicted in Figure 3, where an earth-orbiting Apollo Spacecraft is radiating a phase- (or frequency-) modulated signal of P_T watts, average power. If the energy were radiated isotropically, the power density, ρ_0, at any point in space at a distance R, would be:

$$\rho_0 = \frac{P_T}{4\pi R^2} \text{ Watts/m}^2 , \tag{1}$$

where

P_T = average power radiated (watts),

$4\pi R^2$ = surface area of sphere of radius, $R(m^2)$,

ρ_0 = power density in space a distance R from the transmitter (watts/m^2).

As indicated in Table 1, maximum P_T for the Unified S-Band Transponder is 2 watts (7 db below 11.3 watts) for both the high-gain and omnidirectional antennas. Since the power is not radiated equally in all directions, the maximum power density ρ at a distance R is given by $\rho_0 G_T$, where G_T is the transmit antenna power gain relative to isotropic radiation. For the CSM, the maximum value of G_T for the high-gain antenna is 27.4 db (Table 1), and for the omnidirectional antenna is an average of -3 db. As indicated by Figure 3, the CSM high-gain antenna must, during earth orbit, be continually re-oriented to keep the rather narrow beam (approximately 5 degrees for $G_T = 27.4$ db) directed toward the communication satellite. The connection between beamwidth and gain is quite simple for the ideal case where all of the radiated power is confined to a single narrow beam lobe. If ϕ and θ represent the -3 db beamwidths in 2 orthogonal planes, then all of the radiated power can be considered to be contained in a spatial rectangle of area $R\theta$ by $R\phi$. In the absence of gain, this power would be distributed over a surface area of $4\pi R^2$. The power gain is the ratio of these two areas:

$$G = \frac{4\pi R^2}{\phi\theta R^2} = \frac{4\pi}{\phi\theta}, \tag{2}$$

where

G = power gain,

θ = beamwidth in one plane (radians),

ϕ = beamwidth in an orthogonal plane (radians),

or

$$G = \frac{41253}{\phi\theta} \tag{3}$$

for ϕ and θ in degrees. If $\theta = \phi$ (i.e., a conical beam), then

$$G = \frac{41253}{\phi^2}. \tag{4}$$

The departure from Equation 4 in any practical antenna performance is due to the power radiated by minor lobes. This is generally taken into account by multiplying Equation 4 by a correction factor α, where $0.6 < \alpha < 1.0$. The value of α may be relatively constant for patterns of a given class of antennas (Reference 7). An average expression often used is:

$$G = \frac{27000}{\phi\theta} \tag{5}$$

for ϕ and θ in degrees (Reference 8).

This result is plotted in Figure 4.

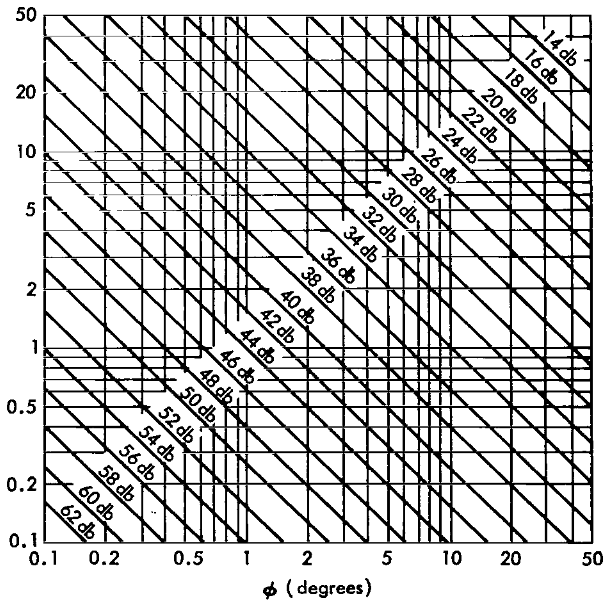


Figure 4—Antenna gain vs. half-power beamwidth ($\theta\phi$) $G = 27000/\theta\phi$.

For the CSM high-gain antenna (where $\phi = \theta$ and for $G_T = 27.4$ db), the beamwidth by

Equation 5 is 7 degrees, compared to the value of 4.8 degrees stated in Reference 9. The important point here is the strong interdependence of antenna on-axis gain and beamwidth. While the foregoing concepts were introduced by considering the antenna gain of a transmitting antenna, theoretically the same gain is applicable when the antenna is receiving. That is, the reciprocity theorem as applied to networks can be extended to show that at a given frequency, the radiation and absorption patterns of a properly terminated antenna are, for all practical purposes, the same (see for example, Reference 10). However, in the Apollo CSM system, the receive and transmit frequencies are different, and at present the antenna is peaked for the transmit function. As indicated in Table 1, the maximum receive gain is currently 23.7 db.

The geometry appropriate for a communication satellite above the earth's surface is shown in Figure 5a. The antenna conical beamwidth θ required to provide coverage to all earth or near-earth stations capable of viewing objects above a minimum elevation angle of ϵ_m is given by

$$\theta = 2 \arcsin \left[\frac{a + h_1}{a + h_2} \cos \epsilon_m \right] , \tag{6}$$

where

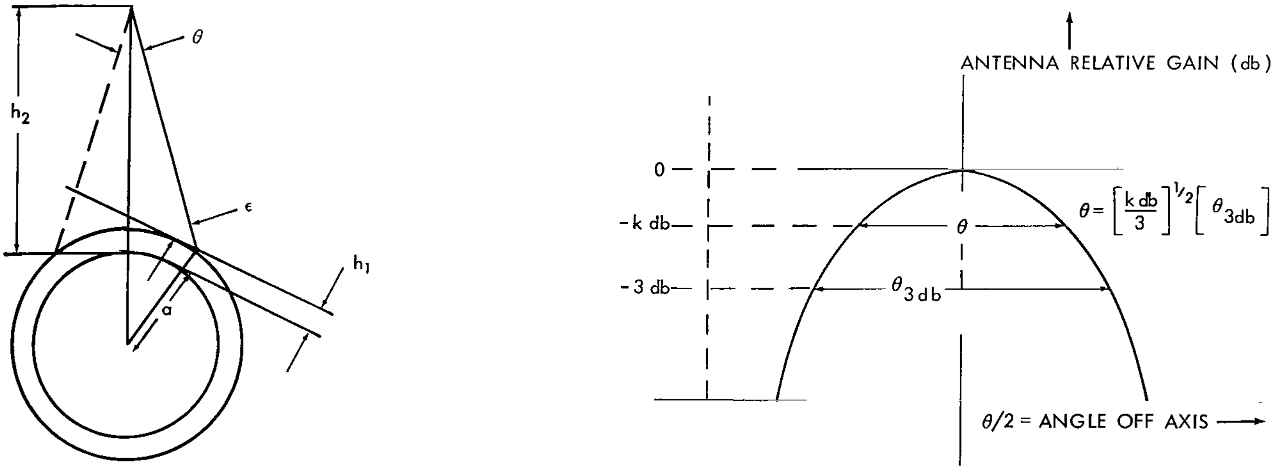
a = mean earth radius $\doteq$ 6378 km,

h_1 = height of near earth station above mean earth radius (for case of earth orbit spacecraft, h_1 is mean orbit height),

h_2 = height of communication satellite above mean earth radius,

θ = conical look angle at communication satellite which subtends all earth or near earth terminals capable of viewing at elevation ϵ,

ϵ_m = minimum usable elevation angle ϵ at near-earth terminal.



(a) ANGLE OF ILLUMINATION

(b) ANTENNA BEAMWIDTH

Figure 5—Communication satellite antenna coverage characteristics.

The antenna 3 db beamwidth should be somewhat greater than the angle θ indicated in Figure 5a in order to minimize the amplitude variation of the received signal level at the communication satellite. A useful approximation in determining antenna beamwidths (other than 3 db beamwidths) can be obtained for antennas having, in each of two orthogonal planes, radiation patterns of the form

$$G(\theta) = A e^{-K\theta^2} , \tag{7}$$

where A and K are constants.

Near the main lobe peak, most antenna patterns can be approximated by this exponential function, in which case the ratio of the beamwidth for any degree of decay to the 3 db beamwidth (Figure 5b) is given by

$$\theta = \left(\frac{k_{db}}{3}\right)^{1/2} \left(\theta_{3\,db}\right) , \tag{8}$$

where

θ = angular width of main lobe for decay of k_{db},

$\theta_{3\,db}$ = 3 db beamwidth.

Effective Antenna Aperture

The foregoing has shown that the on-axis spatial power density ρ, a distance R from the transmitter is given by

$$\rho = \frac{G_T P_T}{4\pi R^2} \text{ watts/m}^2 , \tag{9}$$

where

G_T = on axis transmit antenna gain,

P_T = total radiated power (watts),

R = distance between transmitter and receiver (m).

The maximum power available for transfer to a receiver is Equation 9 multiplied by an effective receiving antenna aperture or capture area. At microwave frequencies, the "effective area" is on the same order as the physical cross-sectional area of horn, lens, and reflector type antennas (Reference 11). For example, the ratio of maximum effective aperture to physical aperture for an optimum horn antenna is approximately 0.6 (Reference 7). A parabolic reflector type of antenna with a proper feed has been found experimentally to be approximately two-thirds of the projected area of the reflector (Reference 6). The relationship between effective antenna area and gain is important in spacecraft antenna calculations, since physical size constraints will dictate maximum antenna aperture limits, whereas minimum allowable beamwidths dictate maximum gain limits.

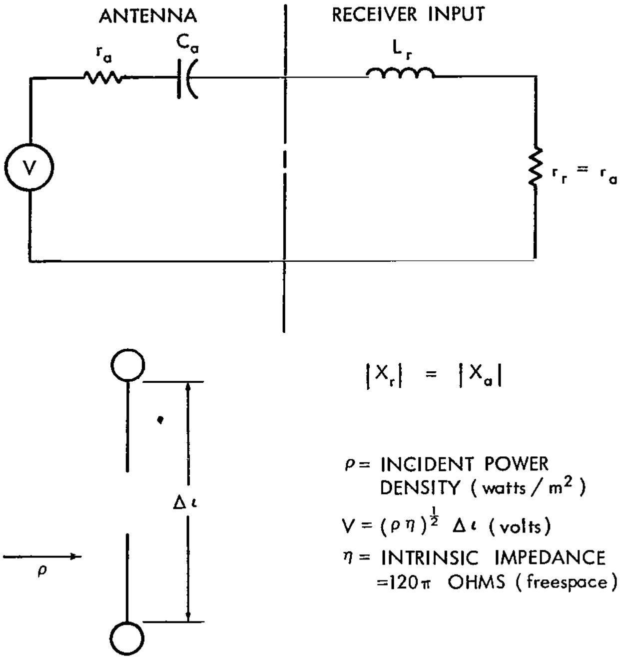


Figure 6—Equivalent circuit for an electrically short dipole.

The concept of effective aperture is usually introduced by considering an elementary antenna having mathematically defined gain and radiation resistance functions. Such an antenna is the electrically short dipole in free space of length, $\Delta\ell$, having $\Delta\ell \ll \lambda/8$, where λ is the operating wavelength.

For such an antenna, the induced voltage is linearly related to the incident field strength such that $V = \Delta\ell\,|\vec{E}_\theta|$, where $\vec{E}_\theta$ (volts/m) is the electric field vector of a linearly polarized plane wave and $\Delta\ell$ is the length of the receiving dipole which is oriented parallel to the direction of $\vec{E}_\theta$. For this elementary antenna, the effect of the antenna impedance reactive component is, in practice, removed by means of series tuning as indicated in the equivalent circuit of Figure 6. For the electrically short dipole, the power delivered to a matched receiver is given by

$$P_r = \frac{V^2}{4r_a} = \frac{|\vec{E}_\theta|^2 \Delta\ell^2}{4r_a} = \rho A_r \text{ watts} , \tag{10}$$

where

V = voltage induced into an optimally oriented antenna = $|\vec{E}_\theta|\,\Delta\ell$ (volts),

$\vec{E}_\theta$ = electric field intensity of a linearly polarized plane wave (volts/m) of wavelength λ,

$\Delta\ell$ = dipole length $< \lambda/8$ (m),

r_a = radiation resistance (ohms),

ρ = incident power density (watts/m^2),

A_r = antenna effective receiving aperture (m^2).

