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ADVANCED WEAPON SYSTEMS STUDY

PART III - ADVANCED MILITARY SATELLITES

VOLUME II

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ADVANCED WEAPON SYSTEMS STUDY

PART III - ADVANCED MILITARY SATELLITES

VOLUME II

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SPACE TECHNOLOGY LABORATORIES
P.O. Box 95001
Los Angeles 45, California

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CHAPTER 1

INTRODUCTION AND SUMMARY

Chapters 2 to 6 of this volume describe the results of an investigation of the feasibility of various applications of high-altitude satellites. Applications analyzed in detail in the course of this study include (1) communications relay; (2) relay of electronic or photographic reconnaissance data from low-altitude satellites; (3) early warning of ICBM attack utilizing infrared detection; (4) interception of communication signals for communications intelligence purposes; and (5) jamming of enemy radar and communications systems. The investigation of the feasibility of other applications, including bombing, direct electronic or photographic reconnaissance, navigation, and guidance, was not included in the present study because it appeared that other techniques for accomplishing the same objectives were more effective or much simpler and cheaper.

The use of a high-altitude satellite for communication relay purposes offers the possibility of eliminating the deficiencies of present long-range communication techniques. This investigation indicates that satellites in 24-hour orbits are best suited for this application. Furthermore, since the great majority of communications will occur between a relatively limited number of points on the earth's surface, and also since a less specialized system (which attempts to provide relay service between points anywhere within line-of-sight of the relay) is necessarily inefficient in its power utilization for high-density traffic, a system of maximum efficiency requires separate provision of high-traffic and low-traffic-density service. Thus, it has been determined that an initial global communication system providing primary coverage of both high- and low-traffic-density areas of the earth can be obtained with not more than eight 24-hour satellites, five of which are situated in equatorial orbits and the remaining three in polar orbits. Furthermore, if booster payload capabilities should prove sufficient, two of these satellites could be eliminated by combining appropriate low- and high-density relays into single satellites. If the desired system components are available at the time of development of this system, the equipment required for an initial global communication relay system would weigh from 75 to 100 pounds and would require a total power of about 1700 watts. Equipment for a global communication system of greater capabilities would entail an increase in weight and power requirements.

The study also includes an investigation of the feasibility of a number of interim communication relay systems which would not provide a global communication capability, but which nevertheless present a great improvement over present communication techniques. Although the weight and equipment required for these interim systems is not substantially less than for equipment of the global system, power requirements are only about one-eighth those of the global system equipment, thus permitting the use of a smaller, more immediately available power supply and less severe weight restrictions on the other components because of weight saved in the vehicle power supply. Moreover, the resultant narrowing of bandwidth simplifies the ground stations such that presently available equipment, properly modified, will suffice, whereas the global system requires a sizeable development program in ground multiplexing equipment if the full bandwidth capability is to be utilized.

Investigation was made of the feasibility of using a satellite in a 24-hour equatorial orbit to relay electronic or photographic data obtained by a low-altitude satellite. This relay would eliminate the necessity for storing such data in the low-altitude satellite, and would thus simplify the problem of data recovery. It has been found that one 24-hour satellite will permit direct relay of such data to the North American continent, while two such satellites will permit direct relay to the United States proper. Weight and power requirements for the high-altitude reconnaissance data relay would be similar to those given above for the initial global communication relay equipment. This application would permit a substantial increase in the over-all capabilities of a low-altitude reconnaissance system.

The feasibility of an ICBM early warning system utilizing detection of ICBM rocket flames by an infrared detection system in a 24-hour equatorial satellite has been investigated. This system has been compared with the

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low-altitude (1000 miles) infrared early warning system presently planned as a part of the 117L program. In contradistinction to the low-altitude system, the 24-hour satellite would search for rocket firings above the horizon, using a space background, since from this altitude it does not presently appear feasible to effect a detection against the infrared background emanating from the earth and cloud cover. The 24-hour satellites provide the advantage that continuous rather than statistical coverage of the USSR is provided. Moreover, for similar detection capability (coverage of the USSR above 55° N latitude; seven detections with a 14-db signal-to-noise ratio), only seven satellites are required in comparison with 20 for the low-altitude system. Balanced against this advantage is the relative complexity and difficulty of establishing these satellites in orbit.

The derivation of maximum communication intelligence from intercepted communication signals requires continuous reception of such signals. Thus, the use of a 24-hour satellite for this purpose, because its position is stationary with respect to the earth's surface, would permit such continuous reception instead of the intermittent interception usually obtained by present techniques. However, although sufficient sensitivity can be provided to intercept many signals, directional discrimination is so poor that a high probability exists of mutual interference. If the probability of mutual interference is made sufficiently small by decreasing the system sensitivity, the number of signals which can be intercepted becomes extremely small. Thus, the feasibility of a communication interception system cannot be determined on technical grounds but rather on the basis of the value attributed to whatever information can be received under conditions when mutual interference is very probably and directional information is lacking.

The use of a 24-hour satellite for jamming enemy communications and radar systems presents the possibility of jamming from an unexpected source in a previously unknown location. However, although a single frequency could be jammed, the jamming of an entire band in which the operating frequency of a communications or radar system might be located requires power which is one to two orders of magnitude above that which seems feasible in the relatively near future. Therefore, it may be concluded that jamming is not a feasible application of a high-altitude satellite, except possibly for any minor advantage which might be derived from jamming of a narrow frequency band.

CHAPTER 2

COMMUNICATION RELAY SERVICE

2.1 DISCUSSION OF PRESENT COMMUNICATION CAPABILITIES

The deficiencies of present-day communication methods become increasingly important as the distance over which communication must be effected increases. For purposes of this discussion, long-range communication will be defined as communication over ranges exceeding 300 or 400 miles. However, if the communication stations are in line-of-sight of each other, distance plays a negligible role, and a satellite-borne communications relay system presents a unique opportunity for overcoming the deficiencies of present long-range communications systems since it can relay by line-of-sight between two or more widely spaced ground stations.

Communication to such long ranges is presently effected by means of radio transmissions and transmissions over wire-line circuits. However, wire-line circuits require a direct physical connection between both ends of a circuit. Since such direct connections are difficult to establish for certain classes of service and are relatively easy to break in most other circumstances, wire-line circuits have a relatively limited usefulness outside of the Zone of Interior (ZI) (the United States proper). Even in the ZI and in other applications where direct connections can be established, such as between continents, wire-line circuits suffer from the fact that each line requires a large number of repeater stations to attain a long-range capability. In addition, although almost any transmission performance is possible, in theory, if repeater spacing is very short and if very heavy cable is used, cost and speed of installation combine with cost of maintenance and over-all system complexity to limit impractice available wire-line circuits to relatively low bandwidths (a few tens of kilocycles to a few megacycles are standard). Thus wire-line circuits tend to require a multiplicity of expensive, cumbersome equipment to provide a long-range, large-bandwidth capability even when the direct physical connection between stations can be established.

Radio communication over long ranges can be established by using transmissions in the low-frequency or very-low-frequency ranges (below

300 kilocycles), by standard high-frequency transmissions in the 3- to 30-megacycle range, or by utilizing ionospheric or meteoric scatter mechanisms in the VHF range above 30 megacycles. Medium frequencies (300 kilocycles to 3 megacycles) may also be used for long-range communication at night, but extremely high ionospheric absorption restricts such transmissions to short ranges in the daytime. For this reason, the medium-frequency range will not be considered further in the following discussion. Long-range communication may be effected also by utilizing a series of short-range links such as the microwave relay links which are in common use in the ZI and in certain areas overseas. However, this technique also requires a multiplicity of equipment which tends to decrease the over-all system reliability as well as to increase the problem of system maintenance and, of course, its over-all cost.

The attenuation of signals transmitted in the low- and very-low-frequency bands is quite small, and diurnal and seasonal variations are relatively small in comparison with those observed at high frequencies. Thus, it would seem that propagation at these frequencies would provide an efficient mechanism for transfer of information. Unfortunately, however, the propagation of atmospheric noise from its points of origin to the vicinity of a receiver is equally efficient, so that noise levels in these bands are extremely high and the required transmitted powers are correspondingly large. Furthermore, because of the large wavelengths of such transmissions, it is almost impossible in practice to construct an antenna of sufficient length to be more than a very small fraction of a wavelength. Thus, LF and VLF antennas are notoriously inefficient as compared with antennas for higher frequencies, and therefore the power required to obtain any reasonable bandwidth capability makes LF and VLF completely impractical. Finally, even if the power were available, an LF or VLF antenna having any reasonable efficiency also has such a high Q that the over-all system is limited to a bandwidth of a few tens of cycles per second, certainly not the type of bandwidth capability desired for a military long-range communication system.

Under normal conditions, signals transmitted in the high-frequency band will propagate to long ranges with quite high efficiency. Unfortunately, high-frequency transmissions are subject to severe disturbances caused by solar flares and various other solar emissions. Most of the absorption experienced by a high-frequency wave reflected from the ionosphere occurs in the D-region of the ionosphere, which is located below the point at which the wave is reflected. During a solar flare, the ultraviolet radiation emitted by the sun causes an abrupt increase in the ionization of the ionosphere D-region, with a correspondingly sharp, and very large, increase in the absorption of high-frequency transmissions. This effect is observed over all of the sunlit hemisphere of the earth, and the only way to maintain communication during such a fadeout is to transmit with greatly increased power. Experimental data indicate, however, that an increase in transmitted power of as much as 80 to 90 db may occasionally be required, a completely impractical value when normal transmitter powers are of the order of kilowatts.

Additional high-frequency absorption phenomena are observed in the polar regions of the earth. The sun is continually emitting charged particles, and those incident upon the atmosphere of the earth are guided by the earth's magnetic field to the polar regions. Here these particles cause an increase in the ionization of the lower ionosphere, resulting in a consequent increase in the absorption of high-frequency transmission. During a solar flare, the rate of emission of charged particles from the sun is vastly increased, and a corresponding increase in absorption or "polar blackout" is observed on high-frequency transmissions. Such polar blackouts have been observed to continue as long as several days and, as with fadeout caused by solar flares, can be overcome only by transmitting with very much increased power.

Finally, the high-frequency range is used throughout the world for normal long-range transmission, with the result that the spectrum in the 3- to 30-megacycle frequency range is extremely crowded. Thus, it would not be practical to expect that bandwidths of the order of megacycles could be made available for services such as would be possible with a satellite-borne communication relay system.

The last long-range propagation mechanism to be considered in this section is that of VHF ionospheric and meteoric scatter. It has been found recently that radio waves in the lower VHF range will be scattered due to the turbulent structure of the lower part of the ionosphere. Also, a very large number of meteors impinge upon the atmosphere of the earth each day, which, although not visible to the naked eye, produce trails of ionization which are capable of scattering radiation in the lower VHF range. Because of the altitude at which such scattering takes place, however, the maximum range over which such propagation can be effected is limited to about 1200 to 1400 miles.

Although longer ranges can be obtained with such scatter links by using several links in series, such a multiplicity of equipment has the same disadvantages that were discussed above in connection with microwave relay links. Also, because of the inefficiency of the scattering process, this type of propagation requires extremely high transmitter power, high gain, and carefully oriented transmitting and receiving antennas. Finally, these scattering mechanisms are such that bandwidths no higher than a few kilocycles can be realized even if special modulation techniques are used. Thus, VHF ionospheric and meteoric scatter provide a limited-range communication capability at the expense of low efficiency and limited bandwidth, and do not seem to warrant more than passing consideration as a possibility for providing the type of long-range communication service that could be rendered by a satellite-borne relay system.

It is evident from the foregoing discussion that all present-day communication methods suffer from one or more deficiencies which render them far less than ideal for transmission of information over long ranges. In fact, a relatively small number of submarine coaxial cables and high-frequency radio channels, with sharply limited over-all bandwidth capabilities, are the only means existing today of obtaining long-range intercontinental communications. On the other hand, the use of a satellite-borne communication relay system to effect long-range transmission of information seems to hold great promise for eliminating the deficiencies in present techniques. The investigation of the feasibility of such a satellite-borne communication relay system has formed a major part of the present study, and such a system is discussed in detail in the following sections.

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2.2 TYPES OF COMMUNICATION SERVICES AND RECOMMENDED ORBITS

2.2.1 High-Density Service

The natural tendency, when considering the service to be provided by a satellite-borne communication relay system, is to require that communication be possible between any two points within the direct line-of-sight of the relay. However, careful consideration shows that such a procedure results in extremely inefficient use of the power radiated by the satellite. A large proportion of the area of the earth which will be seen by any satellite is ocean, an area in which the relative density of communication sources may be expected to be fairly low. On the other hand, the majority of the sources of communication will be located on the land areas of the earth--in fact, upon a relatively small fraction of the land areas of the earth--and the relative density of these communication sources will be extremely high. Thus, efficient use of the capabilities of satellite-borne communication relay systems can be obtained by providing high-traffic-density (or large-bandwidth) capabilities between restricted portions of the surface of the earth, and relatively low-traffic-density capabilities to the remainder.

This conclusion is graphically illustrated by Figures 2-1, 2-2, and 2-3. Figure 2-1 is a Mercator projection of the earth with those areas from which originate almost all of the communication signals of importance to U.S. military forces indicated by heavy shading. Figures 2-2 and 2-3 are pictures of a globe taken from a distance equivalent to the radius of a 24-hour equatorial satellite orbit and aligned with the meridians corresponding to longitudes 170° W and 30°W, respectively. (The reasons for recommending such orbits are discussed in a later paragraph.) Again, those sources of the great majority of communication signals of interest to this government are indicated by black outlines.

From these figures, it may be seen that two types of high-density traffic exist which must be handled by a communication relay system. First, a great amount of traffic will exist between various points in the ZI which otherwise would have to be handled in its entirety by some presently available long-range communication method. For example, communication would be

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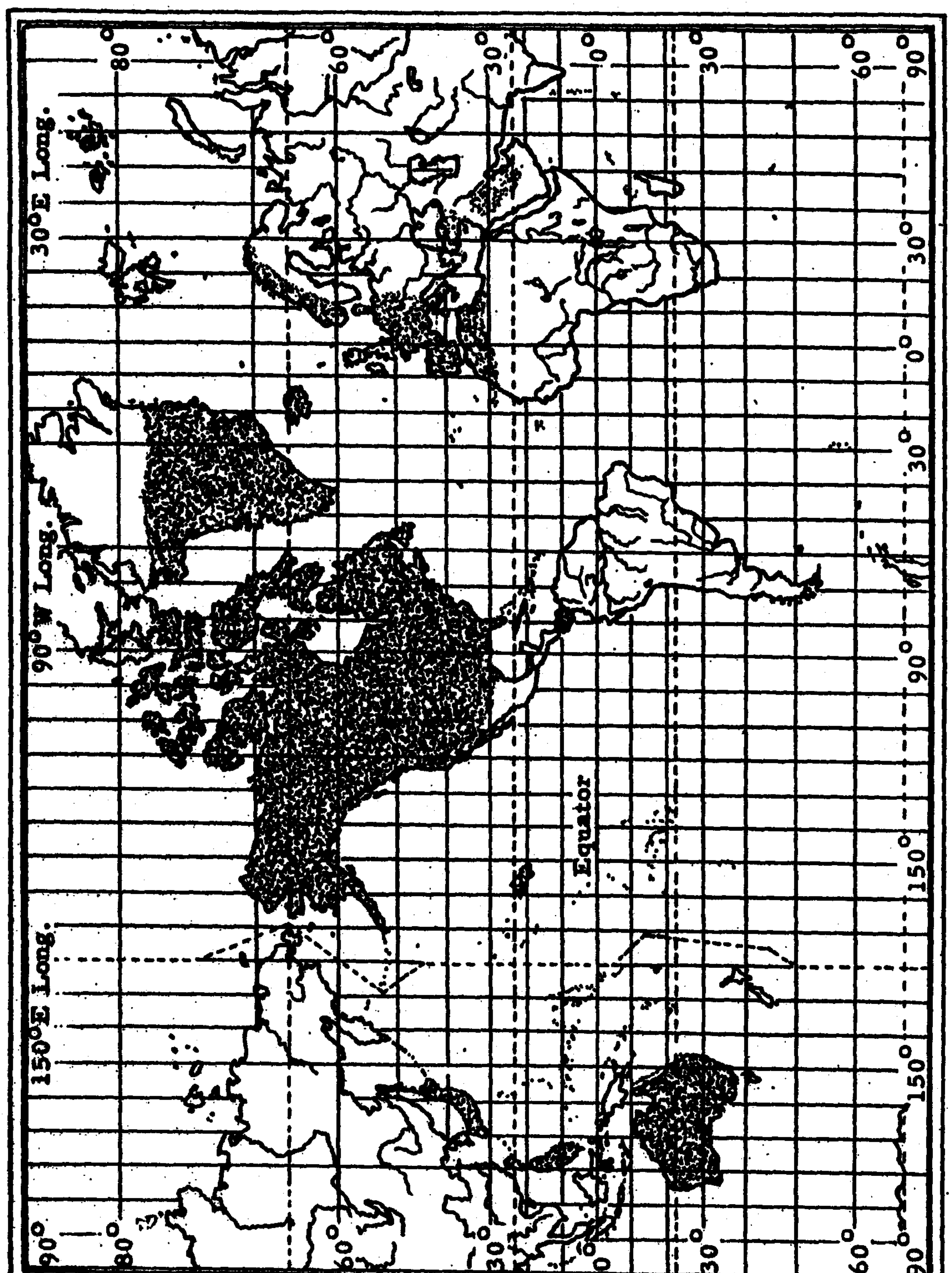

Figure 2-1. Areas (shaded) Originating Great Majority of Communications of Military Interest.

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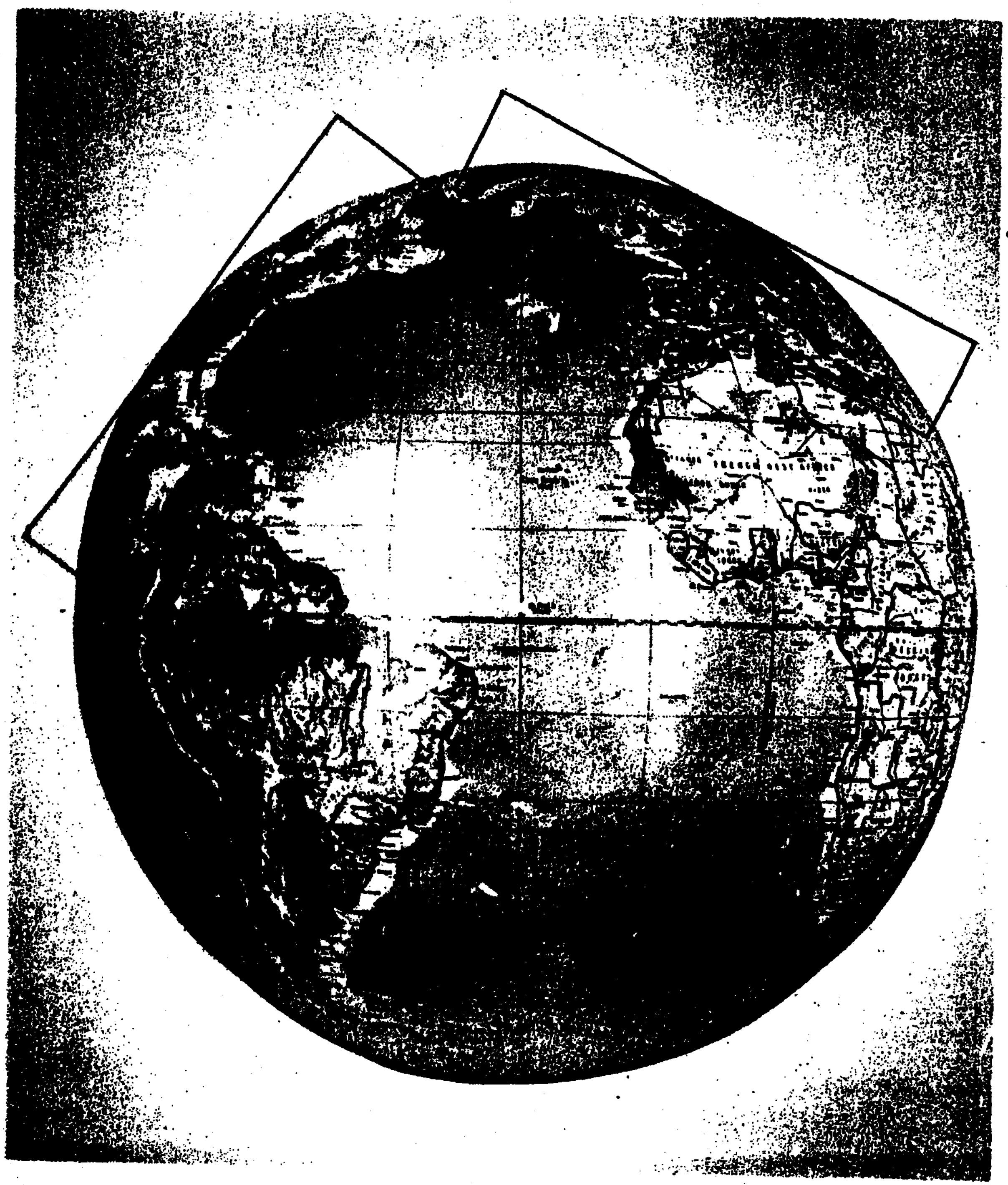

Figure 2-2. Earth as Seen from Satellite in 24-Hour Orbit at Latitude 30°W (coverage areas outlined).

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Figure 2-3. Earth as Seen from Satellite in 24-Hour Orbit at Latitude 170°W (coverage areas outlined).

desired between Washington and Omaha, between Washington and Colorado Springs, between Washington and various points on the West Coast, and so on. Furthermore, because of the extremely high-density traffic which may be expected for this type of service, it seems reasonable to allocate the complete capacity (if necessary) of a relay system carried by a 24-hour satellite to such ZI communications. The second type of high-density traffic, which may be expected from an inspection of Figures 2-1, 2-2, and 2-3, is traffic between North America and Asia and between North America-Greenland and Europe. As shown in Figures 2-2 and 2-3, all of the areas of interest indicated in Figure 2-1 can be seen from one or the other of two satellites positioned in 24-hour equatorial orbits above longitudes 170°W and 30°W, and, as outlined in Figures 2-2 and 2-3, only relatively small parts of the visible portion of the earth would have to receive radiated power from the satellite in order to provide the desired coverage. Of course, these are nominal coverage areas and may be modified to fit specific requirements.

