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MULTIBEAM AERONAUTICAL SATELLITE SYSTEM DESIGN

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16. Abstract

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The author wishes to recognize the significant contribution made to this report by Mr. Alex Robb of the Service Technology Corporation. Mr. Robb extended a computer program which he had developed previously with C. Murphy of DOT/TSC that calculated and projected constant signal level contours onto a Mercator plot. He modified it to accept a more extensive characterization of the spatially variant link parameters which the author specified and to provide polar projections of the contours. He also developed and programmed the equations which describe the great circle routes between the major air terminals.

Thanks are also due to Messrs. D. Brandel, C. Murphy and P. Engels of DOT/TSC for their helpful comments during the preparation of the report.

INTRODUCTION

A method is described in this report which allows the identification of favored beam distributions for multiple beam aeronautical satellites. It is used to synthesize beam designs and compare the capacities of two satellite system configurations which cover the major Pacific routes. The first configuration has two satellites with eclipse capability adequate for housekeeping and independent aircraft surveillance; the second has additional battery capacity to provide 50% of the daylight communications capability in each satellite during eclipse. In this case, each satellite covers a limited portion of the full coverage area.

BACKGROUND

Over the past seven years there have been a large number of government and industry studies aimed at designing a system of earth satellites which would provide services necessary in the future for safe and efficient oceanic aeronautical operations. Announcement by the Office of Telecommunications Policy (Ref. 1) of the Administration's intention to support the development of a preoperational L-band oceanic satellite system has set the stage for the first major step by the U.S. toward operational application of this technology.

While avoiding a great many serious problems that would exist at lower frequencies, the selection of L-band results in certain system design difficulties which must be dealt with carefully. A simple link calculation indicates one fact very clearly for voice communications: moderately high gain spacecraft or aircraft antennas will be necessary. This is true if near oceanic coverage is required, if several voice channels are necessary in the more dense airspace and if the launch vehicle is constrained to the Thor-Delta class.

The Dioscures system (Ref. 2) is the outstanding example of an approach which employs a high gain aircraft antenna (10 dB min) to overcome the link losses which exist at L-band. Another very promising approach, discussed herein, consists of providing an array of overlapping spot beams in the satellite. These operate with a low gain terminal on the aircraft.

ADVANTAGES OF THE MULTIPLE BEAM SATELLITE CONCEPT

Coverage of the major routes by a number of contiguous spot beams in the satellite has several advantages over use of an earth coverage antenna. Lower aircraft and satellite power will provide the same link quality. The lower satellite power (per beam) is accompanied by a proportionate increase in the number of beams required to maintain full coverage. Yet, the number of aircraft to be serviced by each beam is lessened. For a fixed access time, the number of channels required in each beam is therefore reduced. On this basis, total satellite power is diminished. Channels are distributed in proportion to the traffic loading.

Further efficiency in use of the satellite power is achieved by location of the peak of the satellite antenna beams toward the edges of the earth, where losses due to multipath, aircraft antenna patterns and space attenuation are greatest. Some reduction in power required at the lowest elevation angles is achieved in this way at a cost of reducing signal levels at higher elevation angles. Flux densities at the higher elevation angles are more than required for good quality communications, however. Uniformity of quality over the whole coverage area is improved in this way.

Additional flexibilities are possible that could result in operational advantages. For instance, the ability to switch channels between beams during off peak traffic periods in the Principal Area of the Pacific adds to the capability available in other areas for significant periods of time. This could be done on a daily or seasonal basis. Interference problems which develop in certain areas of coverage could be remedied by exchanging frequency assignments between beams.

Finally, the use of high gain satellite antennas with low gain aircraft antennas has other obvious advantages over earth coverage satellite antennas and high gain aircraft antennas. The marginal system cost of several thousand high gain aircraft antennas is an order of magnitude higher than that of several high gain satellite antennas. Serious objections which the airlines have raised with regard to possible reliability maintenance and mounting problems of high gain aircraft antennas are also avoided.

BASIC ASSUMPTIONS FOR SYSTEM DESIGN

The assumptions made for system synthesis and the underlying reasons for their selection are identified below:

1. The satellite antenna aperture was taken to be limited by the diameter of the shroud of the Thor-Delta 2914 to 85". This results in a spot beam width of approximately 6.2° achievable with a rigid satellite antenna. Such an aperture allows a significant increase

in gain over an earth coverage antenna without requiring two beam operation over the Principal Areas of the Pacific or Atlantic. Further reduction in beam size would be accompanied by increasing attitude stabilization losses as well as a requirement for aperture unfurlability.

2. The aircraft antenna assumed in the analysis is the Boeing crossed slot. This antenna has nearly hemispherical coverage with a nominal gain of -1dB at 10° elevation angle in the roll plane of the aircraft. It is a very simple antenna and is desirable from a maintenance and operations viewpoint.

   Full 4π steradian patterns on a scaled jet aircraft were available. Similar patterns were available for the DICO two element slot dipole. However, it is shown to have essentially no advantage over the crossed slot antenna. Limited data on two and three element slot dipoles from Boeing show more promise but unavailability of full 4π steradian patterns prevents a full assessment of the advantage to be gained from their use. Nevertheless, an estimate is made of the system improvement likely to be derived from use of the most promising of these antennas.

3. Two eclipse configurations are examined. Configuration 1 provides enough battery payload for normal housekeeping functions and independent surveillance during eclipse. Two satellites are spaced so that they are never eclipsed simultaneously. This results in a system with an eclipse capacity for surveillance and 50% of the daylight communications.

   Configuration 2 assumes 50% communications capability per satellite in eclipse as well as housekeeping and surveillance. Communications coverage for the more easterly routes is furnished by the eastern satellite and the more westerly routes by the western satellite. Individual routes again have 50% capacity during eclipse, since they are provided for nominally by one satellite.

   A 50% eclipse capability in the Principal Area of the Pacific is compatible with the fact that during eclipse times the peak instantaneous subsonic jet traffic count is approximately 50% of its peak daily value. Thus the number of aircraft per channel is the same at eclipse time and at the peak time of the day.

SATELLITE SYSTEM DESIGN

In order to optimize use of both satellite and aircraft power, all communication channels must operate in both forward and reverse directions through the multibeam satellite antenna. The satellite antenna configuration for surveillance is less obvious however.

The net circuit losses of Tables A-2 and A-6 in Appendix A show that a power advantage of 7.5dB exists when a narrow beam link is compared to an earth coverage link at a 10° elevation angle in the forward direction. The forward surveillance link must be available on an earth coverage basis, however, so the total RF power advantage (or disadvantage) in the satellite is dependent on the number of beams that are required. In the section Beam Location on page 18, five beams are shown to be necessary for configuration 1. Considering this, the overall satellite RF power requirement for either implementation is comparable. Use of the multibeam antenna for surveillance would probably require increases in transmitting circuit losses over those identified in Table A-6 because a single signal must be distributed to all beams. On the other hand, the lower RF powers that result for the multiple beam antenna could be achieved at higher efficiency.

Separation of the forward surveillance signal from the voice channels avoids a potential problem with surveillance signal suppression effects as voice channel occupancy varies. Unless additional margin or a sophisticated power control system is provided, this could cause loss of lock on the surveillance signal at the aircraft.

Final resolution of the question of using either an earth coverage antenna or the multibeam antenna for the forward surveillance channel must await a detailed circuit and satellite design. For the purpose of this report, however, an earth coverage antenna is assumed for the forward surveillance link.