The radiation resistance, r_a, of an electrically short transmitting dipole is obtained by integrating the mathematical expression for the radiated power density emanating from the dipole over an enclosing sphere and dividing by the square of the effective antenna current I_0. The radiated power density ρ of the incident plane, linearly polarized, wave in freespace, is given in spherical coordinates by

$$\rho = \vec{E} \times \vec{H} = \frac{|\vec{E}_\theta|^2 \vec{1}_R}{\eta} \text{ watts/m}^2 , \tag{11}$$

where

E_θ and ρ are as defined previously, and

$\eta = 120\pi$ = the intrinsic impedance of freespace (ohms),

$\vec{1}_R$ = unit vector in direction of propagation.

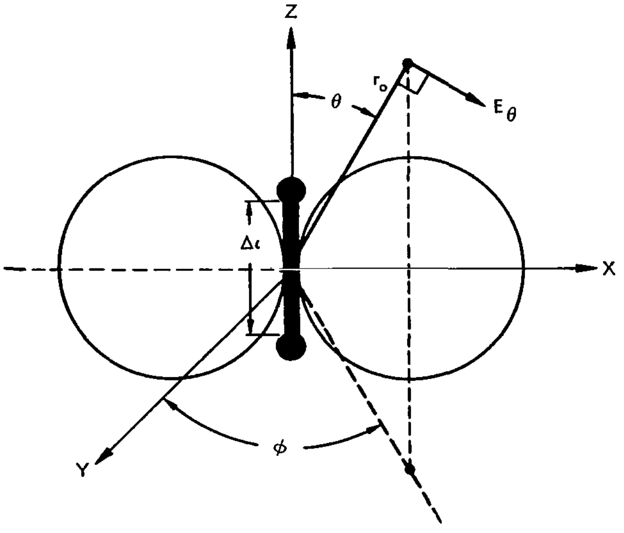


Figure 7—Geometry for an electrically short dipole.

Thus, with reference to Figure 7, the radiation resistance is calculated as

$$r_a = \frac{\int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \rho(\theta, \phi)\, r_0^2 \, d\theta \, d\phi \sin\theta}{I_0^2} , \tag{12}$$

where

r_0 = radius of enclosing sphere (m),

I_0 = RMS value of antenna current (amperes) (uniform current distribution assumed for short dipole),

$\rho(\phi, \theta) = |\vec{E}_\theta|^2 / 120\pi$ power density (watts/m²),

ϕ and θ are the angles indicated in Figure 7.

But the magnitude of E_θ for $r_0 \gg \lambda$ is given by (see for example, Reference 12):

$$|E_\theta| = \frac{60\pi I_0 \Delta\ell \sin\theta}{r_0 \lambda} \text{ volts/m} . \tag{13}$$

The radiation resistance is thus given by

$$r_a = \left(\frac{\Delta\ell}{\lambda}\right)^2 30\pi \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \sin^3\theta \, d\theta \, d\phi \tag{14}$$

or

$$r_a = \left(\frac{\Delta\ell}{\lambda}\right)^2 \left(80\pi^2\right) . \tag{15}$$

Combining Equations 15 and 10, the effective receiving aperture of the electrically short dipole is given by

$$A_r = \frac{V^2}{4r_a \rho} = \frac{120\pi \rho(\Delta\ell)^2}{4r_a \rho} = \frac{3\lambda^2}{8\pi} \text{ m}^2 . \tag{16}$$

The maximum directivity of the short dipole is computed as the ratio of the maximum power radiated per unit solid angle to the average power radiated per unit solid angle, or

$$G = \frac{4\pi}{\int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \sin^3 \theta \, d\theta \, d\phi} = \frac{3}{2} . \tag{17}$$

It is seen that the maximum power gain of a short dipole over isotropic radiation is 3/2 independent of antenna length, providing $\Delta\ell \ll \lambda/8$. That is, for a short dipole, only the antenna impedance changes, not the antenna radiation pattern. The antenna aperture of an isotropic radiator can be defined as Equation 16 divided by 3/2, or $A_{r_1} = \lambda^2/4\pi$ meter^2.

Since the on-axis received power is directly proportional to receiving antenna gain, it follows that, in general, the receiving aperture of an antenna is given by

$$A_r = \left(\frac{G_r \lambda^2}{4\pi}\right) \text{m}^2 . \tag{18}$$

Thus, Equations 9 and 18 can be combined to form the so-called one-way range equation, where the maximum power P_r delivered to a matched receiver is given by

$$P_r = \rho A_r = \left(\frac{G_T P_T}{4\pi R^2}\right) \underbrace{\left(\frac{G_r \lambda^2}{4\pi}\right)}_{A_r} \text{ watts} . \tag{19}$$

For the Apollo spacecraft-to-communication satellite link of Figure 3,

P_r = maximum available signal power at the Comsat antenna terminals,

G_T = 27.4 db maximum (as of June 1966),

P_T = 2 watts (maximum radiated signal power assuming no modulation loss),

R = earth orbit CSM to Comsat slant range 10,000 km $< R <$ 42,000 km for Comsat orbits of 6 hours to 24 hours,

λ = operating wavelength $\doteq$ 13.6 cm at USB frequency,

G_r = communication satellite receive Antenna Gain,

A_r = antenna effective aperture (m^2).

It is seen that under these idealized conditions, the only parameter that can be altered in Equation 19 if the present Apollo type transponder and antenna system are to be employed is the communication satellite gain G_r. If this gain is made consistent with illumination of all points of the earth that can see the satellite down to a zero degree elevation ($\epsilon_m = 0$ in Equation 6), then the realizable gain G_r falls off as orbit height decreases (Table 2). Table 2 assumes a maximum fall off of 1.5 db in antenna performance over the view angle θ (see for example, Figure 5). The relationship between orbital period and the satellite altitude indicated in Table 2 is given approximately by

$$h \doteq \left[\left(\frac{a^2 T^2 g}{4\pi^2}\right)^{1/3} - a\right] \text{km}, \quad \text{(Reference 13)} \qquad (20)$$

where

h = satellite altitude above sea level,

a = mean earth radius $\doteq$ 6378 km (Reference 14),

T = period of orbit (seconds),

g = acceleration due to earth's gravitational field $\doteq$ 9.80 m/sec^2.

Table 2

Communication Satellite Antenna Characteristics.

Orbital Period (hours)	Nominal Altitude (km)	Antenna 3 db Beamwidth (degrees)	G Antenna Gain (db)	Antenna Effective Aperture at f = 2.2 GHz (cm^2)
6	10,400	63	8	135
12	20,000	39	12	260
24	36,000	24	17	690

An immediate conclusion is that if no antenna steering is permitted at the communication satellite, then the effective aperture which results from the beamwidth constraint is (at 2.2 GHz) much less than that dictated by physical space limitations. For example, at synchronous altitudes where the required effective aperture for full earth coverage is on the order of 690 cm^2, the physical aperture for 50-percent aperture efficiency would be only 1380 cm^2, or an area 37 cm by 37 cm (15 inches by 15 inches).

As shown by Table 2, the required effective aperture for maximum near-earth coverage at lower altitudes would be even less. Equation 19 shows that the signal strength received at the communication satellite is directly proportional to the effective receiving aperture. Also, it is noted that as the operating frequency is decreased, the gain for a given physical aperture antenna also decreases, and the beamwidth (Equation 5) increases. Thus one possibility for improving matters, if a constant value of effective radiated power is available $(G_T P_T)$, is to use frequencies lower than 2.2 GHz in the link between the orbiting spacecraft and the communication satellite so that larger antenna sizes can be employed at the communication satellite, and yet the required beamwidth can be retained for maximum earth illumination. While this idea is not compatible with the Unified S-Band approach, it might be considered for voice and telemetry transmission in missions where frequencies in the 100 MHz to 500 MHz range will be employed. This point is considered further in a later section.

The foregoing results are, of course, not new, and it has long been realized (Reference 15) that communication satellite antennas whose directivity is limited to that consistent with the illumination of the entire earth fall far short of the gain that is conceptually possible. Antennas that could be directed to cover only a small region in the vicinity of the near earth station would afford a major improvement. However, the possibility of employing antennas such as electronically steerabl phased arrays to permit high gain tracking of the Apollo steerable CSM antenna involves techniques which, if they are implemented, will most likely require at least another decade of engineering development.

At the Apollo spacecraft, it is possible that a higher gain antenna might be employed. The present high gain design employs four 80 cm (2.6 feet) diameter sensing dishes for the monopulse array (Reference 16). A 6 db increase in antenna gain could be realized if the diameters were doubled (aperture increased by a factor of 4). The antenna array would then attain an overall approximate dimension of 3m by 3m.

The Spacecraft Transmitter

The exact nature of a spacecraft RF transmitter will depend primarily upon the carrier frequency selected, the type of modulation employed, and the average power level desired. Each of these parameters is in turn strongly influenced by such factors as space and weight limitations, as well as cost considerations.

Transmitter Frequency Selection

One of the first problems which appears when one considers using a communication satellite in an Apollo CSM application is the requirement for a frequency translation each time a signal is re-transmitted by means of an active repeater. In pulse radar type modulation schemes, a satisfactory translation is sometimes accomplished in the time domain by means of a time displacement or delay. However, with a phase or frequency modulation scheme such as used in the Unified S-Band System, the output signal must undergo a frequency displacement relative to the input frequency. While coherent repeaters can be built with output signal frequency equal to input signal frequency, the basic limitation is the degree of isolation one can achieve between the transmitting and receiving antennas. In the case of communication satellites, the input receiver sensitivity is on the order of -100 dbm. If a one watt transmitter (Syncom II employs 2 watts, Reference 17) is employed, the required isolation between transmitter and receiver must be on the order of 130 db. Since an isolation of even 80 db at a given frequency is difficult to achieve in practice, an active repeater must certainly utilize frequency translation if it is to be used in the Apollo spacecraft-to-communication satellite link. A brief calculation using Equation 19 shows that, even for the ground terminal-to-communication satellite link, the signal level at the Comsat receiver is not sufficient to permit a "straight-through repeater" at synchronous altitudes. That is, for the typical values of

G_T = ground antenna gain = 44 db (30 foot dish),

R = synchronous Comsat altitude = 36,000 km,

P_T = radiated power from ground station = 10 kw,

G_R = synchronous satellite maximum antenna gain = 17 db,

f = 2.2 GHz.

The received signal level at the synchronous satellite is a maximum of -60 dbm, and if no translation is employed, at least 90 db of isolation is required for a 1 watt Comsat transmitter. At lower altitudes, the one-way range loss decreases by 6 db per octave of range change; however, the antenna gain also decreases in almost the same proportion, since the sine of the required beamwidth angle for maximum coverage varies inversely as the communication satellite altitude R. Thus it might be concluded that a frequency offset is required for all propagation links suggested by Figure 1.

The frequency offset can be achieved by:

1. Heterodyning the incoming signal with an auxiliary oscillator and after amplification adding this difference frequency signal to the transmitter carrier.
2. Multiplying the heterodyned signal frequency by passage through a series of non-linear networks.
3. Demodulating the incoming signal and re-applying the modulation to a new carrier.

The transmitter carrier can be made coherent with the incoming signal, if necessary, by phase-locking all heterodyning oscillators to the incoming carrier. Any practical system will employ one or a combination of the above techniques to achieve the desired frequency separation. For example, Syncom II used straightforward heterodyning to translate the incoming 7362 MHz signal to a transmission frequency of 1815 MHz. The Unified S-Band CSM transponder employs schemes 2 and 3 while coherently translating both ranging code and Doppler shifted carrier.

Since the data transmitted from the Apollo spacecraft directly to the earth terminal and that transmitted via the communication satellite to the earth terminal are necessarily at different frequencies, separate ground receivers as well as separate ground antennas must be installed wherever both links are to be used. By the same token, the up-link voice and data transmissions must be made at two frequencies if both direct and Comsat links are to be employed by the same station. For a ground station, the high gain antenna directed toward a 24-hour Comsat need not have the dynamic tracking capability of an antenna which must track the Apollo spacecraft. If no major changes are to be made in the present Unified S-Band transponder design, then the only frequency selection is concerned with the up- and down-link frequencies between an earth terminal and Comsat. There is no reason to require that these frequencies be near the Unified S-Band frequencies, since a separate ground Comsat antenna and receiver input are required in any case. This is a "strong link" (Syncom II averaged 12 db down-link signal to noise with a 3 MHz equivalent noise bandwidth (Reference 17)), and the ground antenna-receiver performance need not match, for example, that of the deep space facilities. The carrier frequency selection is generally based upon noise considerations, since it is now practical to build reliable microwave oscillators and amplifiers with reasonable efficiencies over the range of 0.1 GHz to 10 GHz. Figure 8 indicates the equivalent noise temperature T_e, which can be attributed to sources external to the earth terminal receiver and receiving antenna.

