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TO COMMUNICATIONS SATELLITES

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TO COMMUNICATIONS SATELLITES

By
R. E. WIMMER

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ERRATA

July 30, 1962

NAA-SR-7408, "APPLICATIONS OF SNAP REACTOR SYSTEMS TO COMMUNICATIONS SATELLITES"

Page 18, Figure 2: Equation should read:

$$(P_r = \frac{P_t \lambda^2}{16\pi^2 r^2} \text{ watts})$$

Figure 3: Equation should read:

$$(P_r = \frac{P_t G_t G_r \lambda^2}{16\pi^2 r^2} \text{ watts})$$

Page 62, 7th line in table under "Variable" should read:

$$G_t$$

8th line in table under "Variable" should read:

$$G_r$$

Page 114, 14th line under "Definition" should read:

Boltzmann's constant (Joules/°K)

19th line under "Symbol" should read:

$$m_f = \Delta f / f_l$$

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I. INTRODUCTION AND SCOPE

The field of satellite communications is one of intense and widespread interest, since potential military communications uses are numerous and it also appears to be the only field in space technology with reasonably immediate prospects for commercial exploitation. This report deals primarily with the technological considerations of satellite communication systems, and determination of the satellite power supply requirements for such systems.

Consideration is restricted to active satellites (satellites with powered transmitters) as opposed to passive satellites which merely reflect signals radiated from the ground. Although passive satellites have demonstrated communications capability, their inherent requirement of extremely high-power ground stations creates a problem of interference with other services, which is expected to preclude any appreciable extension of this type of satellite relay service into the spectrum-crowded communications future.

Nuclear reactor APU's, such as the current series of SNAP (Systems for Nuclear Auxiliary Power) reactor systems, appear particularly attractive for a wide range of satellite communications applications. The degree of attractiveness of SNAP, or any other type of APU, is strongly dependent upon the many details of each specific communications mission, and may also depend upon mission factors not directly related to the communication technology of the mission. An example of the latter is the use of the electric propulsion capability of large nuclear reactor APU's to reduce the cost of booster rockets, or to enhance their payload capabilities.

Special attention has been given to the present SNAP reactor systems, since they represent a range of power output capabilities suitable to a variety of communications missions, and will be available early in the schedule of immediately attractive satellite communication programs.

A major objective of this report is to provide simple methods for determining the electric power requirements of a given communications mission in terms of mission and orbit parameters. This will permit analysis of possible applications for available and projected space Auxiliary Power Units (APU's).

II. THE SATELLITE AS A COMMUNICATIONS NODE

A. BASIC ADVANTAGES

There are two basic facts which make a satellite attractive for communications applications. First, a satellite at even a low altitude "sees" a large area of the earth surface, and can be "seen" simultaneously from widely separated points. Second, a large portion of the useful electromagnetic spectrum propagates reliably only over straight, "line-of-sight" paths. The use of this spectrum region in direct surface links is limited, by the curvature of the earth, to a maximum surface range of about 30 miles.

The basic value of the communications satellite thus lies in the fact that it permits the use of a large new region of the electromagnetic spectrum for direct long-range communications. This new spectrum region is frequently referred to as the "space band," and stretches from about 100 megacycles to about 20,000 megacycles.* (The "space band" is of course used in many surface applications, and will remain useful for many types of short range point-to-point links.)

The new spectrum space, made available through use of communication satellites, promises to alleviate the problem of rapidly increasing crowding in existing global communications capability.

In addition to providing additional traffic capacity, there are several other advantages which will be derived as corollary benefits. One such advantage is the possibility of handling program material which is beyond the capability of existing or foreseeable surface links. Wide-bandwidth signals such as television (about 5 Mc bandwidth) are presently limited to microwave surface links and coaxial cable, both systems requiring closely spaced relay or booster amplifiers. Although it would be possible in principle to design an oceanic cable for television (TV) bandwidths, such a project does not appear economically attractive in the foreseeable future. A relay satellite, on the other hand, does appear practical in the immediate future and can readily be designed for bandwidths capable of simultaneously accommodating several TV programs.

---

*See Section IV for a discussion of propagation limitations.

1. Directivity and Frequency Sharing

The extremely sharp directivity of modest size antennas operating in the upper part of the space band leads to a second benefit; the sharing or simultaneous use of a frequency by two or more programs in the same geographical area. Selection of the desired program is accomplished by directional discrimination, in favor of the desired signal and against the undesired signals which originate from other directions. Frequency sharing is presently practiced by surface microwave links, and extension to satellites merely expands the principle from two dimensions to three. In order to take the greatest possible advantage of frequency sharing, it is necessary to exercise considerable planning and control over transmitter power levels and ground transmitter locations.

A communications link which operates through a satellite based relay has the potential of a very high reliability, particularly when operated on frequencies somewhat removed from the edges of the space band. Other long range communications links such as radio, cables, etc., are subject to interference and perturbations, principally from solar and ionospheric activity. Since the ionosphere is essentially transparent to space-band frequencies, even major perturbations of the medium have little or no effect on the link. At space-band frequencies, propagation is very nearly that of ideal free-space conditions.

Besides point-to-point communications, satellites may also be used to provide a signal to an unlimited number of receivers within a large area. Such coverage may be for the purpose of transmitting programs to conventional ground stations for rebroadcast, or even directly to home receivers, or it may be for such services as news wires, weather information, police, military or other one-way information dissemination channels.

B. ORBIT CONSIDERATIONS

There are a wide variety of possible orbits for artificial satellites. These range upward from a minimum stable altitude of about 200 miles, determined by atmospheric drag, and may have a wide range of eccentricities. Different orbits are suitable to different communication missions, and orbit choice exerts a heavy influence on the entire system. It is more likely the case that the particular system requirements will determine the orbit required.

1. Coverage Area

The size of the coverage area, i.e., the area on the earth's surface from which the satellite is simultaneously visible, is determined by the satellite altitude at any given moment. The maximum surface range between ground stations is given by:

$$R = 2 r_e \cos^{-1} (r_e / r_o)^* \quad \dots (1)$$

where r_e is the radius of the earth, r_o the orbit radius, and $\cos^{-1}$ is in radians. R is also equal to the diameter of the coverage circle for broadcast considerations. It should be noted that the coverage area thus described is not generally fixed with respect to the earth, but moves at a rate determined by satellite altitude.

2. Coverage Time

The length of time for which a satellite is visible from a given ground station is dependent on both orbit parameters and ground station location with respect to the orbital plane. If the orbital period is short compared to one sidereal day, the coverage duration from circular orbits may be approximated by:

$$\Delta t = \frac{\tau}{\pi} \cos^{-1} (r_e / r_o \cos \alpha) \quad \dots (2a)$$

where τ is the orbital period, r_e the earth radius, r_o the orbit radius, and α the latitude of the ground station with respect to the orbital plane.

For circular equatorial orbits of any period, the coverage duration is given exactly by:

$$\Delta t = \frac{\tau}{\pi(1-\tau)} \cos^{-1} (r_e / r_o \cos \alpha) \quad \dots (2b)$$

where Δt and τ are in sidereal days, and α is the earth longitude of the ground station. If the direction of the satellite is the same as the earth's rotation, τ is positive.

---

*See Appendix H.

For a period of one sidereal day, the coverage time becomes infinite. This is the special case of the stationary satellite, which revolves in synchronism with the rotation of the earth. A satellite in such an orbit maintains a constant bearing and elevation as seen from any ground point within the coverage area; in this special case this is a fixed area on the surface of the earth.

3. Tracking Rate

When directional ground antennas are employed, they must be accurately aimed at the satellite. The tracking rate (the rate at which the antenna must be moved in order to follow the satellite) is strongly dependent on orbit parameters. Low-orbit satellites which pass directly over the ground station have the largest tracking rates. In most cases, the ground antenna must be capable of tracking both azimuth and elevation at independent rates which vary as an involved function of time. Several special cases of the tracking function exist. Commensurable orbits, those for which a simple harmonic relationship exists between the periods of the satellite and of the earth, will repeat the same ground track at regular intervals. Circular orbits in the equatorial plane always exhibit this characteristic. In both cases, the time functions of azimuth and elevation repeat themselves periodically. The stationary orbit is also a special case of the tracking function, since both azimuth and elevation remain constant with time and are dependent only on the latitude and longitude of the ground station. Since provision of antenna tracking ability greatly increases the cost of a ground installation, high orbits, and particularly the stationary orbit, are very attractive from this viewpoint.

III. RECEIVING INSTALLATION CONSIDERATIONS

A radio communication link may best be examined by first considering the receiving installation.

A. TYPICAL RECEIVING INSTALLATION

Figure 1 represents a typical receiving installation, which consists of an antenna, transmission line, various components of the receiver, and the output transducer. A received signal undergoes various losses and perturbation in the course of processing for ultimate reproduction in intelligible form. Assume that C watts of signal are intercepted by the antenna and delivered to a perfectly matched transmission line. The antenna will also receive a certain amount of radiative noise (N_1), either natural or artificial in origin, and will deliver this noise to the transmission line. In propagation along the line, both signal and noise will suffer attenuation by the same amount due to line losses. A certain amount of noise (N_2) is generated in the line due to thermal agitation of the line loss resistance. The signal and noise is then delivered to the first stage of the receiver proper, usually a resistive load which generates noise (N_3) due to thermal agitation. At this point, the remaining signal and the total noise are amplified by a necessarily imperfect amplifier which contributes additional noise (N_4) due to shot effect, spontaneous emission, and other mechanisms.

N_3 and N_4 are generally treated as an "effective receiver input noise", N_3' , which is given by:

$$N_3' = kTB F_s \quad . . . (3)$$

where T is the absolute ambient temperature, B the effective noise bandwidth of the system, k Boltzmann's constant, and F_s^* the system noise figure. N_3' is sometimes given as:

$$N_3' = k T_r B \quad . . . (4)$$

---

*Some authors use an alternate definition of noise figure, in which " F " = $F_s + 1$. The usage depends on whether the receiver input resistance is considered part of the source or part of the amplifier. Caution should be exercised in using noise figure references below 10 db as the difference in the two definitions may be striking.

Figure 1. Typical Receiving Installation

where T_r is an effective receiver noise temperature. The latter notation is useful in the analyses of masers and other low-noise systems, and has the advantage of permitting simple summations of line loss noise and antenna noises if these factors are not negligible.

Beyond the first amplifier, the predetection signal/noise ratio C/N does not change appreciably, provided the first amplifier has a reasonable gain. Succeeding amplifiers are usually at least as good as the first amplifier, particularly where the first amplifier is a down-converter. Intermediate amplifiers then function at a lower frequency, where low noise figures are more readily obtainable. In the best of receivers, however, some quantity of unwanted noise inevitably appears in the output.

B. INFORMATION TREATMENT AND IMPROVEMENT FACTORS

Most modulation schemes provide a certain degree of redundancy in the transmitted information. In detection, where the waveform of the original information is reconstructed, some of this redundancy may be utilized to improve the signal/noise (S/N) ratio of the final output signal. It is also possible in some cases to take advantage of statistical knowledge of noise and modulation waveforms to improve the output S/N ratio or to otherwise increase the acceptability of the output signal. Information treatment schemes are discussed in Appendix B.

C. SIGNAL/NOISE RATIO REQUIREMENTS

The overall quality of the reproduced signal is measured by the output S/N ratio, i. e., the S/N ratio at the output transducer. This ratio may be greater or less than the predetection S/N ratio, depending upon the information treatment techniques employed (see Appendix B).

The output S/N ratio required for acceptability varies with the type of signal, with the nature of the information transmitted, and to some extent, with the nature of the noise or interference. A reasonably good television picture is obtained with a S/N ratio of 30 db. TV S/N ratios are referred to peak predetection video sync level, since this quantity is readily measurable. Standard TV signals are amplitude modulated (AM) and the detection improvement factor is unity (no improvement).

High-fidelity music is quite acceptable at about 20 db S/N, and speech is intelligible at S/N less than 10 db. In certain cases, employing elaborate information treatment techniques, it is possible to extract useful information from signals which are actually below the average noise level of the system; this is true for some narrow-bandwidth data signals, and is of academic interest only, for most communication satellite applications. Appendix C gives S/N requirements for various types of signals and for various degrees of acceptability.

Figure 2. Propagation Between Isotropic Antennas

Figure 3. Propagation Between Gain Antennas

IV. PROPAGATION

Unlike surface links which depend on the presence of a reflecting or refracting ionosphere for long-range transmissions, satellite links use frequencies at which the ionosphere is nearly transparent. Propagation in a satellite link is primarily governed by geometric, free-space or line-of-sight considerations.

A. IDEAL PROPAGATION IN A VACUUM

An isotropic antenna* in free space, radiating P_t watts of RF energy, has a spherical wave front that is approximately flat in the vicinity of any point reasonably distant from the radiator, and the energy flux may be calculated from geometric considerations:

$$P_f = \frac{P_t}{4\pi r^2} \text{ watts/m}^2 \quad \dots (5)$$

If an isotropic receiving antenna is employed, its effective capture area is given by:

$$A_c = \frac{\lambda^2}{4\pi} \quad \dots (6)$$

Figure 2 illustrates this hypothetical system. It is now possible to calculate the received power, and, if the receiver characteristics are known, the output S/N ratio.

B. ANTENNA GAINS

A more practical example is illustrated in Figure 3. A reflector is employed to divert some of the wasted transmitter output toward the receiving antenna, and the received power is thus increased. The increase ratio is the gain of the transmitting antenna, G_t . In this report, gains are referred to an isotropic radiator, and not the standard half-wave dipole of frequent engineering usage.

The same principle is applicable to receiving antennas, and the receiving gain of an antenna (G_r) is equal to its gain as a transmitting antenna. It follows

---

*A perfectly isotropic antenna is not realizable, but serves a useful theoretical basis for later calculations.

that a receiving antenna with gain will have a preferential receiving direction. The capture area of a gain antenna may be expressed as:

$$A_c = \frac{G \lambda^2}{4\pi} \quad \dots (7)$$

Transmitting and receiving antenna are interchangeable, i.e., an antenna will have the same directivity pattern whether used for transmitting or receiving. Antenna characteristics are discussed in more detail in Appendix D.

C. COMMUNICATIONS EQUATION – FORM I

Propagation calculation may be summarized in the Communications Equation, which expresses required transmitter power in terms of signal requirements, receiving parameters, and geometric considerations. For the case where the system is dominated by the noise figure of a receiver operating at room temperature (290°K), the Communications Equation takes the form:

$$P_t = 20 \log r + 20 \log f + 10 \log B + L + C/N + F_s - [G_r + G_t + 171.6], \text{ dbw} \quad \dots (8)$$

where

r = distance (km)

f = carrier frequency (Mc)

B = noise bandwidth (cps)

L = miscellaneous losses (db)

C/N = predetection signal/noise ratio (db)

F_s = system noise figure (db)

G_r, G_t = antenna gains (db)

L includes absorption losses in the propagation path (often negligible for space-band frequencies), dissipative and mismatch losses in transmission lines preceding the receiver first amplifier, and losses due to mispolarization or misorientation of the antenna system.

Equation 8 is applicable only to systems where noise external to the receiver is negligible in comparison to N_3' as given by Equation 3. This restriction is satisfied by a large class of receiving installations which include low-cost equipment, such as consumer home receivers, or portable systems where advanced equipment such as masers are not conveniently usable.

D. PERTURBATIONS, LOSSES, AND EXTERNAL NOISE

There are a number of perturbations to which space-band propagations are subject, and they determine the practical low- and high-frequency boundaries of the space-band. Some of the important perturbations are discussed in the following sections.