2.2.2 Advantages of 24-Hour Orbits* for High-Density Service

It will be noted that the foregoing discussion assumes the use of satellites in 24-hour equatorial orbits. It might be argued that, by utilizing orbits of smaller radius, either smaller boosters can be used or larger payloads can be placed in orbit. It is necessary to weigh such possible advantages against the system complexity brought about by not using the 24-hour system. However, as shown in Volume 2, Chapter 1, the payload which can be put into an orbit is relatively insensitive to orbit altitude for orbits having a radius in excess of 10,000 miles. Therefore, if there is to be any substantial increase in payload capability (or reduction in booster size), it must be for satellites having altitudes of less than 10,000 miles.

The primary justification for recommending 24-hour equatorial satellites for ZI and intercontinental communication relay lies in two basic considerations. First, the use of 24-hour equatorial satellite orbits permits

*Actually the period of one revolution is one sidereal day or 23 hours, 56 minutes, 4.09 seconds which is the period of rotation of the earth, rather than the 24-hour interval between successive passages of the sun over a given meridian.

the desired coverage for high-density traffic with three satellites, whereas the use of any other type of orbit cannot decrease this number and will, in general, require a substantially greater number if an appreciable reduction in satellite altitude is to be effected. Figure 2-4 illustrates the particular case where the satellites are evenly spaced in an equatorial orbit. This figure shows the maximum latitude of a ground station at which continuous contact with at least one of the satellites can be provided, as a function of the altitude of the orbit, and with the number of satellites in the orbit being used as a parameter. As can be seen from the figure, for example, continuous coverage of a latitude of 65° (Alaska, Iceland, and Southern Greenland), cannot be provided by any number of satellites having altitudes less than 5500 miles, while even at an altitude of 10,000 miles, four satellites are still necessary.

The minimum number of nonequatorial satellites required to provide continuous contact with the areas to be covered is extremely difficult to determine as a function of satellite altitude because of the very large number of schemes which might be considered. However, regardless of the disposition of the satellites and the inclination of their orbits, it is quite generally true that no fewer than three low-altitude satellites, and in most cases a substantially larger number, are required for continuous coverage of the area of the earth within the latitudes of interest.

It should be noted that if low-altitude satellites are used and if the sending and receiving stations are far apart, then, even if both sending and receiving stations are each within line-of-sight of a satellite, both will not be within the line-of-sight of the same satellite. This will require relaying the message from satellite to satellite, possibly using intermediate ground stations to effect the message transfer. Direct satellite-to-satellite transmission involves either the use of much larger satellite antennas or else (assuming fixed power) the loss of bandwidth. The use of intermediate ground stations permits transmission with large bandwidths because large antennas can be used at the ground stations; however, such a system suffers from the cost and reliability penalties of requiring additional repeater stations all with tracking antennas. Furthermore, because of the rotation of the

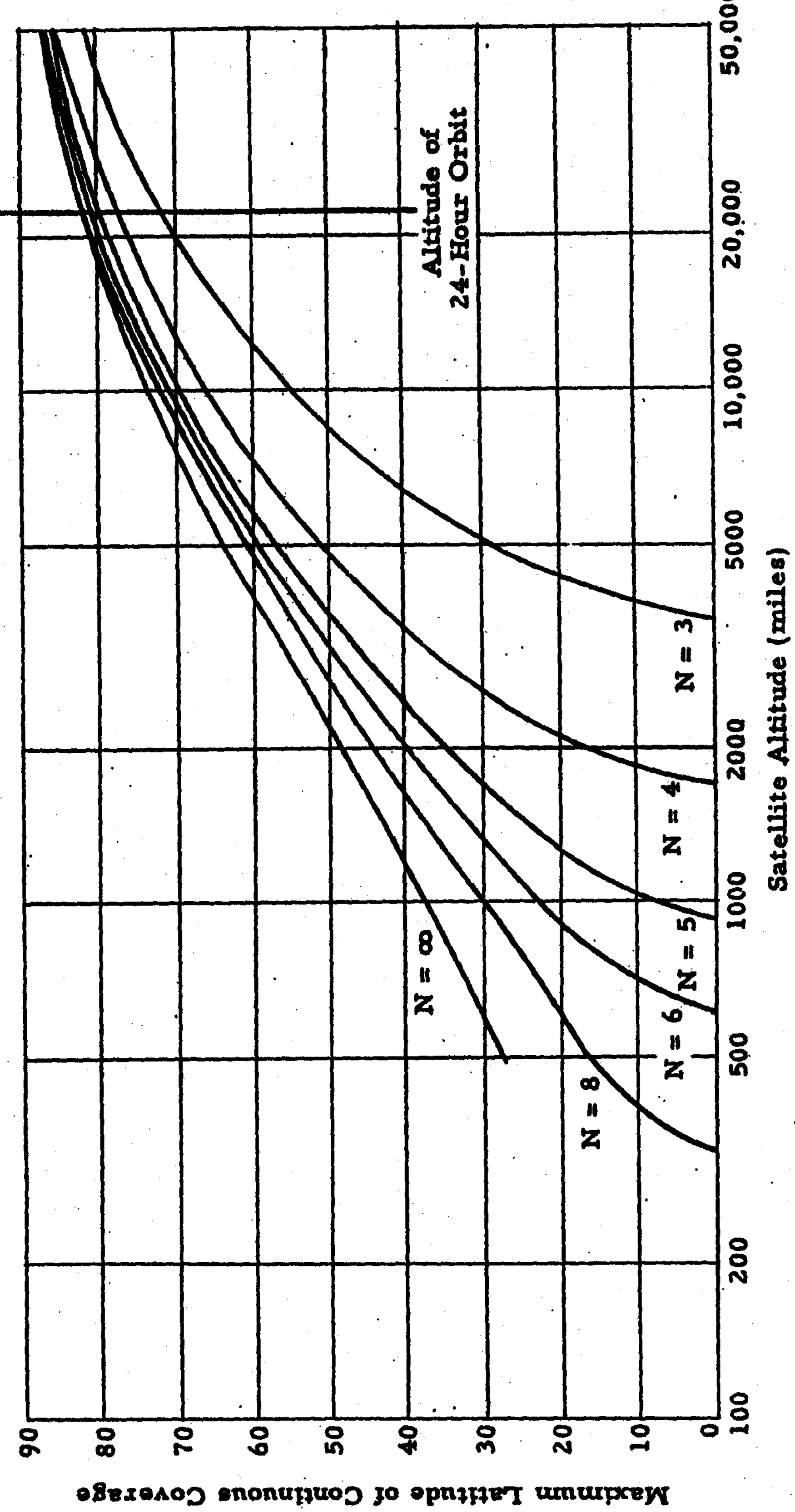

Figure 2-4. Maximum Latitude of Continuous Coverage as a Function of Satellite Altitude for N Equatorial Satellites.

earth, the satellites will cover not only the high-density communications area but will spend much of their time over ocean areas where the necessary relay stations cannot be provided.

Clearly, to minimize the system complexity and also to allow the full bandwidth capability, it is more satisfactory to have the same satellite within line-of-sight of both the sending and receiving stations. However, this can be done only if the satellite is above some minimum altitude. As an example, if one wishes to transmit from the West Coast of the United States to Japan, a satellite at the midpoint of the Great Circle arc connecting these two locations must be at an altitude of about 900 miles to be within the line-of-sight of both ground stations. If the satellite is to retain contact with both sending and receiving stations for a significant segment of its orbit, or if it is to maintain contact when it is not on the Great Circle connecting the two stations, then the altitude must be much higher. For example, in order to maintain contact with both San Francisco and Tokyo for an arc of 30° in longitude (which would require a total of 12 such satellites), an equatorial satellite must be at an altitude of over 7000 miles above the surface of the earth. Furthermore, it may be shown that for San Francisco-Tokyo communication no fewer than five equatorial satellites are required for any altitude, even at infinity, with the single exception of the 24-hour equatorial satellite (in which case only one is required).

The second basic consideration which argues for the use of a 24-hour equatorial satellite is that only such orbits provide satellites stationary with respect to the surface of the earth. Thus, the necessity for antenna tracking is eliminated both on the ground and in the satellite. This permits the use of large antennas both in the satellite and on the ground, and consequently yields an increased communication relay capability with the same amount of transmitted power. Moreover, having fixed antennas permits a substantial simplification of the instrumentation of the system since there is no acquisition problem and no scanning program is required. Since reliability is of paramount importance in a communication relay satellite where maintenance will be impossible, such a simplification in satellite equipment is extremely valuable.

It should be noted that a high-altitude satellite need not require any more power than a low-altitude satellite, providing the cross-sectional area at the earth of the illuminating beam is equal in the two cases. The essential point is that a given area, namely the high-traffic-density area, must be covered and, since the area covered is independent of the satellite height, there need be no power loss due to altitude. If any high-altitude satellite other than a 24-hour satellite is used and if a narrow beam is used to illuminate only the high-density regions and thereby save power, then the satellite antenna must be rotated so that it continues to illuminate the area of interest. This not only leads to additional instrumentation complexities in the satellite but complicates the problem of attitude stabilization because of the reaction torques resulting from the antenna rotation.

The discussion in the foregoing paragraphs indicates that, if the desired ZI and intercontinental communication relay capabilities can be provided by satellites positioned in 24-hour equatorial orbits, such capabilities will be obtained with a system requiring no antenna tracking and the number of satellites required will be at a minimum. The only question remaining is whether or not it is feasible to launch the necessary payloads into 24-hour orbits using boosters which will have early availability. The weights required for the satellite-borne communication system are examined in Sections 2.6 through 2.8 of this chapter. In Volume 2, Chapter 5, they are combined with the other system weights (power supply, guidance, etc.) and compared with the payload capabilities of current boosters. It is there found that even the Thor booster with some modification can place a useful payload into a 24-hour orbit. This feasibility, coupled with the many desirable aspects from the communications system standpoint of 24-hour equatorial orbits, argues very strongly for their use to provide high-traffic-density communication.

2.2.3 Low-Density Polar Service

Since the traffic density from portions of the surface of the earth, other than those specifically designated in Figures 2-1 through 2-3, is expected to be low, a much smaller bandwidth capability will be required of a system providing such service than in the case discussed above. This advantage is offset by the fact that the transmitted power from the satellite must be radiated to a substantially larger area. In addition, communication must be established with aircraft (as well as ships and ground-based stations), so the dimensions (and consequently gain) of the aircraft-borne receiver antennas are substantially less than those which can be used by a ground-based installation.

From the discussion in Section 2.1 of the deficiencies in presently available long-range communication methods, it may be inferred that a much greater problem exists in communicating with stations or signal sources in the polar regions than with stations located in temperate or tropical regions of the earth. But communication to and from points in the polar regions is extremely important to the military forces of the United States. An inspection of a globe will show immediately that any attack upon this country probably would be carried out across the polar regions, as would any retaliatory attack which the United States might dispatch. For this reason a large number of installations are maintained by this country in the polar regions of Canada, Alaska, and Greenland, and a large amount of training, reconnaissance, and other similar activities is carried out on and over these areas. Thus, while the importance of establishing communication to points on or above the ocean areas of the earth should not be minimized, it would seem from the above considerations that communication relay service to the polar regions should be given high priority.

The polar regions to which communication relay service should be established may be determined from Figure 2-5. This figure shows, on a polar stereographic projection of the Northern Hemisphere, the auroral absorption region of the northern latitudes. Although auroral effects can extend beyond this region, its low-latitude limit does provide a reasonably accurate boundary for the polar areas where the most severe effects limiting normal long-range communication methods may be expected to occur. Therefore, the area bounded by the low-latitude limit of the shaded region shown in Figure 2-5 will be defined as the minimum area for which a communication relay capability must be established by a polar communication relay system. However, it would be desirable to have this capability include a capability for effecting

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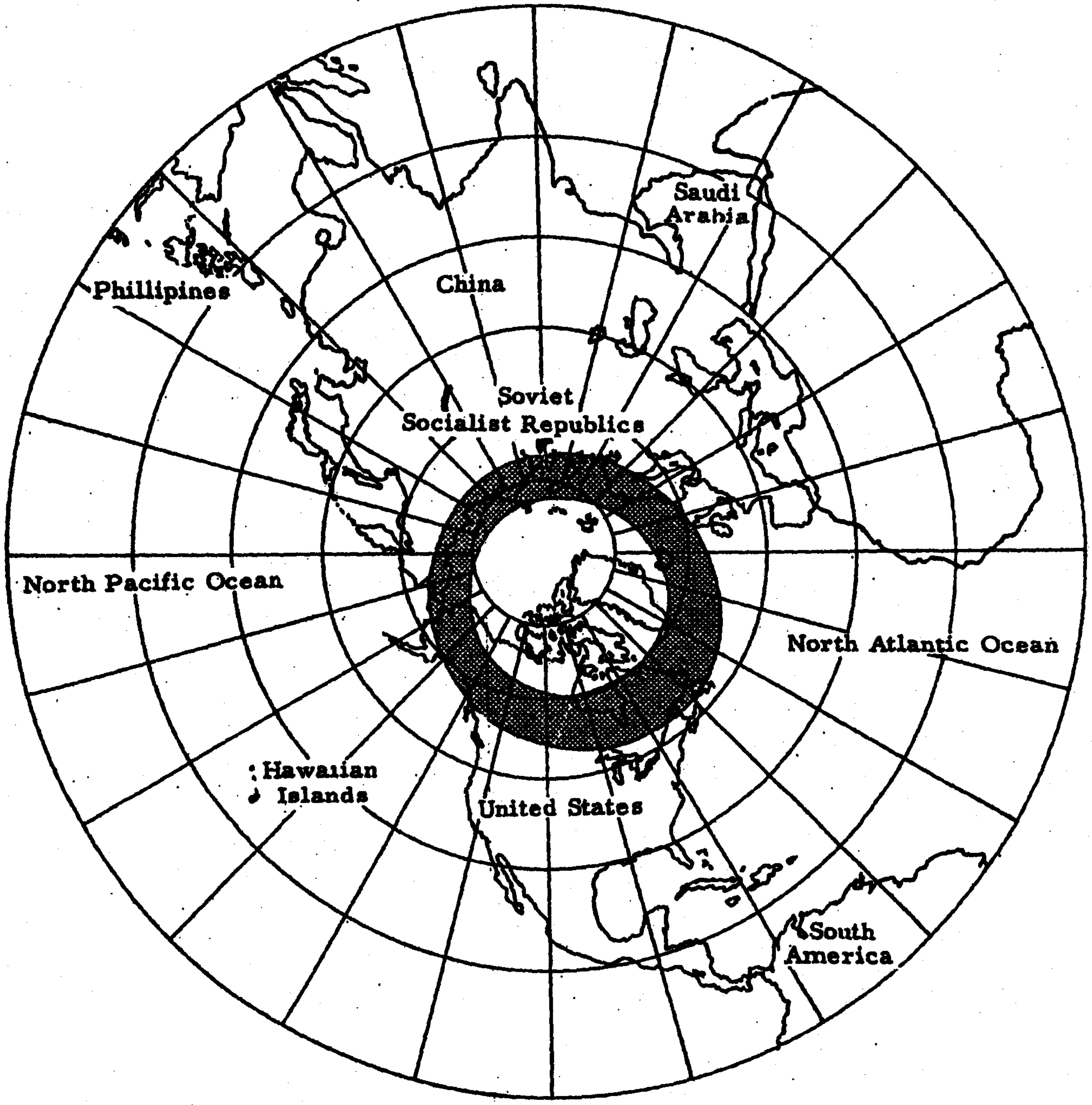

Figure 2-5. Auroral Absorption Region of Northern Hemisphere.

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direct recall from the United States proper of missions launched over the polar regions. For this reason, the orbits recommended in the following paragraphs for a polar communication relay system have been determined so that this desired capability can be provided.

Communication relay service to these polar areas must be established by using satellites in nonequatorial orbits, since no satellite at any reasonable altitude in an equatorial orbit can include latitude 90°N within its line-of-sight. Such nonequatorial orbits, unfortunately, do not permit establishment of a satellite stationary above a given point on the surface of the earth. Thus, more than one satellite will be required to provide the desired coverage even though only one satellite may be used for relay purposes at any given time.

2.2.4 Advantages of 24-Hour Orbits for Polar Service

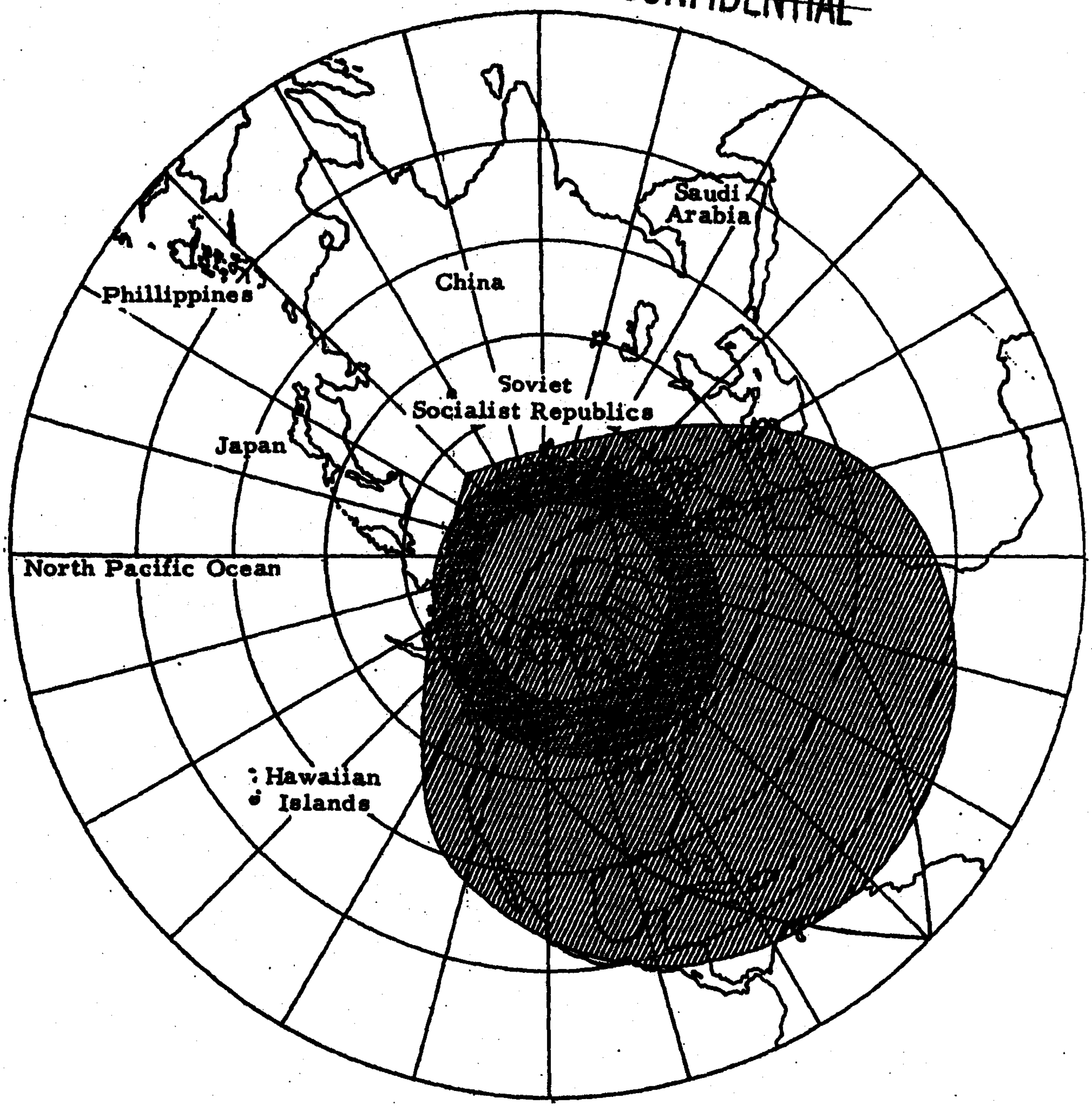
Although many different classes of orbits may be postulated which would provide the desired polar communication relay capability, 24-hour polar orbits (in which the orbital plane contains the axis of the earth) possess certain advantages. The first advantage, of course, is the fact that the satellite will pass over the same point on the surface of the earth each time it passes a given point in its orbit. This substantially reduces the antenna tracking problems which have been introduced unavoidably by the necessity of using nonequatorial orbits. In a system having mobile terminals such as aircraft, ships, etc., this becomes an important factor.

A second advantage of 24-hour polar orbits for a polar communication relay system arises from the fact that the path of the satellite relative to the surface of the earth is what may be termed a figure-eight path. A 24-hour satellite crossing the equator in a northerly direction will cross the North Pole after the earth has rotated by 90 degrees and will cross the equator again (going south) after the earth has rotated 180 degrees. Since the satellite crosses the same point on the equator both in its northbound and southbound path, the resultant path relative to the surface of the earth is essentially a figure eight, as stated above.

The portion of such a path lying in the Northern Hemisphere is shown in Figure 2-6, where the point at which the orbit crosses the equator has been chosen as 60°W longitude. If three satellites are established in 24-hour polar orbits such that the path of each satellite relative to the surface of the earth coincides with the path shown in Figure 2-6, but with their equatorial crossing time 8 hours apart (this requires the orbital planes to be separated by 120°), considerations of symmetry will show that at least one satellite is at or above 30°N latitude at all times. As shown also in Figure 2-6, the area continuously within line-of-sight of such a satellite when it is above 30°N latitude includes both the desired polar areas and the entire United States. Furthermore, inspection will show that the point at which the satellite crosses the equator may vary anywhere from about 60° to 90°W longtitude without altering this conclusion. Thus, the desired polar communication relay service could be established between any point in the United States and the desired polar coverage areas through the use of three satellites properly established in 24-hour polar orbits.

Finally, it may be shown that three satellites are the minimum required to provide continuous relay service between desired polar areas and the United States, regardless of the type of orbit chosen.* For example, four 24-hour satellites would be required if their orbital planes coincide instead of being separated as in the foregoing discussion, and any substantial decrease in satellite altitude would necessitate the use of an even greater number. Similarly, considerations of geometrical symmetry show that the use of nonpolar orbits

*There is an alternative which appears feasible at first sight, the use of 24-hour satellites in a highly elliptic orbit with apogee at the North Pole and perigee at the South Pole. This results in the satellite spending twelve hours within an angle of 14.4 degrees from the North Pole. By having two such satellites 12 hours out of phase, the communications between the polar regions of the earth and the United States can presumably be accomplished. However, the difficulty with this scheme is that the oblateness of the earth causes a rotation of the line of apsides, that is the major axis rotates within the plane of motion so that an orbit which originally had its apogee at the North Pole would later have its apogee at lower latitudes. After the apogee had moved a sufficient distance from the North Pole, the satellites would no longer spend 12 hours in the immediate vicinity of the pole; moreover, the diurnal tracking problem would not repeat from day to day. This is not compatible with the simple antenna systems which are required for aircraft installation.