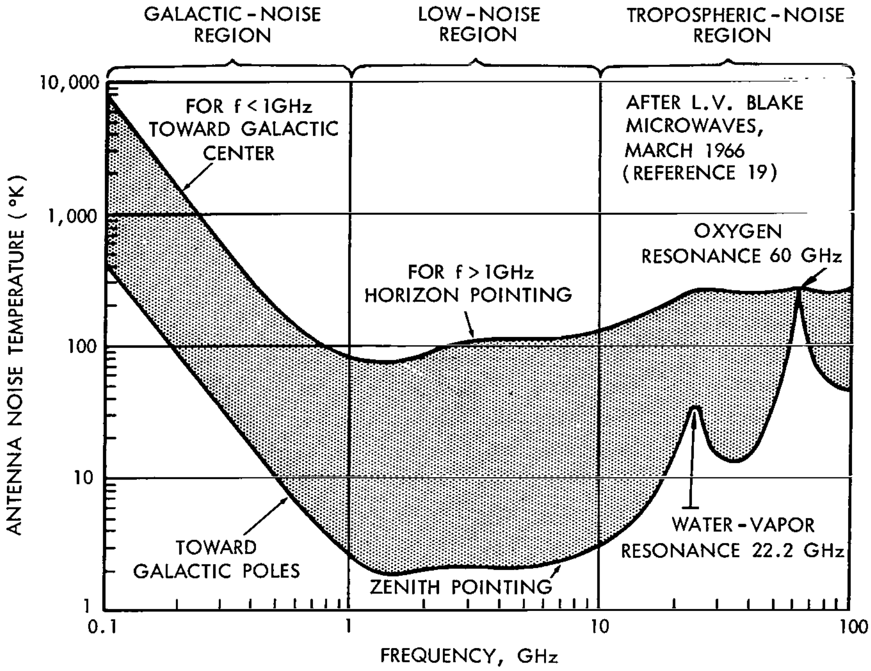


Figure 8—Effective earth based sky noise temperature versus frequency.

The use of "effective noise temperature" rather than "power spectral density" is simply a matter of convention. The noise temperature T_e (°K) is related to ϕ_n (watts per cycle of bandwidth) by

$$\phi_n = T_e \, k \, \text{watts/Hz} , \tag{21}$$

where

k = Boltzmann's Constant = 1.38×10^{-23} (Joules/°K),

T_e = "effective noise temperature" (°K),

ϕ_n = power spectral density (watts/Hz).

At frequencies below 500 MHz, the noise is predominantly due to cosmic noise which comes from our own galaxy (the Milky Way), from extragalactic sources, discrete "radio stars," and the sun. At frequencies above 2 GHz, the received noise is primarily due to atmospheric absorbtion noise. The mechanism involved here is analogous to the noise coupled into a receiver by a non-ideal (or lossy) transmission line. Today (1966), ground-based zenith pointing overall receiving system temperatures on the order of 71°K are feasible at 4 GHz (Reference 18).

Based on a "sky noise" criteria, any frequency in the 1 to 10 GHz range would appear suitable for the translated Unified S-Band signal. Assuming sky noise of random polarization, Figure 8 is appropriate for antennas possessing either linear or circular polarization. Figure 9 shows the average one-way signal attenuation which can be attributed to the atmosphere in the absence of precipitation.

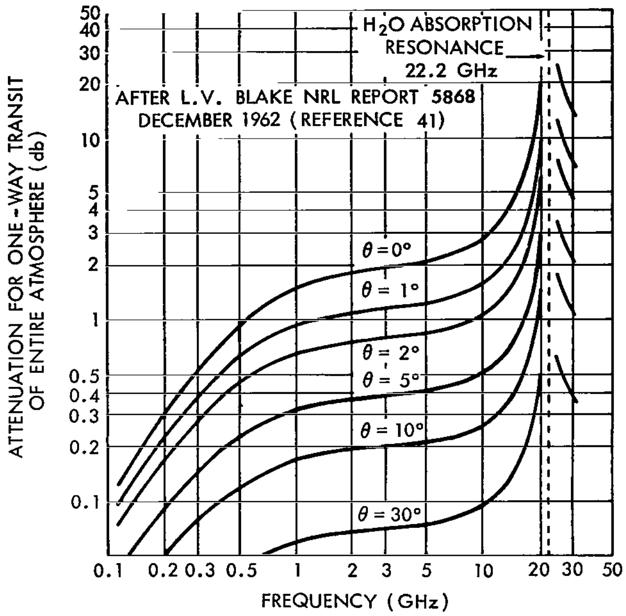


Figure 9—Attenuation due to atmosphere.

The influence of rain on radiowave propagation in the 0.1 to 100 GHz range is summarized in Reference 20. It is seen that the attenuation experienced by a signal due to rain and the noise introduced by rain are also functions of frequency. Figure 10 indicates the estimated attenuation due to various rainfall rates in db per km of path length in the frequency range of 1 to 30 GHz. The maximum thickness of this rain interface would be on the order of 100 km corresponding to a total traverse of the rain cloud region (maximum height $\doteq$ 10 km) at a 5 degree elevation angle. Figure 11 is an estimate of the effective increase in sky noise temperature due to rain. Measured data by Bell Telephone Laboratories (Reference 21) at 6 GHz was used as the starting point for Figure 11. The noise produced by a 156 mm/hour rate is shown to be less than that at 47 mm/hr. This is believed to be caused by a greater rain layer thickness in the latter case. It is seen that the increase in sky temperature due to rainfall should be negligible at 2 GHz, but at 10 GHz might be as high as 250°K. The effects of rain would of course influence only the Comsat-to-earth link.

Another factor in frequency selection is political rather than theoretical. The extent of current Federal Communications Commission (FCC) commercial television and FM radio broadcast frequency assignments between 54 MHz and 890 MHz is shown in Table 3.

A summary of frequencies currently allocated specifically for U.S. Government space technology is indicated in Table 4. These are government frequency allocations, in contrast to the commercial broadcast assignments indicated in Table 3. Government frequency allocations are determined by the Interdepartmental Radio Advisory Committee (IRAC), while commercial allocations are determined by the Federal Communications Commission (FCC).

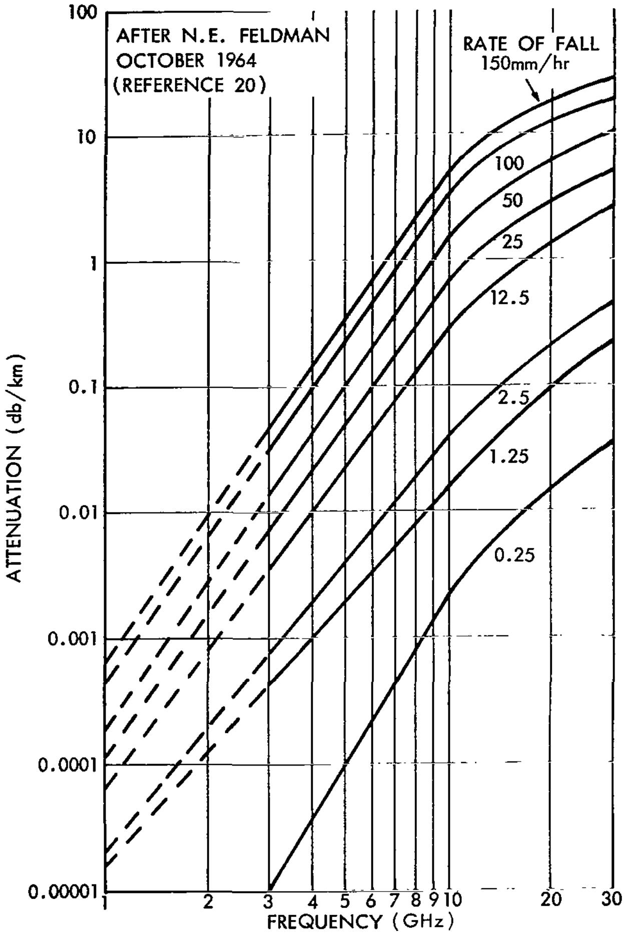


Figure 10—Attenuation at 18°C for a number of rains.

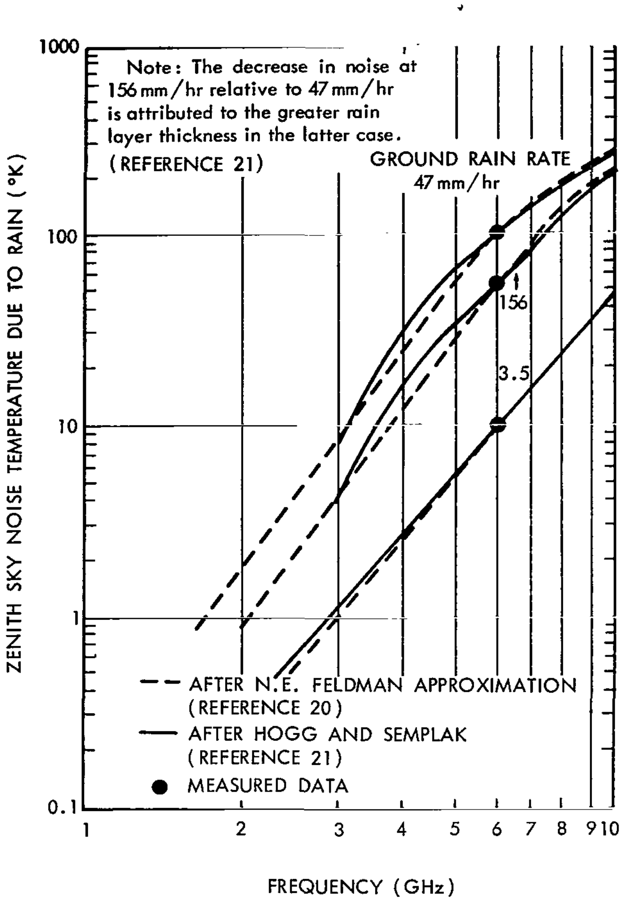


Figure 11—Estimated sky temperature due to rain.

Table 3

Commercial Broadcast Frequency Allocations.

Broadcast Service	Frequency Band MHz
Television	54 - 72
Television	76 - 88
FM radio	88 - 108
Television	174 - 216
Television	470 - 890

(Reference 22)

Table 4

Summary of Radio Frequency Allocations for Space and Satellite Requirements (Reference 23).

Service	Frequency Range (MHz)
Radio astronomy	73.000 - 74.600 79.750 - 80.250
Space communication, research tracking and meteorological	117.975 - 138.00
Space research	143.60 - 143.65 (no U. S. allocation)
Satellite experiments by amateur service	144.0 - 146.0
Space telecommand, radionavigation, radio astronomy, and doppler transmitter	148.25 - 153.0 154.20 - 162.00
Space research	183.10 - 184.10 (no U. S. allocation)
Meteorological telemetering	235.00 - 237.80
Space telemetry and tracking	267.0 - 273.0 (no U. S. allocation)
Radio astronomy	322.0 - 329.0
Doppler transmitter	324.0
Ionospheric sounding	359.89 - 360.29
Radionavigation satellite, meteorological, telemetry, and tracking	399.9 - 402.0
Radio astronomy	404.0 - 410.0
Space telecommand	449.75 - 450.25
Meteorological satellite	460.0 - 470.0 (no U. S. allocation)
Radio astronomy shared with radio broadcasting and radionavigation	606.0 - 614.0
Space research	900 - 960 (no U. S. allocation)
Radio astronomy	1400 - 1427
Space telecommand	1427 - 1429
Space telemetry, tracking communication systems, meteorological	1525 - 1670
Radio astronomy	1670 - 1690
Meteorological satellite	1690 - 1700
Space research	1700 - 1710
Communication, earth-to-satellite	1725
NASA and DOD up-data stations, upward transmissions	1750 - 1850
Communication satellite-to-earth	1814.069 - 1815.794
Satellite tracking	1820.177
Up-data transmission, telecommand, and deep space research	2100 - 2120

Table 4 (Continued)

Service	Frequency Range (MHz)
Space research, down-data link, telemetry and deep space tracking	2200 - 2300
Radio astronomy	2690 - 2700 3165 - 3195
Communication satellite radionavigation, satellite-to-earth	3400 - 4700 (no U. S. allocation 3400 - 3700 and 4400 - 4700)
Radio astronomy	4800 - 4810 4990 - 5000
Space communications and research	5000 - 5255
Space research	5670 - 5725 (no U. S. allocation)
Radiolocation, amateur and communication satellite	5725 - 6425
Space telecommand	7120 - 7250 (no U. S. allocation)
Meterological satellite, tracking and telemetry	7200 - 7250 (no U. S. allocation)
Communication satellite (satellite-to-earth)	7250 - 7750
Communication satellite (earth-to-satellite)	7900 - 8400
Space research	8400 - 8500
Radio astronomy	8680 - 8700
Weather radar, radio location and amateur	9975 - 10025
Radio astronomy	10680 - 10700
Radionavigation	14300 - 14400
Space research, radio astronomy, communication systems and techniques	15250 - 15700
Radio astronomy	19300 - 19400
Space research and radio astronomy	31000 - 32300 (31000 - 31300 and 31800 - 32300 no U. S. allocation)
Radio astronomy	33000 - 34000
Meteorological radar and space research	34400 - 35200 (34200 - 35200 no U. S. allocation)
Radio astronomy	36500 - 37500

NOTE:

1. Only frequencies allocated above 40 MHz are listed. Below 40 MHz (frequency range of ionosphere sky wave propagation) limited United States assignments are available for ionospheric sounding, radio astronomy, search, rescue and space research.
2. All of the services indicated for a particular frequency range may not be authorized simultaneously at a particular frequency within the range. For more detail, see Reference 23.
3. Reference 23 is in accordance with Extraordinary Administrative Radio Conference (EARC), Geneva 1963, except where noted as authorized by Interdepartmental Radio Advisory Committee (IRAC).