1. Low-Frequency Perturbations

Near the low-frequency end of the space-band (100 Mc), the chief propagation perturbations are Faraday effect, external noise, and ionospheric absorption. It is also difficult to obtain large signal bandwidths or antenna gains at these frequencies, and it is therefore impractical to operate high-capacity systems in this region. There are a few applications in this region, however, which merit a further analysis of propagation perturbations.

a. Faraday Rotation

Faraday effect occurs when propagation takes place through a medium such as the ionosphere, where free electrons and a magnetic field are present, and results in a rotation of the polarization plane of a linearly polarized wave. The Faraday angle is given by:¹

$$\Omega_f = - \frac{e^3 \mu_o}{8\pi^2 m^2 C_o \epsilon_o} \frac{1}{f^2} \int_{\text{path}} nH \, dr, \quad \dots (9)$$

or

$$\Omega_f = - \frac{2.97 \times 10^{-2}}{f^2} \int_{\text{path}} nH \, dr,$$

where f is in cps, n in e/m^3 , r in meters, and H in amp turns/meter in the direction of propagation. At frequencies above a few hundred Mc, Faraday rotation is generally

negligible.^{2,3} At lower frequencies, however, Ω_f may amount to several complete rotations, and is a sensitive function of rapidly varying ionospheric parameters.⁴ It is thus impossible to continuously align a linearly polarized receiving antenna with the incoming wave, and a variable loss equal to $\cos^2 \Omega_f$ results.

This loss may be mitigated by using a circularly polarized antenna at either the transmitter or the receiver; in either case a constant loss of 0.5 (3 db) results. Polarization-diversity reception, in which cross-polarized antennas combine signals in a special receiver, can circumvent Faraday losses; however, such a receiver is fairly complex and experiences a somewhat greater total external noise input. The loss due to Faraday rotation may be completely avoided by using circularly polarized antennas of the same sense at both transmitter and receiver.

b. External Noise

With high quality low-noise receivers, it is not appropriate to ignore the effects of external noise, since this may be the dominating factor in determining the system S/N ratio. For systems in this category it is most convenient to deal with effective noise temperatures as defined by Equation 4, and contributions to the system noise temperature from sources external to the receiver. Figure 4 shows the temperature contribution due to cosmic noise for narrow-beam antennas pointed at the noisiest and quietest regions of the sky.^{5,6} The average sky temperature is much closer to the minimum than the maximum, the latter occurring only near the direction of the galactic center. Astronomical bodies such as the sun and moon also radiate thermal noise. Figure 5 shows the noise temperature of the undisturbed sun.⁷ The moon behaves nearly like a black-body radiator, with surface temperatures ranging from 120 to 400° K, depending on the lunar phase. At extremely high frequencies (~ 25 Gc), surface temperatures are moderated (210 to 300° K) by what appears to be a radio-transparent layer of thermally insulating dust.⁷

In cases where the angular extent of a discrete noise source is smaller than the antenna beamwidth, the noise contribution is reduced by the ratio of solid angles subtended. It is also often important to include noise contributed by antenna side lobes, which may be focused on a discrete noise source of high intensity. For most antennas this will include some thermal noise from the nearby ground at about 290° K, and may amount to a 20 to 30° K or more increase in antenna temperature even in well designed reflector antennas with small side lobes.

Figure 4. Cosmic Noise Temperature vs Frequency

Figure 5. Noise Temperature of Undisturbed Sun

c. Ionospheric Absorption

Figure 6 shows the dissipative losses suffered in propagation through the ionosphere.⁷ These losses are generally small except for propagation paths nearly tangent to the earth, and become negligible at frequencies above a few hundred Mc. However, the effect of these losses is augmented by an increase in system noise. Since the loss is dissipative, it may be treated as a resistive network which generates thermal agitation noise in its equivalent resistances. For these small attenuations, the noise contribution is well approximated by adding 7° K to the effective antenna temperature for each 0.1 db of dissipative attenuation.⁷

2. High-Frequency Perturbations

Near the high-frequency end of the space band (20 Gc), the chief propagation perturbations are tropospheric absorptions and the noises arising from them. Equipment is also strongly state-of-art limited, and it appears unlikely that any extensive use of the region above 20 Gc can be made during the near future.

a. Atmospheric Absorption

Figure 7 shows absorption through the atmosphere, due primarily to its normal water vapor and oxygen content. Associated with this absorption is a sky temperature contribution shown in Figure 8.⁷

b. Absorption Through Rainfall

Falling rain in the path of high-frequency propagation may cause very large additional losses. Figures 9 and 10 illustrate the losses incurred for rainfall, in terms of db/km of vertical rain depth.^{7,8,9} The antenna noise contribution from this source is also about 7° K per 0.1 db of loss, for small losses and low basic antenna temperatures.

3. Composite Sky Temperature

If only cosmic noise and atmospheric absorption are considered, these input temperatures alone will serve to define the space-band. Figure 11 represents a composite of these two quantities. It is readily seen that the sky temperature rises rapidly near either end of this 100 to 20,000 Mc spectrum segment. If noise contributions due to ionospheric attenuation or absorption in rainfall are also included, the effect is to increase the slope of sky temperature at the lower

Figure 6. Ionospheric Absorption as Functions of Frequency and Path Angle with Horizontal

Figure 7. Tropospheric Absorption (International Standard Atmosphere)

Figure 8. Temperature Contribution Due to Tropospheric Losses

Figure 9. Path Loss Due to Rainfall (Light, 0.1 cm/hr)

Figure 10. Path Loss Due to Rainfall (Heavy, 1.6 cm/hr)

Figure 11. Cosmic and Tropospheric Noise vs Frequency
(Target Near Galactic Pole)

and upper edges of the band. Authorities differ as to the proper manner in which to deal with the effective sky temperature, and often include discrete noise sources and antenna side-lobe effects. The treatment presented here deals with these items separately but includes light rainfall and ionospheric noise as usual perturbations in satellite communication problems. Figure 12 shows what may be expected as a minimum sky temperature.

4. Large Dissipative Losses

Any path loss which is dissipative (as opposed to geometric dispersion) will behave as a dissipative resistance network and will contribute noise to the network output if the effective temperature of the network is above the effective input temperature to the network. For small losses and low input temperatures, each 0.1 db of loss in a network at room temperature will contribute about 7° K to the system noise temperature. For large losses, or where the loss occurs at other than room temperature, the network output temperature is given by:

$$T_o = \left(1 - \frac{1}{L}\right) T_L + \frac{1}{L} T_i \quad , \quad \dots (10)$$

where $L = (\text{power at input})/(\text{power at output})$, $T_L =$ temperature of loss network, and $T_i =$ noise temperature at input of loss network.⁷ For large losses the output temperature approaches the loss temperature.

5. Communications Equation – Form II

The Communications Equation may now be more conveniently stated as:

$$P_t = 20 \log r + 20 \log f + 10 \log B + L + C/N \\ + 10 \log T_s - [G_t + G_r + 196.2], \text{ dbw} \quad , \quad \dots (11)$$

where L includes all system losses, dissipative or otherwise, and T_s is the sum of the receiver and source noise temperatures. Source noise temperature here means the effective noise temperature presented to the input terminals of the receiver, usually by a transmission line, and is the sum of all external noise temperature contributions, modified by any losses which may occur in the transmission line (see Large Dissipative Losses, IV-D-4). Form II of the Communications Equation is not limited to systems dominated by receiver noise figure, as is Form I.

Figure 12. Composite Sky Temperature (Includes Cosmic, Tropospheric, Ionospheric, Rain Noise)

V. EQUIPMENT CONSIDERATIONS

Cost, convenience, and attainable quality of electronic equipment are major factors in determining required satellite communications system parameters. Equipment considerations are thus an analysis of available state-of-the art, and a selection of a near-optimum compromise. Certain combinations of requirements frequently occur, or are frequently excluded; e.g., there is little value in using a 10°K maser in a low frequency system where external noise may run several thousand degrees. Similarly, there is little point in considering cosmic and side lobe noise where the system is constrained to use poor quality ($F_s = 15 \text{ db}$) receivers.

Equipment considerations may be conveniently divided into four categories:

- 1) Up-link (ground transmitter and satellite receiver)
- 2) Down-link (satellite transmitter and ground receiver)
- 3) Cross-links (satellite-to-satellite)
- 4) Accessory subsystems.

A. UP-LINK

The up-link is usually not a limiting factor in a communications satellite system, since large quantities of cheap power are usually readily accessible on the ground and large, high-gain antennas may be used. The S/N ratio in the up-link may thus be adjusted to whatever level is required merely by increasing the ground transmitter power and/or transmitting antenna gain. A possible exception to this generalization would be the military satellite communications system, where portable field units might be both power- and antenna-size limited. Some limits may be imposed on ground transmitter powers by interference considerations, either to other satellite systems or to surface systems sharing the same spectrum allocations. Careful attention to transmitter location and antenna side lobe restriction would probably permit the use of any ground transmitter power necessary from a viewpoint of up-link S/N ratio.

Satellite receiving systems are expected to have an effective system temperature of about 3000°K ($F_s = 10 \text{ db}$), at least in the near future. Cryogenic techniques are not yet sufficiently advanced to permit the use of low-noise masers

or parametric amplifiers in space. By 1965 to 1970, however, we can expect to have 200° parametric amplifiers suitable for use in satellites.

Even highly directive satellite receiving antennas must view at least two major discrete noise sources, the earth and the sun. Fortunately, the sun subtends only a small solid angle and is in view of a narrow-beam satellite antenna only a small fraction of the time. The sun view may be avoided completely by selecting a receiving beamwidth less than the angle subtended by the earth. For very wide-beam antennas, the sun's temperature contribution is reduced by the ratio of solar solid angle to beam solid angle. Care must also be exercised to avoid having the sun in a major side lobe of the antenna, since this might also contribute substantial noise. The earth view is unavoidable and contributes a noise temperature of 250 to 300°K.

Power consumed by the satellite receiver is fairly independent of everything except requirements for complex information processing. In the future it may become desirable to incorporate complex switching and logic functions in the satellite, but this would be for highly flexible systems such as direct global telephone service, or for a military system with high resistance to jamming. At present, however, it appears that all necessary information processing and switching may be performed more economically at the associated ground terminals.

The power requirement of satellite receivers may be considered to have an upper limit of 10 watts; actual power consumption, using modern solid-state electronics, is expected to be much less. An alternative viewpoint is to consider the receiver as an amplifier comprising part of the satellite transmitter, and to include the receiver power consumption in calculating the overall efficiency of the transmitter. For high-power satellite transmitters the receiver power requirement becomes negligible in comparison to the power demand of the final amplifier in the transmitter.

It will probably be desirable to use the same antenna for simultaneous transmission and reception at both ground and satellite stations. This places some restrictions on the type of antennas used and the separation between transmitting and receiving frequencies. Parabolic antennas are well suited in this respect, since they can be made to operate over a wide frequency range and may have separate feed systems for transmitting and receiving. Even without separate feed systems, considerable isolation between transmitter and receiver

may be realized by using opposite senses of circular polarization for transmission and reception. Helical antennas are less suitable for simultaneous transmission and reception, since they accept only the same polarization as is transmitted, and can be designed to cover only a relatively narrow frequency range.

Antenna choice is further limited by the accuracy with which attitude control can be maintained. This does not appear to be a severe problem as far as high-quality ground stations are concerned. Automatic tracking of the antenna is possible, but this imposes additional subsystem requirements which may prove awkward, particularly in the satellite or in power- and size-limited ground stations. When precise attitude control cannot be maintained, the antenna beamwidth must be broadened to compensate for attitude variations. This, of course, results in a reduction of usable gain. (See Section V-D for a discussion of attitude control.)

B. DOWN-LINK

The down-link is the weakest link in most satellite communications systems and, therefore, the link which most influences the overall system S/N ratio. Available transmitter power is limited by considerations of satellite weight and size, and for broadcast systems the design must include allowance for poorly operated and maintained receiving stations of medium to low quality. The ground receiving installation must also be designed to perform satisfactorily in the face of possible interference from nearby sources.

Fortunately, both natural and man-made interference die out rapidly above 100 Mc. Nonincidental man-made interference from surface services can be avoided by careful planning of spectrum allocations and by imposing tight quality regulations on potential sources of interference such as diathermy equipment, radar ovens, etc., which operate in other spectrum regions.

Ground station cost is a major consideration in fixing the signal strength requirements in the down-link. If only a few ground stations are to participate in the system, it is economical to invest large amounts in each ground station and thus relieve the cost and power demands in the satellite. However, for a system with hundreds of ground installations it is considerably more economical to reduce the quality and cost of each by a small amount and invest part of the difference in a higher-powered, more sophisticated satellite. For broadcast service, one must be satisfied with whatever quality standards are currently

available in millions of mass-produced home receivers. Further, a system designer cannot expect a private individual to invest much money, skill, or effort in the installation and operation of a sophisticated antenna system.

Antenna considerations are discussed in Appendix D. Table I summarizes present and projected receiver noise factors, with costs indicating the applicability of each type to systems of high, intermediate, and low ground investment.

Satellite transmitting equipment may have a variety of forms. Except for very low-power transmitters, the final radio-frequency (RF) amplifier stage of the transmitter will consume most of the APU output. Transmitting equipment with power outputs of 20 kw and more are currently available, and power outputs of over 100 kw should be available within a few years. Fairly long transmitter lifetimes have already been attained (thousands of hours), and demonstrated lifetimes of 10 to 30,000 hours are expected shortly. Table II summarizes pertinent characteristics of various possible satellite transmitters.

TABLE I
RECEIVER NOISE FIGURES*

Type	F_s (db)	T_r	Cost and Complexity
Present frequency-modulated (FM) tuner	6 to 10	1,200 to 3,000	low
1965 FM tuner	~3	~600	low
Present TV ultra-high frequency (UHF)†	10 to 20	3,000 to 30,000	low
1965 TV tunnel diode (TD)	5	900	low
Advanced TD		300	low
Traveling wave tubes (TWT)		600 to 1,000	high
Advanced TWT		~400	medium
Parametric amplifiers (PA)		100 to 200	medium
Cooled PA		50 to 100	high
Advanced PA (cooled)		< 50	high
Masers		10 to 100	very high
Advanced masers		~2	very high

*Noise temperatures do not include external sources of noise.

†Present very-high frequency (VHF) receivers have F_s of 6 to 12 db. There is little likelihood of VHF TV broadcasting from satellites because of both technical and political difficulties.

TABLE II

POSSIBLE SATELLITE TRANSMITTERS
(FINAL RF AMPLIFIER, FM RATINGS)

Frequency (Gc)	RF Output (kw)	Efficiency*	Weight (lb)	Basis of Design
0.8	0.2	0.12	73	TWT, Varian VA-132
0.8	2.0	0.40	247	Klystron, Eimac 4KM3000LQ
0.8	10.0	0.28	550	Klystron, Varian VA-833C
0.8	75.0	0.33	1040	Klystron, Varian VA-853
2.0	0.01	0.20	0.75	TWT, Hughes 349H
2.3	0.025	0.55	1.0	Amplitron, Raytheon QKS997
2.0	1.0	0.30	86	Klystron, Varian VA-802B
2.0	10.0	0.30	275	Klystron, Varian VA-800
7.1	0.01	0.08	10	TWT, Raytheon QKW928
10.0	0.01	0.18	1.5	TWT, Sperry, STX-186
10.0	1.4	0.31	17	Klystron, Varian VA-822
10.0	8.8	0.40	206	Klystron, Varian VA-823

*Efficiency = RF power output/conditioned power input.

Focused electron-beam tubes such as klystrons, magnetrons, and traveling-wave-tubes (TWT's) appear to be the most promising devices for the generation of RF power at space-band frequencies. Efficiencies as high as 60% are quoted in the literature, but these are beam efficiencies and do not include power required to operate filaments, focusing solenoids, etc. Permanent magnet assemblies may be used at low power levels, thus saving appreciable power. At RF outputs of several kw the subsidiary loads are generally negligible compared to the beam power input. Nevertheless, it appears that the overall ratio of RF output to APU load seldom exceeds 30% in practical operating devices.

It may be generally stated that transmitter weight is an inverse function of frequency and a direct function of power level. Some indication of these relationships is given by the weight figures in Table II. A factor not indicated in Table II is the dependence of efficiency and power capability of a transmitter upon the character of the signal to be transmitted. For AM signals, the power capability of the transmitter is reduced 3 to 6 db, and the overall efficiency is limited to about 25%.