Area of continuous coverage

Region of high auroral absorption under normal conditions

Figure 2-6. Area Continuously with Line-of-Sight of 24-Hour Polar Satellite [redacted] N Latitude.

cannot reduce the required number of satellites below three, regardless of the type of orbit or orbital altitude chosen. Thus, the use of 24-hour polar satellites, in orbits chosen to ensure that each satellite traces the same path relative to the surface of the earth, permits obtaining the desired polar coverage with a minimum number of satellites and with the advantage of a substantial reduction in the antenna tracking problems. For these reasons, the feasibility of a polar communication relay system using such orbits, as determined in the course of this investigation and described in later sections of this report, has caused such orbits to be recommended for this purpose.

2.2.5 Other Low-Density Service

The final communication relay capability to be considered in detail in this report is that of providing low-traffic-density communication relay service to and from the ocean areas and less important land areas of the earth. One of the most important communication requirements of the Strategic Air Command today is the requirement for a recall capability to aircraft over any portion of the earth. Means for satisfying this requirement do not exist today, but certainly could be provided by satellite-borne communication relay facilities.

The polar orbits discussed in the preceding section, and recommended for use in providing polar communication relay service, possess as additional important property in that they can provide communication relay coverage of much of the ocean and less important land areas of the earth. Both shaded and cross-hatched areas outlined in Figure 2-7 are areas in the Northern Hemisphere continously within line-of-sight of at least one of the three 24-hour polar satellites positioned in the polar orbits as previously described. (The continuous-coverage area in the Southern Hemisphere will be symmetric about the equator with that shown for the Northern Hemisphere.) These polar satellites can provide continuous coverage of the entire Atlantic Ocean with an exception of the relatively small segment off the extreme southwest tip of Africa, and in addition can provide continuous coverage of a fairly substantial portion of the Pacific Ocean as well.

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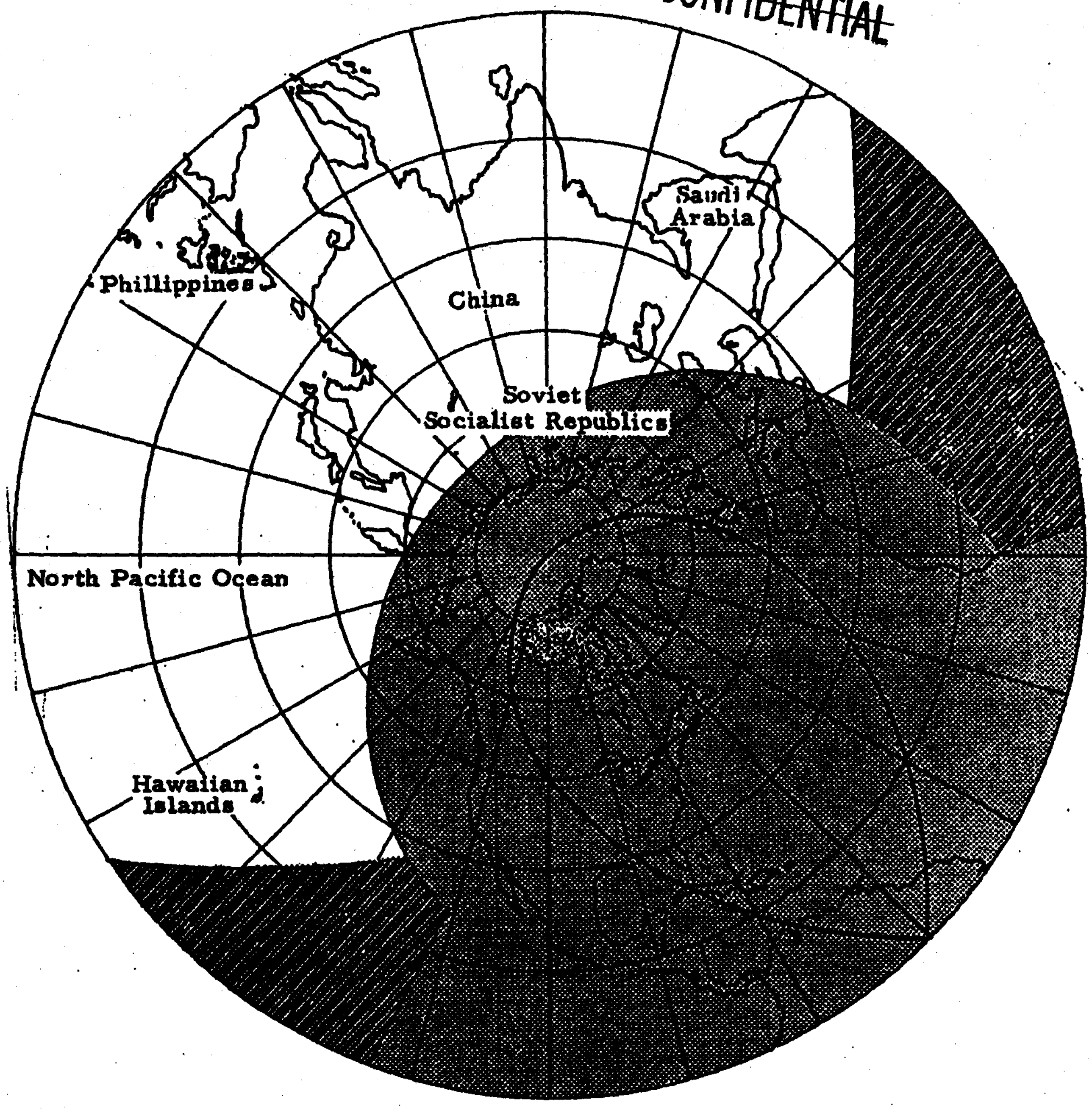

Area within continuous line-of-sight of recommended polar satellites when they are also within line-of-sight of central U. S. A.

Additional area within continuous line-of-sight of recommended polar satellites.

Figure 2-7. Continuous Coverage Areas for Low-Density Polar Relay Satellites.

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[redacted]

The cross-hatched areas in Figure 2-7 represent those portions of the continuous-coverage area in the Northern Hemisphere for which continuous relay service cannot be provided from the central United States using the recommended polar satellites. However, such satellites will permit continuous and direct relay service between the central United States and any part of the shaded area including the North Atlantic Ocean (except the Gulf of Guinea) as well as much of Europe, North Africa, and Sibèria. In addition, service to much of the South Atlantic and South America (not shown in the figure) is provided.

The polar orbits do not cover large portions of the Pacific Ocean. But, as may be seen from an inspection of Figure 2-3, continuous coverage of this area may be obtained from a single equatorial satellite positioned above about latitude 170°W, and such a satellite can provide continuous relay service from any point in this area to the central United States.

The combination of three polar satellites and the low-density traffic satellite over the Pacific would provide communications between aircraft (or ships) in the polar regions or over the North Atlantic and Pacific Oceans. An extension of coverage to the Asian and African continents and the Indian Ocean could be provided by a 24-hour equatorial satellite over about 65°E longitude, but the satellite could not communicate directly with the United States. It could, however, communicate with either a European base (say London) or Japan (or the Philippines) for relay to the United States via the high-density intercontinental satellite links. This relayed information would use only a very small fraction of the channel capacity of the high-density link.

2.2.6 Summary

The geometrical considerations discussed in this and the foregoing section indicate that primary coverage of both high-and low-traffic-density areas of the earth could be obtained with the following 24-hour satellites:

High-Density Traffic

ZI to Europe	Equatorial, Longitude	= 30° W
ZI to Asia	Equatorial, Longitude	= 170° W
ZI Internal	Equatorial, Longitude	= 145° W to 130° W

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Low-Density Traffic to Aircraft, etc.

Polar Region, Siberia, North America, North Atlantic, Europe, North Africa, and portions of North and South Pacific Ocean, South Atlantic Ocean, and South America

	3 Polar Satellites crossing equator at 60°W
Pacific Area	1 Equatorial, Longitude ≅ 170°W
Asia, Africa and Indian Ocean	1 Equatorial, Longitude ≅ 65°E

It should be noted that, on a purely geographical basis, the 24-hour satellites used for high-density intercontinental relay service could be used also to provide low-density service to the Pacific Ocean and Atlantic Ocean areas. Furthermore, an equatorial satellite placed at 40°W could perform both the ZI service and partial ZI-to-Europe service. Therefore, if payload capabilities of the satellite vehicle permit multiple functions to be carried out, then fewer satellites will be required. This possibility will be discussed in somewhat more detail in a later section.

The foregoing discussion of areas of coverage has neglected the increase in coverage which can be attained by use of the refraction of radio waves in the atmosphere. The effect of refraction for a normal atmosphere is to increase the coverage by about 1 degree, or 60 nautical miles. Since this is a relatively small amount compared to the coverage of interest, and since it will vary with variations in the refractive index of the atmosphere, this effect has been omitted in all foregoing and subsequent calculations.

2.3 TRANSMISSION CONSIDERATIONS

Having determined recommended satellite orbits and positions from the geometrical considerations of the foregoing sections, the power requirements of a communication relay system utilizing such satellites must be established. The factors which determine such power requirements are discussed in the following sections, and required transmitter powers are obtained for each type of communication relay service discussed above.

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2.3.1 Basic Relationships

The power at the input terminals of a receiver at a distance R from the transmitter, is given by the expression

$$P_r = \frac{P_t G_t \eta_t}{4\pi R^2} A_r \eta_r , \qquad (2.1)$$

where P_t is the transmitter power, G_t is the gain of the transmitting antenna in the direction of the receiver, and η_t is the radiation efficiency of the transmitting antenna. A_r is the receiving aperture (or effective receiving area) of the receiving antenna and η_r is the efficiency of this antenna. In any practical communications system, the received power P_r must exceed the noise by a factor equal to the signal-to-noise ratio, establishing the requirement that $P_r = (S/N)N$. Substituting this expression into Equation (2.1), we obtain an expression for the required transmitter power, P_t, given by

$$P_t = \frac{4\pi R^2 (S/N) N}{G_t \eta_t A_r \eta_r} . \qquad (2.2)$$

An alternative, and possibly more familar, relation is obtained by expressing the receiving aperture in terms of the antenna gain and operating wavelength,

$$A_r = \frac{\lambda^2}{4\pi} G_r .$$

This yields the equation,

$$P_t = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{(S/N) N}{G_t \eta_t G_r \eta_r} , \qquad (2.3)$$

in which the factor $(4\pi R/\lambda)^2$ corresponds to the free-space transmission loss between isotropic antennas. Equation (2.3) shows complete symmetry between sending and receiving antennas (the well-known reciprocity relationship). Assuming that each antenna is used both for transmitting and receiving, and that the noise levels at ground and satellite receivers are equal, the power requirements will be equal for ground and satellite transmitters. Since power is more readily available at the ground station, the more critical link will be from satellite to ground. Consequently, in the subsequent treatment, we shall be concerned primarily with evaluating the power required for transmission from the satellite.

Equation (2.2) shows that the required transmitter power for any given transmission range is directly proportional to the noise level (which depends upon the bandwidth) and to the required signal-to-noise ratio, and is inversely proportional to the transmission gain, receiving aperture, and efficiency product of the antennas. In general, the efficiency of an antenna, being virtually independent of size and operating frequency, is determined once the type of antenna is chosen. Furthermore, the coverage requirement established in the preceding paragraphs for a satellite-borne communication relay system will determine, in turn, the transmission gains of the satellite antennas. Consequently, assuming signal-to-noise ratio requirements and noise characteristics have been established, the transmitter power required to effect such coverage will be determined only by the receiving aperture of the ground antennas. These system parameters--antenna gain and aperture, signal-to-noise requirements, and noise characteristics--are discussed in the following sections. The results are then used to determine the transmitter power required for the particular communication relay systems considered in this investigation.

2.3.2 Antenna Gain and Aperture

As stated in the preceding paragraph, coverage requirements determine the maximum gain which can be achieved with the satellite antennas. However, since the gains of an antenna is proportional to the product of the antenna's area, or receiving aperture, and the square of the operating frequency, the dimensions of the antennas satisfying these gain requirements will decrease with increasing operating frequency. Therefore, since the dimensions of the satellite antennas may be expected to be limited to approximately the order of the physical dimensions of the satellite itself, the foregoing considerations suggest the use of the highest possible operating frequency to minimize antenna packaging problems. This is particularly true of those narrow-beam antennas which would be necessary to minimize jamming (see Section 2.9) and (for interim systems) to provide point-to-point communication relay service. Of course, use of higher operating frequencies must depend on the availability of the necessary components, and the fact that amplifier tubes are not available at frequencies above 12 kmc (see Appendix C) has led to the use of 10 kmc in subsequent calculations of power requirements.

It is clear from the discussion of Equation (2.2) of the preceding section that the receiving aperture or equivalent area is the only parameter of the ground antennas affecting the power requirements for transmission from the satellite to the ground. Because of the theorem of reciprocity, therefore, we may conclude that their aperture or size is the only parameter of these ground antennas affecting the power requirements for the reverse transmission, i.e., from the ground to the satellite. Nevertheless, the antenna gain or beamwidth of the ground antennas is a consideration in determining the accuracy with which the satellite must be established in its orbit and subsequently tracked by the ground antennas. Therefore, at the high frequencies required to limit satellite antenna sizes, the extremely large (narrow-beam) ground antennas which might otherwise prove feasible will have their dimensions limited by the severe tracking and satellite orbit control problems which such narrow beams would introduce.

Design considerations for 24-hour satellite antennas are discussed in detail in Appendix A. It is concluded that polyrod antenna arrays are the most suitable type of antenna for a communication relay satellite in all cases where size limitations prevent the use of the larger, but more efficiently fed, parabolic dish antenna. Since antenna size is also an important factor for the aircraft installations of the low-traffic-density systems, such arrays seem most suitable for this application as well. The total weight of the largest array considered (16 rods $\lambda/2$ in diameter and 10λ in length) should not weigh more than 10 to 20 pounds at S-band or a pound or so at X-band.

2.3.3 Signal-to-Noise Ratio Requirements

Signal-to-noise ratio requirements must be established on the basis of the quality of service as well as the medium over which the information is to be transmitted. For example, the signal-to-noise ratio required of a beyond the

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horizon radio link, whether it be a scatter link or a normal ionospheric-reflection link, must be determined using the statistics of signal fading. To obtain the desired reliability with such links, the average signal-to-noise ratio must be substantially higher than the minimum allowable signal-to-noise ratio (about 15 db). On the other hand, with line-of-sight radio links or with wire-line systems, the absence of fading permits a substantially better quality of service and a minimum allowable signal-to-noise ratio of 20 to 25 db is common.

A communication relay system utilizing satellites in appropriate orbits is a completely new type of service, and, in view of the difficulties of establishing and maintaining such a service, it is important to be conservative in the design. Therefore, if it is feasible from the standpoint of satellite weight to establish an extremely high-quality service (one with a high signal-to-noise ratio), we feel that this should be done. (It should be noted that a high signal-to-noise ratio will also reduce susceptibility to enemy jamming, although jamproof operation will also require the use of one of the several techniques for spreading the signal over the total available bandwidth to deny the enemy an effective spot-jamming capability.) For these reasons the calculations carried out in the course of this study have utilized a peak signal-to-noise ratio of 30 db, with a minimum allowable peak signal-to-noise ratio of 20 db established for cases where the power (and satellite weight) required to provide acceptable bandwidths would be excessive with a 30-db signal-to-noise ratio. The 30-db figure will permit transmission of high-quality video and voice information, while providing an error rate for normal digital signals (such as teletype) which is so small as to be negligible. For the low-density relays, which are the only cases where the minimum allowable signal-to-noise ratio must be accepted in the initial global system, the limited bandwidth obtainable even under these conditions prevents the transmission of video information. Nevertheless, the error rate for digital signals will still be comparable to that obtained with wire-line transmissions.

2.3.4 <u>Desired Bandwidth</u>

A satellite-borne military communication relay system would be so useful that any bandwidth capability provided would be completely utilized.

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However, limitations on the weight of the payload will cause a corresponding limitation in the bandwidth capabilities. Therefore, it is evident, at least for the early stages of the satellite program, that the number of users of such facilities and the information transmitted must be restricted.

A reasonable estimate of the bandwidth capabilities which an initial global communication relay system should provide may be obtained by considering the types of transmissions the system might be required to handle. In general, the signals might consist of video transmissions (used in a quite general sense and including facsimile), voice transmissions, and teletype transmission, with data-link transmissions possibly being included under certain circumstances. The bandwidth of a video signal, as estimated from the bandwidth requirements for a television signal, will be taken as about 4.5 megacycles, since the remainder of the 6-megacycle band normally allocated for a television channel is used for sound, chromatic information (in color TV), and guard band. The bandwidth required for a voice signal may vary, depending upon the quality desired. However, it is felt that toll-quality speech should be a design objective for this system, so a 4-kilocycle bandwidth requirement will be assumed for voice signals. Finally, teletype and data-link transmissions normally occur in digital form, and bandwidth requirements may be determined according to accepted practice. The bandwidth of typical teletype circuits may vary between about 30 and 300 cycles per second, with the latter value coming into more and more common use as the necessary equipment is developed. Thus, 13 or more teletype signals, depending upon their pulse transmission rate, may be multiplexed into the bandwidth required for each voice signal. Similarly, although data-link requirements may vary widely, a value of 20 kilocycles will be assumed as typical of a relatively high-speed link. Thus, 66 or more teletype signals, up to 5 voice signals, or some appropriate combination of these, may be multiplexed into the bandwidth required for a single data-link transmission.

From these probable bandwidth requirements for the various types of possible signals, the bandwidth requirements for an initial satellite-borne global communication system may be estimated. When a high-traffic density capability is required, an over-all bandwidth of a few megacycles is obviously not sufficient since it would not permit more than one video channel to be provided. On the other hand, a bandwidth of the order of hundreds of megacycles or more would provide bandwidth for some tens of video channels, a capability which, although useful, undoubtedly exceeds that required of the high-traffic-density relay in an initial global system. Thus, a reasonable estimate for this type of service may be taken to be some tens of megacycles; for purposes of calculation, a figure of 50 megacycles total, or 25 megacycles each way between the terminals of an intercontinental relay, has been chosen. This 50-megacycle system capability would provide, for example, sufficient bandwidth for 5 video channels and 625 voice channels in each direction for a two-way system. Teletype or data-link channels could be substituted for the voice channels in the ratios given in the foregoing paragraph.

In the case where low-traffic-density service must be provided, the requirement for transmission of video data may be eliminated as unnecessary for a minimal system. Furthermore, because of the difference in class of service, it may be expected that a low-traffic-density system need not provide more than 5 to 10 per cent of the capability for voice, teletype, or data-link signals required of the high-traffic-density relays. Therefore, the bandwidth requirement for an initial low-traffic-density global communication relay system will be taken as 100 kilocycles, a value which provides a capacity either for 5 high-speed, data-link channels, 25 voice channels, or over 300 teletype channels, or for an appropriate combination of these types of signals as desired.

It should be emphasized that, although the bandwidth figures chosen above are considered reasonable design objectives for a fully operational initial global communication system, it may prove desirable for certain reasons to obtain increased bandwidth by reducing system signal-to-noise ratio, or conversely, it may be desirable to exchange bandwidth capability for higher signal-to-noise ratio. Alternatively, by reducing bandwidth one could effect a reduction in power requirements and thus in the weight of the power supply and cooling systems; the weight allowance could then be used to provide reliability by providing equipment redundancy. Thus, these bandwidth figures are only nominal figures to be used in the following sections to provide estimates of power requirements for an initial global system. In a later section, the objectives will be compromised to provide interim systems with reduced bandwidth capabilities (although still a great improvement over all present techniques for long-range communication), and thereby permit their early achievement.

2.3.5 <u>Noise Level Considerations</u>

Appendix B presents a general discussion of the various types of radio noise together with a preliminary evaluation of their relative importance for the various types of satellite-borne relay and reconnaissance systems investigated in this study. In the case of the communication relay system considered in this section, these results, summarized below, show that set noise will limit reception under all conditions except for short intervals during the vernal and autumnal equinoxes, when solar noise can become important once each day for the ZI and intercontinental relays.

At an operating frequency of 10 kmc, the maximum cosmic noise which can be received from the galactic plane, even on high-gain antennas, is less than set noise. Furthermore, the cosmic noise from discrete radio stars, when received by aircraft-borne antennas with the relatively small gains appropriate to the polar relay system (the only case where the important radio stars are within the beam of the receiving antenna), is also less than set noise at 10 kmc. Thus, cosmic noise is not important in limiting reception in this frequency range. Even with solar noise, the antenna gains will not be sufficient to cause set noise to be exceeded except for the ground antenna used in the high-traffic-density systems. The narrow beamwidth of this high-gain ground antenna, however, limits the time interval during which solar noise exceeds set noise to, at most, 3 minutes each day for, at most, 3 days at each equinox, since only during such a period could the sun fall within the beam of any given ground antenna. Therefore, since the interruptions in relay service which may be caused by solar noise represent such a negligible fraction of the total time available for transmission, and since, moreover, such interruptions can be predicted with very high accuracy, set noise will be considered the factor limiting reception for both the low-traffic-density and high-traffic-density communication relay systems investigated in this study.

2.3.6 Power Requirements*

The results of the foregoing sections may now be used, together with Equation (2.2) of Section 2.3.1, to determine the transmitter power required for the various satellite-borne communication relay services investigated in the course of this study. The discussion in Section 2.3.1 of the effect of the operating frequency upon the required transmitter power indicated that the highest possible operating frequency should be used. This conclusion, coupled with the fact that the necessary amplifier tubes are not available at frequencies above about 12 kmc (see Appendix C), has led to the use of an operating frequency of 10 kmc in the calculations of required transmitter power for initial global communication relay service. Furthermore, the calculations use a noise level based upon an absolute temperature of 300° Kelvin for the input impedance of the ground-station receiving tube, and a noise figure of 7 db for the receiver itself. This 7-db noise figure represents a value which is commerically available today at 7 kmc and which may reasonably be expected to be achieved at the slightly higher X-band frequencies by the time this system could be operational.

a. Zone of the Interior Relay System

The United States covers about 60 degrees of longitude and about 25 degrees of latitude. It may be shown that, for a satellite positioned in a 24-hour orbit above about 95° W longitude, the vertical angle subtended by the United States will be a little less than 4 degrees, while the horizontal angle will be about 10 degrees. At 10 kmc this would require an antenna array having dimensions of only about 5 inches by 10 inches by 1 foot or so in depth, and would provide a gain of about 30 db with about a 50 per cent radiation efficiency.

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*The power requirements calculated in this chapter are based upon the assumption that relatively unsophisticated modulation techniques are used, so that transmission bandwidth and information bandwidth can be considered essentially equivalent. It is recognized that sophisticated modulation techniques present attractive possibilities for improving system performance, but evaluation of their relative merits requires detailed knowledge of such parameters as the number of transmitting stations served by a given relay, the information bandwidth required for each station, allowable intermodulation and crosstalk, and so on. Hence, full evaluation of such techniques must await the detailed system design study which would logically follow the feasibility study reported herein.