It should also be noted that whenever precise radio ranging is to be implemented, frequencies above 1 GHz should be employed to avoid the time delay and refraction effects attributable to the earth's ionosphere (see for example, Reference 24).

Transmitter Power Level

Reliability and efficiency coupled with lightweight are the primary goals in spacecraft radio frequency power amplifier design. While solid state amplifiers appear desirable from a reliability standpoint, they do not yet offer efficiencies competitive with the traveling wave tube amplifier at frequencies above 1.5 GHz and power levels greater than 10 watts. Figure 12 shows the locus of equal efficiencies for traveling wave tubes and solid state amplifiers as based upon a 1965 review of the projected "state-of-the art" (Reference 25). To date, microwave traveling wave tube amplifiers of sufficient reliability for space applications are still in the 20- to 30-watt average power class. By 1971, the hope is to have a 50-watt capability, and in the more distant future, possibly 100 watts (Reference 26). During the interim, much research will be undertaken in the area of nuclear power supplies, which might afford a means of eventually overcoming the primary power limitation imposed by unoriented solar cells, storage batteries, and, more recently, hydrogen-oxygen fuel cells. In the case of solar cells, as of 1963, primary power required several pounds per watt (Reference 27). As shown in Reference 28, this has been reduced to less than one pound per watt.

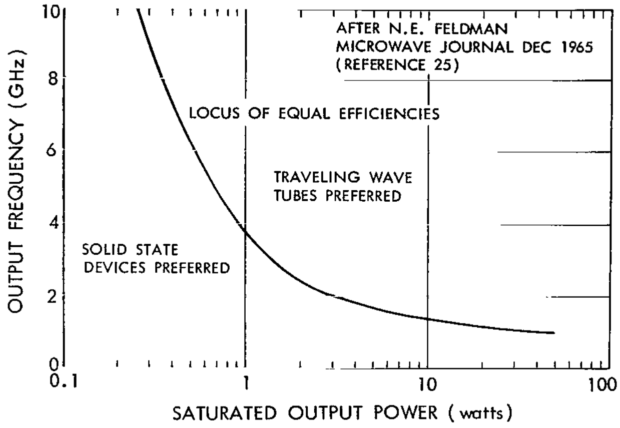
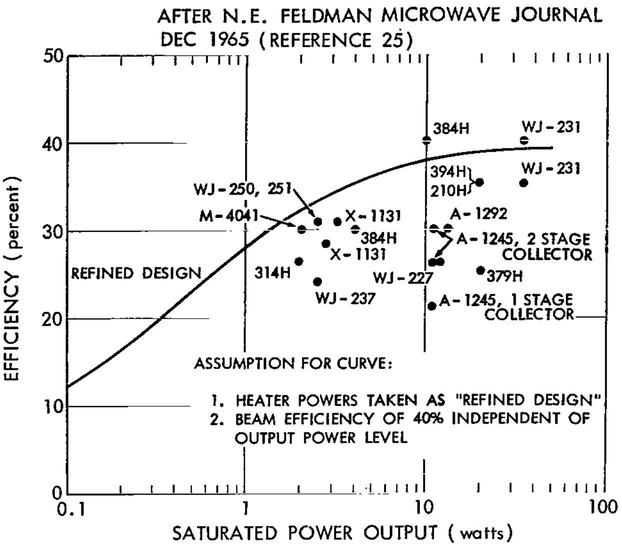


Figure 12—The traveling wave tube compared with solid state amplifiers.

At full theoretical performance, present spacecraft power systems can deliver primary power at 200- to 300-watt levels. Nuclear-reactor-type power supplies offer promise of increased primary power, even though problems such as weight control and heat removal remain to be solved. Such power supplies have the potential of delivering electrical power over extended periods of time. Nuclear reactor primary power systems capable of delivering from 0.5 kw to 20 kw of electrical power could be made operational in the 1970-75 period (Reference 28). The operating principle of the nuclear supply is to use the heat generated by controlled fissioning of uranium-235 to establish a temperature gradient across a bank of thermoelectric couples (such as silicon-germanium thermoelectric elements) to directly produce electrical energy.

It should be pointed out that large panels of fully oriented solar cells (i.e., capable of tracking the sun) should not be excluded as a possible high power source in future systems once a reliable solar tracking scheme has been developed.

The traveling wave tube amplifier operates with a maximum efficiency near full power output. The overall efficiency (including heater supply and high-voltage supply losses) is seen in Figure 13



AFTER N.E. FELDMAN MICROWAVE JOURNAL DEC 1965 (REFERENCE 25)

Figure 13—Traveling wave tube amplifier efficiency.

at present to approach 40-percent. The lower power level and efficiency tubes are associated with earlier development. For example the M 4041 was used in Telstar (1962), the A-1245 in Relay (1962) while the 394H is associated with Surveyor and Apollo (1966), and the 384H with the Applications Technology Satellite (1966) At low levels the operating efficiency is on the order of 10-percent. It is desirable to drive this type of amplifier at a constant power level. This can be accomplished in a communication satellite repeater, if a "hard limiter" is employed between the frequency-translated and amplified incoming signal and the output RF power amplifier. An ideal hard limiter is a device which has the transfer function

$$e_0 = -A \quad \text{when} \quad e_i < 0 \, ,$$

$$e_0 = 0 \quad \text{when} \quad e_i = 0 \, ,$$

$$e_0 = A \quad \text{when} \quad e_i > 0 \, ,$$

where

e_i = limiter input (volts),

e_0 = limiter output (volts).

While this ideal transfer function cannot be attained in a practical device, it can be approximated so closely that an analysis based on it will be valid in all cases of practical interest. The output of such a limiter in the absence of an input signal is a set of pulses of constant amplitude and random time displacement, the displacement determined only by the input noise characteristics. To avoid such outputs, the modulation schemes employed must be such that an input signal is present at all times. This is the case for angle modulating schemes such as used in the Unified S-Band System.

Modulation Techniques

Knowledge of the modulation scheme employed is essential whenever system calculations are performed, since in space communication the entire transmitted power is seldom available for one specific function. In general, there will be a modulation loss incurred, and this loss must be included in all point-to-point signal loss calculations.

The Unified S-Band System employs phase-modulation (PM) and frequency-modulation (FM). Two separate transmitters, each employing Hughes type 394H traveling wave tube (TWT) amplifiers with a design goal of 20 watts of RF power, are used for the PM and FM transmissions from the CSM. Normally, the phase-modulated signal carrier is phase locked to the up-link carrier. In the event the up-link signal level drops below a nominal -124 dbm, an auxiliary oscillator is switched in to replace the VCO as the PM-channel RF-driving source. The frequency-modulated carrier is always derived from free-running oscillators aboard the spacecraft. All television data is to be transmitted by the spacecraft FM transmitter. The entire up- and down-link RF Unified S-Band spectrum, including the lunar excursion module (LEM) and instrumentation unit (IU) transmissions, is indicated in Figure 14.

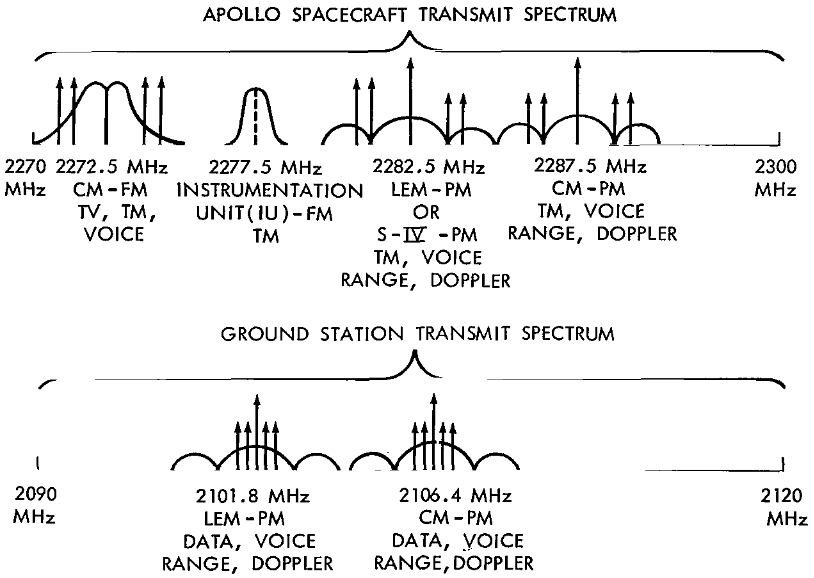


Figure 14—USB system frequency spectrum.

Both phase and frequency modulation are examples of so-called angle modulation, which in the most general form is indicated by Equation 22:

$$V(t) = A \cos \left[\omega_c t + k\phi(t) + \theta_0\right] , \tag{22}$$

where

$V(t)$ = the radiofrequency voltage waveform (volts),

A = a scalar multiplier (volts),

$\omega_c = 2\pi f_c$ = RF carrier angular frequency (radians/second),

t = time (seconds),

$\phi(t)$ = modulating signal,

k = a constant of the modulating system,

θ_0 = initial carrier phase (radians).

If $f(t)$ represents the intelligence signal, then for the case $\phi(t) = f(t)$, Equation 22 is referred to as phase modulation. If $\phi(t) = \int f(t)\,dt$, then Equation 22 is referred to as frequency modulation. The close relationship between phase modulation (PM) and frequency modulation (FM) is clearly demonstrated by commercial FM broadcasting where the audio intelligence is first integrated and then phase-modulated onto a carrier to produce the resultant frequency modulation.

The tentative CSM transponder down-link PM and FM characteristics are summarized in Tables 5 and 6 respectively. The up-link characteristics are presented in Table 7. It is noted (Tables 5 and 6) that in certain modes of Unified S-Band operation, one of the modulating functions is angle-modulated directly onto the carrier, while the remaining functions are angle-modulated onto sinusoidal subcarrier frequencies; that is, for the case of ideally stable carrier and subcarrier frequencies and in the absence of noise,

$$V(t) = A\cos\left\{\omega_c t + \phi_0(t) + \theta_0 + \sum_{i=1}^{n} m_i \sin\left[\omega_i t + \phi_i(t) + \psi_i\right]\right\} \text{ volts }, \tag{23}$$

where

$V(t)$ = transmitter radiofrequency waveform (volts),

m_i = a constant of the carrier modulating system,

ω_c = carrier angular frequency (radians/second),

ω_i = subcarrier angular frequency (radians/second),

$\phi_0(t)$ = a signal angle modulated directly upon the carrier,

$\phi_i(t)$ = a signal angle modulated directly upon a subcarrier,

θ_0 = initial carrier phase (radians),

ψ_i = initial subcarrier phase (radians),

t = time (seconds),

A = a scalar multiplier (volts),

n = number of down link subcarriers for any given modulation mode (in the CSM down link: maximum n = 4 for the FM transmitter and 2 for the PM transmitter).

Table 5

Apollo Command and Service Module (CSM) Phase Modulated Transmission Characteristics (Down-Link).