Solid state devices such as transistors and varactors do not appear feasible for outputs greater than a few watts near the low frequency end of the space band. Tunnel diodes appear to offer future possibilities for high-power, high-frequency output.

A final factor of significance in determining APU requirement is the efficiency of power conditioning equipment. This equipment, which includes transformers, rectifiers, regulators, and filters, is required to convert the APU output to the various voltages and currents required by the electronic equipment, principally the transmitter. Power conditioning equipment may be expected to have an efficiency of 80 to 90%. Overall efficiency of the transmitter may then be estimated at 20% for AM signals and 25% for FM.

The weight of power conditioning equipment will depend on the nature of the APU output. This subject in itself requires an extensive study beyond the scope of this report. It is reasonable to assume, however, that the weight of the power conditioning equipment will not greatly exceed the weight of the transmitter.

C. CROSS-LINKS

Intersatellite relay appears operationally attractive at first glance, since it offers the possibility of linkage between antipodal points without intervening ground relays. When one considers this system more closely, however, it becomes less attractive because:

- 1) intersatellite distances may be very large
- 2) not one, but two low quality receivers must be included in the system, one in each satellite
- 3) attitude control requirements are very severe since high gain antennas are desirable. Two additional axes of control are required for each cross-link operated.

In general, the cross-link suffers from at least every weakness of the ordinary down-link, and power is required for simultaneous operation of both the cross-link and the ultimate down-link.

Since antipodal relay can be accomplished by an intervening ground station/s, intersatellite relay does not appear attractive for use in the immediate future.

D. ACCESSORY SUBSYSTEMS

Probably the most important of subsystem functions is attitude control. In a satellite this consists of maintaining the beam axis of the antenna, and sometimes the whole vehicle, in the proper direction. Long-lived attitude controls* are usually gyroscopic and consume electric power. Average power drain for such a system might range from 10 to 200 watts, depending on the vehicle mass, and including requirements of auxiliary command and control circuits.

At ground installations, attitude control means tracking both azimuth and elevation of the antenna to follow the motion of the satellite. Provision of tracking ability is quite expensive, usually constituting at least half of the total antenna cost. In the case of small and inexpensive antennas, tracking ability may cost many times as much as the antenna proper. Presently available antenna rotators cost \$25 or more and provide manual control of azimuth only. Tracking ability

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*Initial establishment of attitude rates would probably be done with reactive gas jets. It does not appear possible to permanently establish desired rates, and some provision for occasional alterations of beam direction are also usually desirable.

is thus not economically feasible for home broadcast receivers. These factors emphasize the desirability of a stationary orbit, for which the ground antenna position need only be adjusted during initial installation.

Another subsystem of possible importance in communications satellites is station-keeping facilities. These are necessary where the maintenance of one or more specific orbit parameters is essential to the function of the system, as in the case of a stationary orbit depending on fixed ground antennas. Orbit perturbations make permanent establishment of any specific orbit practically impossible, and provision must be made for occasional application of thrust for orbit corrections. For high-powered satellites, these thrusts may be provided by temporarily switching the APU output to an electric propulsion device. In any event, auxiliary command and control circuits are required.

Auxiliary command and control subsystems will, to some extent, be desirable in any satellite. These may do no more than monitor certain basic quantities, such as vehicle and component temperatures, or report and possibly remedy certain system failures by switching to a reserve circuit or component.

VI. MISCELLANEOUS CONSIDERATIONS

There are a number of factors, aside from transmission and orbit considerations, which may influence system operations. Some of these are noted in the following sections.

A. TIME DELAYS IN PROPAGATION

Transmissions are propagated at the finite speed of 3×10^5 km/sec, and for some of the paths to be considered there is an appreciable delay between transmission and reception. In the case of stationary satellites, the delay is 0.27 sec for a path length of 40,000 km. For one-way transmissions this delay is of no serious consequence. In two-way links, however, the delay may have significant consequences. Consider an attempt to control a mechanism such as a remote manipulator by a command and information link relayed via a stationary satellite. The position reported to the operator lags the true position by 0.27 sec, and an additional 0.27 sec must elapse before the operator's control operations become effective at the manipulator. This is more unfavorable than lengthening the operator's reaction time by 0.54 sec.

A second important effect of propagation delays is found in operation of common-carrier telephone circuits. In itself, a delay of less than a few seconds offers no serious conversation impediment. There is, however, a certain amount of coupling between transmit and receive circuits which arises as a result of the nature of standard telephone circuit design, and this causes some of the received signal to be retransmitted as an echo. An echo delay of a few tenths of a second is extremely annoying, leading to drawing, stammering, and often to complete disruption of speech and thought. A variety of techniques exist for mitigating or eliminating the echo effect, with varying degrees of success. It is generally agreed that new, improved techniques can and will be developed to deal with this problem at the ground terminals.

B. DELAYED PROGRAM TRANSMISSION

There are several occasions where an intentionally introduced delay in transmission may be operationally advantageous. An example of this technique is the Courier satellite, which can receive and record a message as it passes over a ground station, and then retransmit the message to a second ground station when

a suitable position is reached. The effective surface range of low altitude satellites may thus be increased. Different recording and playback speeds may be employed, and it is possible to record an extended program into the recorder in a few minutes as the satellite passes over a ground control station. The recording may then be replayed at normal speed, providing program material until the satellite passes within range of another (or the same) ground control station. A low altitude satellite could thus provide broadcasts in appropriate language as it passes in succession over different geographical areas. The bandwidth capability of present recorders suitable for space is somewhat limited. It appears likely however, that recorders capable of dealing with television signal bandwidths will soon be available.

C. PINPOINTING

With extremely high gain antennas, it is possible to discriminate between signals originating within a very small solid angle, and to direct signals to a very small area about a desired destination. The present capabilities of precision for large antenna construction lead to a maximum gain of about 65 db, corresponding to a beamwidth of 0.09° (see Appendix D). From a stationary satellite, this would be a circle of only 28 km radius about the subsatellite point. Employment of such antennas, where wide area coverage is not an objective, would increase the resistance of the system to supurious signals and would provide a degree of privacy for transmitted signals, as well as providing additional transmission gain. High-precision attitude control of the satellite would be required.

VII. EXAMPLE CALCULATIONS

A number of example calculations have been carried out to illustrate the methods developed, to indicate appropriate sets of assumptions, and to provide quantitative indication of the amounts of on-board power required for various types of service. No particular effort has been made to indicate optimum or economical system designs, the intent here being to provide exercises of illustrative value. Unless otherwise indicated it is assumed that the down-link is the system limiting factor.

A "worst-case" philosophy has been adopted; i. e., distances, antenna orientation errors, etc., are assumed to have the maximum values dictated by considerations of orbit geometry. No margin has been allowed for unknown factors. In surface-link design, it has been customary to insert margin allowances ranging from 10 to 50 db, depending on the nature of the system and the communications reliability desired. This is necessary because of the large number of perturbations and interferences to which a surface link is subject. Satellite communications, on the other hand, is subject to only a few fairly well defined perturbations.

There appear to be two schools of thought on the subject of margin allowance in satellite communications. Both groups agree that small margin should be required, but one group contends that a margin allowance of a few tenths of a db indicates "rather sloppy design."⁶ The other group feels that satellite propagation is not yet sufficiently understood, and that a margin of about 6 db should be included after all known factors have been considered.¹¹

Siding philosophically with the first group, the author has included no margin allowance in the following examples. Calculated quantities are thus based on correct operation of equipment which continuously adheres to design specifications. In the case of home receiver installations, this situation will certainly not be realized, and some margin should be allowed for this factor. The amount of margin necessary to maintain acceptable service evolves from a complex economic compromise, on the part of the manufacturer in supplying a reasonably priced equipment of endurance and stability, and on the part of the user in maintenance costs and inconveniences. The early days of consumer TV were plagued by frequent receiver failures and a seemingly constant need for tuning and adjustments. A similar situation will probably occur again with the advent of

satellite broadcasting, but the era of difficulties should not endure so long, nor should it be as severe as was the case with early TV.

A. EXAMPLE A - FM BROADCASTING FROM A LOW ORBIT

1. Mission Specifications

Provide a broadcast signal of at least PASSABLE* quality, receivable by present typical home FM receivers, from a satellite in a 2-hr circular polar orbit. The program may consist of both spoken and musical material and should meet the fidelity standards of present United States FM broadcast practice.

2. Analysis

Present FM broadcast practices call for the transmission of modulating signal components up to frequencies of 15 kc. The modulation index m_f , is 5.0, and above threshold the FM improvement factor is $3 m_f^2 = 75 = 18.7 \text{ db.}^\dagger$ An additional improvement due to standard preemphasis (see Figure B-5), of 19 db can be added, but it is unlikely that many receivers can realize more than 15 db of this potential. The total detection improvement is thus about 34 db and the required predetection C/N is $20 - 34 = -14 \text{ db}$ in a 30 kc bandwidth. This figure is far below the predetection 13 db threshold, however, and most of the FM improvement is lost in the first 3 db below threshold. It thus appears necessary to provide a predetection C/N of about 10 db in the predetection bandwidth of 200 kc for PASSABLE reception, and EXCELLENT reception will be experienced with $C/N = 13 \text{ db}$ or greater.

Since the apparent motion of a satellite in a 2-hr orbit is fairly rapid, and since a receiving antenna tracking system does not appear economically feasible for home installations, a low gain receiving antenna must be selected. A half-wave dipole has a beamwidth of 78° in the horizontal direction and can be made fairly uniform in a vertical plane by proper adjustment of antenna height. A receiving antenna gain of about 2.2 db can thus be realized for satellite passes in the antenna normal plane, and the gain will be no less than -0.7 db for passes within 39° of this plane. The direction of the antenna must be aligned to coincide with the direction of the satellite ground point track for near-overhead passes of

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*See Appendix C for quality definitions

†See Appendix B

the satellite. Alternatively a pair of crossed dipoles may be used to give nearly isotropic pattern of approximate unity gain. We will assume that the receiving antenna has a gain of 0.0 db.

For a 2-hr orbit the height of the satellite above the earth is 1650 km. Its maximum distance from a ground station is 4870 km when the satellite appears on the horizon. If we restrict ourselves to path angles more than 10° above horizontal, the maximum distance becomes 3900 km. The angle subtended by the earth is 103° , the desired beamwidth of the satellite transmitting antenna. From Equation D-8 the optimum transmitting antenna gain is then 3.4, or 5.3 db. We will assume that the direction of this antenna can be maintained within a few degrees of the center of the earth, and signal variations due to attitude errors will be negligible. The approximate dimensions of the satellite antenna may be deduced from Equation D-2 or D-3 to be about 0.6λ , or 0.90 meters for a transmitting frequency of 100 Mc in the standard FM broadcast band. For this low gain a paraboloidal reflector is neither necessary nor practical, and the transmitting antenna will consist of a simple array of linear half-wave elements arranged to emit circularly polarized waves. Faraday effect is thus circumvented, at the expense of a 3 db system loss.

Present home FM receivers have a noise figure of about 10 db at a physical receiver temperature of 290°K . From Figure 12 we see that for path elevations greater than 10° external noise contributions are small in comparison, and Form I of the Communications Equation may be used. The predetection bandwidth of a typical receiver is 200 kc, and transmission line losses should be no more than 3 db in the worst installation.

The variables of the Communications Equation may now be summarized as follows:

Variable	Value	Term Value In Equation 8 (db)
r	3900 km maximum	71.8
f	100 Mc	40.0
B	2×10^5 cps	53.0
L	3 db (Faraday effect)	
	3 db (line losses)	6.6
	0.6 db (ionospheric losses)	

Variable	Value	Term Value In Equation 8 (db)
C/N	10 db	10.0
F _s	10 db	10.0
G _r	0 db	0
G _t	2.3 db (at 51° off axis)	2.3

Substituting in Equation 8, we obtain

$$P_T = 17.5 \text{ dbw} = 56 \text{ watts RF output.}$$

With a transmitter and power conditioning equipment overall efficiency of 25%, the primary power load becomes 224 watts. Allowing 5 watts for the satellite receiver and 100 watts for attitude control and miscellaneous functions, the total prime power supply requirement becomes 329 watts.

3. Service Evaluation

Figure 13 illustrates the geometry of the system, and assumes that the orbit passes directly over Receiver I on the second pass. During the first pass, the satellite will not have risen more than 10° above the Receiver I horizon, providing no useful service. The same conditions apply during the third pass. On the second pass, the satellite will be more than 10° above the horizon for approximately 0.31 hr, or 20 min.

At Receiver 2, located 15.5° west of Receiver I, the satellite will rise higher than 10° above the horizon on both the second and third passes, but will remain there for a somewhat shorter time.

The same conditions will be repeated 12 hr later, with the satellite passing over the ground points in the opposite direction. Duration of coverage during an overhead pass is reasonably independent of receiver latitude, but at high latitudes the duration of coverage during non-overhead passes increases. At the poles, of course, every pass is an overhead pass, for polar orbits.

4. Comments

The usefulness of FM broadcasting from a low orbit is not very great. The conditions stated were deliberately chosen to emphasize the following points:

- a) Present United States standards for FM broadcasting and reception are not amenable to intermediate quality service. The transition between PASSABLE and EXCELLENT is sharp, requiring only a small increase in transmitter output.

Figure 13. Two-Hour Orbit Geometry

- b) Use of a receiver employing FM feedback detection (FMFB) is highly desirable (see Appendix B) since a system of this type is threshold limited. An FMFB receiver with a 6 db threshold would permit a transmitter power reduction of 4 db, and would provide an output S/N of about 48 db.
- c) Low orbits do not provide continuous ground area coverage unless a large number of satellites are employed. The usefulness of any particular satellite will also be a sensitive function of orbit parameters and their relationship to the position of the ground station served.
- d) Service quality from low orbits is very uneven. Note that during most of the second pass over Station I the specified quality standards will be exceeded by a considerable margin. The satellite passes much closer to the station than the 3900 km maximum distance, and the station lies much closer to the center of the transmitted beam than the 51° off-axis angle assumed.
- e) Judgment must be exercised in matching service capabilities to orbit parameters and system performance specifications. The only mission the author can conceive for the conditions stated would be global public-service news and weather broadcasts, which could be readily adapted to the short coverage intervals obtained with a 2-hr orbit. Provision of fidelity capabilities suitable for music is thus superfluous. No appreciable reduction of required transmitter power would result from limiting the modulating signal to speech bandwidth, however, since predetection bandwidth of the receiver is fixed. A modulation index as high as 25 could be used for 3 kc speech bandwidth, resulting in an FM improvement factor of almost 33 db, but this would do no more than permit operation a few more db below the 13 db predetection threshold.

B. EXAMPLE B - FM BROADCASTING FROM A STATIONARY ORBIT

1. Mission Specifications

Provide an EXCELLENT quality home-service FM broadcast, conforming to present United States standard practices, from a satellite in a stationary orbit.

2. Analysis

The detection improvement realizable with standard FM broadcasts is about 34 db (see Example A). By the time it is possible to establish a stationary satellite, we may expect to see FMFB receivers with a predetection improvement threshold of about 6 db (see Appendix B) in common private use. A signal giving a predetection C/N of 6 db thus yields a very high output S/N. Projecting receiver quality is somewhat uncertain, since it will probably hinge on manufacturing economics, which in turn depends on demands established by existing surface broadcast services.

Since a stationary satellite exhibits no apparent motion, a high gain fixed antenna may be used at the receiving station. We will conservatively assume a receiving antenna gain of 6 db, since such antennas are presently on the market at modest cost. Such an antenna may see a noise temperature of as much as 100°K due to earth radiation into the broad main beam and side lobes.