The return surveillance channel benefits significantly by operating through the high gain satellite antenna beams. Comparison of the net circuit losses of Tables A-2 and A-3 of Appendix A at an elevation angle of 10° reveals that a reduction in aircraft power of about 8.5 dB can be achieved in this way.

SATELLITE LOCATION

The farthest East that a geostationary satellite can be located and still cover air traffic to and from Manila is about 165W longitude. The farthest West that a geostationary satellite can be located if the U.S. West Coast to Hawaii routes are to be covered is about 172.5E longitude. As shown in Figure 1, this is true when coverage is defined by a 10° elevation angle. Greater longitudinal separation requires operation at lower elevation angles than 10° as both satellites must necessarily be in view of the user. Further reduction in spacing almost immediately puts the satellites in a relative geometry which will cause simultaneous eclipse. GDOP effects become worse as spacing is reduced, also. Because of these factors, the two Pacific satellites are stationed at 165W and 172.5E longitudes.

BEAM DESIGN METHOD

Much insight can be obtained in the optimum location of beams if a relation can be established between beam displacement at the satellite and coverage contours on the surface of the earth which bound a particular link quality. This is possible on an especially simple basis since the shape of constant quality contours on the surface of the earth can be described solely as a function of angular displacement of the beam from the nadir of the satellite toward the edge of the earth (Φ_b). The shape of the coverage contour is independent of the angular displacement of the beam about the yaw axis of the satellite (θ_b). This simple geometric relationship only holds true if coverage contours are defined on the surface of the earth or some projection of the earth's surface which does not destroy this symmetry. For instance, projection of the contours onto a plane tangent to the earth at the subsatellite point would retain this quality. Projection onto a sphere of arbitrary radius which is centered at the satellite would also preserve symmetry.

The parameters which determine the shape of such a link quality contour are the link transmission factors that vary with Φ and θ. Φ and θ are generalized angles measured exactly as Φ_b and θ_b were, to an arbitrary point on the earth. The varying link transmission factors include the satellite antenna gain G_s, aircraft antenna gain G_a, multipath margin M and space attenuation L. M and L are a function of the aircraft elevation angle (δ) or equivalently the angle from the nadir of the satellite, Φ. For some aircraft antennas G_a is relatively constant in azimuth - for others this is not so. It is possible to create a meaningful aircraft antenna pattern which is azimuthally symmetrical (i.e. which has constant gain in θ) from any arbitrary unsymmetrical pattern by considering

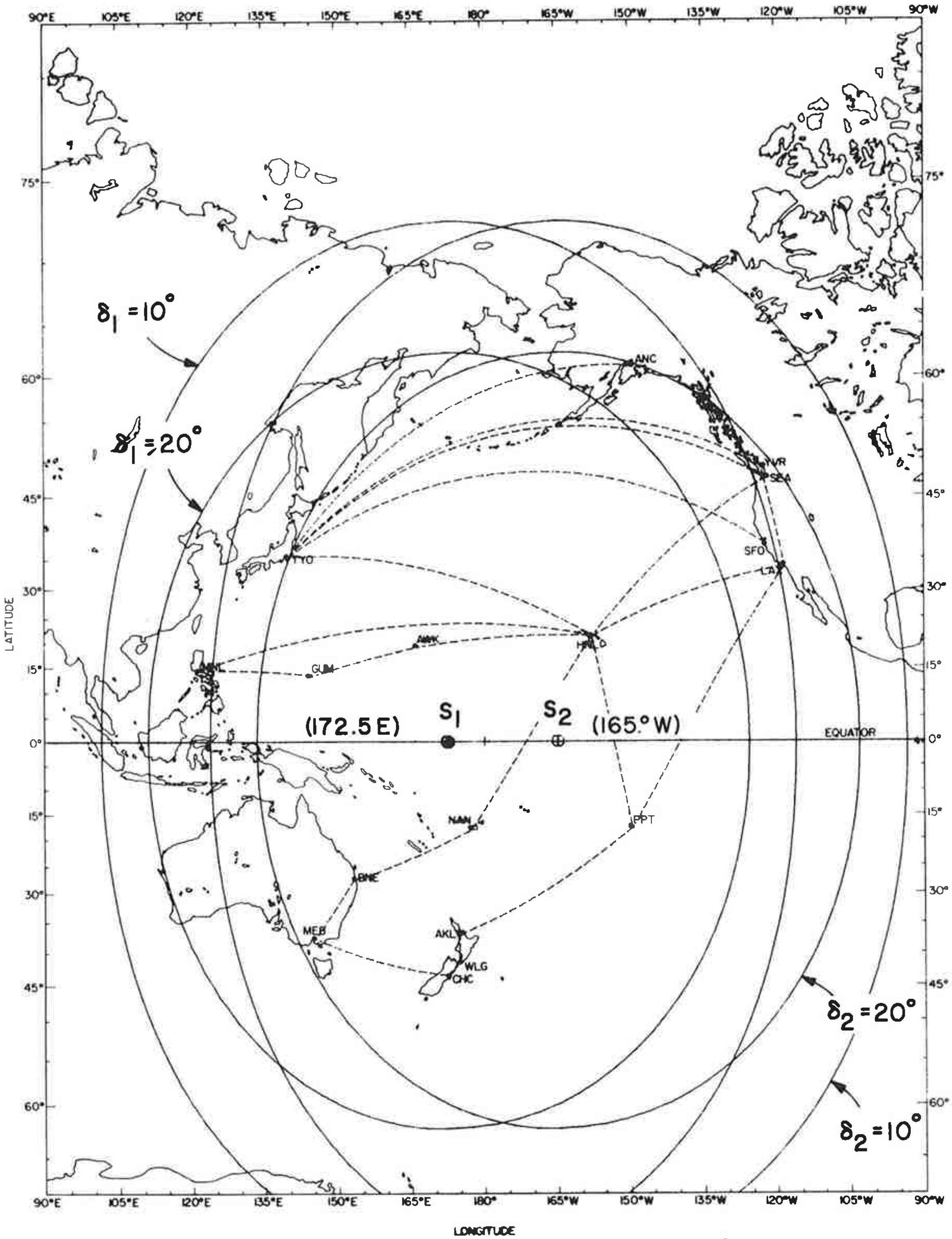


Figure 1. Dual Satellite Coverage of the Major Pacific Routes

the value of gain which is exceeded for a specified percentage of all azimuths at each elevation angle. This is effectively what is done in the analysis to follow. G_a, M and L then all become simple functions of Φ. Contours can then be defined for

$$G_a - M + L = C_i$$

which appear as concentric circles on the surface of the earth with centers on a line between the satellite and earth's center. These are called terminal contours. G_a, M, L and C_i are in decibels. M has positive value and L has negative value.

A set of spacecraft antenna gain contours

$$G_s = C_j$$

can be projected directly onto the earth and combined with the terminal contours to produce the required link quality contours

$$G_s + G_a - M + L = C_k$$

This process can be simplified if the routes on the earth's surface and the terminal and spacecraft contours are projected onto a sphere of arbitrary radius centered at the satellite. In this case, the terminal contours retain their concentric circular nature and the spacecraft contours become totally independent of the beam displacement angles Φ_b and θ_b.

Using this projection, it is an easy matter to construct the link quality contours by a simple search for points on the overlay of the terminal and spacecraft contours such that

$$C_i + C_j = C_k$$

The resulting contours are only a function of Φ_b. Once generated they can be fit to the major air routes which are also projected onto the sphere and the number and location in Φ, θ of all beams identified for full route coverage.

TELECOMMUNICATIONS ANALYSIS - CONFIGURATION 1

A favored beam distribution for configuration 1 is now derived. Two identical satellites are assumed with minimum eclipse capability. Each satellite normally provides one half of the total communications capacity available to any aircraft.