Combination	Information	Modulation Technique	Subcarrier Frequency	Peak Phase Deviation (Radians)[*]
1	Carrier			
	Voice	FM/PM	1.25 MHz	0.7
	51.2 kbps TM	PCM/PM/PM	1.024 MHz	1.2
2	Carrier			
	PRN	PM on Carrier		0.20
	Voice	FM/PM	1.25 MHz	0.70
	51.2 kbps TM	PCM/PM/PM	1.024 MHz	1.20
3	Carrier			
	PRN	PM on Carrier		0.20
	Voice	FM/PM	1.25 MHz	1.20
	1.6 kbps TM	PCM/PM/PM[†]	1.024 MHz	0.70
4	Carrier			
	Voice	FM/PM	1.25 MHz	1.20
	1.6 kbps TM	PCM/PM/PM	1.024 MHz	0.70
5	1.6 kbps TM	PCM/PM/PM	1.024 MHz	1.60
6	Carrier			
	Key	AM/PM	512 kHz	1.00
7	Carrier			
	PRN	PM on Carrier		0.50
8	Carrier			
	Backup voice (square wave)	PM on Carrier		0.70
	1.6 kbps TM	PCM/PM/PM	1.024 MHz	1.10
9	Carrier			
	PRN	PM on Carrier		0.20
	1.6 kbps TM	PCM/PM/PM	1.024 MHz	1.60

[*] With reference to Equation 23, peak phase deviation corresponds to m_i for subcarriers, and maximum $|\phi_0|$ for direct modulation.

[†] Refer to list of abbreviations for meaning of PCM/PM/PM, etc.

In addition to the desired intelligence angle modulated onto the carrier of the Apollo Spacecraft phase-modulated transmitter, during ground track there is also the undesirable noise resulting from the retransmission of the uplink voice and TM. This additional noise is taken into consideration when computing the ratio of maximum available radiated power for a specific function (for example, voice) to total radiated power. This ratio is often termed modulation loss. Table 8

Table 6

Apollo Command and Service Module (CSM) Frequency Modulated Transmission Characteristics (Down-Link).

Combination	Information	Modulation Technique	Subcarrier Frequency	Maximum Frequency Deviation Δf* (kHz)
1	Playback voice at 1:1	FM Baseband		100
	Playback 51.2 kbps TM at 1:1	PCM/PM/FM	1.024 MHz	600
	Scientific data playback at 1:1	FM/FM	95.000 kHz	75
		FM/FM	125.000 kHz	110
		FM/FM	165.000 kHz	170
2	Playback voice 32:1	FM Baseband		100
	Playback 1.6 kbps TM at 32:1	PCM/PM/FM†	1.024 MHz	600
3	Playback LEM 1.6 kbps TM at 32:1		Data not available	
4	Television		Data not available	
5	Realtime scientific data		Data not available	

*With reference to Equation 23, for the subcarriers, the peak frequency deviation divided by the subcarrier frequency $\left(\Delta f/f_i\right)$ corresponds to m_i.

†Refer to list of abbreviations for meaning of PCM/PM/FM, etc.

indicates the minimum modulation loss associated with CSM transmission. Based upon a comparison of calculated and measured signal level margins (Reference 30), the values for modulation loss indicated in Table 8, with the exception of PRN, can be considered to be meaningful within ±1 db. Table 8 also indicates the Comsat RF bandwidths required for satisfactory retransmission of the received information. The modulation loss associated with downlink voice or telemetry is calculated as the ratio of radiated unmodulated subcarrier power to total radiated power. A minimum pre-detection subcarrier power-to-noise power ratio is then specified as being necessary for satisfactory performance. In the case of voice, the required USB ground receiver pre-detection subcarrier signal-to-noise power ratio is specified as 10 db in a pre-detection equivalent noise bandwidth of 20 kHz (Reference 9).

Table 7

MSFN Phase Modulated Transmitter Characteristics (Up-Link).

Combination	Information	Modulation Technique	Subcarrier Frequency (kHz)	Peak Phase Deviation (Radians)*
1	Carrier			
	PRN	PM on Carrier		1.34
2	Carrier			
	voice	FM/PM†	30	1.85
3	Carrier			
	up-data	FM/PM	70	1.85
4	Carrier			
	PRN	PM on Carrier		0.80
	voice	FM/PM	30	1.85
5	Carrier			
	PRN	PM on Carrier		0.80
	up-data	FM/PM	70	1.85
6	Carrier			
	PRN	PM on Carrier		0.50
	voice	FM/PM	30	1.00
	up-data	FM/PM	70	0.76
7	Carrier			
	voice	FM/PM	30	1.10
	up-data	FM/PM	70	1.10
8	Carrier			
	backup voice	FM/PM	70	1.85

*With reference to Equation 23, peak phase deviation corresponds to m_i for subcarriers, and maximum $|\phi_0|$ for direct modulation.
†Refer to list of abbreviations for meaning of FM/ PM.

Table 8

Bandwidth Requirements and Minimum Modulation Loss Associated with CSM to Comsat Transmission.

Function	Minimum Modulation Loss	Required Minimum Overall RF Bandwidth at Relay Transponder	Mode* of Operation for Minimum Modulation Loss
Carrier tracking	-4	50 Hz	PM Mode 2
1.6 KBPS telemetry	-2	6 kHz	PM Mode 9
Voice	-4	20 kHz	PM Mode 4
51.2 KBPS telemetry	-4	150 kHz	PM Mode 1
Television (FM)	0	3 MHz	FM Mode 4
PRN ranging	-9	4 MHz	PM Mode 2

*See Tables 5 and 6 for mode definitions. (Reference 5)

The approximate pre-detection bandwidth required to demodulate the angle-modulated subcarrier indicated in Equation 23 is

$$B = 2f_m (1 + m) , \qquad \text{(Reference 13)} , \tag{24}$$

where

B = required pre-detection bandwidth (Hz),

f_m = highest significant frequency component in the modulating signal (Hz),

*m = modulation index (radians).

The Spacecraft Receiver

A spacecraft receiving system cannot be expected to approach the same quality of performance attained at an earth-based terminal. This stems from the fact that equipment cooling in conjunction with elaborate pre-amplification to improve receiver noise figure is not practical at the spacecraft. Also, equipment complexity, weight, and size preclude the near future implementation of spacecraft data processing techniques such as the MSFN USB PRN ranging signal autocorrelation. In the case of a communication satellite which has the earth continuously in view, the effective antenna temperature is on the order of 300°K (Reference 31). In this situation, even a low noise receiver cannot reduce the noise below this limiting value. The noise input at the spacecraft receiver terminals is generally described in terms of an effective temperature T_e, which can be related to input noise power by means of the relation

$$P = kT_e B , \tag{25}$$

where

P = noise input at the receiver terminals (watts),

T_e = effective temperature (°K),

B = overall noise equivalent bandwidth,

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

For all practical purposes, the noise equivalent bandwidth can be considered as the 3 db bandwidth of the overall receiving system response. The receiving system bandwidth, in turn, is that bandwidth required to reproduce the received signal with the desired fidelity at an acceptable signal-to-noise ratio.

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*For PM, m = maximum phase deviation.
For FM, $m = \Delta f/f_m$, where Δf = maximum frequency deviation,
f_m = highest significant modulating frequency.

The total noise at the receiver terminals is due primarily to three separate sources—namely, the antenna noise as received from sources external to the receiving system, the noise introduced by the lossy transmission line and associated RF hardware connecting the antenna to the receiver input, and the noise generated at the receiver input circuits. With reference to Figure 15, the overall effective noise temperature referred to the receiver IF amplifier input is given by

$$T_e = \frac{T_a}{L} + T_L\left(1 - \frac{1}{L}\right) + \left(F_1 + \frac{F_2 - 1}{G_1} - 1\right)T_r , \tag{26}$$

where

T_e = overall effective noise temperature at receiver input,

T_a = effective antenna noise temperature,

T_L = transmission line temperature,

T_r = receiver temperature,

L = transmission line, coupler, and miscellaneous hardware losses $1 < L < \infty$,

F_1 = noise figure of preamplifier = input signal-to-noise power ratio divided by the output signal-to-noise power ratio,

F_2 = mixer noise figure,

G_1 = preamplifier gain.

The noise figure F, as used in Equation 26, is the ratio of the actual output noise spectral density to the output noise spectral density which would be present if the device (mixer, amplifier, etc.) contributed no noise of its own.

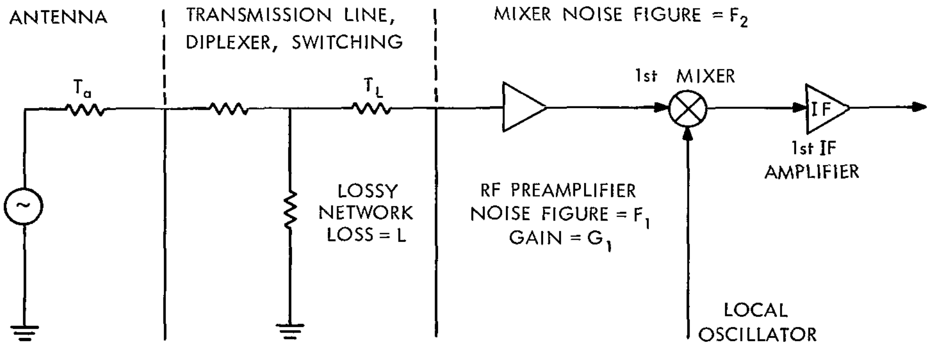

Figure 15—Primary parameters affecting receiver noise spectral density.

F is on the order of 10 db at the RF input of present spacecraft receivers. Most of the noise generated in a conventional superheterodyne receiver lacking any signal preamplification is due to the mixer stage. At a frequency of 2 GHz, present spacecraft mixers consist of semiconductor diodes either in a single-ended or balanced configuration. For reasons of reliability as well as stability, most microwave mixers employ silicon diodes. By careful design, a slight noise reduction might be anticipated in this area. For example, the stated typical noise figure for the SAGE Laboratories 1.7 GHz to 2.4 GHz balanced mixer (Sage Model 22523E) is 7.0 db.

In present communication satellite applications, the Comsat receiver need not be of particularily low noise design, since kilowatts of microwave power can be radiated from the earth terminal. However, when relaying signals originating from another spacecraft, the Comsat receiver design will become more critical and preamplification should be used to advantage. As already suggested by Equation 26, the overall receiver noise figure might be reduced by employing an RF preamplifier, in which case

$$F = F_1 + \frac{F_2 - 1}{G_1}, \tag{27}$$

where

F = overall noise figure,

F_1 = preamplifier noise figure,

G_1 = preamplifier gain,

F_2 = mixer noise figure.

(This is easily shown; see, for example, Reference 32)

Space qualified preamplifiers suitable for use in a communication satellite can be expected to appear during the next decade. An example of the type of amplifier electronically suited for this purpose is the Ferranti model VCA/S20 parametric amplifier which operates at 3 GHz, with an RF bandwidth on the order of 50 MHz, a gain of 20 db, and a 3.0 db noise figure. The physical size of this particular amplifier is approximately 22 by 8 by 8 cm (8.5 by 3 by 3 inches). Such an amplifier could be used in conjunction with a receiver having a 10 db noise figure to achieve an overall noise figure of 3.2 db. However, a parametric amplifier of this type requires a pump microwave frequency source. At present, this RF power is generally supplied by a reflex klystron, which requires several watts of primary power. Future models may employ a solid state pump oscillator with a corresponding improvement in reliability and overall efficiency.

Noise Spectral Density at the Communication Satellite

The 7 db microwave circuit loss in the receiver arm of the USB transponder operating with the high gain antenna (Table 1) is due to the requirement for microwave hardware and associated coaxial cable in order to permit the use of a single remotely located tracking antenna assembly capable of transmitting at two frequencies and receiving on a third (Figure 16). Since the antenna required at the communication satellite for maximum coverage at S-Band need only be on the order of 15 by 15 inches (refer to subsection entitled Effective Antenna Aperture), separate antennas in proximity of the transponder might be employed for the different frequency bands with a resultant lower RF hardware loss. In this case, a loss value L at S-Band of 2 db instead of 7 db would be realizable. For a communication satellite the antenna temperature T_a is on the order of 300°K. The ambient receiver temperature and transmission line temperature depend on such factors as solar radiation, earth radiation, internal energy input, and external energy output (thermal and radio radiation). During the flight of Relay I the average spacecraft temperature was closely correlated with solar illumination and varied from 297°K to 276°K (Figure 17). As a August, 1963, the apogee of Relay I was 7800 km and perigee 1320 km (Reference 33). The extreme values of spacecraft ambient temperature for SYNCOM 2 on 29 December, 1963 were measured as 292°K and 270°K respectively, the lower temperature occurring during eclipsing (i.e., when the spacecraft enters the earth's shadow for a short period—the longest period for SYNCOM 2 being 70 minutes (Reference 34)). An average value of transmission line temperature T_L and receiver temperature T_r of 280°K at the spacecraft is assumed typical. An overall receiver noise figure F (Equation 27) of 3 db is an estimate of what might be achieved with RF preamplification. If the foregoing values are employed in Equation 26, it is seen that the overall effective noise temperature at the communication satellite IF amplifier input is 573°K, corresponding to -111 dbm per MHz of equivalent noise bandwidth.