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The size of the antenna which may be used on the ground is limited by the accuracy with which the vehicle can be tracked by the ground antenna servo system. It is also limited by the dimensional accuracy (in terms of fractional wavelengths) to which the antenna can be constructed and afterwards maintained under conditions of loading by wind, snow, ice, etc. Maintenance of the necessary tolerances for use at 10 kmc is well within the present state of the art for a 60-foot dish, which will provide a beamwidth of 0.1 degree. This beamwidth is quite compatible with the tracking accuracy obtainable with such a system, and will provide a gain of about 63 db. Because of the simplicity of feeding such a dish, its radiation efficiency may be expected to be over 90 per cent. In Chapter 2 of Volume III, it is shown that the satellite may be held to within approximately 1 degree of its nominal position over a lifetime of 6 months to a year. Consequently, the tracking referred to need be only over an angle of about 1 degree, and this may be accomplished without significant loss of radiation efficiency by moving the feed rather than the dish.

Using these results and requiring a 30-db signal-to-noise ratio, we obtain a required transmitted power for ZI communication relay service of 5.0 watts per megacycle, or a total of 250 watts for a 50-megacycle bandwidth. It should be noted that, due to the reciprocity theorem, this figure holds regardless of whether transmission takes place to or from the satellite. However, since the peak power limitation is not as serious for the ground-based equipment as for the satellite-borne relay, it seems advantageous to transmit at a substantially higher power level from the ground and thus decrease the required amplification in the satellite. This results in both a weight saving and an increase in the difficulty experienced by an enemy trying to jam the system.

It should be noted that the horizontal angle subtended by the United States at the 24-hour satellite could be reduced by positioning the satellite over about 50° W longitude instead of over 95° W longitude as suggested above. This would permit a decrease in the diameter of the ground antenna to about 30 feet or, alternatively, a decrease in required transmitter power to about 125 watts for a 50-megacycle bandwidth. However, it will be shown in the following section that the desired intercontinental relay capability can be provided only if

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both a transmitter power of about 250 watts and 60-foot-dish ground antennas are used. Thus, the possibility of modifying the ZI requirements by using the alternate location mentioned for the ZI relay satellite will be considered to be an option whose desirability would be determined more by operational considerations than by basic technical feasibility.

b. <u>Intercontinental Relay System</u>

The coverage areas illustrated in Figure 2-2 for the relay between the eastern North America and Europe require antennas having beamwidths of about 2 degrees by 9 degrees. This may be attained with an antenna array having dimensions about 6 inches by 2 feet by 1 foot or so in depth which would provide a gain of about 33 db. Assuming as above that the ground antennas are 60-foot dishes or their equivalent, and again requiring a signal-to-noise ratio of 30 db, we obtain a required transmitter power of about 125 watts for transmission either to North America or to Europe of a signal having a 50-megacycle bandwidth. However, since the desired initial global communication relay service will require the simultaneous transmission to both America and Europe, the total required transmitter power for the "American-European" intercontinental relay becomes about 250 watts. This requirement will be discussed in more detail under Section 2.4.2.

The coverage areas shown in Figure 2-3 for the intercontinental relay from Asia to western North America require two satellite antennas having beamwidths which are essentially the same as those required for the American-European relay, plus a third antenna to provide coverage for the Hawaiian Islands. A beamwidth of 1 degree will yield the Hawaiian coverage without unnecessarily complicating the attitude stabilization problem of the satellite, and may be obtained with an antenna array having dimensions of about 4 feet by 4 feet by 1 foot in depth. Requiring a 30-db signal-to-noise ratio as above, the transmitter power necessary to provide this additional coverage for the Hawaiian Islands is found to be about 10 watts. Thus, the total required transmitter power for the intercontinental relay between North America and Asia becomes about 260 watts for a bandwidth of 50 megacycles.

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c. Polar Relay System

The coverage capabilities shown in Figure 2-7 for low-traffic-density communication relay service are based upon the utilization of the entire line-of-sight coverage which may be obtained from satellites in the recommended polar orbits. The total angular line-of-sight region subtends an angle of 16 degrees at the 24-hour satellite so antennas must have 16-degree beamwidths. Since the diameter of the necessary parabolic dish is only about 5 inches, a size which does not cause any packaging problems, the high radiation efficiency of such dishes dictates their use for these particular antennas. The attitude stabilization of the satellite ensures that it will always maintain the same orientation with respect to the earth, so fixed antennas may be used to obtain the desired coverage. On the other hand, the ground antennas will be required to track the relay satellite. In addition, the mobile stations with which communications are to be established will include aircraft, so such "ground antennas" will be limited in their maximum dimensions. A 15- by 15- by 13-inch antenna array, whose dimensions seem quite reasonable for an aircraft installation, will provide an antenna beamwidth of about 3 degrees at 10 kmc. Such an antenna beam should not be too narrow to permit tracking from aircraft, and will provide an antenna gain of about 33 db.

Thus, we obtain a required transmitter power of 2.2 kilowatts to provide a 30-db signal-to-noise ratio for the 100-kilocycle bandwidth assumed in Section 2.3.4 for the low-traffic-density relay of an initial global communication relay system. It should be noted, however, that this required transmitter power decreases to a value of 220 watts if the signal-to-noise ratio is decreased to the 20-db minimum value recommended in Section 2.3.3. If higher transmitter powers are available than the 220-watt value thus obtained for this system, the use of the lower signal-to-noise ratio permits a substantial increase in the bandwidth capability of the system. This possibility of trading signal-to-noise ratio for bandwidth capability will be discussed in more detail later as a part of the over-all systems problem of providing the optimum communication relay capability consistent with the useful payload which can be established in a satellite orbit.

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d. Equatorial Relay for Low-Traffic-Density Areas

As in the case of the polar relay satellites, coverage of all areas within line-of-sight is desired from any equatorial satellite providing low-traffic-density service to the Pacific and (possibly) Indian Ocean and environs. Thus, the problem of providing such coverage is identical to that discussed above, and it may be concluded that the required transmitted power for an equatorial low-traffic-density relay is essentially equal to that obtained in the preceding section for polar relays.

2.4 INSTRUMENTATION CONSIDERATIONS

2.4.1 Characteristics of Possible Amplifiers

There are three types of amplifiers which operate in the frequency range above S-band (about 3 kmc) and which have any appreciable bandwidth, namely, traveling-wave-tube amplifiers, klystron amplifiers, and backward-wave amplifiers. The characteristics and availability of these amplifiers are discussed in some detail in Appendix C and are summarized below.

2.4.2 Traveling-Wave-Tube Amplifiers

Traveling-wave-tube amplifiers are inherently broad-band devices, usually operating over an octave band. Even the so-called narrow-band traveling-wave tubes, designed for good noise figure and gain characteristics, have bandwidths of the order of 10 per cent of the operating frequency. A wide selection of types of CW traveling-wave-tube amplifiers is available today in most power ranges up to 200 watts, including low-power receiving tubes with excellent noise figures. Most of these tubes require solenoids to focus their electron beam, and thus are rather heavy and require a substantial amount of power. However, many periodically focused tubes are now under development and by about mid-1959 these tubes should be much lighter.

2.4.3 Klystron Amplifiers

Klystron amplifiers are basically high-Q, cavity-tuned devices with bandwidths limited to a few megacycles. Although a somewhat larger bandwidth can be attained at the cost of a substantially reduced gain, the noise

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figure of klystron amplifiers is high, so that they cannot presently be used as receiving tubes in the low-power ranges. In general, klystron amplifiers are somewhat lighter than presently available traveling-wave-tube amplifiers of comparable output power levels, but the number of these amplifiers from which a selection can be made is limited. Nevertheless, CW klystron amplifiers are available with output powers up to 2 kilowatts or so, and, since attaining 2 kilowatts with traveling-wave tubes requires many tubes operated in parallel, the klystron amplifiers offer attractive possibilities for systems using 2 kilowatts and whose bandwidths do not exceed klystron capabilities.

2.4.4 Backward-Wave Amplifiers

A backward-wave amplifier can amplify a somewhat wider band than a klystron amplifier and, in addition, has the extremely rapid voltage tuning ability of a backward-wave oscillator. In general, a given amplifier will operate over approximately an octave band, with bandwidths ranging from about 0.1 per cent at the lower edge of the band to about 1 per cent at the high edge of the band. Since tuning over this band can be effected in the order of microseconds, this type of amplifier can eliminate the need for a backward-wave local oscillator and mixer combination normally needed when such rapid tuning changes are required in a receiver. Unfortunately, however, backward-wave amplifiers are a very new development in the field of traveling-wave structures. As of the date of this report, only two types of backward-wave amplifiers are commercially available, and although a number of companies are investigating them, the resultant tubes are mostly in the experimental rather than the later developmental stages. Therefore, the use of backward-wave amplifiers will not be considered further in the present feasibility study. However, it is recommended that these devices be evaluated for possible use when they become available in a more useful variety of tube types.

2.4.5 Molecular Amplifiers (Masers)

Recent investigations have disclosed that electromagnetic signals can be amplified through interaction with beams of excited molecules. Although initial experiments have utilized gas molecules, theoretical investigations indicate that similar effects can be obtained with liquids and even solids. In

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many cases, molecular amplifiers operate at extremely low temperatures, and because noise figures of less than 1 db are obtainable, receivers utilizing such amplifiers are capable of yielding extremely high sensitivity in comparison with more standard techniques. Unfortunately, due to the fact that such molecular amplification utilizes extremely high-Q molecular resonance phenomena, the bandwidths obtainable with molecular amplifiers providing reasonable gain have not exceeded about 100 kc or so. Wider bandwidths should be possible in molecular amplifiers utilizing solids, but even so, the obtainable bandwidths are not expected to exceed a few megacycles.

Because of the limited bandwidth, molecular amplifiers are primarily of interest here for possible application in low-density relay systems. A second possibility exists that the use of such amplifiers could reduce power requirements sufficiently to render practical a high-density system composed of a multiplicity of low-power, relatively narrow-band relay links operating in parallel. There is, of course, no necessity for carrying the molecular amplifier in the satellite since the "ground" transmitters are capable of transmitting relatively high power. They would, however, find their principal use in the "ground" receiver which would permit the use of smaller-powered transmitters in the satellite. However, even for ground use, the development of molecular amplifiers is still in the early, predominantly laboratory stages. Furthermore, the size and weight of a molecular amplifier, with its associated cooling equipment, renders such devices impractical at the present time for the aircraft receivers which are used in the low-density communications system. Because of these two reasons, molecular amplifiers have not been considered further in this report for possible application in an initial global communication relay system which would become operational in a time period of 4 to 5 years. However, because of the importance attached to the possibility of reducing power requirements in the satellite-borne communication relay system, it is strongly recommended that the development of molecular amplifiers be encouraged to the maximum possible extent and that the possible application of such amplifiers in systems considered in this report be re-evaluated at the earliest time when such devices can be considered as available for use in a practical operational system.

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2.4.6 Summary

Traveling-wave tubes are the only amplifiers available which can provide wide bandwidths (of the order of some tens of megacycles or more). Furthermore, the obtainable traveling-wave receiving tubes have such low-noise figures in comparison with klystron amplifiers that their use as system input amplifiers is necessary regardless of the system bandwidth. Klystron amplifiers can be used only as the final power amplifier in a narrow-band system, and the available tubes from which a selection can be made is sharply limited. Hence, only traveling-wave-tube amplifiers can be used in the high-density relay, and must be used also as the low-power amplifiers in the low-density relays. The choice between traveling-wave-tube or klystron amplifiers as a final power amplifier for the low-density relay will be dictated by tube availability and the desire to minimize total system power requirements.

2.5 POSSIBLE SATELLITE-BORNE RELAY SYSTEMS

2.5.1 Block Diagram of ZI Relay System

A functional block diagram of a possible satellite-borne communication relay system for ZI relay service is shown in Figure 2-8. Signals are received on a plane-polarized antenna and passed through a low-pass filter to the input of the first traveling-wave-tube amplifier. The low-pass filter is designed to eliminate feedback of signals, retransmitted by the relay, which will be at a higher frequency than any of the received signals. The first traveling-wave-tube amplifier provides a gain of about 50 db and, operating well below saturation, determines the over-all noise figure of the airborne system. The amplified output of the first traveling-wave-tube amplifier is mixed with a variable frequency local-oscillator signal, and the resulting output is filtered in a single-sideband filter to remove the unwanted frequency components resulting from the mixing process.

The output signal from the single-side band filter is amplified in the final two traveling-wave-tube amplifiers, and is then retransmitted from a plane-polarized transmitting antenna whose plane of polarization is orthogonal to that of the receiving antenna. This use of cross-polarized antennas for

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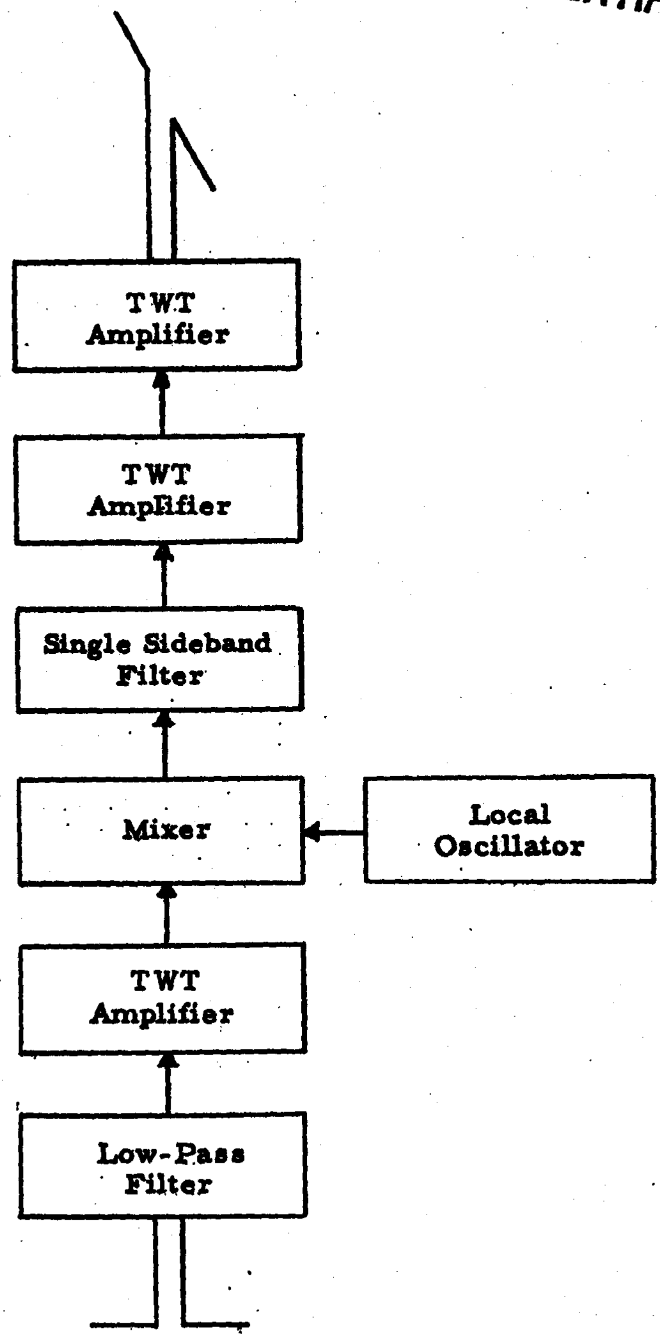

Figure 2-8. Block Diagram of Possible Satellite-Borne Relay System for ZI Service.

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reception and transmission is suggested to decrease the amount of filtering required to obtain the necessary isolation between received and transmitted signals. The input power to the system will be at a level of about -40 dbm, and since the transmitted power level is about 250 watts, or +54 dbm, some 110 db or so of isolation is necessary if any input to the first traveling-wave-tube amplifier at the retransmission frequency is to be substantially below the the level of the desired signal. (This extremely high isolation would not be needed for a system in which jamming need not be considered, but is required if the power needed to jam the relay by merely overloading the input amplifier is to be maximized.) The use of cross-polarized antennas could provide an initial isolation of from 20 to 30 db, thereby substantially reducing the filtering problem which otherwise might be present.

The input signal level of -40 dbm quoted above is 50 db above the noise in a 50-megacycle bandwidth, assuming a 7-db noise figure for the system. The fact that this level is 20 db above that necessary to provide the 30-db signal-to-noise ratio required of the system permits the elimination of the first traveling-wave-tube amplifier from the system, since the 20-db gain which may be expected of such low-level receiving tubes at X-band is thus no long required. In addition, the use of these higher powers in the system require the use of correspondingly higher powers by a jammer. Furthermore, with this input level a traveling-wave-tube amplifier with a 27-db noise figure will provide the same system operation as would a low-level tube, having a 7-db noise figure, with an input level 20 db lower. Of course, the higher input level requires the use of an additional 20 db of power in the ground-based system, but peak power limitations are not as severe on the ground as in the satellite-borne system.

Table 2-1 lists the pertinent characteristics of traveling-wave-tube amplifiers which seem suitable for use in the satellite-borne system, as well as the estimated characteristics of other components required for the relay. Also given are estimates of the weights and power requirements of periodically focused traveling-wave-tube amplifiers which would be comparable to those listed. In cases where exact values are not available, an educated guess has been made from the characteristics of similar tubes and the value given is

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Component	Manufacture and Type Number (solenoid-focused)	Small Signal Gain (db)	Noise Figure (db)	Saturated Power Output (watts)	Total Weight (lb)	Magnet Power (watts)	Tube Beam Power (watts)	Heater Power (watts)	Total Power (watts)	Estimated Total Power if Periodically Focused (watts)	Estimated Weight if Periodically Focused (lb)
1st TWT Amplifier	Sperry STX-76	50	27	0.4	17	160	13	9.5	183	23	7
2nd TWT Amplifier	Sperry STX-77	35		8	22	400	80	12	492	92	12
3rd TWT Amplifier	Sperry STX-105	(20)		200	35	(400)	(1500)	(15)	(1915)	(1515)	15
Low-Pass Filter					2						2
Mixer		(-15)			5						5
Local Oscillator and Associated Circuits					17				130	130	17
Sideband Filter					2						2
Antennas and Feeds					(3)						(3)
Mountings					50						30
TOTAL					153				2729	1760	93

Table 2-1. Typical Characteristics of Components Suitab:e fpr ZI Relay.

indicated in parentheses. These results indicate quite graphically the reduction in weight and power requirements which may be effected when periodically focused traveling-wave tubes become available for use, since the estimated weight and power requirement totals with such tubes are some 60 pounds less and almost 1000 watts less than would be required with tubes available today.

2.5.2 Block Diagram of Intercontinental Relay System

A functional block diagram of a possible satellite-borne communication relay system for intercontinental relay service is shown in Figure 2-9. This system is identical in its basic operation to that described in the above paragraph for ZI relay service, the only modifications being those required to permit the use of two antennas (three, if coverage of Hawaii is provided). In this case the receiving antennas feed two identical low-pass filters and the outputs of these filters are then combined in a directional coupler before being applied to the input of the first traveling-wave-tube amplifier. The output of the final traveling-wave-tube amplifier is fed in parallel to two identical transmitting antennas. Since this will cause a decrease of 3 db in the signal-to-noise ratio of the signal received on the ground, the desired 30 db signal-to-noise ratio may be obtained by increasing the transmitted power from the value of about 125 watts calculated in Section 2.3.6b for a total bandwidth of 50 megacycles to a value of about 250 watts. This latter figure is the same as the 250-watt power requirement for the ZI relay as calculated in Section 2.3.6a.

Thus, the estimated weight and power requirements for the intercontinental communication relay will be the same as those given above for the ZI relay with the exception of the additional weight necessary for a second antenna and its feeds, a second low-pass filter, and a directional coupler. The total weight of these components is estimated to be about 7 pounds so the total estimated weight and power requirements for the intercontinental communication relay become about 160 pounds and 2720 watts, respectively, using present-day tubes, and 100 pounds and 1760 watts if periodically focused tubes are available.

2.5.3 Block Diagram of Low-Density Relay System

The functional block diagram of the satellite-borne system designed to provide polar and ocean-area communication relay service is identical to that shown in Figure 2-8 for the ZI communication relay with the exception that the

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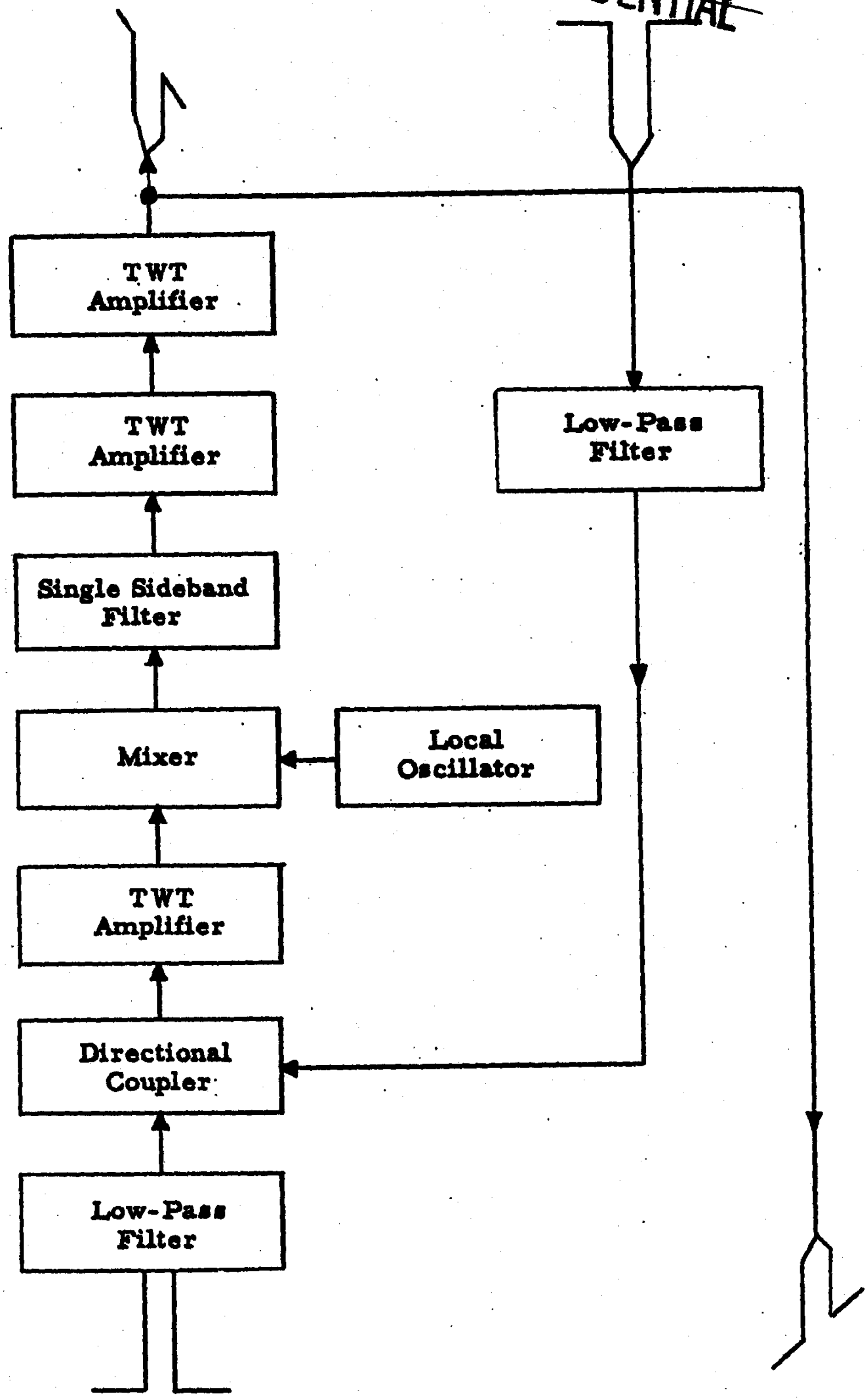

Figure 2-9. Block Diagram of Possible Satellite-Borne Relay System for Intercontinental Service.