Communications

The major great circle routes of the Pacific, taken from References 3 and 4 are projected onto the surface of a sphere of arbitrary radius centered at the satellite. The projection is defined in polar coordinates Φ and θ viewed from the satellite. Φ is the angle off the nadir of the satellite and θ is the yaw angle referenced to the projection of the earth's equator. In Figure 2, the major routes of the Pacific are shown viewed from satellites located at 165W and 172.5E. The same routes are shown in Figure 1 in Mercator projection. The transformation equations are:

$$\text{ctn } \Phi = \frac{6.6228 - \cos \text{LAT} \cos \text{LON}}{\sqrt{1 - (\cos \text{LAT} \cos \text{LON})^2}}$$

$$\cos \theta = \frac{1}{\sqrt{1 + \left(\frac{\tan \text{LAT}}{\sin \text{LON}}\right)^2}}$$

LAT and LON refer to the latitude of the earth terminal and its relative longitude with respect to the satellite sublongitude. The outer extreme in Φ, approximately 8.5°, corresponds to an elevation angle (δ) of 10° at the aircraft. Φ of 8.2°, corresponds to an elevation angle of about 20°.

Figure 3 shows the variable link transmission factors anticipated at L-band (1560 MHz) which change only with Φ (or equivalently δ). There are three contributing elements: space attenuation, aircraft antenna gain and multipath margin. Aircraft antenna gain and multipath margin are accounted for by the curve labled $\overline{(G_a - M)}_{95}$. The total is also shown.

Space Attenuation

Space attenuation is calculated from the equation

$$L = \left(\frac{\lambda}{4\pi R}\right)^2$$

where λ is the wave length at 1560 MHz and
R is the distance between satellite and aircraft

In Figure 3, the variation in space attenuation, $\overline{L}$, is shown over the range of values of δ or Φ. It is normalized to the value of L at $\delta = 90°$.

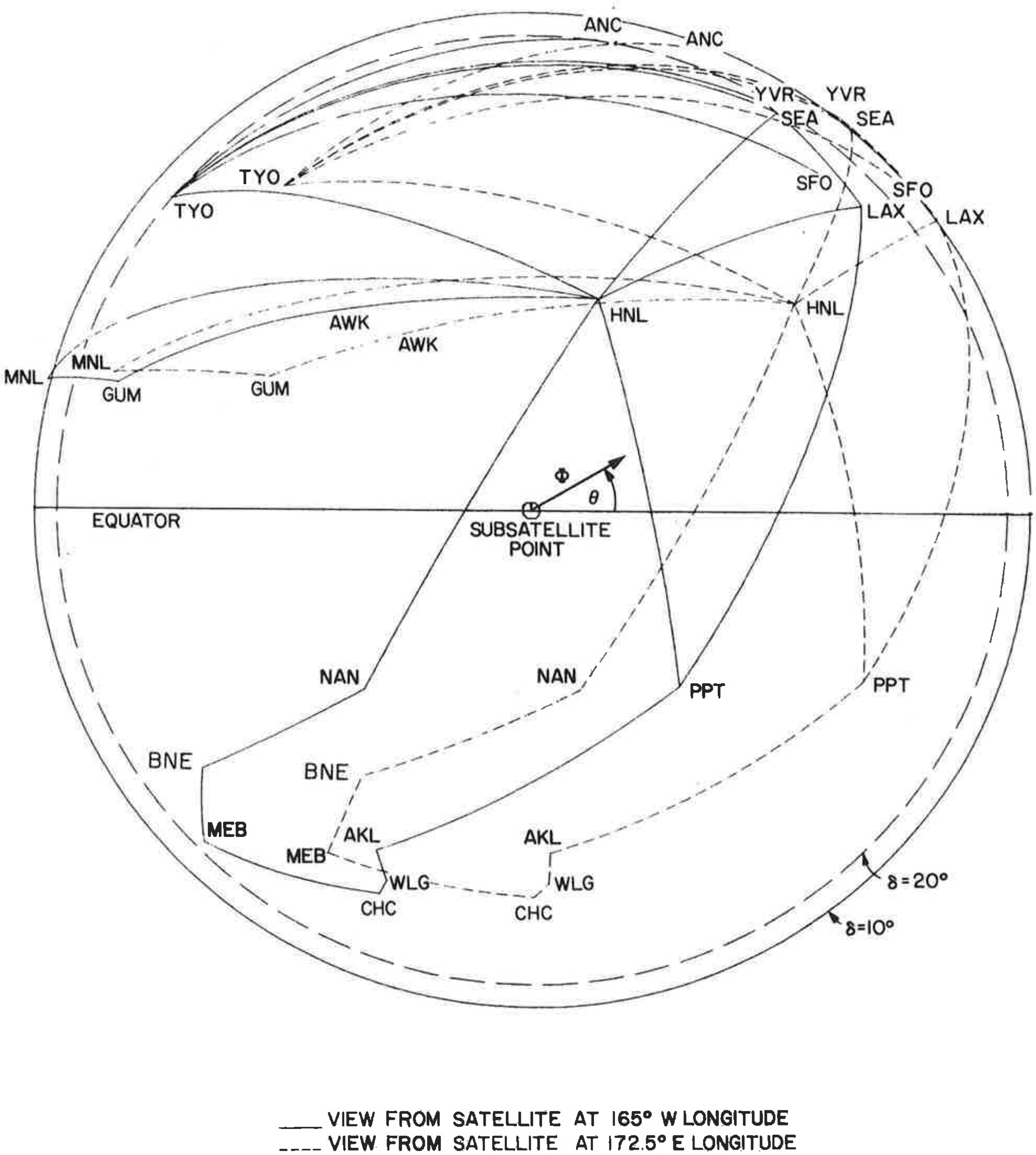
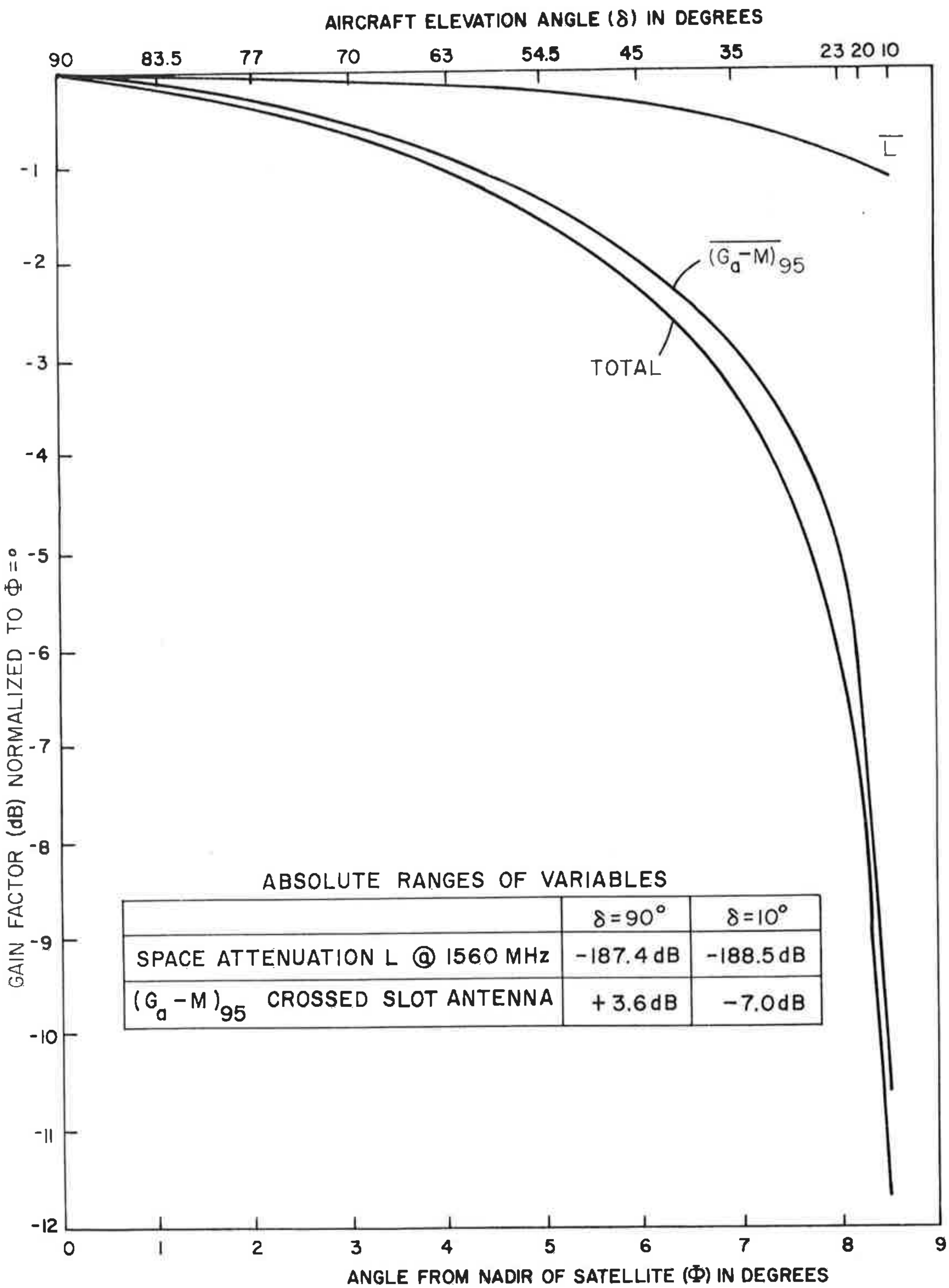