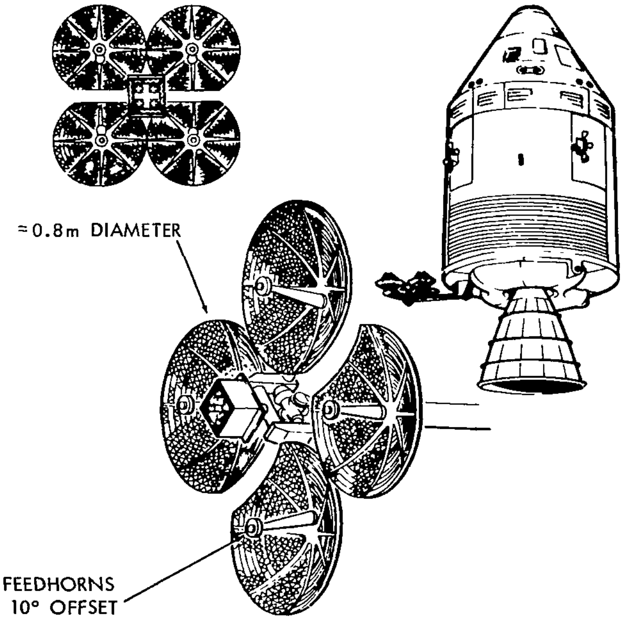

Figure 16—CSM high-gain antenna.

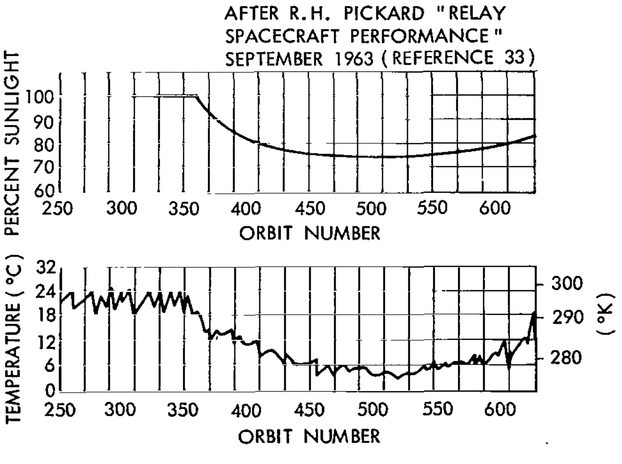
AFTER R.H. PICKARD "RELAY SPACECRAFT PERFORMANCE" SEPTEMBER 1963 (REFERENCE 33)

Figure 17—Relay I spacecraft ambient temperature.

Noise Spectral Density at the Apollo Spacecraft Receiver

With the Apollo CSM high gain antenna pointing away from earth, the high gain antenna temperature T_a could be as low as 2°K (Figure 8). The transmission line loss associated with the high-gain antenna while receiving is 7 db (Table 1), and the receiver noise figure F can be as high as 11 db (Table 1). If a spacecraft average temperature of 280°K is again assumed (Figure 17), then the overall effective noise temperature referred to the USB transponder input (Equation 26) is 3480° Kelvin, corresponding to -103 dbm per MHz of equivalent noise bandwidth. However, even when assuming an antenna temperature of 1000°K, receiver noise and transmission line loss dominate to such an extent that the overall receiver effective noise spectral density is, for all practical purposes, unchanged. The 1000°K antenna temperature is appropriate for a near-earth direct view of the sun with a 5° beamwidth antenna at 2 GHz.

Effects of Orbit Perturbations

The effects of relative motion between an Apollo spacecraft and a communication satellite can introduce two additional sources of radio-link performance degradation. One effect is the Doppler frequency shift associated with the relative Comsat-to-spacecraft radial velocity, which can attain magnitudes up to 8 km per second even if the Comsat is in a 24-hour stationary earth orbit. A second effect is antenna beam-pointing error due to deficiencies in attitude stabilization. In both cases, the disadvantage is at the unmanned Comsat terminal, since any compensating or corrective action such as acquiring and subsequent frequency tracking of the received signal or antenna realignment must be achieved automatically.

Doppler Frequency Shift

The one-way shift in carrier frequency between two isolated terminals of a radio link is given approximately by

$$f_d \doteq \left(\frac{V_r}{c}\right) f_0 , \tag{28}$$

where

f_d = shift in observed carrier frequency (Hz),

V_r = radial velocity of one terminal relative to the other (m/sec),

c = velocity of propagation $\doteq 3 \times 10^8$ m/sec,

f_0 = carrier frequency (Hz).

Figure 18 indicates the maximum Doppler shift as viewed at a 24-hour synchronous Comsat during an Apollo earth orbital flight. At Unified S-Band frequencies, up to ±57 kHz of one-way frequency shift relative to the carrier frequency can be experienced. This implies that a Comsat receiver not employing Doppler tracking must maintain a signal RF bandwidth of at least 114 kHz throughout the receiver, independent of the bandwidth required in the absence of Doppler shift. For example, the required RF bandwidth for USB voice is 20 kHz (Table 9) compared to a 134 kHz

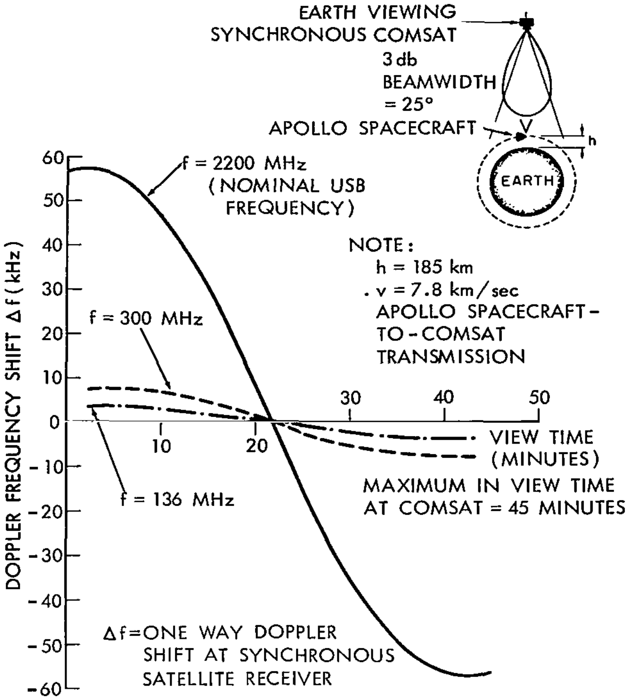

Figure 18—Maximum doppler shift at synchronous communication satellite during Apollo spacecraft earth parking orbit.

Table 9

Examples of Signal Requirements at Comsat Receiver.

Function Transmitted From Apollo Spacecraft	Required RF Bandwidth	Required Predetection Signal-to-Noise Power Ratio (see notes 1, 2 and 3)
Carrier	50 Hz	12 db threshold
Telemetry		
51.2 kbps	150 kHz	9.7 db for 10^{-6} bit error rate
1.6 kbps	6 kHz	8.5 db for 10^{-6} bit error rate
Voice	20 kHz	10 db
Voice plus EVA	40 kHz	10 db
Playback voice	1 MHz	10 db
Television	3 MHz	10 db
PRN ranging	4 MHz	10 db

1. Main carrier-to-noise for carrier tracking. (Ref. 5)
2. Unmodulated subcarrier-to-noise for voice and telemetry.
3. Total signal power-to-noise ratio for television and playback voice.

bandwidth requirement to accommodate voice plus Doppler shift. If the carrier frequency associated with the incoming signal is tracked by the Comsat receiver to obviate the need for wideband operation, then some means of acquisition, such as Comsat local oscillator frequency sweep is required to obtain a phase lock at the Comsat receiver. Such considerations have not been necessary in the past with communication satellites such as Relay and Syncom, where the up-link signal originates with 10- to 20-kw transmitters, which in turn drive antennas having diameters up to 20 m. This is in constrast to the Apollo spacecraft-radiated maximum power of 2 watts, by an antenna having a maximum dimension on the order of 2.5 m. Thus the wideband performance achieved with Syncom III (13 MHz of video bandwidth, Reference 17) cannot be attained with the near-earth USB transponder. As a matter of interest, Figure 18 also indicates the Doppler frequency shift associated with carrier frequencies, at 300 MHz (maximum shift ±8 kHz) and 136 MHz (maximum shift ±3.5 kHz).

It is seen that at VHF frequencies the Doppler frequency shift is much less of a potential problem insofar as receiver bandwidth requirements are concerned, although, as pointed out in Reference 24, the ionospheric-caused distortion of ranging data increases as the square of the operating wavelength, and at VHF is one of the limiting factors in precise ranging.

Antenna Pointing

It would, of course, be most desirable if omnidirectional or wide beamwidth antennas could be employed at both the communication satellite and the Apollo spacecraft. However, as shown previously, antenna gain is inversely proportional to beamwidth. If an Apollo spacecraft-to-Comsat link at S-Band is to be considered, antennas with high gain and, hence, appreciable directivity must be utilized. There are a number of schemes currently being explored for the purpose of obtaining increased antenna gain at the communication satellite. One of these is the so-called despun antenna (Reference 35), where the antenna beam is caused to continuously illuminate the earth while the spin-stabilized Comsat is rotating. The despun antenna pattern is achieved by using a phased array consisting of a number of antenna elements, each energized through an appropriate RF phase shifter. An 8 by 8 matrix of elements with half-wavelength spacing, for example, will result in an antenna beamwidth, consistent with maximum earth illumination with a 24-hour synchronous orbit Comsat. The phase shifters can be ferrite "Faraday rotation" type devices through which the RF phase shift is made proportional to either a mechanical rotation or to a varying control current. In this way the Comsat antenna gains indicated in Table 2 can be achieved even though the satellite is mechanically spinning. The forthcoming flight of ATS (Applications Technology Satellite—GSFC) will further demonstrate the feasibility of this concept. The despun antenna is not a tracking antenna and, therefore, the maximum gain realizable at S-Band is dictated by the desired earth coverage, since the required physical aperture for conical beamwidths down to 5 degrees at S-Band is not a limiting factor.

Another scheme under consideration for alleviating the Comsat antenna-pointing problem involves a self-phased array, where the antenna is automatically phased to track continuously, by electronic means, an incoming RF pilot signal. Such a scheme can be made retrodirective; that is, the Comsat transmission can be directed toward the interrogating station (Reference 36). While such a system has been demonstrated as feasible for the relay of signals originating from high RF-power (10 kw to 20 kw) earth-terminal sources, the requirement of a CW (continuous wave) pilot signal into an equivalent isotropic antenna at a level on the order of -78 dbm prevents such a scheme from being useful in the relay of Apollo CSM S-Band transponder data. For example, if the high gain antenna is employed at the CSM transmitter ($G = 27.4$ db, losses $= 7.2$ db; Table 1) and maximum RF power is generated (11.2 watts out of power amplifier), then at synchronous Comsat distances ($R = 36{,}000$ km), the absolute maximum signal level (i.e., with no modulation) into an isotropic Comsat pilot receiving antenna is, by Equation 19, -129 dbm, or about 51 db below the required signal level.

A third scheme, which is more appropriate for an Apollo vehicle-to-Comsat link is a switched multiple-beam Comsat antenna, where the beam pointing is programmed by the earth terminal, which in turn has access to the spacecraft orbital data. With this configuration, a synchronous Comsat satellite might use a single wide-beam antenna of fixed pointing for the relatively strong Comsat-to-earth link, and an electronically steered high-gain antenna continuously directed toward the Apollo spacecraft. The practical problems of such an arrangement, where two narrow-beam S-Band antennas are required to accurately track each other, are apparent. If the relay of only voice and/or telemetry is required, then the use of lower frequencies such as 136 MHz can greatly reduce both the problem of antenna tracking (wider beamwidths for a given antenna aperture) and, as already shown in Figure 18, the problem of Doppler-shifted frequency tracking.

Synchronous Versus Sub-Synchronous Comsat Orbits

The advantages of a 24-hour synchronous Comsat over lower altitude randomly or spatially phased Comsats include the use of low cost non-tracking ground terminal antennas and the use of a small number of satellites compared with other geometries. Figure 19 indicates how 3 synchronous-orbit satellites can provide coverage for the entire globe. Lower orbit Comsats, while providing shorter radiowave propagation distances, require wider beamwidths (hence, lower gain) to obtain optimum coverage, and, as a result, not much improvement is realized unless sophisticated antenna steering techniques are implemented.