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output traveling-wave tube is replaced by a klystron amplifier. For the low-density relay system, the 200-watt Sperry SAS-28 (weighing just over 5 pounds and requiring a total input power of about 1550 watts) or its equivalent is suggested, since the size of the antenna required for the desired coverage does not preclude operation at S-band frequencies. Furthermore, the 30-db gain of this tube would permit a tube such as the 500-milliwatt Sperry STS-75 traveling-wave tube to be used for both of the remaining amplifier stages, resulting in weight and power savings of about 5 pounds and either 310 or 70 watts, respectively, over the totals given in Table 2-1 for the first two traveling-wave tubes. Thus, the total estimated weight and power requirements for the low-traffic-density relay system become about 103 pounds and 2045 watts, respectively, using present-day tubes, and about 73 pounds and 1725 watts if periodically focused tubes are available.

2.5.4 Reliability and Lifetime Considerations

Since the global communication relay system discussed in the preceding sections must operate unattended, the reliability which may be attributed to such operation is an important factor in determining the feasibility of the over-all system. For this reason, the simplest possible relay systems have been described above, and the number of components comprising such a system should be held to an absolute minimum. Because the traveling-wave-tube amplifiers suggested for use in this system are a relatively new type of tube, data regarding expected tube lifetimes have not been available in sufficient quantities to permit reliable statistical evaluation. However, with careful design and construction techniques there is no reason why the life of such tubes should not equal or exceed that which may be expected from more common types of electron tubes. Recent measurements have indicated that, at least for lower powered tubes, useful lifetimes well in excess of 5000 hours are not unusual. It is expected that similar lifetimes may be obtained with high-power traveling-wave-tube and klystron amplifiers, particularly by the time this system would become operational. Furthermore, system lifetime could be substantially prolonged through the incorporation of spares, with fail-safe detection circuitry to detect unit failure and switch a replacement into the circuit. Hence, it is expected that the useful lifetime of the electronic portion of the global communication relay system should be at least 6 months or so. Furthermore, as design techniques improve, this expected system lifetime may well exceed a year or more in later models of the system.

2.6 HIGHER CAPABILITY GLOBAL COMMUNICATION RELAY SYSTEMS

2.6.1 Requirements for Communication Relay Systems of Higher Capabilities

The communication relay systems described in the foregoing sections were designed to provide an initial global communication relay capability. As such, the estimated weight and power requirements obtained above represent more or less of a lower bound for satellite-borne global communication relay systems. However, if the various techniques described in Volume 2 of this report for providing the ascent vehicle with an increased payload capability prove successful, the additional weight and power which may be allocated to the relay system itself would permit a substantial increase in the system capabilities. The following paragraphs describe briefly the progression in which system capabilities might be increased, together with an estimate of the necessary incremental weight and power requirements. (The results of this section are summarized, for convenience in Table 2-2.)

The first step to be taken, if an increased satellite payload should be available, would be to increase the over-all system reliability. This would be accomplished by providing a spare for each unit of the system, together with circuits to sense unit failures and switch the proper spare into the circuit. In this manner, a sort of elementary fail-safe operation is added to the system, and its useful life could be substantially prolonged. For the high-traffic-density systems, the estimated weight and power requirements for this additional reliability would be about 180 pounds and 10 watts, respectively, using present-day tubes, and 120 pounds and 10 watts if periodically focused tubes are available. For the low-traffic-density systems, these estimated additional weight and power requirements become about 130 pounds and 10 watts using present-day tubes, and about 100 pounds and 10 watts using periodically focused tubes.

Table 2-2. Weight and Power Requirements for Initial Global Communication Relay Systems of Various Capabilities.

System	Incremental Weight (lb)		Incremental Power (watts)		Total Weight (lb)		Total Power (watts)	
	A	B	A	B	A	B	A	B
1. High-Density Intercontinental								
a. Initial					160	100	2,720	1,760
b. Initial with spares and fail-safe equipment	180	120	10	10	340	220	2,730	1,770
c. System 1b, plus initial low-density system with spares and fail-safe equipment	233	173	2,055	1,735	573	393	4,785	3,505
d. System 1c, with capacity of low-density system doubled	76	56	947	813	649	449	5,731	4,318
2. Low-Density								
a. Initial					103	73	2,045	1,725
b. Initial with spares and fail-safe equipment	130	100	10	10	233	173	2,055	1,735
c. System 1b with capacity doubled	76	56	947	813	309	229	3,002	2,548
d. System 1c with capacity quadrupled (eight times capacity of system 1b)	74	74	3,263	3,397	383	303	6,265	5,945

Legend: A - Using present-day tubes
B - Using periodically focused tubes

The capability of the high-density satellites could be further increased by adding a low-density coverage system. This would eliminate the necessity for a separate satellite to provide low-density coverage of the Pacific Ocean areas. Including spares and fail-safe circuitry, the additional increase in weight and power requirements for such coverage would be 233 pounds and 2055 watts using present-day tubes, and 173 pounds and 1735 watts if periodically focused traveling-wave tubes are available. The capability of the high-density satellites could then be further increased by doubling the capacity of the low-density equipment. This could be accomplished by replacing the SAS-28 output amplifier by the 500-watt Sperry SAC-33 klystron amplifier, with the necessary drive power being supplied from a tube such as the Geisler G210 or Sylvania TW621. The input traveling-wave-tube amplifier would be replaced by a C-band tube such as the Sperry STC-67. Again including spares and fail-safe circuits, the estimated additional weight and power requirements for this increased capacity would be about 76 pounds and 947 watts using present-day tubes, and 56 pounds and 813 watts if periodically focused tubes can be used.

The next increase in the capability of the low-density systems could be to double their bandwidth capabilities as described above. As before, the estimated increased in weight and power requirements for this system, including spares for all units and the necessary failure detection and switching circuits, is 76 pounds and 947 watts, respectively, if present-day tubes are used, and 56 pounds and 813 watts if periodically focused tubes are available.

Finally, the capacity of the low-density system may be increased to a value eight times that of the original system by using the Varian VA-806 klystron amplifier as an output tube. The high gain of this tube permits the use of a Sperry STX-76 traveling-wave-tube amplifier for both of the first two amplifier stages. Assuming the provision of spares for each unit of the system, and fail-safe circuitry, as before, the increased capability of this system over the double capacity low-density system described above requires additional weight and power of 74 pounds and 3263 watts if present-day tubes are used, and 74 pounds and 3397 watts using periodically focused tubes.

The results given above illustrate clearly the large increases in system capabilities which can be obtained if sufficient satellite payload capabilities can be provided. Of course, further increases in system capabilities could be achieved using additional and/or higher powered components, in the manner used to obtain the above results, with consequent increases in weight and power requirements of a magnitude comparable to those shown in Table 2-2. However, it is probable that a limit exists beyond which point any additional payload capabilities which could be provided would be utilized for other purposes. A determination of this "point of diminishing returns," so to speak, for communication relay systems is far beyond the scope of the feasibility study reported herein, and no attempt will be made even to estimate such a "maximum required capability."

2.7 INTERIM COMMUNICATION SYSTEM FOR A 24-HOUR SATELLITE

2.7.1 Reasons for and Types of Interim Communication Systems

Achieving the initial global communication system described in the preceding sections would require an appreciable developmental program even if it were developed gradually. Standard modulation and multiplexing techniques would have to be modified to meet the requirements of this system, and new techniques would be necessary in certain areas. For example, power requirements are such that a nuclear power supply would be desirable, which would necessitate considerable development in a new technology and so on. Thus, a realistic estimate of the time required for developing an initial global communication system is around 4 or 5 years. However, other communication requirements exist today which can be satisfied by a satellite-borne relay system. Hence, it is reasonable to investigate the feasibility of various interim communication relay systems which, although not possessing the full capabilities of the initial global system described above, nevertheless represent a substantial improvement over presently available communication techniques.

If an initial global system is scheduled for completion in 4 or 5 years, the development of an interim system might be accomplished in 2 years. Thus, maximum possible utilization should be made of existing techniques and equipment, particularly for any ground equipment where multiplexing may be necessary. Furthermore, the time required for developing and establishing such a system in orbit will be strongly affected by the power requirements of the satellite-borne equipment, since these will determine whether or not a nuclear power supply (and the attendant refinement of a new technology) is necessary. Hence, an interim communication relay system should also have substantially lower power requirements (and if possible should weigh appreciably less) than the initial global communication system. Moreover, if weights can be kept down, particularly the significant weight of the power supply, then somewhat less refined rocketry may be used for establishing the orbit and more weight can be allotted to the guidance system used to establish the interim satellite in orbit. Two general classes of systems which meet these requirements have been investigated: (1) those systems providing point-to-point or, at most, restricted-area-to-restricted-area relay of multiplexed signals having a total information bandwidth of no more than a few megacycles; and (2) those systems providing relay service between any two points within a large area with a bandwidth of at most a few kilocycles.

For point-to-point systems, FM transmission of frequency-division-multiplexed signals seems the most likely technique which would permit development of the necessary equipment within approximately 2 years. Frequency modulation tends to reduce any effects of system nonlinearities, and use can be made of presently available frequency-multiplex equipment (except possibly the equipment necessary to multiplex a number of subchannel signals into the final wide-band signal). Accordingly, three such systems have been investigated which provide a reasonable range of capability and from which the requirements for this class of systems as a whole may be estimated. The systems investigated include: (1) point-to-point simplex (one way at a time, but reversible) transmission of FM-multiplexed signals with a nominal information bandwidth of 5 megacycles;* (2) point-to-point duplex (simultaneous two-way) transmission

*It should be noted that simplex transmission of multiplexed signals is far from satisfactory, particularly for voice and teletype signals, since all base-band signals must be interrupted whenever the direction of transmission is reversed. Consequently, elaborate storage is required to obtain even a semblance of normal duplex operation. Simplex systems are investigated here primarily to provide a comparison to the requirements for full duplex operation.

of FM-multiplexed signals of the same nominal bandwidth; and (3) restricted area-to-restricted are simplex transmission with a nominal total bandwidth of 2.5 megacycles.

The second class of interim systems, those providing service between points within a large area, should permit communication between mobile stations, including aircraft. Therefore, relaying voice transmissions is desirable, although a high-speed teletype capability might be quite acceptable. However, because of the large number of potential users of such a relay service, and because of the limited time available for system development, the use of existing equipment, instead of the manufacture of new equipment, becomes even more mandatory in this case than in the case of the point-to-point relays. For this reason, the one possibility investigated of this second class of systems utilizes transmission in the 200- to 400-megacycle UHF communication band, with a bandwidth nominally chosen at 3 kilocycles. Dipole antennas are chosen to eliminate the necessity for antenna tracking, with the result that the UHF equipment now existing for aircraft communications may be used in its entirety, and new development is necessary only for the satellite-borne equipment.

It should be noted that each of the systems chosen for investigation satisfies, to a greater or lesser extent, an existing communication requirement which is not fulfilled using present techniques. Nevertheless, a useful generality has been retained in that the particular points to which communication is to be established, and types of transmissions themselves, have not been specified. For example, a point-to-point relay could be established within the continental limits of the United States, or perhaps from the United States to Europe to Asia, and so on, and a similar flexibility exists with the UHF voice relay. The frequency-multiplexed signal may consist of a large number of voice signals or, with suitable restrictions, one or two video signals may be substituted. Similarly, the UHF voice relay might be utilized instead for a number of multiplexed teletype signals if such a capability were desired. Thus, a flexibility of application exists which permits conclusions regarding the power and weight requirements (and, consequently, feasibility) for a large number of possible interim systems to be derived from the results of this investigation.

2.7.2. Transmitter Power Requirements

a. FM Multiplex Systems

The transmitter power requirements for the interim FM multiplex systems may be established most easily by determing the modifications in coverage, bandwidth capability, and system signal-to-noise ratio (and resultant power requirement changes) which must be made in the appropriate relay of the initial global communication system. The reasons for choosing 10 kmc as an operating frequency for the initial global communication relays apply also to the interim relay systems, so the system noise levels used previously for operation in this frequency range apply as well.

It will be assumed that the FM multiplex systems will utilize a deviation ratio of five, where the deviation ratio may be defined for a sine-wave modulating signal as the ratio of the frequency deviation at the peak of the input signal to the frequency of the input signal. For example, if the intelligence to be transmitted consists of a sine wave with a frequency of 5 megacycles, the carrier signal will swing 25 megacycles on each side of its center frequency for a deviation ratio of five. But operation with a frequency-modulated system requires a certain threshold signal-to-noise ratio if the final output signal-to-noise ratio is not to be degraded. This threshold signal-to-noise ratio, measured at the wideband input to the discriminator, is a function of the deviation ratio, and about 13 db is found to be quite adequate for the assumed deviation ratio of five. Thus, since the transmission bandwidth of such an FM signal is some ten times the information bandwidth, provision of a transmission-band signal-to-noise ratio of 13 db requires an equivalent information-band threshold signal-to-noise ratio of 23 db. (This equivalent information-band signal-to-noise ratio is necessary since all previous calculations of required power have been on the basis of information bandwidth.) It should be noted that operation at threshold is quite satisfactory with multiplexed speech signals, since the nominal 4-kilocycle base band for this case yields very good final signal-to-noise ratios when the FM signal detected under these threshold conditions is demultiplexed. However, the base band for a signal such as a video signal is of the same order of magnitude as the 5-megacycle information bandwidth assumed above, and a sufficiently high final signal-to-noise ratio will not be attained unless detection of the FM signal occurs at several db above threshold to obtain additional FM noise-suppression gain.

Additional modifications necessary for the point-to-point systems include a decrease in the bandwidth of the satellite-borne antennas to about 1 degree since wider coverage than this is not required and the necessary (4-foot-square) antenna arrays can be packaged to meet the size limitations imposed upon the system while being launched into orbit. Also, the diameter of the ground antenna assumed for the high-density relays in the initial global system should be decreased to about 30 feet for an interim system, since this will somewhat simplify the problem of meeting the dimensional tolerances necessary for operation at 10 kmc. Finally, the duplex system will be derated by 6 db instead of the 3 db which would normally be expected in an attempt to compensate for (unknown) effects of system nonlinearities.

The adjustments in the 250-watt power requirement, obtained in Section 2.3.6b for the intercontinental relay of the initial global system, are summarized in Table 2-3 for each of the FM multiplex systems. It will be noted that a bandwidth of only 2.5 megacycles is used for the last case, namely, the restricted-area-to-restricted-area simplex system. This reduction is necessitated by the fact that no klystron or traveling-wave-tube amplifier is presently available or in late developmental stages with precisely the saturation power output required for a 5-megacycle operation. The reduction to 2.5 megacycles permits the use of a tube at its maximum capability, and thus provides a more efficient system.

b. UHF Voice System

The required transmitter power for the UHF voice system can be calculated as easily from basic transmission relationships (see Equation (2.2), Section 2.3.1) as by modification of the required powers calculated for the low-density relay in the interim global communication system. Assuming operation at 300 megacycles, dipole receiving and transmitting antennas with high efficiencies, and a receiver noise figure of about 5 db, the transmitter power required to attain a 15-db signal-to-noise ratio in a 3-kilocycle voice band is

Table 2-3. Power Requirement for FM Multiplex Systems.

System	Description of Modification	Power Reduction (db)	Required Power (watts)
FM Multiplex point-to-point, simplex transmission	Decrease signal-to-noise ratio for FM operation at threshold	+ 7	
	Decrease total bandwidth to 5 mc	+10	
	Decrease ground antenna diameter to 30 ft	- 6	
	Decrease beamwidth of satellite antennas to 1 deg	+12	
	Total	+23	1
FM Multiplex point-to-point, duplex transmission	Decrease signal-to-noise ratio for FM operation at threshold	+ 7	
	Decrease total bandwidth to 5 mc (2.5 mc each way)	+10	
	Decrease ground antenna diameter to 30 ft	- 6	
	Decrease beamwidth of satellite antennas to 1 deg	+12	
	Derate system 6 db for duplexing	- 6	
	Total	+17	5
FM Multiplex, restricted area-to-restricted area, simplex transmission	Decrease signal-to-noise for FM operation at threshold	+ 7	
	Decrease total bandwidth to 2.5 mc	+13	
	Decrease ground antenna diameter to 30 ft	- 6	
	Total	+14	10

found to be about 135 watts. Assuming AM voice transmission, this transmitter power is an average value which will yield the 15-db minimum average signal-to-noise ratio necessary for reliable reception of voice information.

2.7.3 Detailed Description of Possible Systems

A block diagram of the FM multiplex systems would be identical in all essential factors with the block diagram of the initial global communication system's intercontinental relay shown in Figure 2-9. Similarly, the operation will be identical with that described in Section 2.5.1. As in the intercontinental relay of the initial global system, traveling-wave-tube amplifiers would probably be used for all amplifier stages in the FM multiplex systems. In this case, however, TWT amplifiers are used, not to provide the necessary transmission bandwidth but because a greater selection of TWT's is available than klystron amplifiers (see Figures C-1 and C-2), and the ability to choose a final output tube which most closely fits the system requirements permits attaining maximum over-all system efficiency and minimum total power requirements.

The weight and power requirements for the various components of the FM multiplex systems are summarized in Table 2-4. It will be noted that periodically focused tubes are available today which can completely satisfy the amplifier requirements of the point-to-point simplex system, so the estimated total weight and power requirements for this system become about 80 pounds and about 174 watts, independent of any future tube developments. Furthermore, periodically focused tubes are available for the low-power amplifiers in the other two systems, so only a periodically focused tube with characteristics similar to those of the Sperry STX-77 need be developed* to permit utilization of periodically focused tubes for all amplifiers in all three FM multiplex systems. The total weight and power requirements for both the point-to-point duplex and restricted-area-to-restricted-area simplex systems are estimated to be 101 pounds and 610 watts, respectively, using presently available tubes, and 86 pounds and 210 watts if all tubes are periodically focused.

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*Such a tube could probably be developed and produced in the small quantities required for this system within 2 years of the initiation of such development.

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System	Component	Weight (lb)	Weight if Periodically Focused (lb)	Beam Power (watts)	Solenoid Power (watts)	Heater Power (watts)	Total Power: with Presently Available Components (watts)	Total Power: Using Periodically Focused Tubes (watts)
Point-to-Point Simplex	TWT Amplifiers							
	Huggins HA 20	3-3/4	3-3/4	3	-	6	9	9
	Huggins HA 20	3-3/4	3-3/4	3	-	6	9	9
	Huggins HA 21	5-1/4	5-1/4	50	-	6	56	56
	Low-pass filters and directional couplers	5	5	-	-	-	-	-
	Mixer	5	5	-	-	-	-	-
	Local oscillator and associated circuits	17	17	-	-	-	100	100
	Sideband filter	5	5	-	-	-	-	-
	Antennas and feeds	10	10	-	-	-	-	-
	Mountings	25	25	-	-	-	-	-
		80	80				174	174
Point-to-Point Duplex	TWT Amplifiers							
	Huggins HA 20	3-3/4	3-3/4	3	-	6	9	9
	Huggins HA 20	3-3/4	3-3/4	3	-	6	9	9
	Sperry STX-77	22	12	80	400	12	492	92
	Mountings	30	25	-	-	-	-	-
	Other components	42	42	-	-	-	100	100
		101	86				610	210
Restricted-Area-to-Restricted-Area Simplex	Same as Point-to-Point Duplex above							

Table 2-4. Estimated Weight and Power Requirements of Interim FM Multiplex System Components.

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As with the high- and low-density relays for the initial global communication system, the desirability of maximizing the reliability of these interim systems indicates that spare components should be provided throughout the entire system together with fail-safe detection and switching circuits. The additional weight required by this procedure is estimated at about 85 pounds for the point-to-point simplex system and either 105 or about 90 pounds for the other two systems, depending upon whether periodically focused tubes are available. In all three cases, increasing reliability by the above technique should not add more than about 10 watts to the total estimated power requirements. For purposes of convenience, these results are summarized in Table 2-5 along with estimated weight and power requirements for the UHF voice relay discussed in the following paragraph.

A block diagram of the UHF voice relay would be identical in all essential features with that of the ZI relay for the initial global communication systems shown in Figure 2-8. In this case, however, the fact that the operating frequency is in the UHF communication band permits the use of more commonly known amplifier tubes and design techniques, including the use of a tetrode power amplifier such as the 4X250 as a highly reliable output tube. The estimated weights and power requirements for the UHF voice system are summarized in Table 2-6, indicating that this system should not weigh more than about 20 pounds and would require a total power of about 258 watts. If spares are supplied for all electronic components and fail-safe detection circuits are added, these estimated weight and power requirements increase by about 33 pounds and 10 watts, respectively. These results are summarized also in Table 2-5 for comparison with the FM multiplex systems.

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Table 2-5. Summary of Weight and Power Requirements of Interim Communication Relay Systems.