For a stationary (24 hr) orbit, the height of the satellite above the earth is 35,790 km. Its maximum distance from any ground station is 41,680 km. If we restrict ourselves to path angles more than 10° above horizontal, the maximum distance becomes 40,600 km. The angle subtended by the earth is 17° and the optimum antenna gain is then about 20 db for coverage of the entire surface area from which the satellite has an apparent elevation of more than 10°. The diameter of a paraboloidal antenna with this gain at 100 Mc would be about 47 ft, assuming an aperture efficiency of 0.5. Circular polarization will again be used.

A somewhat advanced home FM receiver employing FMFB detection is also likely to have an improved noise figure over that assumed in Example A. A vintage 1965 FM receiver may be expected to have a noise figure of 3 db, corresponding to a noise temperature of about 600°K. Since the composite sky temperature at 100 Mc is about 400°K (Figure 12), external noises are not negligible and Form II of the Communications Equation should be used.

The variables of the Communications Equation may be summarized as follows:

Variable	Value	Term Value In Equation 11 (db)
r	40,600 km	92.2
f	100 Mc	40.0
B	2×10^5 cps	53.0
L	3 db (Faraday effect)	
	3 db (line losses)	6.6
	0.6 db (ionospheric atten.)	
C/N	0.6 db (FMFB threshold)	6.0
T_a (at antenna)	400° (sky temp)	
	100° (ground temp)	
T_o (at line output)	388° (from Equation 10)	
T_r (receiver)	600°	
T_s (overall system)	988°K ($T_o + T_r$)	29.9
G_r	6 db	6.0
G_t	17 db (8.5° off axis)	17.0

Substituting in Equation 11, we obtain:

$$P_T = 8.5 \text{ dbw} = 7.1 \text{ watts}$$

With an overall efficiency of 25%, the transmitter primary power load is 28.4 watts. Again allowing 100 watts for attitude control and 5 watts for receiver, the total prime power supply requirement becomes 133.4 watts.

3. Service Evaluation

Figure 14 illustrates the geometry of this system. The primary coverage zone (satellite 10° or more above horizon) extends 7950 km in all directions from the sub-satellite point, and is fixed with respect to the earth. Coverage is thus continuous within this zone, and uniform with time at any particular point within the zone.

A fringe zone, where the satellite is visible within 10° of the horizon, extends out to a distance of 9000 km from the ground point. Coverage in this

(VIEW FROM NORTH POLE)

Figure 14. Stationary Orbit Geometry

area would be of poor quality and subject to perturbation by variations of the ionosphere. Some erratic coverage might extend beyond this distance due to ionospheric refraction effects.

For receivers near the ground point, reception would be somewhat better than that calculated at the edge of the primary coverage zone. The signal would increase 0.4 db due to the greater path elevation, 1.2 db due to the shorter transmission distance, and 3.0 db due to the transmitting antenna pattern; a total of 4.6 db.

Figure 15 is a conventional map showing the primary and fringe coverage zones for a stationary satellite ground point at 105° West longitude. An overlay is included so that coverage zones for other ground points may be readily visualized.

4. Comments

This system is still primarily a threshold-limited system, and reception quality is a sharply decreasing function of signal level below the design point. Above the design point (threshold) quality is high and does not increase greatly with further increases in signal level. This behavior is a consequence of the choice of modulation standards, and it appears that present United States standards of FM transmission are eminently well matched to subjective evaluations of high-fidelity program quality. When the signal is good, it's very good, and when it's bad, it's essentially non-existent for the purposes of most home receivers.

The differences between Examples A and B are considerably more striking than implied by transmission distances alone: the distance factor is almost completely compensated by the increase in transmitting antenna gain. An obvious improvement is the factor of continuous and uniform service, making practical a wide variety of types of broadcast program material. Compared to ordinary design criteria of surface broadcast service, a variation in signal level of only 4.6 db over a 7950 km surface range is amazingly small, and permits close and therefore economical design of receiving equipment.

The ability to use a fixed antenna with gain is a very valuable aspect of the stationary orbit, in this example worth 6 db or a factor of four in transmitter power.

In this example, as in the others, calculations are based on the assumption that an essentially clear channel is available, and that only random noise need be

Figure 15. Coverage Zone, Stationary Satellite

reckoned with. This assumption may prove difficult to justify, since it depends primarily on the effectiveness of legal measures regulating and restraining potential sources of interference.

A second questionable assumption is the ability to produce and operate a 20 db space antenna at this frequency. Progress in this direction, however, is presently encouraging (see Appendix D).

C. EXAMPLE C - UHF TELEVISION BROADCASTING FROM A STATIONARY ORBIT

1. Mission Specifications

Provide a standard television signal of at least PASSABLE quality, directly receivable on UHF Channel 35 of a typical home receiver.

2. Analysis

The video carrier of a standard television transmission is amplitude modulated, and no detection improvement factor is realized. PASSABLE reception (see Appendix C) thus requires a C/N ratio of 27 db at the input of the receiver, reckoned on the basis of sync peak level measurements and a 6 Mc noise bandwidth.¹² A peak/average power normalization factor of unity will be assumed. This considers a very dark picture and an accompanying standard sound transmission (see Appendix B).

A fixed, high-gain receiving antenna may be used. For Channel 35 (600 Mc), the dimensions and cost of a 16 db helical antenna are reasonable for home installation. Faraday effect is small at 600 Mc, and will be completely eliminated since the helical receiving antenna is circularly polarized in the same sense as the transmitting antenna. Earth radiation should contribute no more than about 75°K noise at the lowest antenna angle. Coaxial cable is required for helical antennas, and a typical line loss would be about 1.5 db.

Geometry of the stationary orbit has been described in Example B. If we assume a helical transmitting antenna in the satellite, Equations D-6 and D-7 yield, for a beamwidth of 17°, a forward gain of 21.5 db. The helix would be about 15 cm in diameter and 450 cm in length.

We may assume a receiver noise temperature of about 900°K. With a sky temperature of 14°K, an earth radiation contribution of 75°K, and considering the effects of line losses, external noise is not negligible. Form II of the Communications Equation will be used:

Variable	Value	Term Value In Equation 11 (db)
r	40,600 km	92.2
f	600 Mc	55.6
B	6×10^6 cps	67.8
L	1.5 db (line losses)	1.5
C/N	27 db	27.0
T_a (at antenna)	14°K (sky temp) 75°K (ground temp)	
T_o (at line output)	148°K	
T_r (receiver)	900°K	
T_s (overall system)	1048°K	30.2
G_r	16 db	16.0
G_t	18.5 db	18.5

Substituting in Equation 11, we obtain

$$P_t = 43.6 \text{ dbw} = 22.9 \text{ kw}$$

With an overall efficiency of 20%, the primary power load is 114.5 kw. Power requirements for attitude control and miscellaneous functions are negligible in comparison.

3. Service Evaluation

The service area is the same as described in Example B, and the service is about as uniform. For receivers near the ground point, the signal increases 1.2 db due to the shorter transmission distance, 3.0 db due to the transmitting antenna pattern, and, since the receiving antenna is pointed nearly vertical, input temperatures due to sky and sidelobe noises are reduced by about 0.2 db.

4. Comments

Several design variations are worthwhile considering in this example. If the first amplifier of the receiver, which determines the receiver noise temperature, is located directly at the antenna, the 1.5 db line loss is effectively

eliminated. In addition, the source noise temperature is reduced by 59°K since the dissipative noise contribution of the line is also effectively avoided.

A slight improvement of the receiver noise figure will make a significant improvement in the system performance. If the receiver temperature can be reduced to 700°K, the corresponding transmitter power reduction is 1.0 db. Receivers of this quality or better should become economically feasible before 1970.

If the transmitting beamwidth is reduced to 15° and the satellite ground point located at 90°W longitude, better than 99% of the land area of the United States and South America is included within the beamwidth. The minimum receiving antenna elevation within this area is 30° (see Figure 15), and the minimum effective transmitting gain is 19.5 db.

The total effect of these system refinements is to permit a transmitter power reduction of 4.5 db, yielding $P_t = 39.1$ dbw = 8.14 kw, and a primary power requirement of 40.7 kw.

A second type of system refinement might consist of limiting the transmitting beamwidth to cover only a specific geographical area of particular social, political or economic interest. For coverage of English-speaking North America, a beamwidth of about 5° would be appropriate. Transmitting gain at the boundary of the primary coverage zone would be about 28 db instead of the 18.5 db assumed for complete hemispheric coverage.

If one is willing to consider modifying the standards for the accompanying sound transmission, an additional 2.2 db of power savings may be effected by reducing the level of the sound transmission to 0.1 that of the video sync peak (see Appendix B). This would require no modification of the receiver, and would maintain appropriate sound quality in all cases where the picture quality was MARGINAL or better.

D. EXAMPLE D - FM TV BROADCASTING

1. Mission Specifications

Provide an FMTV broadcast suitable for reception by a special home receiver or an adapter-standard-receiver combination. Picture quality should be FINE or better.

2. Analysis

Since no restrictions have been placed on operating frequency, it is possible to select an optimum frequency. This would be a compromise between a number of factors. For considerations of antenna aperture and equipment state-of-the-art, the lower frequencies are preferred. For considerations of antenna size and beamwidth, the higher frequencies are preferred. In any event, the edges of the space band should be avoided for external noise considerations. A reasonable compromise appears to be 1.5 Gc.

With a modulating signal bandwidth of 5 Mc, a modulation index $m_f = 3$ appears to be readily attainable and offers threshold attainment at reasonable signals levels.⁵ The minimum predetection signal bandwidth is 40 Mc and the FM improvement factor is 14.3 db. An additional improvement of 9 db due to preemphasis will be assumed (see Appendix B). Since most viewers will rate a S/N ratio of 35 db FINE or better, this figure will be assumed. An input C/N ratio of 11.7 db per 10 Mc bandwidth is thus required. This is below threshold for an FMFB system with a 40 Mc predetection bandwidth.⁵ A predetection C/N of 10 db will be assumed.

In order to enjoy the advantages of a low-cost high-gain receiving antenna, a stationary orbit will be assumed. A paraboloidal antenna with a gain of 20 db and an aperture efficiency of 0.6 would be 82 cm in diameter, and appears feasible for home installations. A similar antenna would be employed in the satellite providing coverage of the visible surface as described in Example B. Circular polarization will be used at both antennas, not for Faraday effect which is negligible at this frequency, but for the convenience of not requiring a specific polarization alignment between transmitter and receiver.

An antenna-mounted preamplifier will be employed, using an advanced tunnel diode and fixing the receiver noise temperature at 300°K. Subsequent line losses are then quite small. Sky temperature at 1.5 Gc is 13°K or less, and ground noise temperature contributions to the side-lobes of a well designed paraboloidal antenna should be 25°K or less for elevations of 10° or more.

Variable	Value	Term Value In Equation 11 (db)
r	40,600 km	92.2
f	1500 Mc	63.5
B	40×10^6 cps	76.0

Variable	Value	Term Value In Equation 11 (db)
L	1 db (miscellaneous)	1.0
C/N	10 db	10.0
T _a (at antenna)	13°K (sky temperature) 25°K (ground temp contribution)	
T _r (receiver)	300°K	
T _s (overall system)	338°K	25.3
G _r	20 db	20.0
G _t	17 db (at 8.5° off-axis)	17.0

Substituting in Equation 11, we obtain:

$$P_t = 34.8 \text{ dbw} = 3.02 \text{ kw}$$

With an overall efficiency of 25%, the primary power load is 12 kw. Power requirements for attitude control and the accompanying sound transmitter are negligible in comparison.

3. Service Evaluation

Service is essentially the same as described in Example C.

4. Comments

This example represents a system of possible interest in the more distant future (1970's to 1980's). It is indicative of the advantages of FM techniques for home TV broadcasting. Substantial advancements in state-of-the-art would have to be accomplished to make home receivers of this quality economically feasible. In addition, an entirely new type of receiver would have to be developed for mass production. Adapters for conventional receivers are technically feasible, but they would require inconvenient modifications to the existing receivers, and relative performance would probably be even less satisfactory than present UHF adapters. A further deterrent to this type of system is the premium which will be placed on spectrum space at these frequencies. As described, each channel would occupy a bandwidth of about 40 Mc, compared to 6 Mc for conventional AM television channels.

E. EXAMPLE E - BROADBAND COMMON-CARRIER RELAY SERVICE

1. Mission Specifications

Provide a broadband satellite relay suitable for television or multi-channel voice relay between major surface communication centers.

2. Analysis

Since a relatively small number of ground stations are being considered here, extremely elaborate ground installations may be assumed. This example will be patterned after the ground installation proposed by Bell Telephone Laboratories.⁵ Since Reference 5 describes an FM multiplex voice relay this example will describe a single-sideband (SSB) system of similar channel capacity.

An operating frequency of approximately 4 Gc has been tentatively assigned for common-carrier satellite-to-ground links, and will be assumed for this example. The ground-to-satellite link is assumed to have negligible influence on system performance. Paraboloidal horn antennas have been constructed with very high gains at these frequencies, and have the advantage of extremely small sidelobes and consequently minor interference and ground noise problems. A receiving antenna gain of 57 db is assumed. In the interests of economy and satellite simplicity, a transmitting antenna gain of 0 db (near-isotropic) will be assumed.

With trackable ground antennas, there is no particular advantage in using a stationary orbit. Satellite altitude may be reduced to the minimum compatible with maintenance of satisfactorily long intervals of mutual coverage between desired ground stations. Low orbits also have the advantage of relatively small rocket vehicle costs. The length of mutual coverage is important when continuous communication is to be maintained from one station to more than one other station. Since an 18-ton antenna cannot be quickly slewed from one satellite to another, a standby antenna is required to acquire the next satellite to serve in a link before the first satellite drops out of view at either station. A minimum of two antennas are thus required at any ground station. However, for a station maintaining links with more than one station, a single standby antenna is all that is required, provided that coverage intervals are long and the probability of having to make satellite changes simultaneously in two links is low.

A suitable compromise in satellite height appears to occur at about 5000 km. Approximately 50 satellites in random polar orbits are required to provide 99% assurance that one will always be mutually visible between ground stations (e.g., Maine and Land's End, England). The maximum distance between satellite and ground station is 8360 km.

A receiver using low noise masers is feasible for an elaborate ground installation. Such systems, operated in conjunction with a paraboloidal horn antenna and low temperature accessories, have demonstrated system noise temperatures of 50°K or lower.

For multiplexed telephonic voice communications, about 4.2 kc of modulating bandwidth should be allowed for each channel in order to permit satisfactory ultimate reparation. A 600 channel system thus has a modulating bandwidth of about 2.5 Mc. For purposes of this example, it is satisfactory to calculate the power requirement for each individual channel, and to then assume that 600 separate SSB transmissions are conducted on adjacent 4.2 kc channels.

The output S/N ratio customarily required in common-carrier links is somewhat higher than would be required for a single link directly between users, since the signal may be expected to experience cumulative degradations in possible successive and preceding links. For this example 30 db will be assumed. Allowing 2.5 db benefit from preemphasis, the predetection average C/N ratio must be 27.5 db.

For multichannel voice service:

Variable	Value	Term Value In Equation 11 (db)
r	8360 km	78.4
f	4000 Mc	72.0
B (per channel)	4.2×10^3 cps	36.2
L	3 db (1/2 circular polarization) 0.5 (miscellaneous)	3.5
C/N	27.5 db	27.5
T _s (overall system)	50°K	17.0
G _t	0	0
G _r	57 db	57.0

Substituting in Equation 11, we obtain:

$$P_t = -18.6 \text{ dbw} = 11.4 \text{ dbm} = 13.8 \times 10^{-3} \text{ watts/channel}$$

This amount of power is only required on the average of 0.5 of the time or less for an average conversation. Averaged over 600 channels and assuming an efficiency of 20%, the total primary power load is 20.7 watts for the transmitter, and no more than 25 watts for the entire system, since no attitude controls are used.

For television relay, FM transmission in a 40 Mc bandwidth will be assumed. This corresponds to a modulation index of 3.0 and a total detection improvement of 23.3 db, including preemphasis. For common-carrier relay an output S/N of 50 db is not excessive, so a predetection C/N of 26.4 db in a 10 Mc bandwidth is required. This is equivalent to a C/N of 20.4 db in the 40 Mc predetection bandwidth, well above threshold.