One of the disadvantages of the synchronous satellite is the slight time dependent drift in Comsat position arising from the perturbing forces of the sun, moon, and earth. The synchronous satellite orbit is corrected to maintain a stationary orbit, and the correction process is termed station-keeping. While station-keeping adds a stringent requirement to the 24-hour Comsat design, it has been successfully implemented by both Syncom and Early Bird spacecraft (Reference 37).

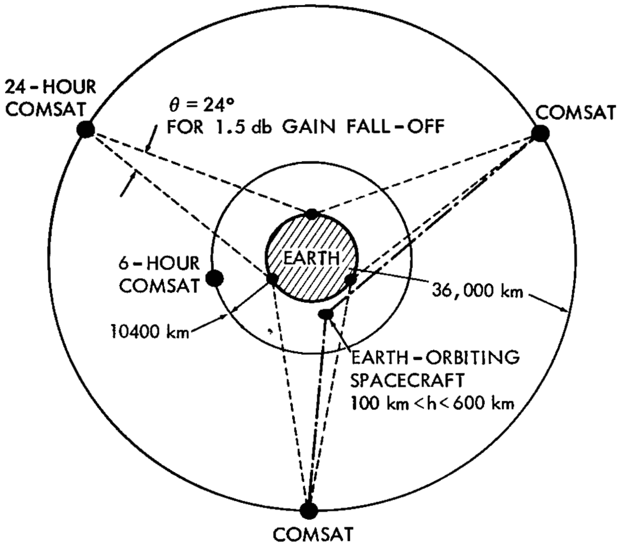

Figure 19—Synchronous satellite complete earth coverage.

DIRECT COMMUNICATION FROM AN APOLLO SPACECRAFT

The purpose of the second section of this report was to define as accurately as possible the parameters which enter into any calculation involving the relay of Apollo spacecraft radio transmission by way of communication satellite. It was pointed out that the weakest link in such a relay was the Apollo spacecraft-to-Comsat link. Thus the following analysis of Apollo spacecraft-to-Comsat transmission, which is based on the parameters presented previously, is taken as a measure of the extent to which communication satellites can be employed in the next decade for a direct Apollo spacecraft-to-earth relay via Comsat.

Unified S-Band Transmission

The two most critical parameters in the Apollo spacecraft-to-Comsat link are the spacecraft transmitter power level and the Comsat receive antenna gain. The extent to which a particular function, such as voice or television, can be relayed can be conveniently related to these two parameters by means of the relationships developed earlier. That is,

$$G_R P_T = \frac{(T_e KB)\left(\frac{S}{N}\right)(16\pi^2 R^2)}{G_T \lambda^2 L_T L_R L_M}, \tag{29}$$

where

G_R = Comsat receive antenna gain,

P_T = Unified S-Band power amplifier output (watts),

G_T = Apollo spacecraft transmit antenna gain,

S/N = required RF signal-to-noise power ratio at Comsat for a particular function,

T_e = Comsat effective noise temperature (°K) corresponding to -111 dbm/MHz,

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

B = required RF bandwidth (Hz),

λ = operating wavelength (m),

R = separation between spacecraft and Comsat (m),

L_T = Apollo spacecraft RF losses,

L_M = modulation loss,

L_R = Comsat receive RF losses.

The CSM transmitter characteristics are:

G_T = 27.4 db high gain, G_T = -3 db omni,

L_T = -7.2 db high gain, L_T = -6.7 db omni,

f = 2287.5 MHz,

P_T = 11.2 watts at present (maximum); however, higher power levels are feasible in future systems.

The Comsat receiving characteristics are:

G_R = variable; however, for maximum earth coverage, G_R = 17 db for a 24-hour orbit or 8 db for a 6-hour orbit,

F = receiver noise figure = 3 db,

L_R = -2 db,

T_e = 573°K,

B = RF bandwidth 50 Hz $< B <$ 4 MHz, depending on nature of the signal modulation,

S/N = 10 db for the 8 types of modulation indicated in Table 9.

The maximum range separation between Comsat and an earth orbiting spacecraft is approximately 42,000 km for the synchronous Comsat and 15,500 km for a 6-hour orbit Comsat. Table 8 indicates the required RF bandwidth, as well as minimum modulation loss for the types of data transfer considered.

It should be noted that the Comsat merely relays an incoming signal to another terminal with a minimum of data processing. Hence the Comsat receiver bandwidth required to receive and permit retransmission of a wideband signal such as the ranging code is much greater than that required at the ground terminal receiver, where signal integration and correlation techniques are employed for range code acquisition. Once an initial range measurement is made, subsequent ranging at the ground terminal is maintained by integrating the Doppler frequency associated with the relayed carrier signal. Figure 20 indicates the transmitter power and synchronous Comsat antenna gain requirements needed to achieve the relay of various functions for the case of the high-gain Apollo spacecraft antenna. It is seen that the PRN ranging code would require a 47-db Comsat antenna gain with a corresponding beamwidth of approximately 0.7 degrees. Such an antenna at the Unified S-Band frequencies would be approximately 12 m in diameter. At the other extreme, carrier tracking could be achieved even if the Comsat antenna were omnidirectional.

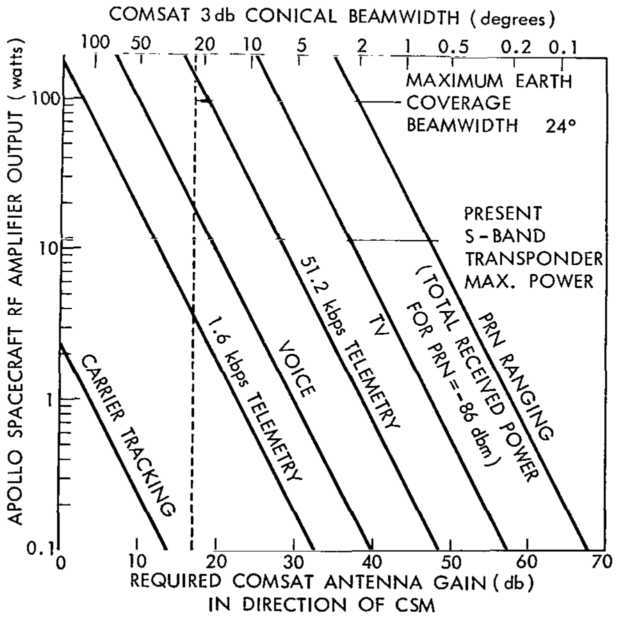

Figure 20—Synchronous Comsat relay of high-gain Apollo spacecraft data.

It should be mentioned that USB transponder techniques have been assumed at the Comsat and that at present Apollo PRN ranging transponder characteristics are specified over the range of -80 dbm to -50 dbm of total input power. Operation at levels above -80 dbm (a level exceeded during all normal MSFN Apollo CSM (or LEM) interrogation) assures a demodulated range code amplitude independent of received input power level. This demodulated code is then remodulated onto the PM transmitter carrier for transmission to the MSFN. The PRN calculations in this paper result in a total incident power of -86 dbm at the Comsat receiver input corresponding to an input total signal power-to-noise ratio of 19 db in a 4 MHz bandwidth. It has been argued theoretically that a PRN ranging code can be detected by a

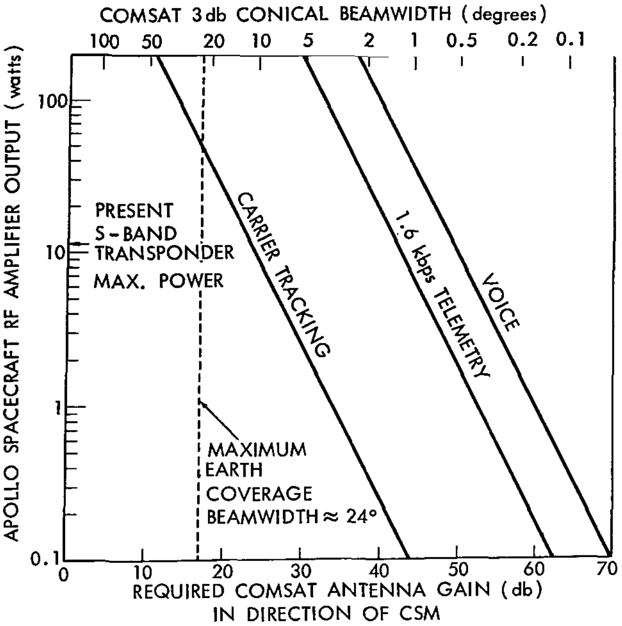

Figure 21—Synchronous Comsat relay of omnidirectional Apollo spacecraft data.

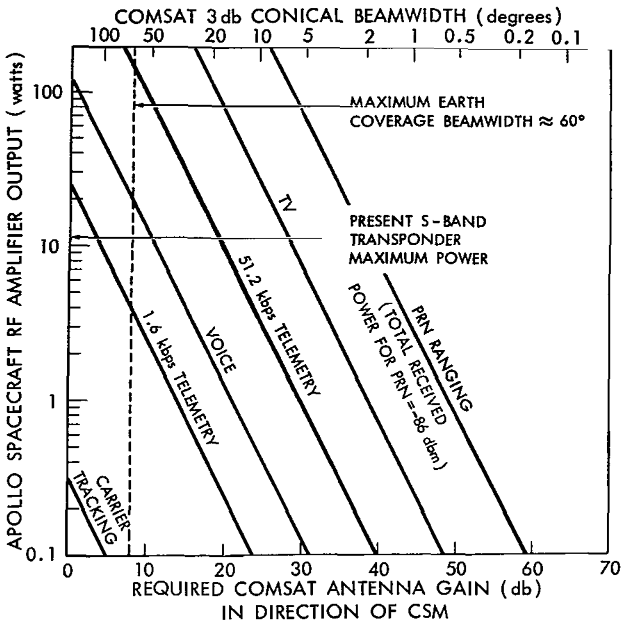

Figure 22—6-hour Comsat relay of high-gain Apollo spacecraft data.

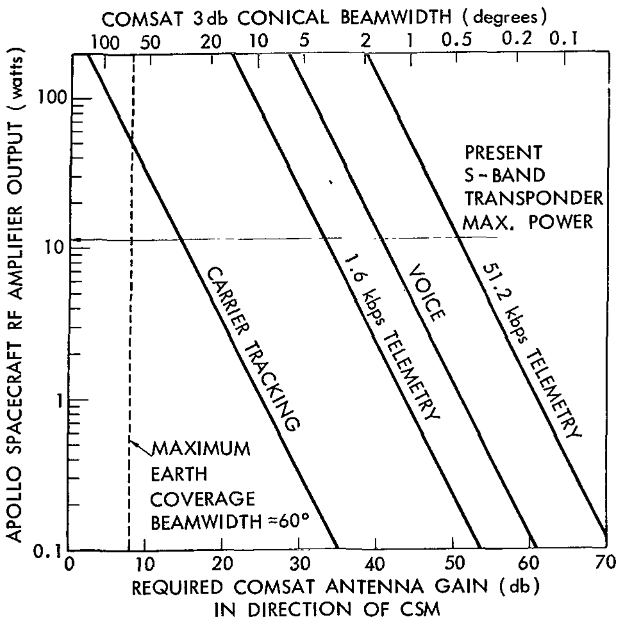

Figure 23—6-hour Comsat relay of omnidirectional Apollo spacecraft data.

transponder receiver at total input signal power-to-noise power ratios as low as -17 db in a 3 MHz bandwidth (reference 43) which in this paper corresponds to a total Comsat received power level of -122 dbm. It can be further argued that by increasing the MSFN integration time such noise corrupted signals are recoverable. However, this is yet to be demonstrated. If such levels (-17 db S/N) are capable of being "turned-around" at the Comsat, then the effect would be to translate the PRN curves of figures 20 and 22 to approximately coincide with the 1.6 kbps curves.

Figure 21 is appropriate for the case where the CSM omnidirectional antenna is employed. For this case, even carrier tracking would require appreciable Comsat antenna gain.

Figure 22 is for the 6-hour orbit Comsat and the high-gain Apollo CSM antenna. Note that while the Comsat gain required to relay any particular function is less than that for the 24 hour synchronous case, the beamwidth required for maximum earth coverage has also decreased. Consequently no improvement is realized over the synchronous orbit Comsat if maximum earth illumination is required.

Figure 23 is again for the 6 hour Comsat relay but with the omni CSM antenna. As in the case of the synchronous Comsat relay, it would appear that the relay of any type of signal emanating from the CSM omnidirectional antenna is impractical, because of the high gains and consequently narrow beamwidths required of the Comsat antenna.

It should be pointed out that whenever the CSM high-gain antenna is employed, it must be redirected by its sequential lobing scheme, which requires a constant carrier input. The Comsat receiver is assumed to frequency track the Apollo CSM carrier while it is frequency-shifted ±57 kHz (Figure 18).