System	Incremental Weight (lb)		Incremental Power (watts)		Total Weight (lb)		Total Power (watts)	
	A	B	A	B	A	B	A	B
1. FM Multiplex, Point-to-Point Simplex	-	-	-	-	80	80	174	174
a. Same, with spares and fail-safe equipment	85	85	10	10	165	165	184	184
2. FM Multiplex, Point-to-Point Duplex	-	-	-	-	101	86	610	210
a. Same, with spares and fail-safe equipment	105	90	10	10	206	176	620	220
3. FM Multiplex, Restricted-Area-to-Restricted-Area, Simplex	-	-	-	-	101	86	610	210
a. Same, with spares and fail-safe equipment	105	90	10	10	206	176	620	220
4. VHF Voice Relay (see Table 2-6)	-	-	-	-	20	-	258	-
a. Same, with spares and fail-safe equipment	33	-	10	-	53	-	268	

Legend: A - Using presently available tubes
B - Using periodically focused tubes

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2.10 ALTERNATIVE APPROACHES TO GLOBAL COMMUNICATION SYSTEMS

The detailed parameters and resultant configurations of the satellite-borne communication systems recommended here depend rather markedly upon the requirements assumed for the system and upon the equipment assumed to be available. If any of these requirements should be changed or if other equipment becomes available, the resulting system could very easily differ in both coarse as well as fine detail from that described above. For example, if it is assumed that a solid-state molecular amplifier will be available for use in the ground equipment, providing a decrease in effective receiver noise level of 17 to 20 db; that a signal-to-noise ratio of 20 db instead of 30 db may be sufficient; and that a bandwidth of 5 mc instead of 50 mc would be adequate, these assumptions would permit the postulation of a system in which a spinning satellite, stabilized only with respect to the plane of its orbit, would require no azimuthal transmission directionality (in its orbital plane), and would need only a 16-degree vertical bandwidth to ensure complete coverage of the earth. The system gains obtained by the above revised assumptions thus permit the elimination of accurate attitude stabilization and still provide sufficient excess gain to allow decreasing transmitter power requirements to as little as 2 watts, a value which could possibly yield longer system lifetimes and which would definitely reduce system weights.

However, as usual, a gain in one respect is not obtained without increasing losses in others. As discussed in the preceding section, the provision of a jam-resistance capability for high-density relays (which may be considered to include this modified case) would probably necessitate the use of highly directional antennas to prevent jamming transmitters from falling within the main beam. The modified system would be extremely subject to jamming of the satellite receiver by a ground jammer, since it has been postulated that the entire earth will fall within the main beam of the satellite antenna. A similar problem exists with the ground receiver; lowering the level of the received signal, by using a molecular amplifier, and decreasing signal-to-noise ratio, both tend to render the system susceptible to jamming through antenna side lobes from transmitters in such sources as submarines, balloons, low-altitude satellites, and so on. Hence, this discussion points up the fact that, while such modifications in system parameters to decrease required transmitter power might be quite desirable for a system intended for peacetime communication applications, the high reliability (and consequent high jam-resistance capability) which is of utmost importance in a military system almost invariably leads to the conclusion that the highest possible power level should be used for transmission in order to maximize the problems facing an enemy jammer.

In addition, the modifications described above would result in a system of substantially reduced capabilities when compared with the global system described in the foregoing sections. It may be argued, and quite rightly, that the reductions in bandwidths and signal-to-noise ratios postulated above still provide capabilities far in excess of those available at the present time. Nevertheless, it is felt that the importance placed in this report upon providing high quality service with bandwidth capabilities is by no means over-emphasized. All communications experience tends to indicate that the bandwidth capabilities provided by any new system are almost invariably saturated shortly after, if not even before, the system becomes operational. Similarly, the statements that a 20-db signal-to-noise ratio is adequate, and that a 30-db signal-to-noise ratio will provide good quality service, should not be taken to imply that higher signal-to-noise ratios may not be desired. Signal-to-noise ratios of 40-, 50-, and even 60-db values obtained on wireline circuits, are by no means excessive in terms of the quality of communication obtained. Therefore, degradation of system performance by reducing signal-to-noise ratios from say, 30 to 20 db should not be undertaken without substantial reason. Therefore, it is our feeling that the general characteristics of the system described before represent an excellent but reasonable system chosen from competing alternatives. Moreover, since characteristics indicate the present feasibility of a high quality system, any lowering of the quality of the system would, *a fortiori*, make the system even more feasible.

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CHAPTER 5

INFRARED EARLY WARNING METHODS FROM 24-HOUR SATELLITES

A brief study of the feasibility of detecting ballistic missiles from the 24-hour satellites using infrared methods was made. However, because the study is not sufficiently complete to be included here, it will be issued at a later date, either in the final version of this volume or under a separate cover.

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APPENDIX A

ANTENNA DESIGN CONSIDERATIONS FOR 24-HOUR SATELLITES

Designing antennas for systems carried in 24-hour satellites requires careful consideration of a number of closely interrelated factors. Certain [redacted] include the bandwidth over which the antennas must operate, the polarization of the signals to be received, and the magnitude of the side and back lobes relative to the main antenna beam. More fundamental considerations, however, arise from the unique physical surroundings of a satellite, both during ascent and while in its orbit, which affect its size, weight, and over-all construction.

Probably the most obvious restriction placed upon a satellite antenna is the requirement for minimum weight imposed by the limited payload capacity of the ascent vehicle. However, since all elements of the satellite are in essentially a free-fall or weightless condition once the satellite is established in its orbit, the forces exerted on an antenna under such conditions are practically zero. Thus, extremely lightweight materials may be used for its construction if proper packaging techniques are used for protection from the forces present during the initial ascent. This absence of weight for a body in free fall introduces new concepts into the design of an airborne antenna with respect to size as well as weight, since it now becomes possible to consider the use of an antenna of almost unlimited size providing, once again, that it can be packaged to conform to the dimensional and environmental requirements imposed upon the ascent vehicle. It must be remembered, however, that large dimensions may be highly detrimental if tracking is required of the satellite antenna, since an antenna of appreciable size may have a high moment of inertia, and thus require a high torque for its rotation, even though its over-all weight may be quite small. Nevertheless, within reasonable limits, the size and weight limitations on a satellite antenna will be determined, in the final analysis, by the effectiveness and ingenuity displayed in packaging the antenna for ascent.

The final factor which must be considered in the design of a satellite antenna is its susceptibility to damage by meteoric impact. The impact probability on an antenna of any reasonable size by a meteorite capable of penetrating, say, a millimeter of aluminum is small but not negligible, and the reliability required of a satellite-borne system dictates careful consideration of this factor.

The design problem for a satellite antenna may be defined conveniently [redacted] provide the necessary coverage at the operating frequency, although if tracking antennas are required the size of the aperture thus defined may become important. Therefore, when these considerations are added to the fact that freedom of choice of operating frequency exists only in the case of the relay system, it may be concluded that antenna aperture limitations will have their most serious effects in reconnaissance and jamming applications.

The aperture provided by the satellite antennas may be fed by a horn, by a parabolic segment reflector with driver arrangement, or by a linear array of elements. The last arrangement is the most promising of the three when a requirement for a large aperture antenna precludes the use of the relatively simple parabolid reflector. However, the wide bandwidths required for most of the applications of interest in this investigation sharply restrict the class of antennas which may be used as the elements of an array. A number of types of feed elements have been investigated during the course of this study, several of which have properties worthy of discussion here and which are described further in the following paragraphs.

A number of types of feed elements may be formed by a conductive coating plated on a flexible dielectric backing, and could be fed in phase by a Christmas-tree feed structure, also plated on the dielectric backing to form the desired antenna array. Because of the bandwidth requirements, and also because of packaging difficulties, no cavity backing would be provided for the antennas and consequently their beam would be bidirectional. An array of such antennas mounted upon a thin flexible backing could be packaged during vehicle take-off and ascent in a form similar to a rolled-up window shade. When the satellite is established in its orbit, compressed gas, spring tension, or some other similar force would unroll the antenna array to its full extent with telescoping tubes or some similar mechanism being used to guide this process. Since the length of the final satellite vehicle will probably be from 8 to 10 feet, it is quite conceivable that an antenna array packaged in the above manner could provide a final antenna aperture some 8 feet square.

Another possible feed element is the dielectric rod or polyrod antenna. Such an antenna is essentially a traveling-wave structure which radiates appreciable energy in only one direction, so an antenna array composed of polyrod radiators would not have the rear lobe present with the plated element arrays referred to above. The polyrod array would be fed by a strip-line feed structure incorporated in the base plate. If the polyrods are to be efficient radiators, however, they must be of appreciable length in terms of wavelengths at the operating frequency of interest. For this reason, a relatively rigid base plate would be required and the maximum aperture which would be provided would be about one-fourth (4 feet square) that which seems possible for a plated-element antenna array. However, this disadvantage is compensated in part by the fact that a polyrod antenna array has no rear lobe, as well as by the fact that the relatively limited beam of the polyrod antennas tends to minimize any side lobes of the array.

Once having chosen a basic feed element, the efficiency of an antenna array is determined by the number of elements constituting the array since this will determine the over-all mismatch, feed line losses, and similar factors which establish the final antenna efficiency. Experience has shown that 16 elements are about the maximum number which can be fed with reasonable efficiency, and that a net antenna efficiency of about 50 per cent may be obtained using this number of elements. It should be noted that the limitation on the number of elements constituting an array results in an increase in the spacing of these elements, in units of wavelength, as the operating frequency of an array is increased. This causes a group pattern to be generated with side lobes, of the same amplitude as the main beam, spaced at angles determined by the relation $d_\lambda \sin \theta = n\lambda$. Since d_λ, the element spacing in wavelengths, does not exceed 4λ for any array considered below, the first such side lobe would occur some 14 degrees off the main-lobe axis. For a reconnaissance antenna, the fact that the earth subtends an angle of only 16 degrees at the satellite precludes this side lobe from intercepting extraneous signals, and the only effect would be a reduction in over-all gain and (possibly) introduction of extraneous solar noise. In addition, if a polyrod array is considered, the fact that the unit pattern of the polyrods are relatively narrow, ranging from 30 degrees for a 6λ rod to 22 degrees for a length of 10λ (see Figure A-1), will cause suppression of the side lobes to quite reasonable amplitudes.

It should be noted that the arrays described above are almost completely insensitive to any effects of meteoric impact. The only possible event which could significantly alter the operation of the arrays would be the complete severance of a portion of the feed structure, and the probability of such an occurrence is so small as to be completely negligible.

The approximate beamwidth of an array of linear elements is shown in Figure A-2 as a function of the aperture dimension for parametric operating frequencies. The gain and effective aperture of any given antenna may be calculated from the results of this figure by standard formulas, proper account being taken of antenna efficiency and whether or not the rear lobe of the antenna pattern has been suppressed. The parameters of an 8-foot-square array of plated element antennas without cavity backing, calculated in this manner, are given in Table A-1. The parameters of arrays with dimensions smaller than 8 feet square may be scaled directly from the results given in this table. Theoretically, the results for a polyrod array may be obtained also from Table A-1 merely by increasing gains by 3 db and effective

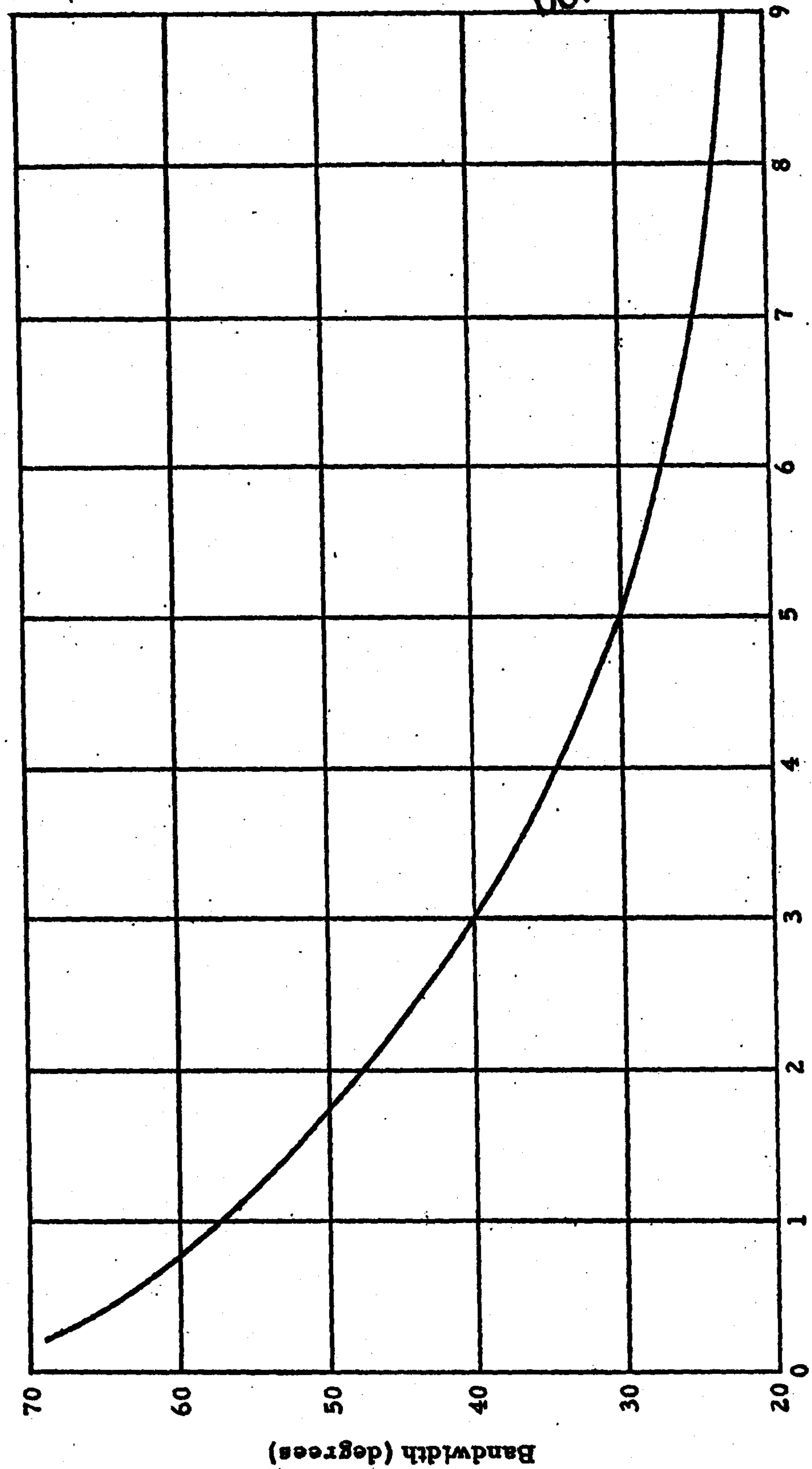

Figure A-1. Beamwidths of a Single Polystyrene Dielectric Rod Antenna of Varying Length.

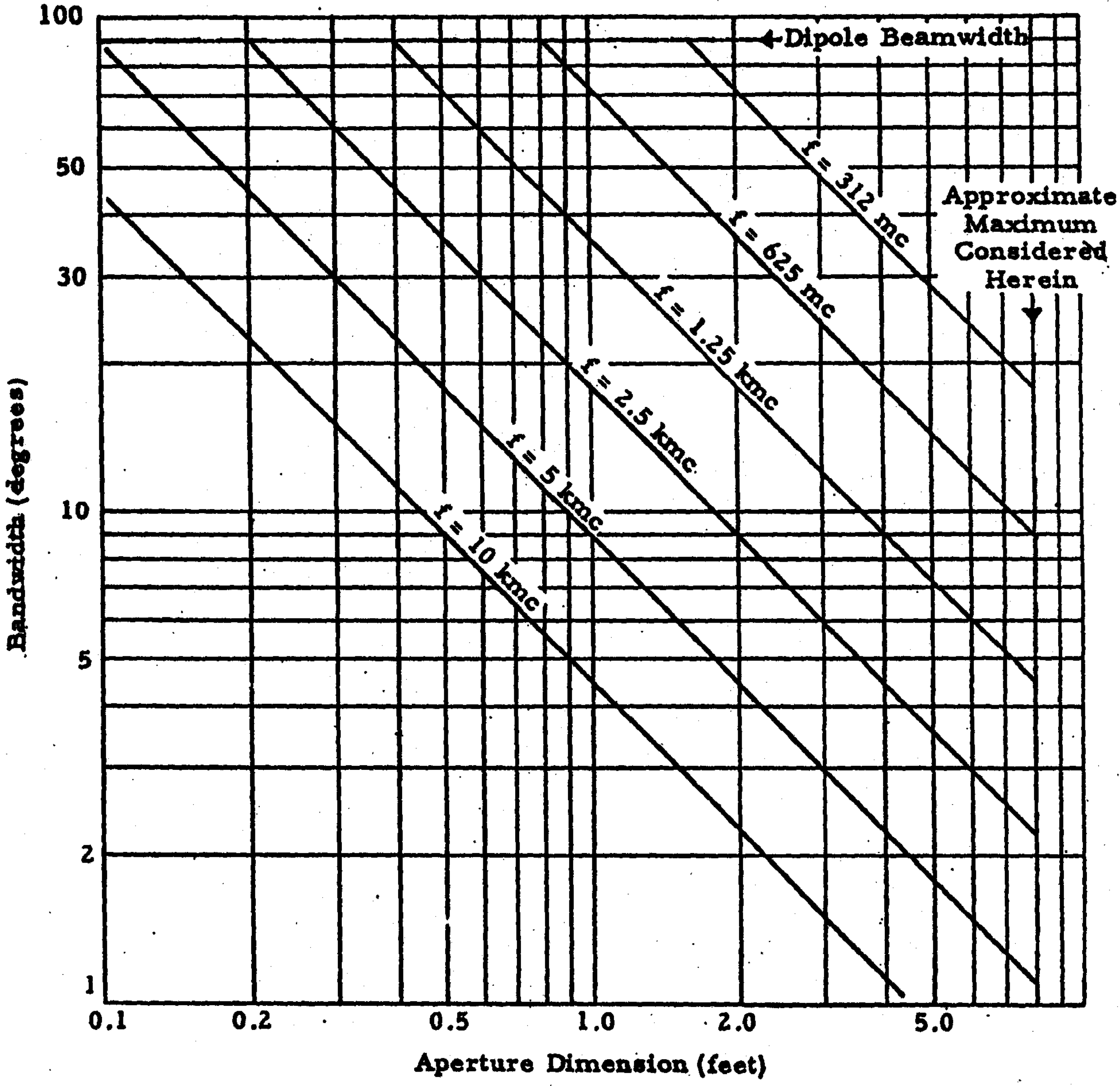

Figure A-2. Approximate Antenna Beamwidth as a Function of Aperture Dimension.

apertures by a factor of two. However, the dimensions of a polyrod antenna become cumbersome at frequencies below S-band or so, and for this reason such antennas are not considered below this point.

Table A-1. Parameters of 8-Foot-Square Array, No Cavity Backing.

Frequency (mc)	No. of Elements	Electrical Spacing	Beamwidth (degrees)	Assumed Eff. Factor (db)	Gain* (db)	Effective Aperture (m^2)
75	1	--	72	-1.5	3.5	2.70
150	4	λ/4	36	-3	8	1.83
300	4	λ/2	18	-3	14	1.83
625	16	λ/2	9	-3	20	1.83
1250	16	λ	4.5	-3	26	1.83
2500	16	2λ	2.25	-3	32	1.83
5000	16	4λ	1.12	-3	38	1.83

*Includes -3 db for unsuppressed rear lobe, as well as appropriate antenna efficiency factor.

APPENDIX B

NOISE CONSIDERATIONS

Regardless of whether the system considered in this report is used for communication relay purposes or for the interception of enemy communications, the minimum signal which can be received with a given reliability will be determined by the noise level of the system. The noise existing in a radio system arises from several sources, with the contribution from each source being a function of the operating frequency, the electrical parameters of the system, and the actual physical location and orientation of the system. The various types of radio noise are discussed in the following paragraphs and their contribution in limiting signal reception is assessed with respect to the applications of interest in this study.

A basic source of radio noise is the thermal noise caused by the thermal agitation of electrons in resistance elements of the system. For an ideal receiver, the set noise level is determined by the thermal noise generated in the resistive component of the input impedance. This noise power for the ideal receiver is given by the expression $N = kT\beta$, where k is Boltzmann's constant, T is the temperature of the input impedance in degrees Kelvin, and β is the effective bandwidth of the receiver. From this expression it may be seen that, for a given temperature, the set noise of an ideal receiver is proportional only to the bandwidth of the receiver. To a good approximation, this proportionality of noise to bandwidth is true also for all other types of noise of importance in this study. Therefore, the contributions from the various types of noise may be compared directly if the bandwidth chosen in each case is the same. This comparison is made in this report after assuming a temperature T of 300° Kelvin for evaluation of set noise.

The quality of a receiver, as far as noise is concerned, is determined by means of its noise figure. The noise figure, F, of a receiver is defined by the relation $(S/N)_o = (1/F)\,(S/N)_i$ where $(S/N)_{o,\,i}$ is the output signal-to-noise ratio of the actual receiver and input signal-to-noise ratio of an ideal receiver, respectively. Thus, the noise figure of a receiver is a measure of the amount by which the actual receiver degrades the signal-to-noise ratio possible with an ideal receiver, or, in other wards, the noise figure indicates the amount of noise which the actual receiver adds to the ideal receiver noise. Curve A of Figure B-1 indicates what may be expected from a good receiver relative to the noise in an ideal receiver. As indicated by the above discussion, the noise figure of these good receivers is given directly by the values plotted in this curve.

Cosmic noise is defined as that noise originating from sources in space other than the sun. Most of the cosmic noise incident upon the earth originates in the plane of the galaxy, with the primary source being located in Sagittarius towards the galactic center. However, a substantial number of point sources or "radio stars" have been located also, with the principal sources lying in Cassiopeia and Cygnus. The cosmic noise level received on a half-wave dipole antenna from the galactic plane in the direction of the center of the galaxy is shown, relative to the noise in an ideal receiver, as curve B in Figure B-1. The noise levels from other parts of the galactic plane are between 10 and 20 db below the level given by this curve. Shown also in Figure B-1 is the cosmic noise level, relative to ideal receiver noise, received on a half-wave dipole antenna from Cassiopeia (curve C), which is the most intense discrete source of cosmic noise known at present time.

Another source of radio noise is the sun. The intensity of this noise will vary depending upon solar activity, with solar noise from a quiet sun, when there is little or no sun spot or solar flare activity, being substantially less than the noise from the sun when it is "disturbed." Curve D of Figure B-1 shows the solar noise level from a quiet sun as received on a half-wave dipole antenna, again with respect to the noise of an ideal receiver. Curve E of Figure B-1 gives an indication of solar noise level from a disturbed sun, but it should be emphasized that observed values of noise from the disturbed sun may vary by 10 db or so from the indicated value due to variations in the intensity of the solar disturbances.