Figure 2. Polar Projection of Major Pacific Air Routes to Satellites at 172°.5E and 165°W



ABSOLUTE RANGES OF VARIABLES

	δ = 90°	δ = 10°
SPACE ATTENUATION L @ 1560 MHz	-187.4 dB	-188.5 dB
$(G_a - M)_{95}$ CROSSED SLOT ANTENNA	+ 3.6 dB	-7.0 dB

Figure 3. Variable Link Transmission Factors

Aircraft Antenna Performance

Variations in multipath fading and aircraft antenna gain are somewhat more difficult to deal with. The fading margin required for multipath is a strong function of the effective surface reflectivity (Γ) at L-band and the rejection ratio of the aircraft antenna. Γ includes actual reflection losses at the surface and polarization isolation of the antenna. In addition, gain and rejection ratio vary widely at different azimuth angles for different aircraft antennas. In order to deal with these factors, a probabilistic model of the aircraft antenna pattern could be developed which is uniform in azimuth having a gain at varying elevation angles defined by the value of gain which is exceeded for a fixed percentage of all azimuth angles. All azimuth angles are weighted equally in this way.

Such an antenna pattern could be constructed if full aircraft antenna patterns with reasonable resolution were available. A full 4π pattern for the crossed slot antenna was available from Boeing with gain measured in 2° increments in azimuth and elevation angle. Similar data were derived in 10° increments in elevation angle and azimuth angle for the DICO slot dipole antenna from the patterns of Reference 5. In this case, gain measurements were unavailable below -40° elevation angle, without consequence. All antenna patterns were made mounted on scaled jet aircraft.

At every azimuth and elevation angle on the true antenna pattern there is a uniquely identifiable aircraft antenna gain (G_a) and antenna rejection ratio (r). The factor which determines the link power requirement is actually the difference (expressed in decibels) between the aircraft antenna gain G_a and the multipath margin M. M is determined by the rejection ratio (r) and the effective surface reflectivity (Γ). If a direct relationship can be established between the rejection ratio (r) and multipath margin M a link gain factor G_a-M is calculable for each elevation and azimuth angle. The factor (G_a-M) can be treated probabilistically to generate a "pattern" of (G_a-M) in elevation. That is, if G_a-M is computed at each azimuth angle for a constant elevation angle, then a cumulative distribution of G_a-M can be developed and a value of G_a-M identified which is exceeded for a fixed percentage of azimuths. This is done at all elevation angles to generate the "pattern" of G_a-M.

Multipath margin M is estimated in the following way. An effective surface reflection coefficient (Γ) of -6 dB is assumed. While an adequate data base does not exist to confirm this selection, -6dB is not inconsistent with the unpublished experimental results of Boeing and the Transportation Systems Center to date.

If a diffuse model is used to characterize the surface at L-band, the total power received at the aircraft will consist of a coherent (direct) signal and a noiselike (multipath) signal which is Rayleigh distributed. Norton et al (Reference 6) have tabulated the fading levels of such a signal for different link reliabilities as a function of the ratio of mean power in the multipath signal to power in the direct signal. Norton's calculations have been used, together with the assumption of a - 6 dB effective surface reflectivity to produce the curve of Figure 4, relating the multipath fading margin necessary for a link reliability of 99% to antenna rejection ratio. From this, rejection ratios taken from the antenna patterns are translated into fading margins at each point in azimuth.

Cumulative distributions of G_a-M are shown in Figures 5 and 6 for the Boeing crossed slot antenna and the DICO slot dipole. Cumulative distributions of G_a-M are also shown in Figure 7 for the Boeing two element slot dipole at $\delta = 10°$ and the Boeing 3 element slot dipole at $\delta = 10°$ and 20°. The data for these two antennas were limited and taken from Reference 7. Again, they were based on scaled B707 patterns.

It is interesting to note the relative performance of the antennas at low elevation angles. Taking the Boeing crossed slot antenna as the reference, at a 10° angle for 95% of the azimuth angles, comparison of the DICO two element slot dipole shows a performance improvement of only .2dB, the Boeing two element slot dipole 3.3dB, and the Boeing three element slot dipole 4.1dB. The cumulative distribution of G_a-M may be a rather good overall indicator of antenna performance.

The pattern of G_a-M is derived for the Boeing crossed slot from Figure 5 by taking values of the ordinate at a constant value of the abscissa for the different elevation angles. Patterns of G_a-M are presented in Figure 8 for the Boeing crossed slot for azimuth probabilities between 90 and 100%. A value of 95% has been selected for further analysis. This pattern, normalized to G_a-M at $\delta = 90°$ is shown in Figure 3, denoted $\overline{(G_a\text{-}M)}_{95}$.