VHF Voice Transmission

The ideal situation in the Comsat relay of signals originating at an earth-orbiting spacecraft would be the use of an omnidirectional antenna at the spacecraft and a fixed spatial beam at the Comsat. As shown by Figures 21 and 23, this is out of the question at S-Band frequencies, even for the relatively narrow carrier-tracking bandwidth requirement. The antenna physical aperture at a synchronous Comsat for full-earth illumination at S-Band is on the order of 37 cm by 37 cm. As shown by Equation 19, it would be advantageous to use a larger aperture at the Comsat if an omnidirectional antenna is employed at the manned spacecraft. However, in order to maintain the required conical beamwidth ($\phi \approx 24°$, Table 2), the wavelength of transmission must be decreased. This can be seen as a consequence of Equations 5 and 18; that is,

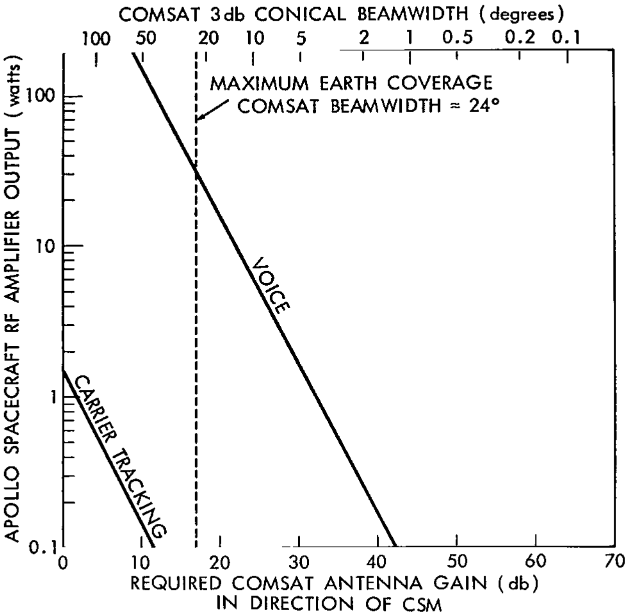

Figure 24—Synchronous Comsat relay of omnidirectional 136 MHz signal.

$$\phi \doteq \frac{\lambda}{2}\left(\frac{27000}{\pi A_r}\right)^{1/2} = \frac{45.2\lambda}{A_r^{1/2}} \text{ degrees ,} \tag{30}$$

where

λ = wavelength (m),

A_r = effective antenna aperture (m^2), and $1.7A_r \doteq$ physical aperture.

It is seen that an increase in effective area requires a decrease in wavelength λ if a constant conical beamwidth ϕ is desired. At 136 MHz, the refraction and time delay errors introduced by the ionosphere limit tracking measurement accuracy. There is however the possibility of continuous voice relay at VHF. In fact, such experiments at 136.47 MHz have already begun with the relay of signals to an aircraft via Syncom III (Reference 38). In this experiment, the power transmitted by Syncom III was less than one watt. The aircraft receiver employed a pre-amplifier having a 2.7 db noise figure.

In order to obtain an estimate of what would be required for a voice relay at 136 MHz from a manned spacecraft, Equation 29 was again plotted (Figure 24) for a synchronous Comsat relay of omnidirectional 136 MHz data based on the following characteristics.

Manned spacecraft VHF transmitter requirements:

G_T = -3 db transmit antenna gain,

L_T = 1 db coaxial cable RF losses,

L_M = -3 db modulation loss (clipped 100-percent amplitude modulation assumed),

P_T = variable.

Comsat 136 MHz receiving requirements:

F = noise figure = 2.7 db,

B = signal bandwidth of 6 kHz,

S/N = predetection ratio = 20 db (carrier-to-noise ratio),

L_R = 1 db receiving coaxial losses,

Φ_n = noise spectral density of -111 dbm/MHz.

The results are indicated in Figure 24. Full earth coverage at 136 MHz ($\phi \approx 24°$) could be achieved with a 20 ft. diameter parabolic dish antenna. In the forthcoming GSFC Applications Technology Satellite (ATS) experiment, earth illumination will be achieved by a 136-MHz, 8-element electronically despun phased array energized by 40 watts of RF power.

If Figure 24 is compared to Figures 21 and 23, the latter figures indicating S-Band omnidirectional radiation, it is seen that only at VHF can voice relay be realized while utilizing widebeam antennas. Also, as indicated previously by Figure 18, Doppler frequency tracking at 136 MHz is required over a maximum of only ±3.5 kHz, compared to ±57 kHz at S-Band. The desirability of 136 MHz for satellite relay applications is also brought out in Reference 39.

SUMMARY

From the investigation it can be seen that the question of feasibility is directly linked to the degree of antenna complexity allowed. The following general principles affect the selection of CSM and Comsat antennas:

1. Antenna conical beamwidth is inversely proportional to the square-root of antenna power gain.
2. For a given antenna aperture, as frequency increases beamwidth decreases.
3. Energy transfer between an omnidirectional antenna and a fixed aperture antenna is independent of frequency providing the omnidirectional pattern falls within the beamwidth of the latter.

The use of USB omnidirectional antennas at both Comsat and CSM eliminates the pointing problem. However, because of low antenna gains, this combination does not permit the relay of even the Doppler shifted carrier, the minimum bandwidth signal. It is shown that for USB relay neither the CSM nor the Comsat antenna can be omnidirectional. Thus, at S-Band, the CSM RF tracking (27 db) antenna must track the Comsat antenna. It is therefore desirable that the Comsat antenna view a maximum of the earth's surface to minimize the antenna pointing problem. With this restriction, lowering the Comsat's orbit below synchronous altitudes to decrease range loss requires a wider Comsat antenna beamwidth and the resultant loss in gain just offsets the improvement due to decreased range separation.

Consequently only the 24-hour synchronous satellite should be considered since it minimizes spacecraft as well as ground tracking problems. Three such synchronous satellites can provide complete earth coverage. With a 24-hour synchronous Comsat, CSM positionable antenna, and Comsat fixed maximum earth viewing antenna; the relay of USB carrier tracking, 1.6 kilobits per second telemetry, and voice is considered feasible. Insufficient antenna gain, however, prevents the relay of wider bandwidth signals such as 51.2 kilobits per second telemetry, television, and PRN ranging. If signals such as television are to be relayed, the Comsat must employ a high gain steerable antenna capable of tracking the CSM positionable antenna. This latter scheme is considered impractical for missions taking place prior to the early 1970's.

For the relay of narrow band signals such as voice or 1.6 kilobits per second data, VHF should be considered. VHF is much more favorable from the antenna pointing standpoint since a much larger antenna "capture area" or aperture (relative to S-Band) can be employed at the Comsat yet retaining the desired maximum Comsat earth view. The use of VHF also requires a relatively simple Comsat carrier tracking receiver since the Doppler frequency shift at 200 MHz, for example, is only 10 percent of that at USB frequencies. The use of VHF, however, requires modification to the existing CSM VHF 5-watt transmitter to achieve an RF power level at least comparable to the S-Band nominal 20 watts. Also, a somewhat more elaborate CSM array than the present VHF omnidirectional antenna would be required.

Therefore, for low data rate relay the use of USB is preferable from the standpoint of minimum CSM modification. The use of VHF is preferable from the standpoint of equipment and operational simplicity. Neither frequency can be used to relay wide bandwidth signals without incorporating the complexity of two steerable arrays tracking each other.

CONCLUSION

The system analysis in this report was based, whenever possible, upon the measured performance characteristics of the USB equipment, along with an estimate of the performance capability of future Comsats as based upon an extensive review of the current literature. The following conclusions of this analysis can be regarded as a starting point if the actual implementation of a CSM-to-Comsat USB link is undertaken.

1. The relay of voice transmission, 1.6×10^3 bits per second telemetry, and carrier tracking can be considered feasible via Comsat if the high-gain CSM antenna is employed ($G = 27$ db), and if the Comsat antenna beamwidth is on an order consistent with maximum earth coverage. For a 24-hour synchronous Comsat, this is on the order of 24 degrees.
2. The CSM S-Band omnidirectional antenna (gain = -3 db) could not be used in a Comsat link even for voice transmission (required RF bandwidth on the order of 20 kHz), since the required Comsat receive antenna size is prohibitive.

3. A 24-hour synchronous orbit relay satellite is preferred over the 6-hour Comsat. This choice minimizes spacecraft as well as ground tracking problems.
4. The relay of the PRN ranging signal is considered not feasible using current USB transponder techniques because of the 19 db total signal power to noise ratio required in a 4 MHz bandwidth in order to detect the PRN code and satisfactorily remodulate it upon the RF carrier associated with the Comsat-to-earth link. In contrast, the ground receiver recovers the ranging code by means of an autocorrelation technique which permits satisfactory operation at extremely low signal-to-noise ratios. This technique results in a reduction of the effective noise bandwidth at the expense of increased acquisition time. Such techniques, however, are considered not practical when applied to near future Comsat installations. The "turn-around" of low level PRN ranging signals is a subject of continuing study (e.g. Reference 44).
5. The Comsat receiver would have to be a phase-locked Doppler frequency tracking receiver, since at the USB frequencies up to ±57 kHz of received carrier Doppler frequency shift would be experienced at the Comsat. While such a receiver can be implemented, it represents a certain degree of complexity over the present wideband Comsat receivers such as employed in Syncom and Early Bird communication satellites, which can function satisfactorily over bandwidths up to 30 MHz as a result of the relatively high RF power (10 to 20 kw) available at the interrogating station which, of course, also incorporates a high-gain antenna.
6. A pilot signal from the Comsat to CSM would be required to permit automatic antenna tracking by the CSM antenna. This would require no modification of the CSM high-gain antenna, since it is already an RF tracking array. Using a Comsat antenna having a conical beamwidth less than that required for maximum earth coverage to achieve more gain would require the additional complexity of two movable antennas tracking each other.

Finally, if only voice transmission from CSM to MCCH via a Comsat is desired, frequencies in the 136 MHz to 400 MHz range can be used to advantage. That is, for a Comsat of fixed beamwidth an omnidirectional transmission from the CSM at VHF (136 MHz) will result in about 24 db less transmission loss than that at the nominal USB frequency of 2.2 GHz. Since the CSM carries a 296.8 MHz amplitude modulated voice transmitter in addition to the USB equipment, this frequency range should not be excluded from consideration.

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National Aeronautics and Space Administration
Greenbelt, Maryland, December 30, 1966
150-22-12-00-51

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Appendix A

ABBREVIATIONS USED IN THIS REPORT

AM	amplitude modulation
AM/PM	data which is amplitude modulated onto a subcarrier, which in turn is phase-modulated onto the main carrier
ATS	Applications Technology Satellite
Comsat	Communication satellite
cm	centimeter
CM	Command Module
CSM	Command and Service Module
CW	continuous wave
db	decibel
despun	antenna array—a phased array capable of being automatically redirected to produce a constant pointing, despite satellite motion resulting from spin stabilization
EVA	extra vehicular activity
F	noise figure
FM	frequency modulation
FM/PM	data which is frequency modulated onto a subcarrier, which in turn is phase modulated onto the main carrier
GHz	10^9 Hz
GSFC	Goddard Space Flight Center
Hz	unit of frequency (one cycle per second)
IF	intermediate frequency
IU	Instrumentation Unit
°K	degrees Kelvin
kbps	kilobits per second
km	kilometer
KW	kilowatt
LEM	Lunar Excursion Module
m	meters

mm	millimeter
MCCH	Mission Control Center-Houston
MHz	10^6 Hz
MSFN	Manned Space Flight Network
NASA	National Aeronautics & Space Administration
NASCOM	NASA Communications
omni	omnidirectional
PCM	pulse code modulation (analog information converted to digital data)
PCM/PM/FM	pulse coded data, phase modulated onto a subcarrier, which in turn is frequency-modulated onto the main carrier
PCM/PM/PM	pulse coded data, phase modulated onto a subcarrier, which in turn is phase-modulated onto the main carrier
PM	phase modulation
PRN	Pseudo Random Noise
RCP	right-hand-circular polarization
RF	radiofrequency
sec	second
S-Band	2 to 4 GHz
S-IV	third powered stage of the Saturn V vehicle. During the lunar mission, the S-IV separates at a distance of approximately 10,000 km from the earth's surface
S/N	signal to noise power ratio
TM	telemetry
TWT	traveling wave tube amplifier
TV	television
USB	Unified S-Band
VCO	voltage controlled oscillator
VHF	very-high-frequency 30 MHz-300 MHz

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