The final sources of radio noise are atmospheric noise and man-made noise. Atmospheric noise is produced mainly by lightning discharges in thunderstorms, while man-made noise includes any interference from sources such as rotating machinery, ignition discharges, etc. Although the frequency spectrum of atmospheric noise may extend well above the high-frequency band,

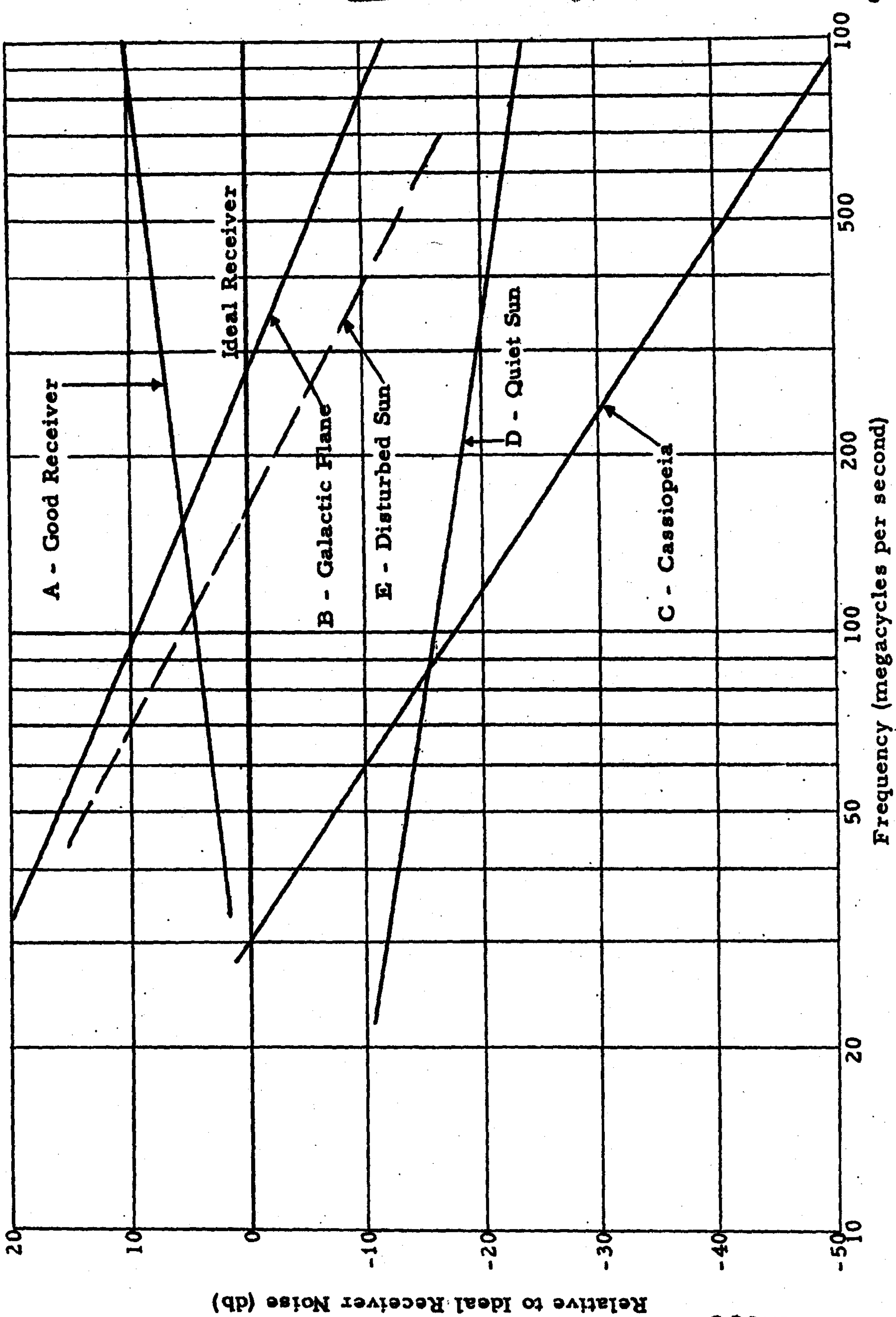

Figure B-1. Noise Levels from Various Sources, Half-Wave Dipole Receiving Antenna (after Federal Handbook).

the energy in the portion of the spectrum above about 30 megacycles or so is substantially less than the energy produced by cosmic noise. For a variety of reasons, which are discussed in more detail in other sections of this report, frequencies below about 40 megacycles are not useful for the purposes of interest in this study, so atmospheric noise will not be considered further. Also, since the effect of man-made noise can usually be eliminated or reduced to negligible proportions by good design practices and adequate shielding, man-made noise will not be considered further in this report.

The curves of Figure B-1 indicate that cosmic noise will limit reception in a dipole antenna at frequencies up to about 160 megacycles or so, at which point the receiver noise takes over as the limiting factor. However, both cosmic and solar noise originate in sources external to the receiving system, so these noise levels will vary with the gain, or receiving aperture, of the receiving antenna. Since the galactic plane is an extended nonuniform source, the antenna gain normally obtained with radiation from a point source cannot be realized. For this reason, obtainable antenna gains must be limited to about 15 db when considering this source. Thus, the cosmic noise received from the center of the galaxy cannot exceed the values shown in Figure B-1 by more than about 15 db. Also, since the cosmic noise from other parts of the galactic plane are 10 to 20 db below that from the galactic center, this maximum gain limits the noise which can be received from the other portions of the galaxy to maximum values approximately equal to those shown in curve B of Figure B-1. On the other hand, the sun and the discrete sources of cosmic noise such as Cassiopeia are point sources, and antenna gains of 50 to 60 db or more can be realized in these cases.

Figures B-2 and B-3 show the various noise levels indicated in Figure B-1 adjusted for antenna gains of 15 to 30 db, respectively. With a 15-db antenna gain, Figure B-2 shows that cosmic noise from the galactic plane and receiver noise are still the limiting factors, but the cross-over frequency has increased to about 480 megacycles or so. When higher antenna gains are used, however, the curves of Figure B-3 (for the case of a 30-db gain) show that the noise from the disturbed sun replaces the noise from the center of the galactic plane as a limiting factor. For this particular case, solar noise remains the limiting

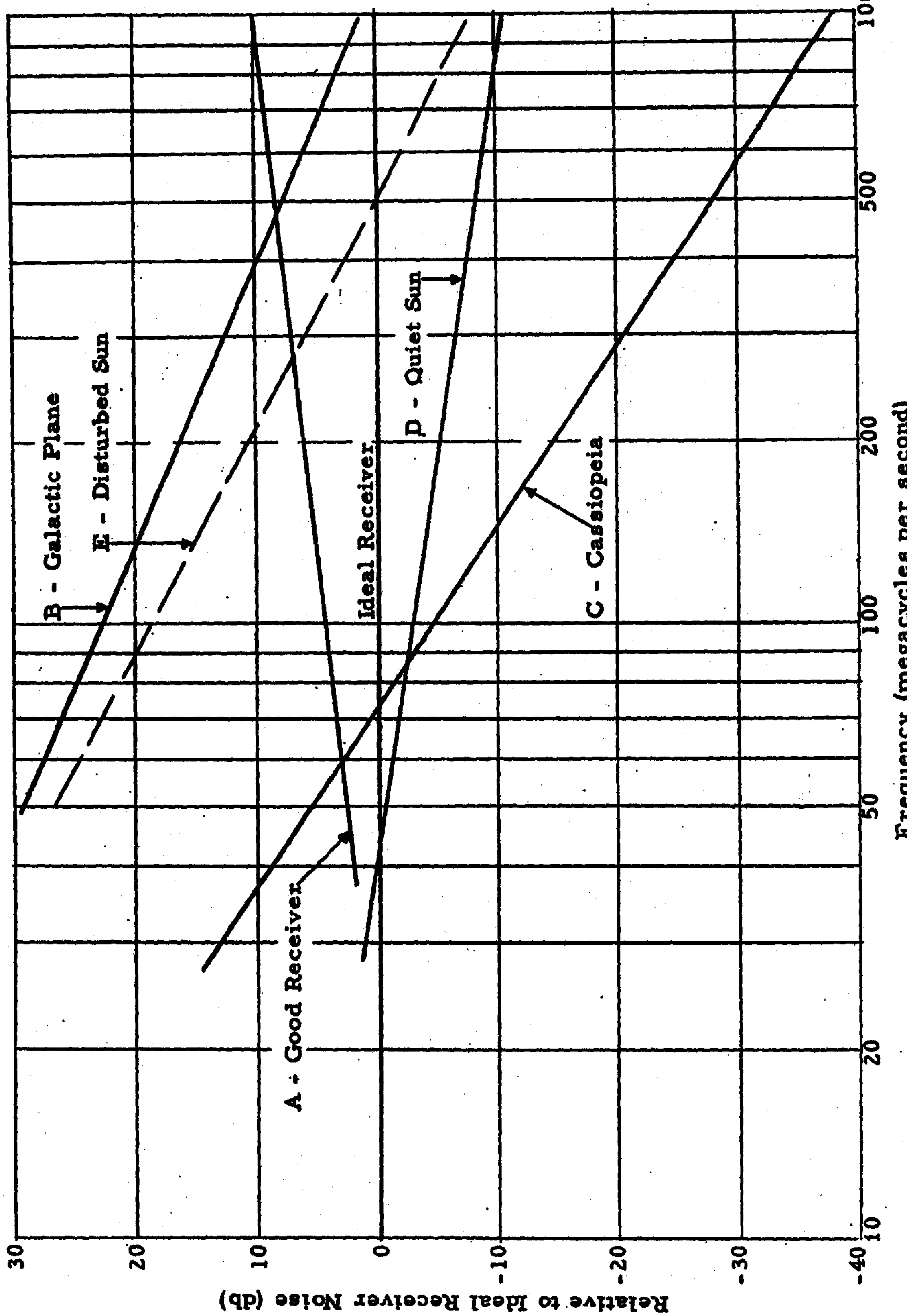

Figure B-2. Noise Levels from Various Sources, 15-db Receiving Antenna Directed at Noise Source.

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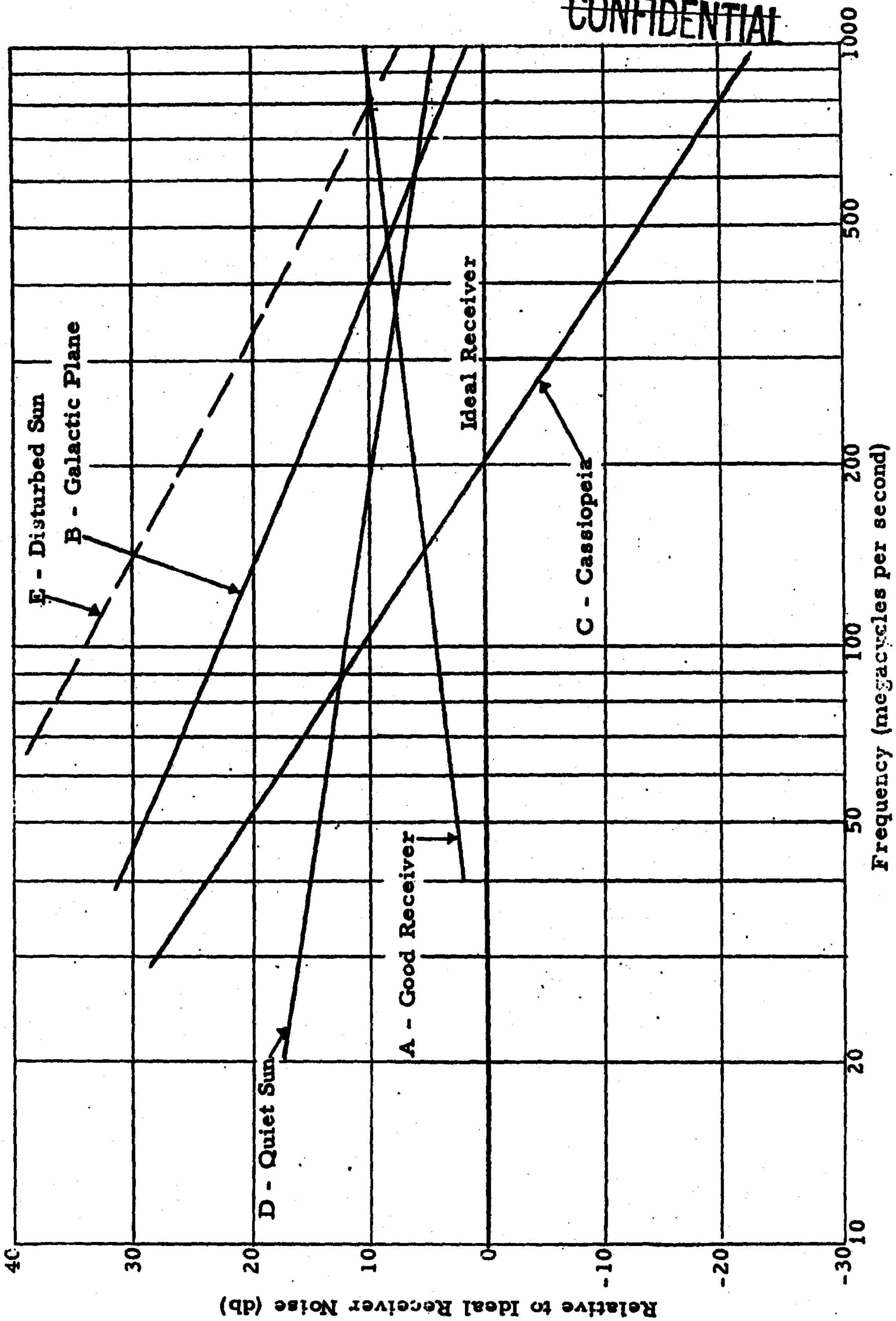

Figure B-3. Noise Levels for Various Sources, 30-db Gain Receiving Antenna.

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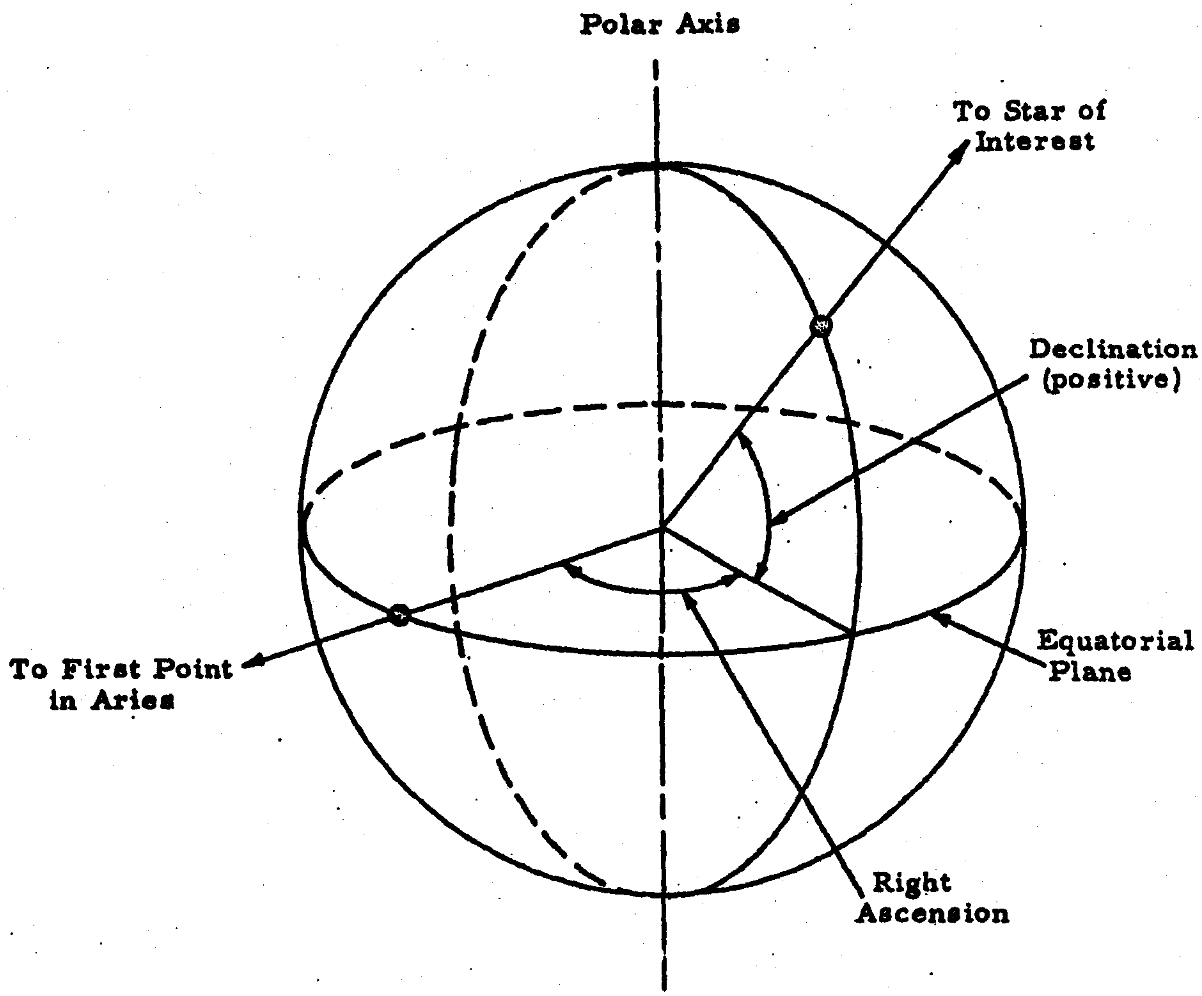

Figure B-4. Illustration of Definitions of Celestial Coordinates.

factor up to almost 1000 megacycles, but if higher antenna gains are available, the frequency at which set noise replaces solar noise as the limiting factor may increase to 10 kmc or above.

The final conclusion regarding the type of noise which will limit reception under any particular conditions cannot be reached without consideration of the geometry and orientation of the receiving antenna beam. All of the sources of external radio noise discussed in the above paragraphs are localized to a greater or lesser extent, so an antenna will not receive the noise from these sources unless it is pointed toward them. For this reason, it is useful to digress at this point so that the celestial coordinates used to define the position of these cosmic noise sources may be defined. As the earth rotates about its axis, any given star will maintain a fixed vertical angle above the equatorial plane. This angle, indicated as positive when measured northwards from the equator and negative when measured southwards, is called the declination of the star and is its first celestial coordinate. The second celestial coordinate, termed the right ascension, is defined by the angle, measured in the equatorial plane, eastward from the plane containing the earth's axis and the first point in Aries to the plane containing the earth's axis and the star in question. These definitions of the celestial coordinates are illustrated in Figure B-4.

Since the equatorial plane is inclined to the plane of the ecliptic, which is the plane defined by the earth's orbit about the sun, the celestial coordinates of the ecliptic (or of the sun) will vary throughout the year. Thus, the sun cannot be included as one of the so-called "fixed" stars. This variation of the celestial coordinates of the ecliptic is illustrated in Figure B-5, which shows the earth in its orbit around the sun, and in Figure B-6 which is a Mercator projection of the heavens showing some of the more prominent fixed stars as well as the path of the ecliptic.

The several sources of radio noise may now be considered with respect to their location relative to the orientation of the receiving antennas which will be used in the various applications of interest in this study. The galactic center is located at a declination of from about -20 to -30 degrees. As shown in Figure B-7, any antenna with a relatively narrow beam pointed toward satellite in a 24-hour equatorial orbit from any point on the earth or from any satellite

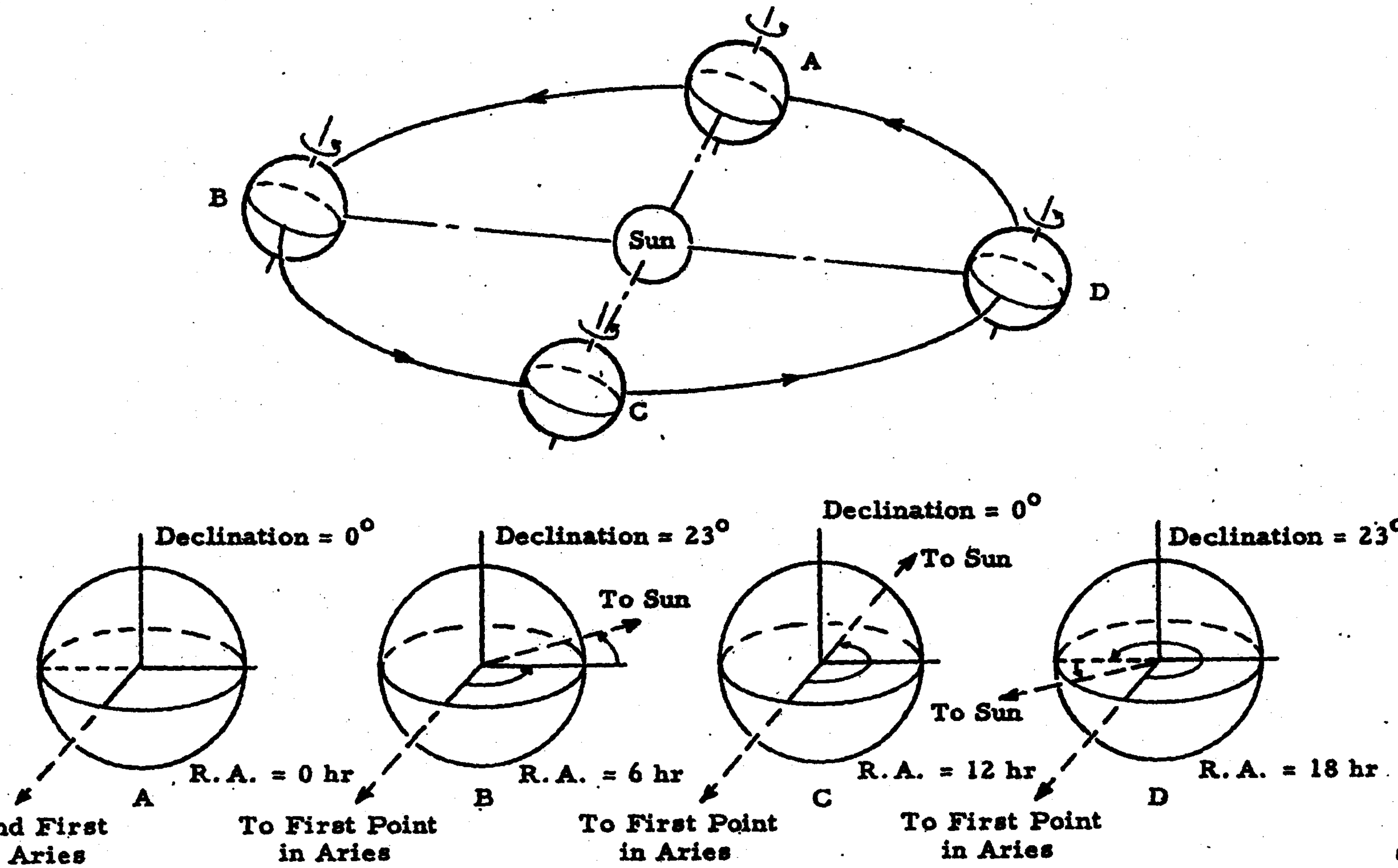

Figure B-5. Illustration of Variation of Celestial Coordinates of Ecliptic.