If a link design proceeds on this basis, the voice quality achieved will be valid for 95% of the azimuth angles at the minimum elevation angle specified. Over all elevation angles, the design voice quality will be achieved for a far greater percentage of azimuths than 95%. Note also that the worst that can happen with the Boeing crossed slot antenna at the design elevation of 10° is that the link transmission factor drops by about 1.8dB. This can be seen by comparison of the 95% probability patterns with 100% probability at 10° elevation angle. A S/N_o ratio will be chosen for the link

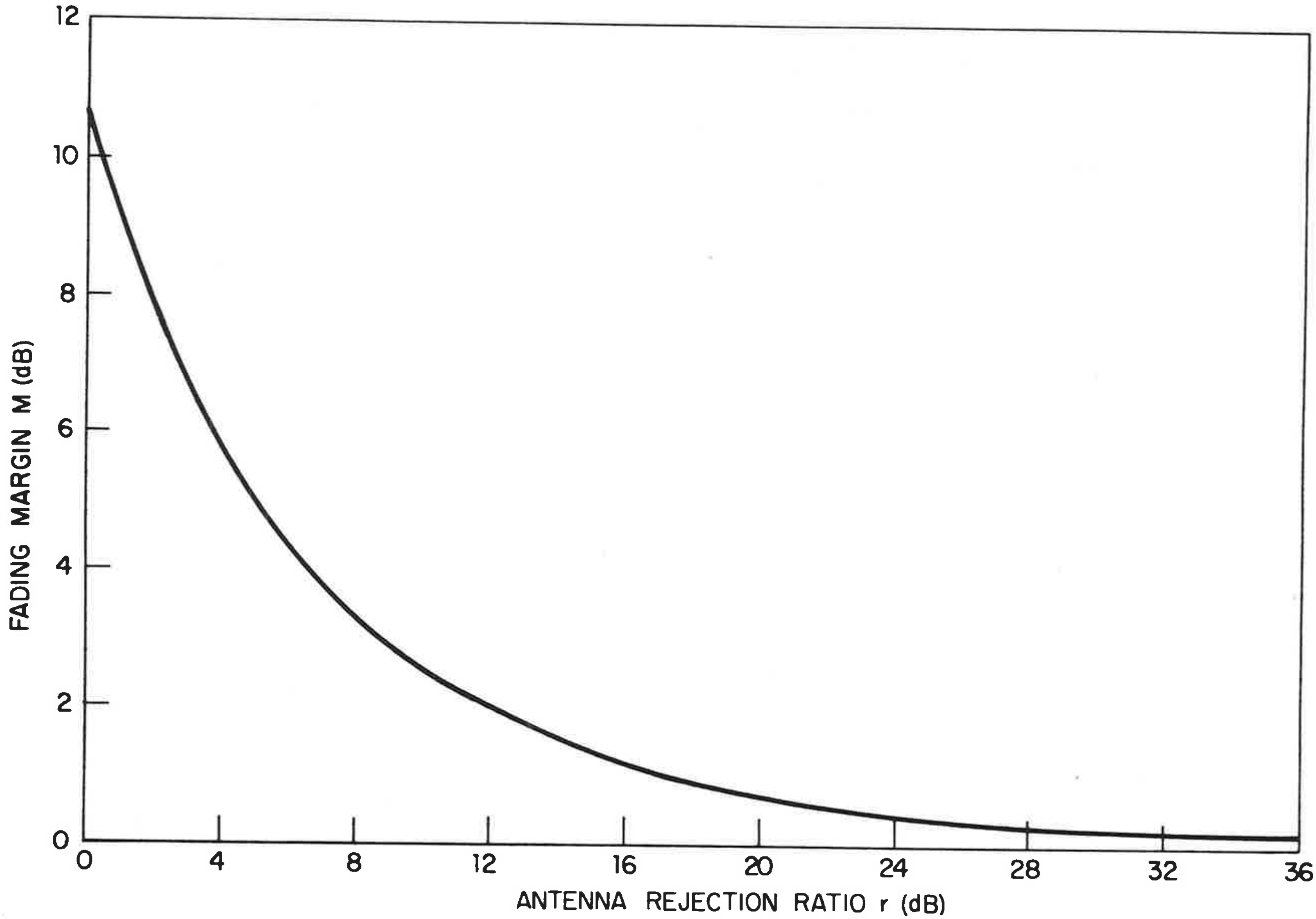


Figure 4. Multipath Fading Margin - 99% Link Reliability

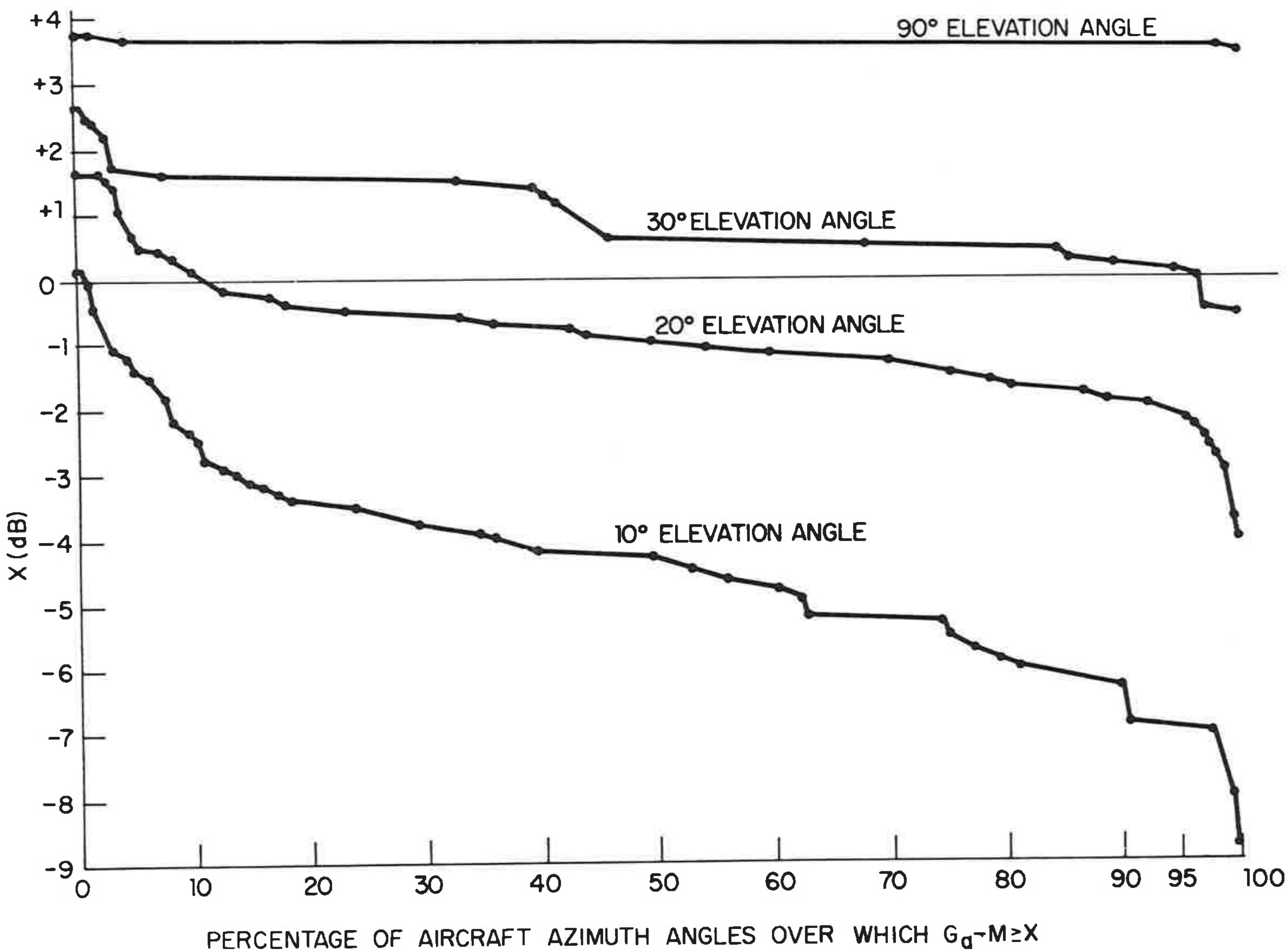


Figure 5. Cumulative Azimuth Distribution of G_a-M For Boeing Crossed Slot Antenna