Variable	Value	Term Value In Equation 11 (db)
r	8360 km	78.4
f	4000 Mc	72.0
B	4.0×10^7 cps	76.0
L	3.0 db (1/2 circular polarization) 0.5 db (miscellaneous)	3.5
C/N	20.4	20.4
T_s	50°K	17.0
G_r	0	0.0
G_t	57 db	57.0

Substituting in Equation 11, we obtain:

$$P_t = 14.1 \text{ dbw} = 26 \text{ watts}$$

Since the satellite transmitter must be designed to accommodate both AM and FM, its efficiency is assumed to be 20%. The total primary power load is then 135 watts, including receiver.

3. Service Evaluation

For satellites at an altitude of 5000 km, communication may take place for a short interval between ground stations as far apart as 10,250 km, or

6350 miles. The satellite is in view of one station for a maximum of 49 min, and will be in simultaneous view of a pair of stations for a smaller time dependent on the range and direction between stations. A pair of widely separated ground stations will probably be obligated to switch from one satellite to another at intervals on the order of 10 min minimum. Figure 16 shows the orbit geometry for this system.

4. Comments

Elaborate automatic computing facilities will be required to keep track of all satellites in the system to determine which satellite is in the most suitable area for relaying between a given pair of ground stations, and to determine which satellite is to be used next. In principle, one computer could control the operation of an entire global system, provided that close and continuous coordination were maintained between the central computer and subsidiary information storage and servo units at each ground station. In practice, it will probably prove more practical to have a computer at each ground station which controls the operation of that station. Some coordination between computers will still be required, since it is necessary that both ground stations agree upon the use of particular satellites; this may be accomplished by a very narrow bandwidth data signal transmitted along with the regular traffic.

Only a small allowance (0.5 db) was made for miscellaneous losses, since it is assumed that a common-carrier installation will use components of the highest quality, and will receive a high level of preventive and corrective maintenance.

Use of an essentially non-directive satellite antenna permits random orientation of the satellite with accompanying savings in weight, power, cost, and complexity, but prohibits use of a circularly polarized antenna. Therefore, 3 db loss has been allowed for coupling between a circularly polarized antenna and a linearly polarized antenna.

Note that for the voice channels, a preemphasis time constant of 75×10^{-6} sec was assumed. This is suitable for standard broadcast practices but is not necessarily optimum for telephonic speech. A much longer time constant would undoubtedly yield a greater preemphasis improvement.

Figure 16. 5000 km Orbit Geometry (Example E)

F. EXAMPLE F - WIDEBAND MILITARY COMMUNICATION SATELLITE

1. Mission Specifications

Provide satellite relay between military field units, and between field units and military communications centers. Field units may be located anywhere on the surface of the earth further than 18° latitude from either pole. Capability of retransmitting signals with bandwidths up to 10 Mc is required. Field units should employ paraboloidal antennas with a maximum diameter of 1 meter.

2. Analysis

Three satellites in equally spaced stationary orbits will provide the required surface coverage and some additional coverage up to within 9° of the poles, as illustrated in Figure 17. The stationary orbits have the advantage of not requiring trackable antennas in fixed or portable ground stations. Mobile stations will require trackable antennas in any case.

Since high-latitude coverage is required, nearly horizontal propagation paths must be tolerated. An operating frequency of 1000 Mc appears sufficiently high to avoid any deleterious ionospheric effects, and is still low enough to permit reasonable noise figures in rugged, portable equipment. A receiver noise temperature of 1000°K will be assumed for both satellite and ground receivers.

Calculation of power requirements will be based on the establishment of a single voice channel to and from a portable ground station which sees the satellite on the horizon. An FM signal will be used, having a modulation index of 5 and thus requiring a channel bandwidth of 50 kc in order to insure that spurious sidebands in the adjacent channels are at least 40 db below the reference channel carrier level. There is then sufficient space in a 10 Mc satellite bandwidth to accommodate 200 voice channels. The FM improvement factor is 18.7 db, and an additional improvement of 2.1 db can be realized from preemphasis.

This detection improvement of 20.8 db applies only to the ground receiver, since detection does not take place in the satellite. Any noise present in the satellite receiver output becomes part of the retransmitted signal, i.e., the ground receiver must contend with transmitted noise as well as the usual sources of noise. This factor may be made negligible by requiring a C/N ratio at the satellite about 10 db greater than the desired output S/N ratio at the ground receiver. Thus, if a minimum output S/N of 15 db is desired, the C/N at the satellite should be at least 25 db.

(VIEW FROM NORTH POLE)

Figure 17. Military Communications Satellite System (Example F)

At the ground receiver, the 20.8 db detection improvement is realized, and the down-link signal level requirement is set by the improvement threshold, 6 db for an FMFB receiver. This yields an output S/N of 30 db, less about 3 db for degradation in the up-link.

The forward gain of the satellite antenna is fixed by orbit geometry at 20 db. The ground antenna, with a diameter of 1 meter and an assumed aperture efficiency of 0.6, has (from Equation D-4) a gain of 18.2 db.

The satellite antenna, whose beam looks directly at the earth, will see a sky temperature of 290°K. The ground antenna will see a sky temperature of about 90°K in a nearly horizontal direction, and will also experience a ground temperature contribution of as much as 150° due to the fact that half of the main beam sees the ground.

For the up-link:

Variable	Value	Term Value In Equation 11 (db)
r	41,679 km	92.4
f	1000 Mc	60.0
B	5×10^4 cps	47.0
L	1 db (miscellaneous)	1.0
C/N	25 db	25.0
T_a (at antenna)	290°K	
T_r (receiver)	1000°K	
T_s (overall system)	1290°K	31.1
G_r	17.0 (at 8.7° off-axis)	17.0
G_t	18.2	18.2

Substituting in Equation 11, we obtain:

$$P_T = 25.1 \text{ dbw} = 324 \text{ watts}$$

With a transmitter overall efficiency of 25%, the prime power requirement for a single-voice-channel ground station is 1.3 kw.

For the down-link:

Variable	Value	Term Value In Equation 11 (db)
r	41,679 km	92.4
f	1000 Mc	60.0
B	5×10^4 cps	47.0
L	1 db (miscellaneous)	1.0
C/N	6 db	6.0
T_a (at antenna)	90°K (sky temperature) 150°K (ground temperature)	
T_r (receiver)	1000°K	
T_s (overall system)	1240°K	30.9
G_r	18.2 db	18.2
G_t	17.0 db (at 8.7° off-axis)	17.0

Substituting in Equation 11, we obtain:

$$P_t = 5.9 \text{ dbw} = 3.9 \text{ watts per channel, or:}$$

$$P_t = 780 \text{ watts for 200 channels.}$$

Operating as a linear amplifier with an overall transmitter efficiency of 20%, the primary power load is 3.9 kw.

3. Comments

For most military purposes, teletype could be substituted for voice communication. With a bandwidth requirement of only 100 cps, ~30 channels of teletype could be handled by the same ground transmitter in the same transmitted bandwidth.

Considering the minimum satellite antenna temperature of 290°K due to the presence of the earth, there is relatively little incentive for a better quality satellite receiver. Reducing the receiver noise temperature from 1000°K to 355°K would result in a 3 db system improvement, and an ideal, noiseless receiver (0.0°K) would only yield a 6.5 db reduction in ground transmitter power.

There is considerable incentive toward a better quality ground receiver. Although both satellite and ground receiver temperatures are nearly equal in the assumptions, they were based on a near-horizontal transmission path. At higher antenna elevations the antenna noise drops rapidly, reaching a minimum of about 30°K for vertical-pointing ground antennas.

A system employing multiplexing prior to modulation would make somewhat more efficient use of the spectrum space and power available. This is not possible, of course, when many physically separated transmitters are used. It is possible however, to employ this technique for high-density traffic between military communications centers. In this common-carrier mode of operation more channels of the same quality could be carried, or signal quality could be improved for the same transmitted power and bandwidth.

As described, the example system is not very resistant to jamming. This quality may be improved by a variety of techniques, all of which involve some sort of tradeoff between information transmission rate and degree of resistance to jamming. One such tradeoff might be to use the entire bandwidth and power capability of the satellite to transmit a single channel of information in the form of a highly redundant, prearranged code. Arrangement might also be made to permit temporary use of high modulation indices on individual channels to pass high priority traffic in the presence of unusual noise levels or other difficulties. Such a practice would unfortunately generate intermittent interference in adjacent channels. Alternatively, the power level of the ground transmitters could be increased, or elaborate signal analysis techniques could be carried out on board the satellite.

One rather serious drawback to the example system is that it provides poor coverage in the polar regions, where communications to aircraft is needed. This fault may be corrected by supplementing the system with inclined-orbit satellites. The supplementary satellites could have a variety of orbits, restricted only by the requirement that at least one satellite have the polar region in view at all times, and simultaneously maintain contact with at least one operative ground communications center. Some additional burden would be placed on the system by the need for computer facilities to select and track an appropriate satellite.

Table III summarizes the characteristics of the example systems calculated.

TABLE III
SUMMARY OF EXAMPLE CALCULATIONS

Example		Height (km)	Orbit Radius (km)	G_t (db)	G_r (db)	P_t	APU Load
A	FM Broadcast	1650	3900	2.3	0	56w	329w
B	FM Broadcast	35,790	40,600	17	6	7.1w	133w
C	TV Broadcast (Std)	35,790	40,600	18.5	16	23kw	115kw
D	TV Broadcast (FM)	35,790	40,600	17.	20	3kw	12kw
E_{voice}	Common Carrier (SSB)	5000	8360	0	57	8.3w	25w
E_{tv}	Common Carrier (FMTV)	5000	8360	0	57	26w	135w
F_{up}	Military Comm. Sat.	35,790	41,679	18.2	17	324w	1.3kw
F_{down}	Military Comm. Sat.	35,790	41,679	17	18.2	780w	3.9kw

VIII. POTENTIAL UTILITY OF NUCLEAR REACTORS IN COMMUNICATION SATELLITES

It is not a purpose of this report to determine the most suitable type of power source for communications satellites; this question can be decided only by careful consideration of the many factors influential in each specific communication system. The general areas of applicability of various types of power sources can be discussed, however, and some of the significant interactions between the power source and the rest of the system can be indicated. Nuclear reactors exhibit many advantages over other sources, particularly at the high power levels required for broadcast service to low quality ground installations.

A. SPECIFIC WEIGHT OF POWER SOURCES

Probably the most important single factor in judging the merits of a power source for space use is its weight. This will depend on the nature of the power source, the power level at which it will operate, and the length of time for which it must supply electric power. Figure 18 compares various types of power sources on the basis of weight, and indicates the type having minimum weight for various power duration areas.¹³ It is apparent from the figure that any mission with a duration longer than about a week will require either nuclear or solar energy. Communication satellites will undoubtedly require long-lived power sources.

At power levels above 1 kw, weight considerations generally exclude solar cells and radioisotope sources, and above 10 kw, nuclear reactors appear to be the only feasible choice. Nuclear reactor systems become increasingly attractive at higher power levels because they are nonhomogeneous systems; different components of the system increase in weight at varying rates, as a function of system electric power output, and the resultant system specific weight, in lb/kw, is a strongly decreasing function of power level. This function for the present family of SNAP reactors is illustrated in Figure 19.

Solar mirror systems are also somewhat nonhomogeneous, exhibiting decreasing specific weight as a function of power level up to a certain point. They are ultimately limited by the solar energy flux density. The limitation occurs at a power level where the mirror becomes the dominant system weight, since the system power output is limited by available collector area.

Figure 18. Weight Comparison of Space Power Sources

Figure 19. SNAP Specific Weight vs Power Output

B. ATTITUDE CONTROL REQUIREMENTS

Nuclear energy systems have an obvious advantage over solar energy systems in that they are not dependent on sun-orientation. At low power levels, it is sometimes convenient or economical to use random-attitude-oriented solar cell arrays. This is the case when the power supply constitutes an only small part of the payload weight or operates at very low power levels, since the power supply specific weight is degraded by a factor of four due to integration of a cosine incidence function over 4π steradians. Solar energy systems employing focusing mirrors or reflectors must be accurately oriented, since their efficiency fall off rapidly with misorientation.

A certain amount of interaction will exist between power supply orientation requirements and other orientation requirements. If an antenna must be oriented on at least one axis, the penalty for requiring orientation on an additional axis may be either greater or less than the penalty for the first orientation alone. For small payloads, where sensing and control equipment constitute the major orientation burden, the additional requirement may come quite cheaply. In large systems, however, momentum wheels, reaction mass, and electric driving power are the major items of orientation burden, and each additional control axis adds appreciably to this burden.

C. VEHICLE CONFIGURATIONS

Size, shape, placement, and packaging of payload components must be considered in selecting the power source to be used in a particular mission. Shield requirements for nuclear systems are based on the radiation sensitivity of transistors, but care must be exercised that payload components, such as large antennas, do not protrude beyond shielded areas to become sources of scattered radiation. Thermal radiations and the temperature environment of sensitive components must also be considered. Interferences may arise between the orientation of large solar mirrors and large antennas, and in some cases the mere presence of vehicle and appendages will influence the gain and directivity pattern of an antenna.

D. MISCELLANEOUS CONSIDERATIONS

It is reasonably safe to state that in a communications satellite system, practically everything interacts. The vulnerability of exposed surfaces or

elements to the space environment influences the weight of these components and the protection which must be provided for them. Space environment may, in the case of military applications, include the effects of nuclear weapons to which nuclear reactor power systems can fortunately be expected to be highly resistant.

Duty cycle has an influence on the selection of a power source. For systems with short, high-power load periods and long, low-power load periods, energy storage devices of some sort are usually employed, and the weight, cost, and characteristics of these devices must be incorporated into the system design.

With nuclear power sources, appreciable shield weight savings may be realized by selecting payload components and designs of high radiation tolerance.

Certain interactions are best considered in a relative way. Let us assume a system designed to provide 100 communications channels to an area 500 miles in diameter, and that this system requires a power supply of 1 kw. Increasing the power supply capability permits some combination of the following improvements:

- 1) Increased channel capacity
- 2) Decreased satellite antenna size and weight
- 3) Increased coverage area
- 4) Increased signal quality or reliability
- 5) Decreased required quality of ground installations
- 6) Providing or increasing resistance to jamming
- 7) Decreased required antenna orientation precision.

Since the power supply constitutes only a part of the payload weight, doubling the power supply weight will less than double the total weight. In addition, in the case of a nuclear reactor system, the specific weight of the power supply will be lower. The satellite weight and cost per unit-quality channel will thus decrease with increasing power supply capabilities.

An additional mission interaction of importance in satellite communications is the possibility of using electric propulsion techniques to reduce the cost of rocket boosters or to augment their payload capability.²⁵ Electric propulsion appears to be practical only at the high power levels available from nuclear reactor systems.

E. SNAP REACTOR SYSTEMS

The SNAP reactors constitute the present generation of space power reactors, and can provide electric power at levels up to 150 kw or higher. Table IV summarizes the characteristics of the three specific systems of this family currently under development. These systems are indicated by points in Figure 19. Two additional points shown in Figure 19 indicate possible extensions of the same reactor technology. At 150 kw electric output, the specific weight of a power supply of this family would be 30 to 40 lb/kw, shielded.

Considering the example calculations previously discussed and the earlier comments of this section, several communications missions may be described for the SNAP reactors under development:

SNAP 10A (0.5 kw)

- 1) FM broadcast from a low orbit
- 2) Several channels of FM broadcasting from a stationary orbit
- 3) Many channels of common-carrier relay, any orbit.

SNAP 2 (3.0 kw)

- 1) Several channels of FM broadcasting, any orbit
- 2) FM broadcast to minimal-quality receivers
- 3) TV broadcast (FM) with low duty cycle or limited coverage areas
- 4) Broadband military communications with limited duty cycle.