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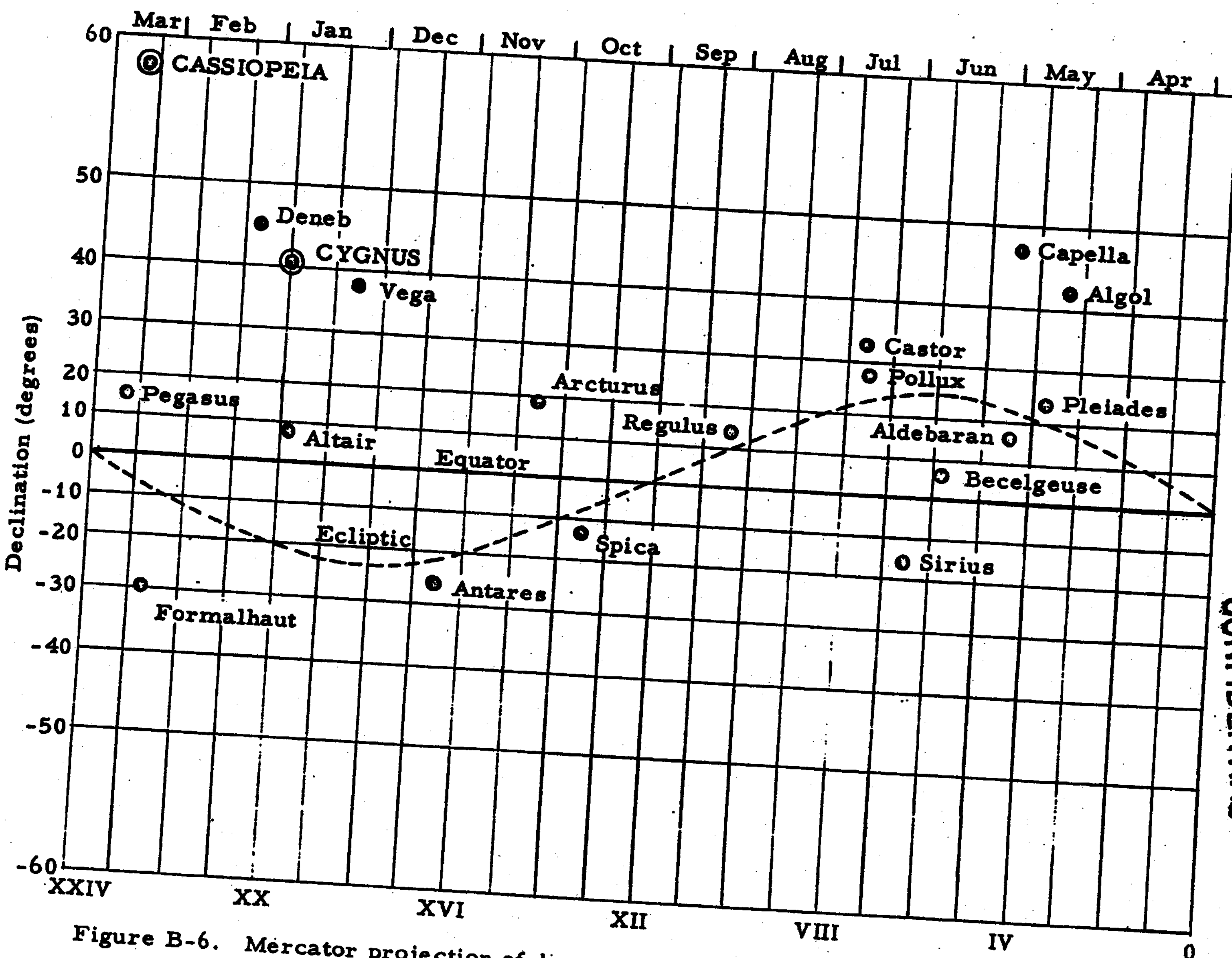

Figure B-6. Mercator projection of heavens, showing some of the more prominent stars between December ±60 degrees and the two most intense radio stars. Hours of R.A. are shown along the bottom of the map, and dates at which the sun reaches different points on the ecliptic are indicated approximately along the top (after Lovell and Clegg).

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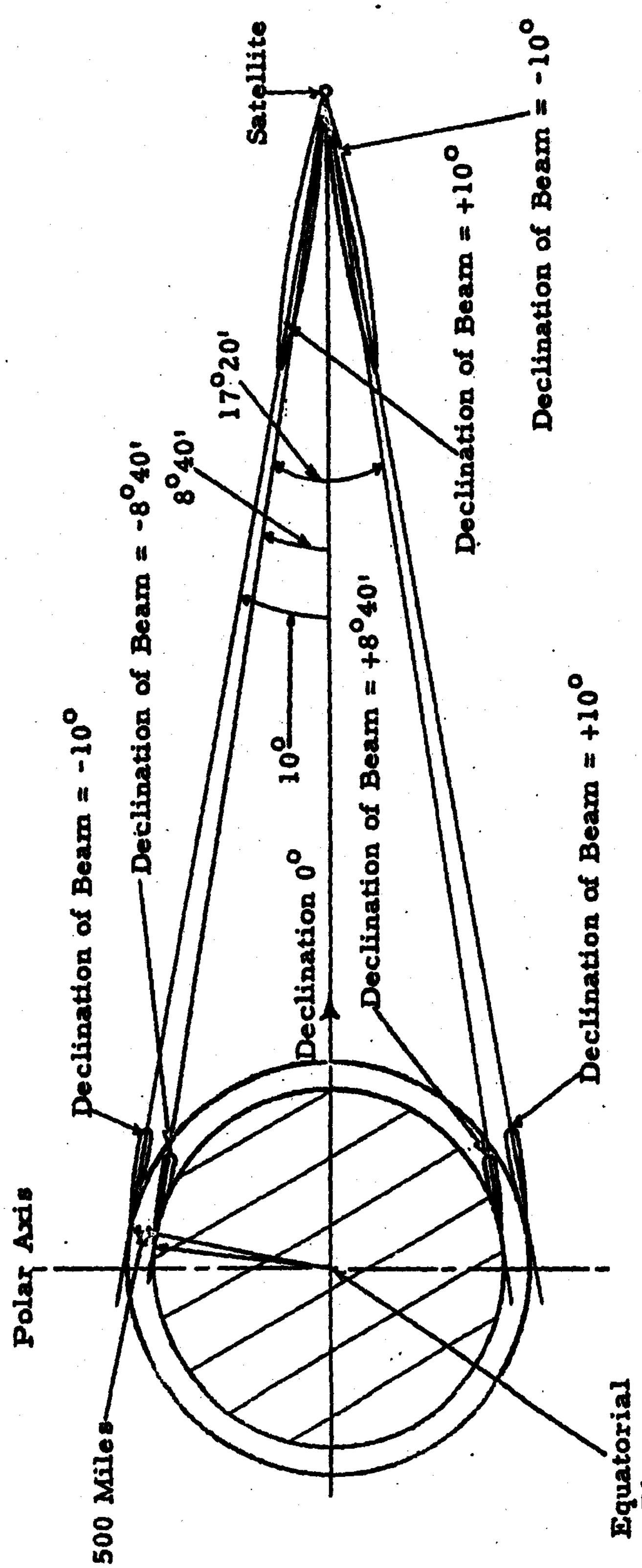

Figure B-7. Declination of Antenna Beams to or from Satellite in 24-Hour Orbit and Any Point Within 500 Miles of Earth's Surface.

at an altitude of, say, 500 miles or less above the earth, will be pointed at declinations above -10 degrees. Of course, this statement holds also for an antenna pointing from satellite to these points within 500 miles of the earth's surface. Thus, the noise from the galactic center must be considered for the applications investigated in this study only in the case of the polar orbits recommended for low-density communications relay service and in the case of the equatorial communications interception satellite where narrow antenna beams cannot be obtained at the lower frequency ranges of interest.

As shown in Figure B-6, the declinations of the discrete noise sources located in Cassiopeia and Cygnus are greater than +40 degrees, and from the preceding paragraph and Figure B-7 it is evident that noise from these sources cannot be received by relatively narrow-beam antennas pointed between a satellite in a 24-hour equatorial orbit and any point within 500 miles of the earth's surface. An antenna oriented for transmission to a satellite in a polar orbit may intercept these discrete sources of cosmic noise, but if the antenna has a relatively narrow beam, this will occur, in the worst case, only once each day and then only for a short period whose time of occurrence can be predicted with very high accuracy.

Finally, reference to Figures B-1 through B-3 will show that solar noise can become important only if the antennas have a high gain and consequently a narrow beamwidth. But solar noise can be received by a narrow-beam antenna only when the declination of the point at which the antenna is aimed coincides with the declination of the ecliptic. As shown in Figure B-6, this cannot occur unless the declination of the antenna beam is between +23 and -23 degrees. From the discussion in the preceding paragraphs, it is clear that, in the case of reception from a 24-hour equatorial satellite, solar noise can be intercepted only during the relatively short (and predictable) time once each day during the two periods (of a few days each) throughout the year when the receiving antenna beam actually points at the sun. When receiving signals from polar satellites, on the other hand, antennas at certain points on the earth's surface may intercept solar noise once each day for nearly a month at a time. Thus, the possible effects of such noise on the communication relay application (wherein the problem arises) are evaluated in more detail in the specific discussion of Chapter 2, Section 2.3.5 of this particular application. Finally, it should be noted that the results shown in Figures B-2 and B-3 indicate that some care might be necessary, in designing antennas for intelligence applications, to keep the side lobes sufficiently small so the solar noise received through such lobes does not set the limit to the system performance.

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APPENDIX C

AMPLIFIER CHARACTERISTICS

Traveling-Wave-Tube Amplifiers

Traveling-wave-tube amplifiers are broad-band devices which usually operate over an octave bandwidth and rarely have bandwidths less than about 10 per cent of the operating frequency. These amplifiers utilize the interaction between a beam of electrons and a slow-wave structure which either surrounds or is surrounded by the electron beam. As a signal travels along the slow-wave structure, the interaction of the field with the electron beam causes the electrons to slow down; the energy thus lost by the electron beam is transferred to the wave propagating along the slow-wave structure to cause amplification. Since the electron beam is present continuously, a traveling-wave tube acts as a class-A amplifier with maximum power amplification efficiencies of the order of 10 to 20 per cent. In addition, an axial magnetic field is required in the tube to prevent defocusing of the electron beam by mutual repulsion effects. At present, the magnetic focusing field is supplied in most tubes by a solenoid electromagnet surrounding the tube. These solenoids may weigh anywhere from about 6 to 60 pounds and will draw a direct-current power of from 100 to 400 watts, depending upon the output power of the tube, upon whether the solenoid is designed to obtain minimum weight, or upon other similar factors.

More recently, periodically focused traveling-wave tubes have been developed in which permanent magnets are used to provide focusing action at periodic intervals along the tube. The total weight of periodically focused tubes now available runs from about 5 to 12 pounds, depending upon the power output of the tube, and, since no solenoid is necessary, there is no solenoid power dissipation. At the present rate of development, it may be expected that periodically focused tubes will begin to become available in about mid-1959 in a variety of types comparable to the variety of solenoid-focused tubes which are either available or in the late development stages today.

Although it is probable that some tubes have unintentionally been omitted, the traveling-wave-tube amplifier chart shown in Figure C-1 serves to indicate that a reasonable amount of choice exists over most of the frequency range up to 12 kmc and at most power levels up to about 200 watts (for CW tubes). Higher powers are available in pulsed tubes, but the low duty factor required with such tubes precludes their use in the systems investigated herein.

The noise figure of a traveling-wave tube will depend upon the power level of the tube, its gain, its operating frequency, and its bandwidth. The low-power receiving tubes are specially designed for low-noise characteristics at some expense in bandwidth and gain. Traveling-wave-tube amplifiers are available today in the 1-milliwatt saturation power range which have noise figures of 6.5 db at S-band, 8.5 db at C-band (5900-7400 megacycles), and 10 db at X-band. It is probable that tubes with 7-db noise figures will be available throughout this range by the time this system could be operational. Thus, a 7-db noise figure has been used in all calculations of required power for the communication relay system investigated in this study.

<u>Klystron Amplifiers</u>

Klystron amplifiers are basically narrow-band amplifiers with bandwidths limited to a few megacycles by high-Q cavity tuning. It is possible to increase the operating bandwidth of an operating amplifier to some 20 or 30 megacycles (at 10 kmc) by loading the cavities to decrease their Q, but the available gain of the amplifier is sharply decreased. The operation of a klystron amplifier depends upon the velocity modulation of an electron beam by the input signal. After modulation, the electron beam travels through a drift space where electron bunching occurs due to the velocity variations of the individual electrons. The bunched beam then enters a second cavity, which is tuned to the operating frequency, and induces an amplified rf voltage. This amplified voltage remodulates the electron beam, and a cascade amplification effect is produced until the final amplified rf output is obtained from the final cavity. As with the traveling-wave-tube amplifier, these tubes act essentially as class-A amplifiers, with power

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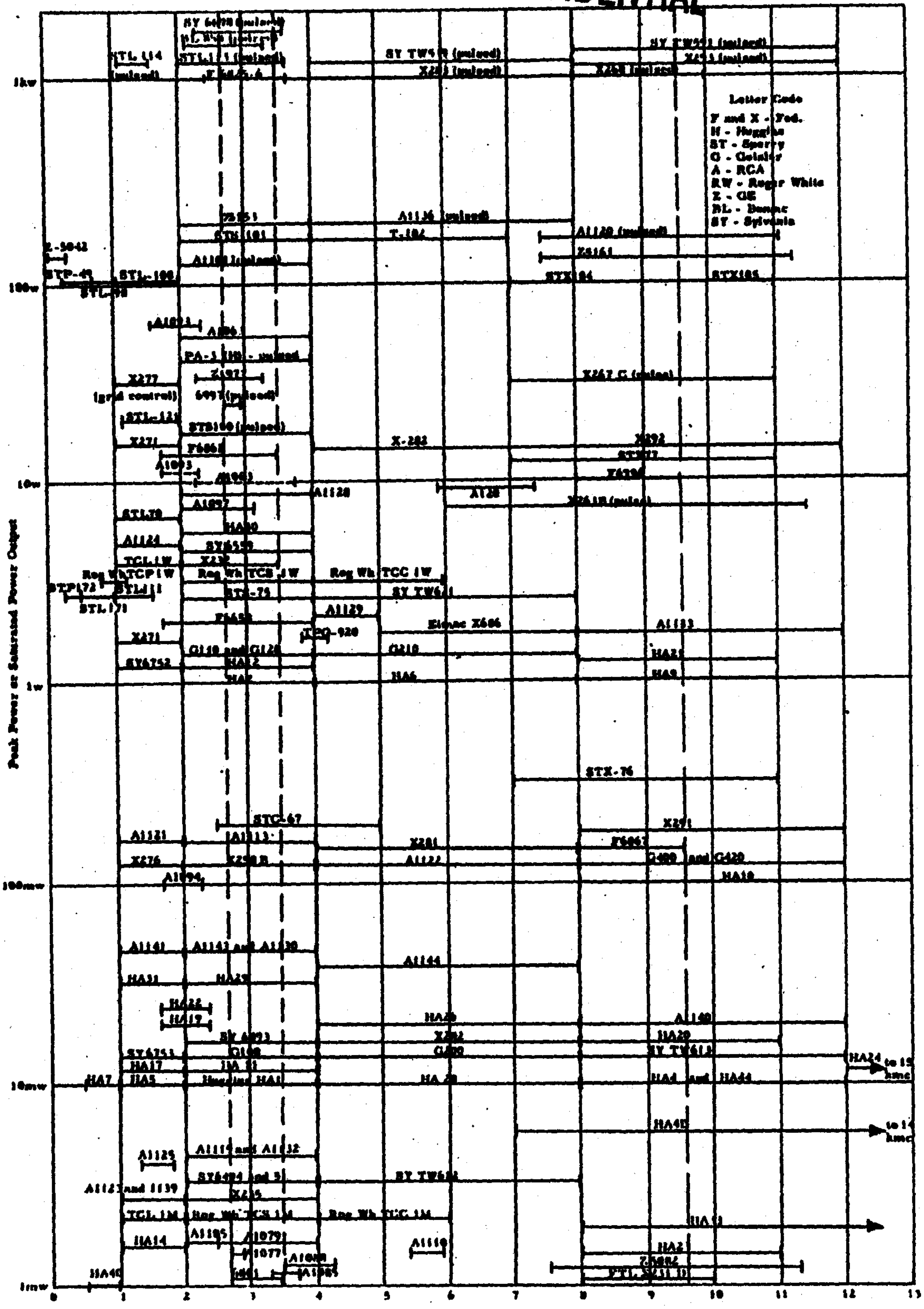

Figure C-1. TWT Amplifier Chart.

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amplification efficiencies for the higher powered tubes ranging from 15 to 20 per cent.

From the klystron amplifier chart shown in Figure C-2 (again, some tubes may have been unintentionally omitted), it will be noted that no klystron amplifiers exist in the range above about 8.5 kmc which can produce the 200-watt power required for the polar-area and ocean-area relays. However, five klystron amplifiers with output power levels ranging from 200 watts to 2 kilowatts are now available at S- and C-bands, and at least three more 1-kilowatt tubes at S-, C-, and X-bands are in the advanced design stages. Of the tubes currently available, the Sperry S-band SAS-28 (a 200-watt tube) is the lightest, weighing 5-1/4 pounds. This is about one-third the estimated weight of a periodically focused 200-watt CW traveling-wave-tube amplifier. Thus, since a decrease in operating frequency from X-band (as used in the required power calculations) to S-band can be compensated by a corresponding increase in the size of the satellite antenna, and, since the diameter (about 20 inches) required for the low-density satellite antenna dish at this frequency is still small, klystron amplifiers merit serious consideration for the power amplifier stages of the low-density relay in the initial global system.

Relatively strong magnetic focusing of the electron beam is required in the higher powered klystron amplifiers, and the permanent magnets (or electromagnets) required to obtain such focusing cause a rapid increase in weight of such tubes with increasing power. This effect is clearly illustrated by the weight and power characteristics of the klystron amplifiers discussed in the preceding paragraph: The SAS-28 (200-watt) tube weighs only 5-1/4 pounds; the SAC-33 (500-watt) tube with permanent-magnet focusing weighs 28 pounds. The electromagnets alone of the Varian 2-kilowatt tubes weigh from 50 to 170 pounds. It should be noted, however, that the electromagnets of these last tubes are not designed for airborne applications; it is estimated that these weights could be reduced by about 25 per cent without a major development program, and that a complete redesign could yield a reduction of up to 50 per cent or so.

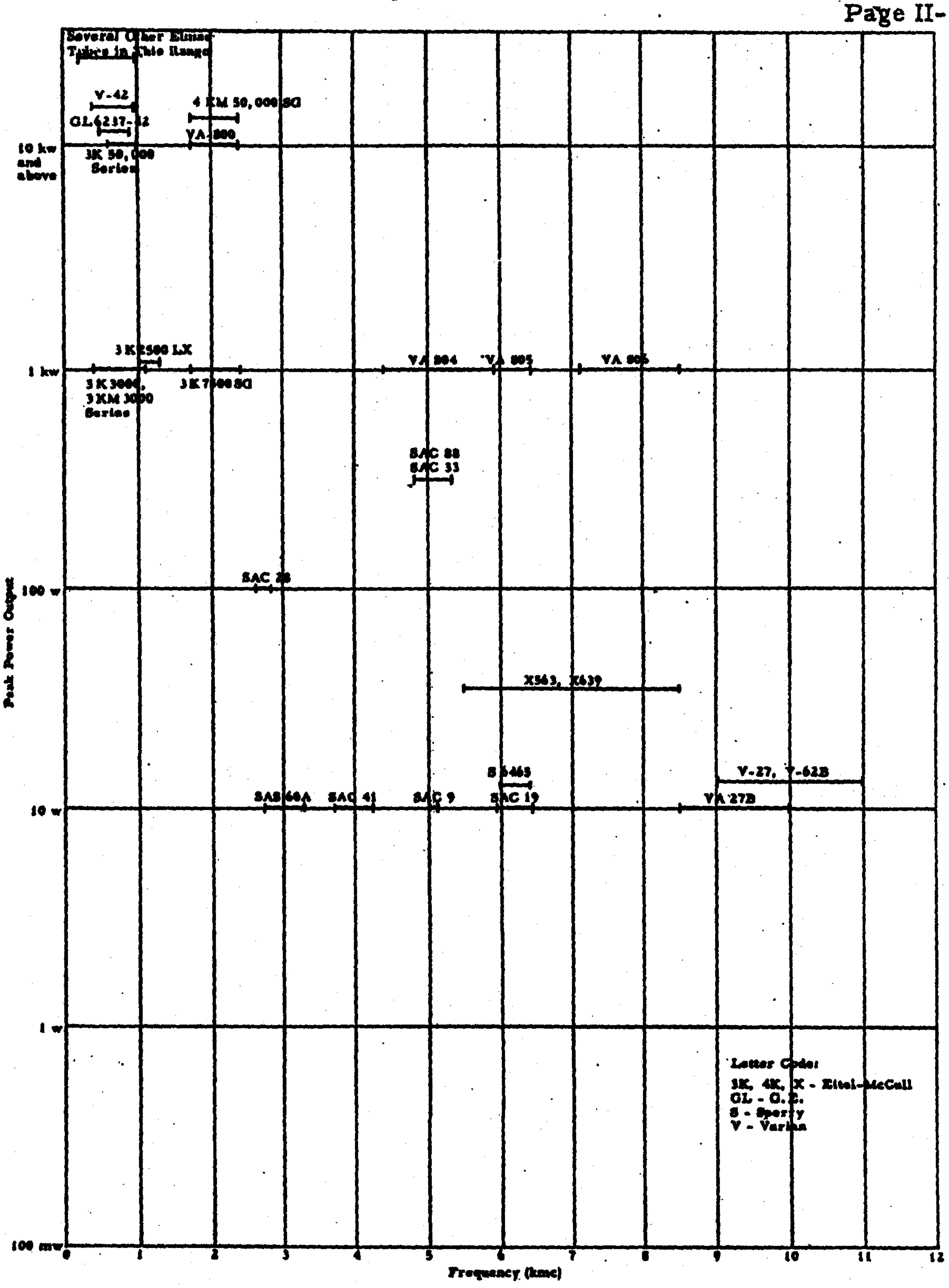

Figure C-2. Klystron Amplifier Chart.

Finally, the high noise figures of klystron amplifiers make such tubes unattractive for use as input amplifiers where they would determine the over-all noise figure of a receiving system. For this reason, the development of low-power klystron amplifiers for receiving applications has not been pursued and, as shown in Figure C-2, no such tubes are commerically available.

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