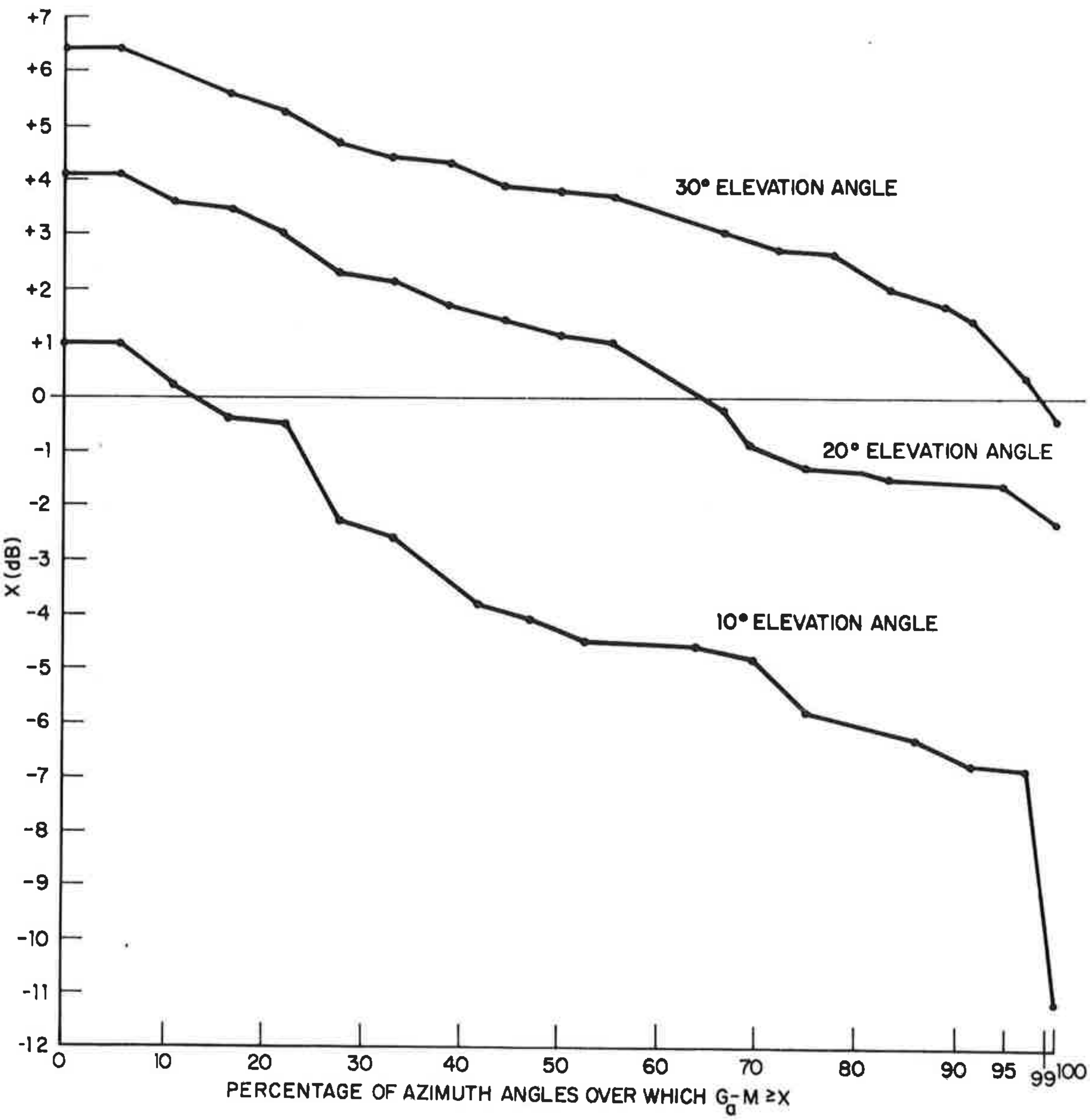


Figure 6. Cumulative Azimuth Distribution of G_a-M
DICO 2 Element Slot Dipole Antenna

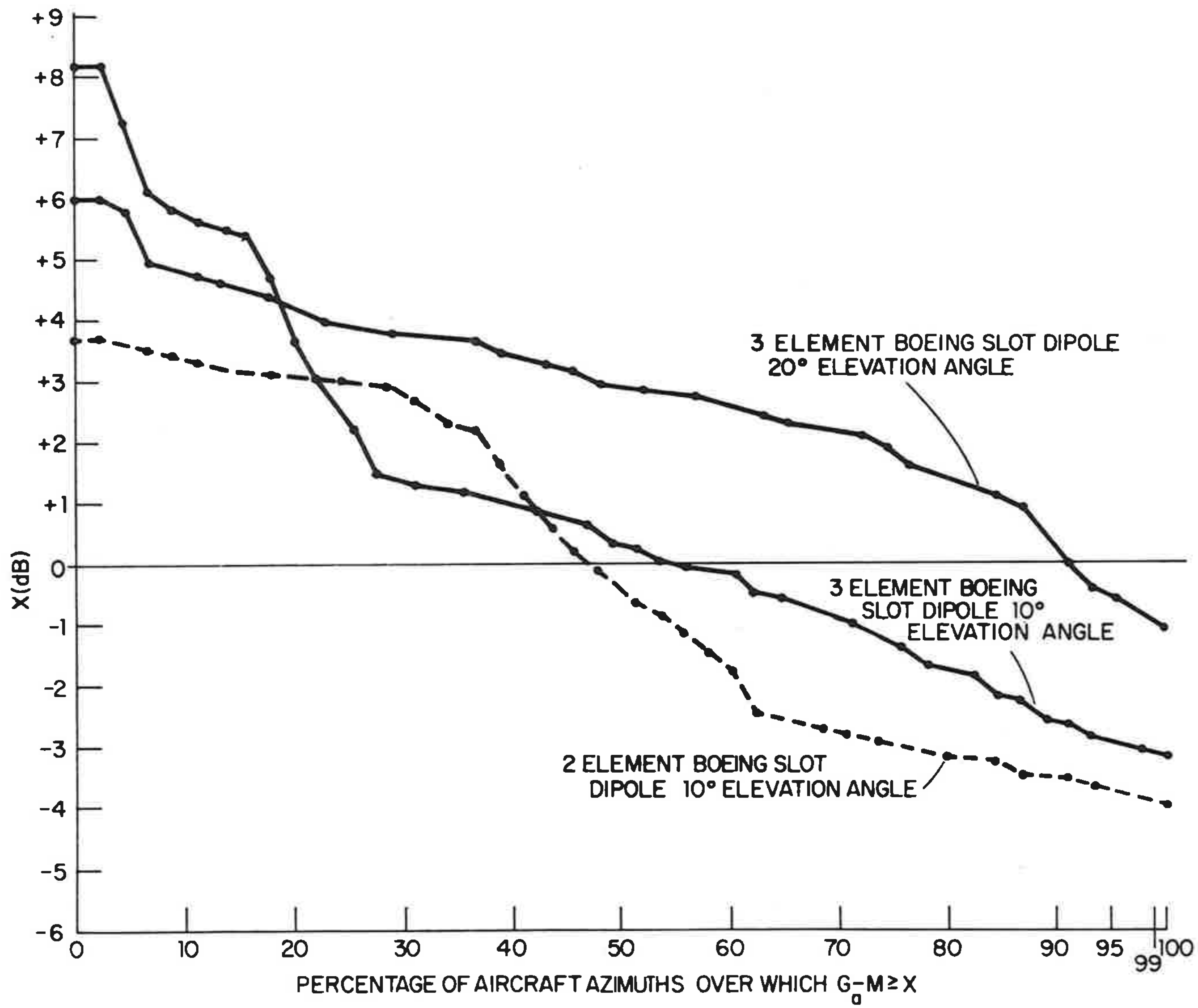


Figure 7. Cumulative Azimuth Distribution of G_a-M For Boeing Slot Dipole Antennas