SNAP 8 (30.0 kw)

- 1) Broadband military communications, many channels
- 2) TV broadcast (standard) to near-hemispheric areas.

These hypothetical missions represent a few of the communications tasks within the power output capabilities of three specific SNAP reactors. They are loosely defined missions, and no effort has been made to optimize the many pertinent system parameters. As communication requirements become more clearly defined and specific communications satellite programs arise, it will be desirable to design nuclear reactor systems which are tailored to the mission requirements of each specific program and which permit an optimum, integrated, overall system performance.

TABLE IV
SNAP REACTOR SYSTEM CHARACTERISTICS

	SNAP 10A	SNAP 2	SNAP 8
Output, kwe	0.5	3	30
Converter system	Thermoelectric	Mercury turbogenerator	
Life	1 to 3 yr	1 yr	10,000 hr
System weight, lb			
Unshielded	525	865	~1700
Shielded*	775	1100	~2000
Specific weight*, lb/kw	1550	367	67
Payload dose			
Neutron, nvt	10^{12}	10^{12}	10^{13}
Gamma, radiation	10^7	10^7	10^7
Overall efficiency, %	2	6	10
Core volume, ft ³	0.3	0.3	0.48
Radiator area, ft ²	63	110	400
Radiator temperature, °F	600	600	700

*Shielded for transistor payload, 1-yr life.

APPENDIX A

THE USE OF DECIBEL NOTATION

Decibel notation is a highly useful mathematical tool in communications engineering. There are several derivative uses of the basic decibel definition. A few words on the subject are in order, since this report is intended for the non-specialist in communications engineering.

The decibel was originally developed as a unit of measurement for sound intensities, tailored to the logarithmic response of the human ear. The decibel is a unit relating a ratio of two quantities of power, and is defined as:

$$10 \log_{10} (P_1/P_2) = \text{decibel difference} \quad \dots (A-1)$$

The average human ear is capable of discriminating between two sound intensities if they differ by at least 2 db, or a ratio of 1.585.

Decibel notation is commonly employed to express the gain or loss of an electronic network. The loss in an attenuator where $P_i/P_o = 2$ is thus 3.01 db. Alternatively, the gain of this attenuator is expressed as -3.01 db. If several attenuators and amplifiers are connected in cascade, such that the output of one network is the input to the succeeding network, the overall gain in db is the sum of the db gains of the individual networks. Decibel notation is also used for receiving antennas, referring to the ratio of antenna power output to power output that would have been obtained from a standard reference antenna in the same electromagnetic field*, and for noise figure of amplifiers, referring to the ratio of noise power output to noise power output expected from only thermal agitation noise at the amplifier input.

Although the decibel is basically a relative unit, it is frequently used as an absolute unit of power by specifying some standard reference power level. This practice is indicated by appending a suffix letter indicating the reference level. The suffixes "w" and "m", indicating references of 1 watt, and 0.001 watt respectively, are frequently used; thus 10 watts = 10 dbw = 40 dbm.

The decibel is often used to compare voltages as well as powers, since voltages are usually more readily measured. A comparison of two signal voltages

*In this report, an isotropic antenna is used as the reference standard.

in the same load resistance is given as:

$$20 \log_{10} (V_1/V_2) = \text{decibel difference} \quad \dots (A-2)$$

It is important to note that the impedances across which the voltages are measured must be numerically equal, although not necessarily physically identical. Thus a network decibel loss or gain may be given in terms of voltage measurements only if the input and output impedances are equal. With this restriction, decibels have compatible meanings in both Equations A-1 and A-2.

Voltage-defined decibels are also frequently used as an absolute measure by selecting some standard voltage and impedance reference. Thus 10 volts = 20 dbv across a particular impedance. Electromagnetic field strengths are usually given as $\mu\text{v}/\text{meter}$ (electric vector amplitude). One $\mu\text{v}/\text{meter}$ is a useful reference; thus 1000 $\mu\text{v}/\text{meter}$ = 60 dbu, and the impedance is that of free space.

There are a few additional, highly specialized uses of decibel notation, e.g., dba for telephonic channel usage, dbR/cbw for frequency modulation spectrum analysis. Caution must be used to determine the appropriate definition and usage in each case. It is usually, but not always, the case that decibel differences are compatible with the basic power ratio definition given in Equation A-1.

APPENDIX B

MODULATION SCHEMES AND SIGNAL IMPROVEMENT FACTORS

There are a variety of modulation schemes employed to impress information on a radiated electromagnetic wave. All of these schemes are redundant to some degree, and with ordinary intelligence waveforms such as speech or music, cannot function near their optimum efficiency. If the nature of a system's redundancies and inefficiencies is understood, it is often possible to employ information treatment techniques at either transmitter or receiver to improve the quality of the ultimately reproduced signal.

A. STANDARD AMPLITUDE MODULATION

A detailed analysis of this system is in order, since it is a simple, widely used system and serves as a comparison standard for other systems.

An AM transmitter radiates a wave whose amplitude is varied by the modulating waveform. For an unmodulated wave described by:

$$e_o = E \sin (2\pi f_c t) \text{ (volts) } , \quad \dots (B-1)$$

and a modulating waveform by:

$$e_m = M(t) , \quad \dots (B-2)$$

the modulated wave is then:

$$e_o = [1 + M(t)] E \sin 2\pi f_c t . \quad \dots (B-3)$$

If $M(t)$ is a simple sinusoidal wave of frequency f_l , the description of the modulated wave may be written as:

$$e_o = E \sin [2\pi f_c t] + \frac{ME}{2} \cos [2\pi(f_c - f_l)t] - \frac{ME}{2} \cos [2\pi(f_c + f_l)t] , \quad \dots (B-4)$$

where M = degree of modulation. Unity, or 100% modulation, doubles the amplitude of the carrier on positive modulation peaks and reduces it to zero on negative

modulation peaks. This is the optimum degree of modulation, since larger variations of amplitude result in the generation of spurious radiations and a net reduction in intelligibility.

Inspection of Equation B-4 reveals the spectrum of this simple case. The emitted radiation consists of a line at f_c , and two lines (side frequencies) at $(f_c + f_l)$ and $(f_c - f_l)$, respectively. The power content of the f_c component is equal to the average power of the unmodulated carrier, and each of the side frequency components has a power content equal to 0.25 the unmodulated carrier if $M = 1$ (see Figure B-1a).

For complex modulating waveforms such as speech or music, treatment as a Fourier series or Fourier integral will yield similar results. Figure B-1b shows a typical spectrum resulting from speech modulation. The total power content of each sideband may be made to approach 0.25 the carrier power.

With a 100-watt carrier, a continuously active talker will produce up to 150 watts of radiation, of which 25 watts constitute unique intelligence. One sideband is informationally redundant but does serve to improve the information density of the system. The carrier merely conveys the information that the transmitter is operating, a fact which is already known. The efficiency of this system is thus 50/150 or 33.3%. However, since speech is not carried on at a continuous uniform level, the speaker may only be producing sidebands 25 to 50% of the time. The average radiated power is thus 112.5 to 125 watts, which yields efficiencies of 11.1 to 20.0%, respectively.

Optimum receiving bandwidth is a predetection bandwidth just sufficient to pass all important components of the received signal, and a post detection bandwidth which cuts off sharply at the maximum f_l (the maximum frequency component of the modulating signal).

In a conventional AM receiver with optimum bandwidth, the S/N ratio at the output transducer can be shown to be equal to the predetection carrier/noise ratio, for $M = 1$.

B. SINGLE-SIDEBAND-SUPPRESSED CARRIER

Since the carrier component in AM conveys no unique intelligence, it need not be transmitted. Further, if one sideband is omitted and the other is doubled in power, the same information power is transmitted, but requires only half the

Figure B-1. AM Power Spectra

Figure B-2. SSB Power Spectra

Figure B-3. FM Power Spectra

spectrum space (see Figure B-1a and b). These two features result in considerable power savings. An SSB transmitter with an average output of 50 watts conveys the same intelligence as a 100-watt, fully modulated, AM transmitter (150-watt average output), resulting in a reduction of power demand to 1/3, or 4.76 db savings. SSB detection is a voltage dependent process, and hence twice the total sideband power is required to produce the same voltage envelope as is produced by the sum of the two sideband voltages in AM.

Power is not consumed during intervals where modulation is not taking place, resulting in an additional average power savings of 3 to 6 db for the 50 to 25% duty cycles of normal speech. Because of the narrower bandwidth of the radiated signal (0.5 that for AM), the receiver predetection bandwidth may now be narrowed by a factor of 0.5, resulting in a 3-db reduction of the receiver noise level. The overall result is that, watt for watt, an SSB signal produces a 8 to 11 db better output S/N ratio than a standard AM voice signal. The output S/N ratio of an SSB receiver is equal to its short-term-average C/N ratio, and the transmitter may be considered to have a power duty cycle of 0.25 to 0.50 for voice transmission. Figure B-2 shows the spectrum of a typical SSB signal.

C. FREQUENCY MODULATION

An FM transmitter radiates a wave whose frequency is varied in accordance with the modulating waveform. For sine wave modulation, the output wave is described by:

$$e_o = E \cos (2\pi f_c t + m_f \sin 2\pi f_\ell t) \quad , \quad \dots (B-4)$$

where $m_f = (\text{maximum carrier frequency deviation})/(f_\ell)$. The amplitude of the modulation component (m_f) is known as modulation index or deviation ratio, and is equal to the maximum instantaneous frequency deviation from the carrier frequency divided by the maximum modulating frequency.

Series expansion of Equation B-4 in Bessel functions shows the output spectrum to be composed of a carrier term and an infinite series of modulation terms at successive frequency increments of Δf_ℓ above and below the carrier. A typical FM spectrum is shown in Figure B-3.

The amplitudes of the carrier and modulation terms are involved functions of several variables. It is important here only to note that the power integral of the entire spectrum is constant regardless of the modulation, and that the higher order modulation terms become insignificant at frequencies removed from the carrier by somewhat more than $m_f f_l$. Figure B-4 shows the receiver bandwidth required for reception of FM signals, as a function of m_f .

Since the power output of an FM transmitter remains constant under modulation, it is customary to refer signal measurements to the unmodulated carrier power level.

In a receiver with optimum bandwidth and with a detector insensitive to amplitude variations, it can be shown that for strong signals the output S/N ratio is $3m_f^2$ greater than the predetection carrier/noise ratio in twice the modulation bandwidth, or in decibels, $10 \log 3m_f^2$ improvement. This improvement factor is a striking tradeoff of power against spectrum bandwidth. The FM improvement factor is effective when noise peaks exceed the carrier level only infrequently. The statistical nature of common receiver noise is such that a signal/average-noise ratio of about 13 db is required in the predetection bandwidth to obtain this condition. This improvement threshold is reached at relatively low signal levels for narrow-deviation signals, since the receiver bandwidth, and hence received noise, is also low. The improvement is also small. For wide-deviation signals the improvement is much greater, but the signal level must be higher to reach the same predetection C/N because of the increased predetection bandwidth. Signal quality deteriorates rapidly in the first 3 db below threshold, and even more rapidly thereafter. Thus, for any available signal strength there is an optimum modulation index for maximum output S/N, and a wide-deviation FM signal may actually yield a poorer output signal than an AM signal of equal carrier power in weak-signal conditions.

D. FEEDBACK DETECTION OF FM SIGNALS

The tuning of an FM receiver can be controlled by feedback from the detector in such a fashion that the receiver, in effect, follows the deviating signal through its frequency excursions, never quite catching it. The net result is to reduce the modulation index of the signal as seen by the intermediate amplifiers and detector. This, in turn, permits narrowing of the receiver bandwidth and consequent noise reduction.

Figure B-4. Predetection Bandwidth Required to Pass Significant Modulation Terms of FM Signal

A detailed analysis of FMFB systems is beyond the scope of this report. The net result, however, is to reduce the improvement threshold while maintaining the improvement factor calculated on the basis of the original modulation index. A corollary advantage of this system is to make the receiver output reasonably free from internal distortion. A value of 6 db is a representative predetection improvement threshold for FMFB.

Phaselock detection is an extreme case of FMFB. Here the receiver tuning tracks the deviating signal exactly, and the output modulation index is effectively reduced to zero. Output is taken from the feedback servo signal. Phaselock techniques require fairly precise equipment, and provide appreciable advantage only for narrow bandwidth signals. Improvement thresholds, "lock-in," as low as 0 db have been attained with narrow-deviation signals.

E. PREEMPHASIS

Statistical studies of the power spectra of speech and music show that a relatively large fraction of the waveform power is concentrated at low frequencies. On the other hand, studies of typical receiver output noise show that a relatively large fraction of the noise power may occur at frequencies near the upper limit of human hearing. A receiver may be designed with a declining postdetection response in this region, thus reducing the average noise output. Signal output in this region is also reduced by the same amount. No net improvement results, and the output signal is distorted. However, if the modulating signal at the transmitter is passed through a preemphasis filter which has an increasing output in this region, and the transmitter preemphasis is exactly the inverse of the receiver deemphasis, the net result is to accurately reproduce the original modulating waveform while enjoying the benefits of reduced average noise output.

Use of this system requires prearranged agreement between transmitter and receiver as to the shape of the preemphasis-deemphasis functions to be used. In the U.S., a single stage RC low-pass filter with a time constant of 75×10^{-6} sec has been selected for use in standard FM broadcasts.¹⁵ The S/N improvement due to preemphasis is:

$$\psi_{FM} = \frac{(2\pi f_l \tau)^2}{3 \left[1 - \frac{\tan^{-1}(2\pi f_l \tau)}{(2\pi f_l \tau)} \right]} \quad \dots (B-5)$$

Preemphasis is also applicable to AM transmissions, but not with such outstanding improvement:

$$\psi_{AM} = \frac{(2\pi f_l \tau)}{\tan^{-1}(2\pi f_l \tau)}, \quad \dots (B-6)$$

where τ is the deemphasis time constant (75×10^{-6} sec), and f_l is the cutoff frequency of a sharp cutoff low-pass filter in the postdetection receiver circuit, set equal to the maximum modulation frequency to be transmitted. In ordinary AM systems, ψ_{AM} is never fully realized because the average degree of modulation must be reduced to avoid exceeding 100% modulation in the preemphasized region. It appears, however, that ψ_{AM} can be almost fully realized in SSB systems.

Equations B-6 and B-7 are shown graphically in Figure B-5 for a time constant of 75×10^{-6} sec.

F. SUBJECTIVE IMPROVEMENT FACTORS

In addition to signal quality improvements which are purely analytical, there are also several techniques which can improve the subjective quality of a signal without appreciably altering its S/N ratio. One of these is squelching, wherein the receiver output is completely cut off during intervals when the output signal is below some predetermined level. This has the effect of reducing the long term integrated noise output to the ear, while retaining practically all of the intelligence output. The effectiveness of squelching is highly dependent on the listener and the nature of the program material. For voice modulation the squelch may appear equivalent to a 5 db increase in transmitter power.²⁰ Squelching is not effective for video or musical program material.

A second technique which is largely subjective is noise clipping, wherein the receiver output is limited to an instantaneous level equal to the maximum signal level. This has the effect of clipping off noise peaks which exceed the signal, without appreciable effect on the signal itself. This technique is applicable to AM and SSB reception and is effective mainly against external impulse noise. The effectiveness of clipping is dependent on signal strength and the nature and intensity of the noise. For weak signals, the measured improvement in output S/N ratio may be negligible, whereas the subjective effect may be equivalent to as much as a 3 to 4 db increase in transmitter power.

Figure B-5. Improvement Due to Preemphasis

G. CODING AND PREPROCESSING

In certain cases, the original signal may be subjected to extensive coding or preprocessing with advantage. The object of such treatment is usually to reduce any redundancy of intelligence contained in the original signal and avoid the transmission of unnecessary information. Coding and preprocessing thus permit more efficient use of the power and spectrum space available, and make possible a better tradeoff between such factors as transmitter power, signal bandwidth, etc., than is possible with simpler transmission schemes. SSB transmission and pre-emphasis may be thought of as fairly simple preprocessing techniques.