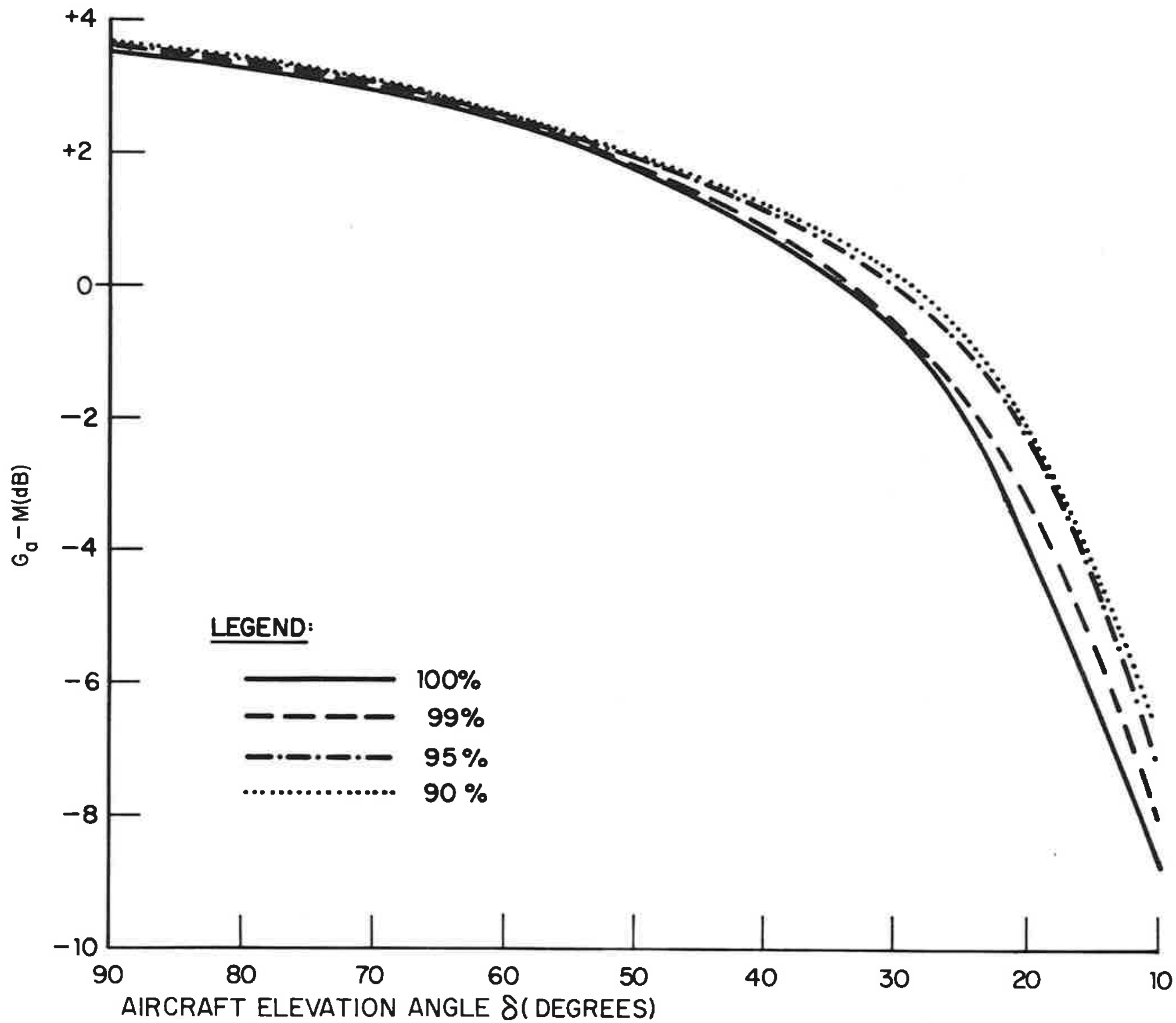


Figure 8. Patterns of G_a-M For the Boeing Crossed Slot Antenna

designs which will allow infrequent excursions below it without great degradation of the voice quality. Rather than add 1.8dB to the satellite power requirement to cover every possibility, it is more effective to allow infrequent excursions below the nominal voice quality, yet provide for acceptably high intelligibilities during these infrequent occurrences.

Terminal and Spacecraft Contours

The terminal contours are shown in polar projection in Figure 9 derived from the "total" curve of Figure 3. The terminal contours are based on $\overline{G_a-M}$ and $\overline{L}$, which have been normalized to the values of G_a-M and L at $\delta = 90°$. The only effect of this is to create a new set of terminal constants, K_i, which are related to the absolute terminal constants C_i by

$$K_i = C_i - (G_a-M)\big|_{\delta=90} - L\big|_{\delta=90}$$

Since there is no normalization for the spacecraft contours

$$K_j = C_j$$ and since

$$K_k = K_i + K_j$$ then

$$K_k = C_k - (G_a-M)\big|_{\delta=90} - L\big|_{\delta=90}$$

The spacecraft contours can be constructed from the pattern of any one beam of the satellite antenna. Figure 10 is the secondary pattern (in polar form) of an 85" diameter circular aperture illuminated with a cosine amplitude taper. It was developed from Reference 8.

Beam Location

If coverage is not sacrificed seriously, it is most desirable to point the peak of the satellite beam toward $\Phi = 8.5°$ in order to counterbalance the great losses at the limbs of the earth with peak satellite antenna gain.

If this is done for the West Coast to Hawaii routes from the satellite at 172.5E longitude, overlaying Figures 9 and 10 on Figure 2 shows that the maximum value of the link constant K_k, which can be employed for the link quality contours, is about 15.8dB (27.5dB - 11.7dB). This occurs because the physical distance between LAX and YVR, at constant Φ, requires link operation about .5dB below the peak gain of the satellite beam. Use of the largest link constant (K_k) over the