The degree to which coding and preprocessing may be beneficial is highly dependent on the nature of the original signal, and on the nature of the deficiency to be corrected. Analysis of complex treatment techniques is beyond the scope of this study.

H. BANDWIDTH REQUIREMENTS AND MULTIPLEXING

For any given modulation scheme, the bandwidth occupied by the transmission of a program is proportional to the rate at which information is transmitted. Table B-1 summarizes the bandwidth requirements of various types of programs.

Several programs may be transmitted simultaneously, or multiplexed through a single transmitter by time or frequency sharing techniques, or by complex coding. The bandwidth required is still proportional to the total information rate, or to the number of similar channels multiplexed. Usually, with large numbers of channels, some additional bandwidth is required to avoid undesirable interactions between channels. Standard telephonic usage allows at least 4 kc per voice channel. Multiplexing does not directly provide power savings, since the

TABLE B-1
BANDWIDTH REQUIREMENTS FOR VARIOUS PROGRAMS

Type	Bandwidth	Information Rate
Morse Code	bandwidth, cps $\cong$ 4	x words/minute (4)
Standard Teletype	0.1 kc	60 wpm (10)
Voice	3.0 kc	$\sim$ 100 wpm
Music	Up to 15 kc	Varies
TV	3 to 5 Mc	Varies

total power content of the signal must be divided among the various channels. However, it is sometimes possible to realize second-order power savings through more efficient operation of the transmitter. This requires sophisticated system planning and careful restriction of operating conditions.

I. TV SIGNALS

The output from an ordinary TV camera is a video signal with frequency components up to about 4.5 Mc; this is the modulating signal fed to a transmitter. The modulation scheme may be either AM or FM; in standard commercial TV broadcasting, AM is used and the lower sideband is partially suppressed. The envelope of a typical transmitter output is shown in Figure B-6. Signal strength measurements are customarily referred to the peak video sync level, since this is the most conveniently measured quantity, and has the advantage of being independent of the nature of the picture being transmitted.

It is apparent from Figure B-6 that the average power output of the transmitter is far less than the peak power output. For typical pictures, the ratio may be as low as 0.25, and the average power output requirement calculated from the Communications Equation is reduced accordingly. This report assumes a peak factor of 0.5, which provides a conservative margin for even near-black pictures.

In the U.S., standard TV broadcasts are accompanied by an FM sound transmission with a power output equal to 0.5 the peak video sync level; this must be considered in calculating power requirements for a TV broadcast transmitter. If a video peak factor of 0.5 has been assumed, however, the standard aural transmission exactly compensates this power saving and the composite normalization factor is unity. Transmitter power output requirements are then given directly by the Communications Equation, using S/N ratio requirements based on conventional sync peak measurements.

Experience has shown that standard aural transmissions, at a level of 0.5 of sync peak, provide a far better audio output signal than is compatible with the accompanying subjective picture quality. Under poor transmission conditions the picture may be no more than an unintelligible mass of snow, while the audio signal shows no appreciable degradation. Experiments have been conducted in which the aural transmission has been reduced to as low as 0.1 of sync peak.

Figure B-6. Typical Power Output Envelope for U.S. Standard TV Video Signal

Subjectively EXCELLENT audio has been received under conditions where the picture is INFERIOR to UNUSABLE.* Although not particularly advantageous in surface commercial broadcast practice, aural transmission reduction would be outstandingly desirable in satellite service, resulting in a reduction of 0.6 in APU requirement. This factor is most easily included in the Communication Equation by assuming a loss of -2.2 db, under miscellaneous losses.

The spectrum of a typical U.S. monochrome TV transmission is shown in Figure B-7. The channel width of 6 Mc provides space for both aural and picture signal components with a little space left over (guardbands) on each side. Color TV occupies essentially the same bandwidth, but at a somewhat higher information density per unit bandwidth.

FM may also be used to transmit video signals. Parameters affecting FM transmission have already been discussed. The FM improvement factor is fully realized, and FMFB reception is also usable and highly desirable. Preemphasis may be used to some advantage, but not as much as implied by Figure B-5. Because of the extremely wide RF and video bandwidths involved, the method and amount of preemphasis usable is considerably different than for low and medium bandwidths. FMTV may require a predetection bandwidth up to 60 Mc or more, and the amount of preemphasis benefit that appears attainable is only about 6 to 9 db.⁵

FMFB techniques may also be applied to FMTV reception, but the threshold reductions have not been as spectacular as with signals of narrower bandwidth. Threshold appears to occur at a C/N ratio of about 10 db in the predetection bandwidth.⁵

Figure B-7. Power Spectrum of TV Transmission

*Quotes here indicate terms used by IRE-TASO Panel, Ref 12. Also, see Appendix C.

APPENDIX C

SIGNAL/NOISE RATIO REQUIREMENT FOR VARIOUS PROGRAM TYPES

Program material can be divided into two categories, programs intended for reception by human sight or hearing, and programs intended for reception by a machine (e.g., data, control signals, etc.). In either category, the program material may be transmitted fairly directly or it may be highly preprocessed. For machine-oriented program material, the test of quality is usually a yes-or-no conclusion. (Is the desired function performed with adequate reliability?) For human-sense-oriented program material, however, program quality is a subjective quantity, not always amenable to simple or straightforward evaluation. In general, the output S/N ratio is the best measure of program quality, although quality may also be subjectively influenced by the time schedule and nature of the unwanted noise. Signal quality rating techniques can be extremely complex and are well beyond the scope of this study. Considerable statistical data exist, however, and empirical conclusions can be drawn regarding quality standards for some types of program material.

A. AUDIO PROGRAMS

Audio programs are either music, speech, or Morse Code. Table C-1 summarizes the output S/N ratios required for various program types and qualities of reception. The quality descriptions have been adapted from those used by the IRE-TASO Panel, and are defined as follows:

EXCELLENT, extremely high quality, as good as could be desired;

FINE, high quality providing enjoyable listening (viewing). Interference is perceptible;

PASSABLE, acceptable quality. Interference is not objectionable;

MARGINAL, poor, wish you could improve it. Interference is somewhat objectionable;

INFERIOR, very poor but could listen (view). Definitely objectionable interference; and

UNUSABLE, self-explanatory.

TABLE C-1
OUTPUT S/N REQUIREMENTS FOR AUDIO PROGRAMS

Program	S/N (db)	Bandwidth (kc)	Quality	Reference
Morse Code (20 wpm)	0	0.08	Inferior	16
Morse Code (20 wpm)	0-6	0.08	Marginal	
Morse Code (20 wpm)	6-10	0.08	Passable	
Morse Code (20 wpm)	10	0.08	Fine	
Morse Code (20 wpm)	>12	0.08	Excellent	
Human Speech (Male)	< 6	3	Inferior	16
Human Speech (Male)	6-10	3	Marginal	
Human Speech (Male)	10-12	3	Passable	17
Human Speech (Male)	>12	3	Fine	
Human Speech (Male)	30-50	3	Toll Tele- phone Stds.	18
Music (Low Fidelity)	~15	5-10	Marginal	*
Music (High Fidelity)	< 20	15	Marginal	
Music (High Fidelity)	20-30	15	Passable	
Music (High Fidelity)	30-40	15	Fine	
Music (High Fidelity)	> 40	15	Excellent	

*Quality evaluation of musical programs is a subject considerably confused by commercial claims in the high-fidelity market. The quality ratings given in Table C-1 represent the author's opinion, and are believed to be fairly conservative. They are based on a private study of claimed and measured home music system performance specifications, and on personal experience.

B. TELEVISION PROGRAMS

Quality rating of TV pictures is highly subjective. Figure C-1 indicates the distribution of opinions in a group of 78 observers in one recent test. Caution must be exercised in interpreting the vertical scale, however, since the qualities indicated are not a smoothly defined continuum of numerical quantities.

Figure C-2 is a cross-plot of Figure C-1. Some estimated curve smoothing was applied in the region above the FINE level in order to emphasize the fact that many viewers experience little subjective improvement as the S/N ratio is increased above 40 db. It must also be admitted, however, that some observers will experience subjective improvements for S/N ratios up to 60 db or more. Fifty percent of all viewers will find a picture at least PASSABLE if S/N is 27 to 28 db, and at least FINE if S/N is 32 to 33 db.

Figure C-1. Subjective Evaluations of TV Picture Quality in the Presence of Random Noise. (from IRE TASO Panel Studies, Proc IRE, June 1960)

Figure C-2. TV Subjective Quality vs Signal/Random Noise Ratio

APPENDIX D

ANTENNAS

The many parameters influencing antenna performance are well beyond the scope of this report. A few notes are in order to provide an indication of antenna parameters which are pertinent to the evaluation of a satellite communications system.^{19, 20, 21, 22}

A. HALF-WAVE DIPOLE

The half-wave dipole is probably the most commonly used antenna, and although not necessarily the optimum choice for a satellite communications application, it may still find wide use in this area. It consists of a thin wire of 0.5λ in length, broken at the middle for connection to a transmission line. The radiation pattern is roughly toroidal, with the axis of the torus coincident with the antenna. Gain in the preferred plane is 1.64, or 2.2 db over isotropic. The effective capture area or aperture is, from Equation 7:

$$A_c = \frac{1.64\lambda^2}{4\pi} = 0.13\lambda^2 \quad . . . (D-1)$$

The beamwidth is 78° when operated in free space. Practical antennas of this type have apertures which are hundreds or even thousands of times larger than their actual physical areas. The main advantages of this antenna are its simplicity, light weight, and low cost.

Half-wave antennas may be arranged in arrays to increase gain and capture area. The elements of the array must be critically spaced, and supporting structures are usually required.

B. PARABOLOIDAL REFLECTOR ANTENNAS

An ideal reflecting antenna, such as described in Section IV-B, would concentrate all incident energy at a focal point and deliver the energy to a transmission line. In transmitting, the antenna would deliver all of the output into a sharply defined cone of uniform angular power density. Unfortunately, such ideal behavior is never encountered. A transmitting reflector can never be perfectly uniformly illuminated, and the radiations taper off smoothly as a

function of angular orientation from the focal direction. In addition, energy is diverted selectively into side lobes or higher-order diffraction patterns. Typical antenna patterns are shown in Figure D-1.

Since antennas are reciprocal for receiving and transmitting, the same side lobes will be experienced in reception, and less energy will be extracted from the wave than is incident on the physical area of the reflector. The ratio of effective capture area/physical area is the aperture efficiency (η) and ranges between 0.5 and 0.7 for antennas of good design.

The gain and beamwidth of a reflecting antenna are dependent on the diameter of the reflector. For uniformly (or nearly so) illuminated paraboloidal reflectors with diameters of a few wavelengths:

$$G = 9.87 (D/\lambda)^2 , \quad . . . (D-2)$$

and

$$W = \frac{58}{D/\lambda} \text{ degrees} = \frac{1.01}{D/\lambda} \text{ radians} , \quad . . . (D-3)$$

where D = reflector diameter and W = beamwidth (angle between half-power points, -3 db). Equations D-2 and D-3 are plotted in Figure D-2. Gains derived from Figure D-2 must be multiplied by η , and beamwidths divided by $\eta^{1/2}$, to obtain actual gains and beamwidths.

Equations D-2 and D-3 may be rephrased in terms of aperture. Thus:

$$G = 12.6 A_c , \quad . . . (D-4)$$

and

$$W = \frac{51.4}{\sqrt{A_c}} \text{ degrees} = \frac{0.90}{\sqrt{A_c}} \text{ radians} , \quad . . . (D-5)$$

where A_c is the effective aperture area in square wavelengths.

It is apparent from Figure D-2 that the gain of a given reflector increases as the square of the frequency. This is indeed true within limits determined by

Figure D-1. Typical Antenna Patterns

Figure D-2. Gain and Beamwidth of Ideal ($\eta = 1$) Paraboloids

the precision of the paraboloidal surface. If the reflector is distorted from true paraboloidal shape by a small fraction of a wavelength, the beam becomes distorted, forward gain is reduced and spurious side lobes develop. Distortions may occur in original manufacture of the reflector, or they may develop as a result of wind and gravitational strains. Large, trackable antennas are particularly subject to these defects. Figure D-3 shows the gain limits for a large antenna with two different degrees of RMS precision, and Figure D-4 indicates approximate frequency limits for present state-of-the-art.

C. PARABOLOIDAL HORN ANTENNAS

Figure D-5 shows a paraboloidal horn antenna of the type developed by Bell Telephone Laboratories. The term horn is a technical misnomer since the antenna is best described as a shielded, paraboloidal-segment reflector antenna. The advantages of this antenna are extremely low side lobes and high mechanical ruggedness. The horn provides good coupling to the paraboloidal surface, and its feedpoint remains reasonably stationary during tracking, thus facilitating the use of masers and their accompanying cryogenic equipment without long transmission lines (waveguides).

D. HELICAL BEAM ANTENNAS

The helical, or corkscrew antenna, is of interest in satellite communications. It will provide appreciable gain with reasonable sized antennas, can be mass-produced cheaply, has reasonably small side lobes, and is sensitive to circularly polarized waves. A typical helical beam antenna is shown in Figure D-6. The reflector (ground plane) is 0.5 wavelengths or greater in diameter, although this has little influence on the antenna gain or beamwidth. Gain and beamwidth are given by:

$$G = 15 C_{\lambda}^2 L_{\lambda} \quad \dots (D-6)$$

$$W = \frac{52}{C_{\lambda}} \sqrt{L_{\lambda}} \text{ degrees} \quad \dots (D-7)$$

where C_{λ} = circumference of helix and L_{λ} = length of helix, both in wavelengths. C_{λ} is constrained to have values between 0.7 and 1.2 for circularly polarized beam mode operation.

Figure D-3. Gain Degradation by Imperfect Reflector
 (After Rechten, Reference 6)

Figure D-4. Maximum Frequency for High Quality Paraboloidal Reflectors
(After Potter, Reference 19)

Figure D-5. Paraboloidal Horn Antenna

Figure D-6. Helical Beam Antenna

E. TYPICAL ANTENNA PARAMETERS

Table D-1 lists parameters typical of antennas of present or possible future interest in satellite communications.

F. SPACE ANTENNA CONSIDERATION

Spacecraft antennas are governed by the same general considerations as ground antennas. Certain advantages accrue from the zero gravity environment, however. Extremely lightweight inflatable plastic structures have been developed for use as space antennas, including paraboloidal reflectors over 30 ft in diameter.^{23, 24}

It is not unreasonable to assume that gains up to 30 db or so are feasible for space antennas. It is therefore convenient to select the space antenna gain on the basis of beamwidth required for coverage of the desired ground area. Combining Equations D-2 and D-3 yields, for paraboloidal reflectors:

$$G = \frac{3.3 \times 10^4}{W^2} \quad (W \text{ in degrees}). \quad . . . (D-8)$$

In some cases, elliptical or rectangular reflectors may be used to advantage. Beamwidth is different in vertical and horizontal directions, and gain is sufficiently well approximated by:

$$G = \frac{3.3 \times 10^4}{W_v W_h}. \quad . . . (D-9)$$

G. ANTENNA COSTS

A variety of large antennas have been built for radio astronomy and space programs. It has been noted that the relative cost of these systems rises approximately as the 2.7 power of diameter.^{19, 21} Figure D-7 is an empirical curve derived from somewhat incomplete data, but is useful for estimating antenna costs. The accuracy of the costs presented is probably no better than +100 to -50%. For fast-tracking, precision-beam antennas, the cost would probably be near the upper limit indicated.

Figure D-7. Cost of Paraboloidal Antenna vs Diameter

TABLE D-1
TYPICAL ANTENNA PARAMETERS

Type	Frequency	Gain Forward (db)	Beamwidth (-3 db)	Side Lobes	Dimensions	Remarks
Dipole, in free space	-	2.2	78°	none	$\lambda/2$	Very low cost
Helical	600 Mc	16	32°	small	133 cm long, 16 cm diam	-
Helical	1500 Mc	20	20°	small	133 cm long, 6.4 cm diam	-
Paraboloidal Reflector	8.7 Gc	64.4	<1°	-	85 ft diam	$\eta = 0.5$ (U. of Mich. Radiotelescope)
Paraboloidal Reflector	<3 Gc	50-60 (max)	-	-	250 ft diam	$\eta \simeq 0.6$ (Manchester Radiotelescope)
Paraboloidal Reflector	6 Gc	~42	0.14°	-	85 ft diam	$\eta = 0.58$ (Goldstone Receiver)
Paraboloidal Reflector	1000 Mc	18	23°	moderate	1 meter diam	$\eta = 0.7$ (Assumed)
Paraboloidal Horn	2.4 Gc	43	1.2°	negligible	40 by 25 ft (approx)	(Holmdell Horn)
Paraboloidal Horn	6 Gc 4 Gc	61 57	0.16° 0.22°	negligible	210 ft diam dome	Weight 18 tons, cost $\simeq \$10^7$ (Rumford Horn, Telstar)
Helical Array	1000 Mc	18-20	22°	-	15 by 15 by 30 ft (approx)	4 Helical Antennas (Johannesburg Tracking Antenna)

APPENDIX E

SPECTRUM NOMENCLATURE AND FREQUENCY ALLOCATIONS

A rather arbitrary system of spectrum nomenclature arose during the early days of radar development, and it has been extended to cover frequencies of interest in satellite communications. It is now obsolescent, but one still finds references to it in the current literature. Table E-1 gives the letter designations associated with the various spectrum segments.

TABLE E-1
SPECTRUM SEGMENTS

Band Letter	Nominal Frequency Limits (Gc)
I	0.1 to 0.15
G	0.15 to 0.225
P	0.225 to 0.390
L	0.390 to 1.55
S	1.55 to 5.2
C	3.9 to 6.2
H	7.0 to 8.5
X	5.2 to 10.9
K	10.9 to 36
Q	36 to 46
V	46 to 56
MM	50 to 120

With the exception of the UHF TV band, which consists of 70 consecutive channels in the 470 to 890 Mc region, all U.S. broadcast service allocations are at G-band frequencies or lower. Table E-2 lists allocations of possible interest for early satellite broadcast services. For the sake of completeness, information on foreign and domestic TV allocations below 100 Mc is also included, although this does not imply that such frequencies are considered technically or administratively feasible for satellite communication applications.

TABLE E-2
SPECTRUM ALLOCATIONS

Service	Channel Numbers	Frequency Range (Mc)
TV, U. S.	2, 3, 4	54 to 72
TV, U. S.	5, 6	76 to 88
TV, U. S.	7 to 13	174 to 216
TV, U. S.	14 to 83	470 to 890
TV, Foreign*	Low VHF (up to 5 channels)	41 to 109 (with gaps)
TV, Foreign*	High VHF (up to 8 channels)	164 to 231 (with gaps)
FM Broadcast		88 to 108

*Technical practices of foreign TV transmissions are not generally compatible with U. S. transmission standards. It is conceivable, however, that a receiver could be designed to accept most present-day standard signals.

Spectrum allocations for the specific and exclusive use of satellite communications systems are currently a matter of international discussion. No commercial allocations have been made. Several bands have been allocated for experimental purposes, though, and many bands are being considered for shared use by both satellite and surface services.

APPENDIX F

SATELLITE COMMUNICATIONS PROGRAMS AND PROPOSALS

There have been a large number of proposals for satellite communications of various types, and additional proposals are forthcoming almost daily. Some of the proposals or programs which have enjoyed widespread interest or activity are summarized in Table F-1. The figures quoted have all been taken from the open literature. In some cases, certain figures were not available, or were in conflict with other published figures. In all cases, the author has attempted to make the table as up-to-date (May 1962) as possible. Where serious conflicts exist, the figure is omitted from the table.

TABLE F-1

SATELLITE COMMUNICATIONS PROGRAMS AND PROPOSALS

Name	Producer	Schedule (first shot)	Number of Satellites in System	Satellite Weight (lb)	Orbit Height (miles)	Orientation	Antenna	Operating Frequencies	Satellite Transmitter				Full Load Power Drain (watt)	APU Output (watt)	APU Type	Ground Antenna (ft)	Comments
									Type	Modulation	Capacity (band- width)	R F Output (watt)					
Courier	Philco	Orbited	1+	~400	700			~2 Gc		FM	32 TWX + 2 voice	~12	225	70	Sol Cells	28	Tape recorder, high speed playback
Advent	G. E. / Bendix	1962	1 to 3	~1200	Stationary 22,300	3 axis	Horn rcvr parabolic trans	8.0 Gc up 4.0 Gc dn	Triode or TWT	PM	96 voice (40 Mc)	4	~480	~650	Sol Cells	30 to 60	
Relay	RCA	1962		135	1200 to 3500	Spin axis	Slotted coaxial array	1.7 Gc up 4.17 Gc dn	TWT	FM	48 voice or 1 TV (11 Mc)	10	100	25	Sol Cells	85	High Redundancy for Reliability
Telstar	AT & T	Early 1962	50+	170	2000 to 3000	Spin axis	Waveguide slots	6.39 Gc up 4.17 Gc dn	TWT	FM	120 voice or 1 TV (50 Mc)	2.5	30	15	Sol Cells	65 horn	
Syncom	Hughes	1962	1+	55	Stationary 22,300	Spin axis	Slotted colinear array	7.5 Gc up 1.8 Gc dn	TWT	PM up SSB dn	<10 voice	2	15	20	Sol Cells	60	May use inclined 24 hr orbit
Comsat	G. E.	1965 (indef)	10	~1000	7000 equatorial	3 axis				FM	1250 voice + 1 TV		~400	~700	Sol Cells		Proposal has been cut for administrative reasons
-	IT & T	(indef)	3+	200 to 300	Stationary 22,300	3 axis		2 to 6 Gc		PCM/FM	1000 voice (50 Mc)	10			Sol Cells	30 to 60	Conceptual description only
-	RCA	1966	3	6000	Stationary 22,300	3 axis	parabolic	0.8 Gc 2 to 6 Gc		AMTV SSB	16,000 voice or 5 TV			60,000	SNAP 8		Uses electric propulsion for orbit transfer
NEC-1	Nippon Electric Co.	1964	3 to 4	106	Stationary 22,300	?		2 to 6 Gc			multi- channel voice + TV				Sol Cells		
Advent II	-	?	3+	3000	Stationary 22,300	3 axis	inflatable parabolic	~5 Gc			6000 voice + 6 TV (600 Mc)	30	~1000	~1000	?		Conceptual description only

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APPENDIX G

ABBREVIATIONS, SYMBOLS, CONSTANTS, AND CONVERSION FACTORS

<u>Abbreviation</u>	<u>Definition</u>
AM	Amplitude Modulation
APU	Auxiliary Power Unit
db	Decibels (See Appendix A)
FB	Feedback detection (applied to an FM signal)
FM	Frequency Modulation
Gc	Gigacycles (10^9 cps)
$^{\circ}\text{K}$	Degrees Kelvin
Kc	Kilocycles (10^3 cps)
km	Kilometers
Mc	Megacycles (10^6 cps)
PM	Phase Modulation
RF	Radio Frequency
SNAP	Systems for Nuclear Auxiliary Power
SSB	Single Sideband (suppressed-carrier transmission)
TWT	Traveling Wave Tube
TWX	Teletype
TV	Television

<u>Symbol</u>	<u>Definition</u>
$A_c = \eta A_p$	Capture area of antenna (meters ² or wavelengths ²)
A_p	Physical area of antenna aperture (meters ² or wavelengths ²)
B	Bandwidth (cps)
C	Predetection signal power (watts)

<u>Symbol</u>	<u>Definition</u>
C_λ	Helix circumference (wavelengths)
c_o	Velocity of light (meters/sec)
c (subscript)	Carrier
D	Diameter of antenna (meters or wavelengths)
e	Charge of electron (coulombs)
F_s	Receiver noise figure (dimensionless)
f	Frequency (cps or Mc)
f_l	Maximum frequency component of modulating signal (cps)
G	Gain (dimensionless)
H	Magnetic field strength (ampere turns/meter)
h	Satellite height above surface of earth (km)
h (subscript)	Horizontal
i (subscript)	Input
k	Boltzmann's constant (watts/ $^{\circ}$ K)
L	Loss, or ratio of input to output power (dimensionless)
L_λ	Helix length (wavelengths)
m	Mass of electron (kg)
M	Degree of modulation for AM (dimensionless)
$m_f = \Delta f/f_e$	Modulation index or deviation ratio (dimensionless)
N	Noise power (watts)
N_1	Radiant noise received by antenna (watts)
N_2	Transmission line noise delivered to receiver (watts)
N_3	Thermal noise generated in input impedance of first amplifier (watts)
N_3'	Equivalent noise at input of perfect amplifier
N_4	Noise generated by first amplifier (watts)

<u>Symbol</u>	<u>Definition</u>
N_5	Noise generated by intermediate amplifiers (watts)
n	Charge density (electrons/meter ³)
o (subscript)	Output
P	Power (watts)
P_f	Radiant power flux normal to propagation direction (watts/meter ²)
R	Diameter of ground visibility circle (km)
r	Range, transmitter to receiver (km or meters)
r (subscript)	Receiving
r_e	Earth radius (km)
r_o	Orbit radius (km)
S	Signal power, after detection (watts)
T	Temperature (^o K)
T_i	Noise temperature at network input (^o K)
T_l	Temperature of dissipative network (^o K)
T_o	Noise temperature at network output (^o K)
T_r	Receiver noise temperature (^o K)
T_s	System noise temperature (^o K)
t	Time (sec, hr, or days)
t (subscript)	Transmitting
v (subscript)	Vertical
W	Beamwidth of antenna (degrees or radians)
α	Latitude with respect to orbital plane
Δf	Deviation from carrier frequency (cps)
Δt	Visibility time (hours or sidereal days)

<u>Symbol</u>	<u>Definition</u>
ϵ_0	Permittivity of free space (farads/meter)
η	Aperture efficiency (dimensionless)
θ	Earth central angle (degrees or radians)
$\lambda = c_0/f$	Wavelength, meters (for f in cps)
σ	Root mean square deviation from paraboloidal shape (meters)
μ_0	Permeability of free space (henrys/meter)
τ	Satellite period, celestial (hr or sidereal days)
τ (alternate)	Preemphasis-deemphasis time constant
τ_e	Satellite period, geocentric (sidereal days)
ϕ	Angle subtended by earth (degrees or radians)
ψ	Improvement factor due to preemphasis (dimensionless)
Ω_f	Faraday rotation angle (radians)

<u>Abbreviation</u>	<u>Constants</u>
r_e	Spherical earth mean radius (6371 km)
k	Boltzmann's constant (1.38×10^{-23} joules/ $^{\circ}$ K)
c_0	Velocity of light in free space (3×10^8 meters/sec)
μ_0	Permeability of free space (1.26×10^{-6} henry/meter)
ϵ_0	Permittivity of free space (8.85×10^{-12} farad/meter)
g_0	Acceleration due to gravity ($9.83 \text{ meters/sec}^2$)

Conversion Factors

1 kilometer	=	0.62 statute miles	=	0.54 nautical miles
1 statute mile	=	1.61 km		
1 meter	=	3.28 ft		
1 foot	=	0.305 meters		
1 sidereal day	=	23.935 hr		

APPENDIX H ORBIT PARAMETERS

A. ORBITAL PERIOD

Orbital period for circular orbits is given by:

$$\tau = \frac{2\pi r_o^{3/2}}{r_e g^{1/2}}, \quad \dots (H-1a)$$

or

$$\tau = 2.76 \times 10^{-6} r_o^{3/2}, \quad \dots (H-1b)$$

where τ = orbital period in hours, and r_o = orbit radius in kilometers. Orbit radius is measured from the center of the earth, which is assumed in all calculations to be a sphere of radius $r_e = 6370$ km. Surface acceleration due to gravity is $g = 983 \text{ cm/sec}^2$. Equation H-1b is represented graphically in Figure H-1.

B. GEOMETRIC FACTORS

Figure H-2 represents the geometry of a satellite at a distance r_o from the center of the earth. Certain trigonometric relationships are apparent:

$$\phi = 2 \sin^{-1} \frac{r_e}{r_o}, \text{ angle subtended by earth.} \quad \dots (H-2)$$

The optimum beamwidth of an antenna intended to provide maximum surface coverage is ϕ :

$$\theta = 2 \cos^{-1} \frac{r_e}{r_o}, \text{ earth central angle.} \quad \dots (H-3)$$

The equatorial longitude coverage span for equatorial orbits, and the maximum latitude span at the longitude of the equatorial sub-satellite point is θ :

Figure H-1. Orbit Parameters

Figure H-2. General Orbit Geometry

$$R = r_e \theta = 2 r_e \cos^{-1} \frac{r_e}{r_o}, \text{ for angles in radians.} \quad \dots (1), (H-4)$$

R is the maximum surface range over which two surface points can have the satellite in simultaneous view.

The maximum distance between the satellite and a visible ground station is the length of the tangent propagation path in Figure H-2, and is given by:

$$r = (r_o^2 - r_e^2)^{1/2} \quad \dots (H-5)$$

Equations H-2, H-4, and H-5 are also represented graphically in Figure H-1.

C. VISIBILITY INTERVAL

Assuming that the satellite has a circular orbit lying in the plane of the page, it has just become visible from Station B at the moment depicted in Figure H-2. If we assume the rotation of the earth is negligible during the interval of interest, the satellite will remain visible at Station B while the radius vector sweeps through an angle θ . The visibility time is thus:

$$\Delta t = \frac{\tau \theta}{2\pi} = \frac{\tau}{\pi} \cos^{-1} \frac{r_e}{r_o} \quad \dots (H-6)$$

if the earth is rotating with axis perpendicular to the page, the effective period of the satellite with respect to the rotating earth is:

$$\tau_e = \frac{\tau}{1 - \tau} \quad \dots (H-7)$$

where both τ_e and τ must be expressed in sidereal days. (τ is positive if the satellite rotates in the same direction as the earth.) Equation H-5 then becomes, for equatorial orbits and stations:

$$\Delta t = \frac{\tau}{\pi(1 - \tau)} \cos^{-1} \frac{r_e}{r_o} \quad \dots$$

For stations not in the plane of the satellite orbit, the situation is somewhat more complicated. Figure H-3 depicts such a case. The XY plane is taken as the orbital plane. Assuming a nonrotating earth, let C be the point of closest approach, lying on the x axis. Plane $\overline{MNPQ}$ is tangent to the earth at the observation station, which is located at latitude α with respect to the orbital plane. The satellite is visible as long as it remains above plane $\overline{MNPQ}$, which it does in the course of sweeping out an angle γ ,

$$\frac{\cos \gamma}{2} = \frac{\overline{OP}}{r_o} ,$$

but

$$\overline{OP} = \frac{r_e}{\cos \alpha} ,$$

therefore,

$$\gamma = 2 \cos^{-1} \left[\frac{r_e}{r_o \cos \alpha} \right] ,$$

and

$$\Delta t = \frac{\gamma}{2\pi} \tau = \frac{\tau}{\pi} \cos^{-1} \left[\frac{r_e}{r_o \cos \alpha} \right] . \quad \dots (2a), (H-9)$$

Similarly, for equatorial orbits of any period:

$$\Delta t = \frac{\tau}{\pi(1 - \tau)} \cos^{-1} \left[\frac{r_e}{r_o \cos \alpha} \right] , \quad \dots (2b), (H-10)$$

where Δt and τ are in sidereal days.

The general solution of visibility intervals, for arbitrary ground station locations, orbit periods and orbit inclinations, is an extremely complex and tedious problem not suitable for treatment here. Elliptical orbits have also been neglected in this treatment.

Figure H-3. Satellite Visibility from Ground Stations Out of Orbit Plane

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