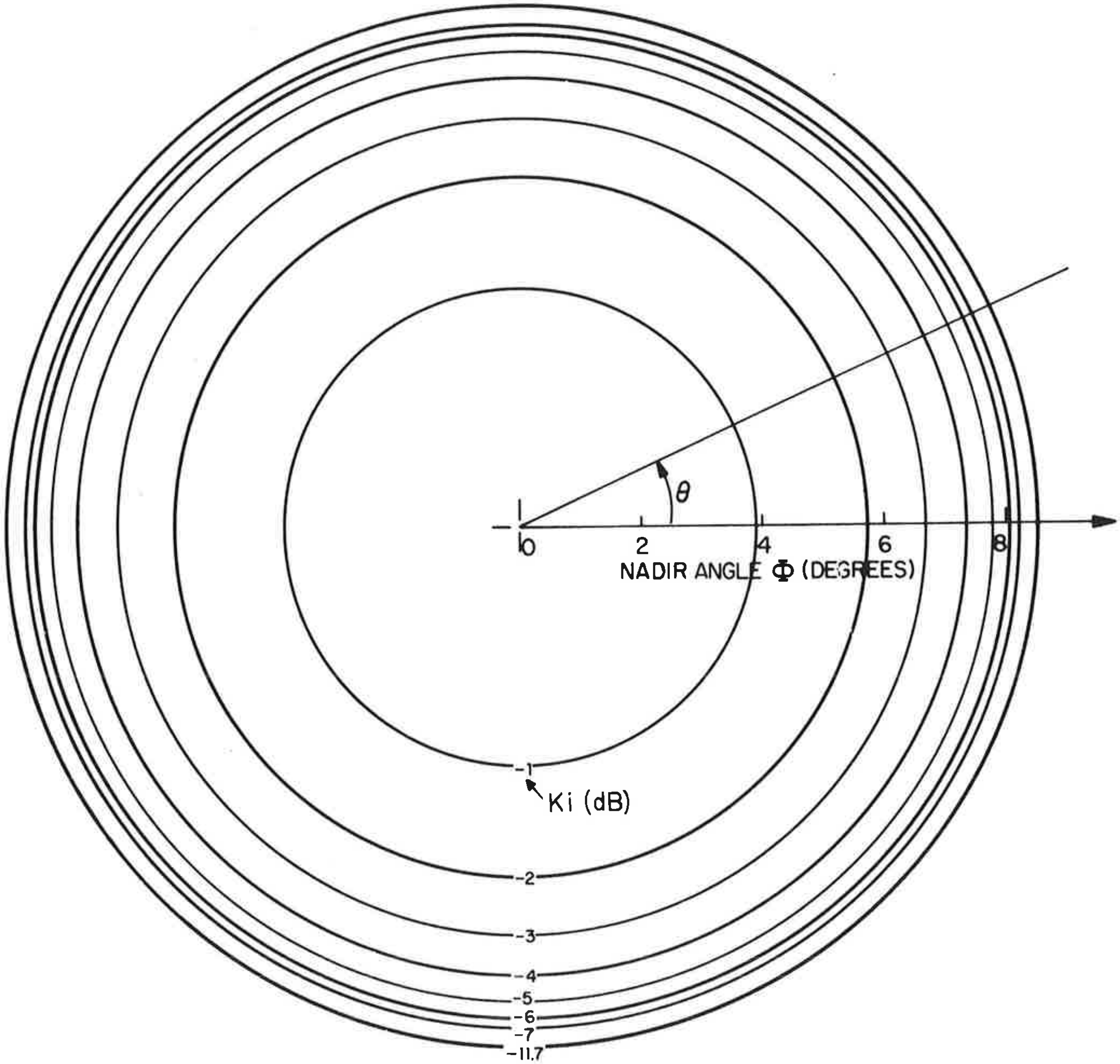


Figure 9. Polar Projection Terminal Contours

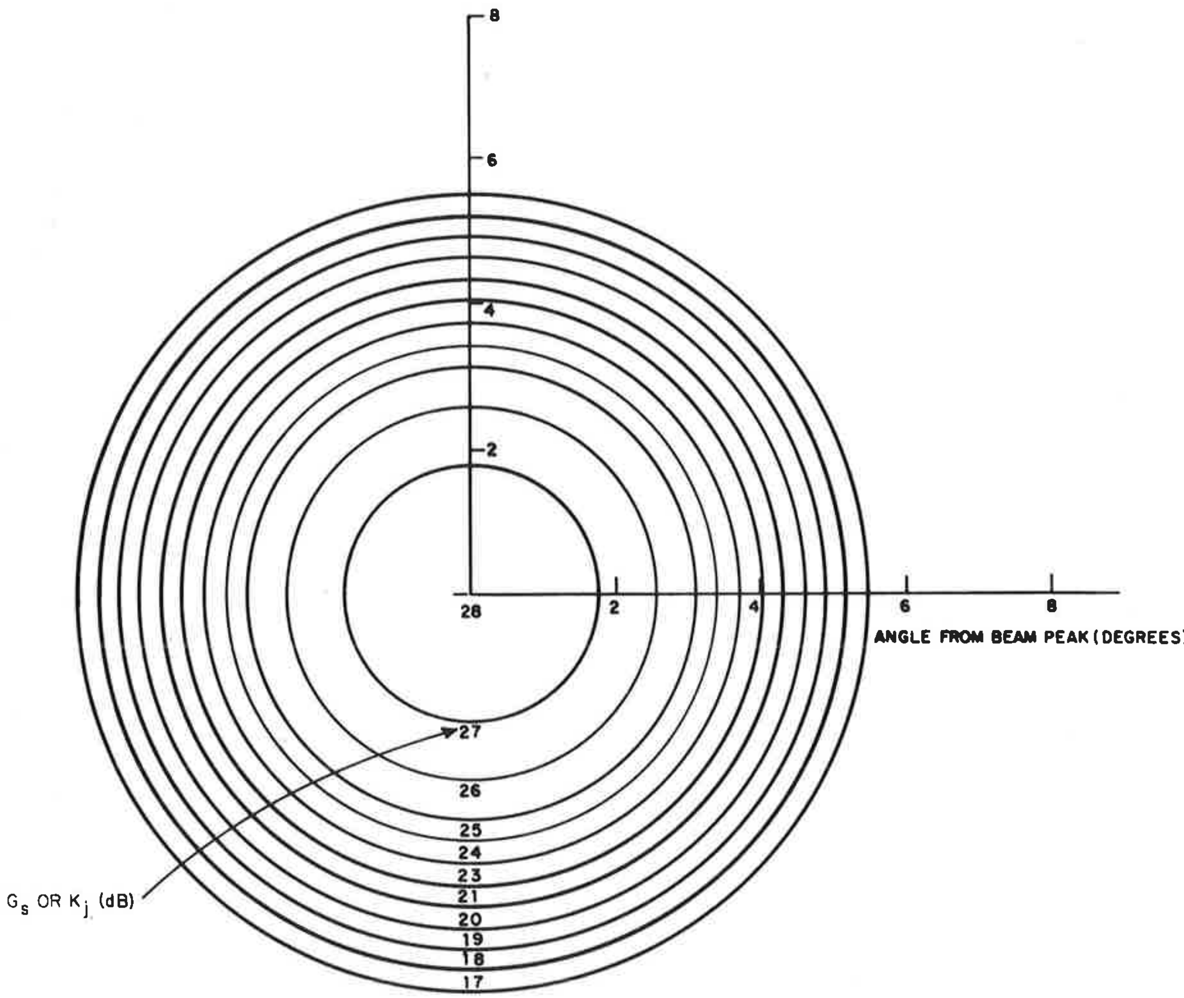


Figure 10. Polar Projection of Satellite Antenna Gain Contours

required coverage area results in minimum power for a fixed required communications quality.

Contours of coverage of constant link quality are found by overlaying Figures 9 and 10 at different displacements, Φ_b, and performing the necessary additions. The result is shown in Figure 11 for a link constant K_k = 15.0dB, slightly less than the maximum identified above. The slight lowering (.8dB) of K_k from maximum will allow some movement in location of the beam in θ when the total beam configuration is synthesized without significant cost in satellite power.

The link quality contours are independent of the angle θ_b and can be overlaid on Figure 2 and by trial and error used to synthesize a best fit to the major Pacific routes. Figure 12 is a polar projection of one favored beam distribution which was arrived at in this manner. Figure 13 shows the equivalent contours in Mercator projection. There are slightly different configurations that will cover the routes in somewhat different ways. It does not appear that less than five beams will be adequate however, except at much lower link constants.

This selection resulted after a number of trials which attempted to:

1. Cover all the major routes,
2. Minimize the number of beams,
3. Minimize the number of beams required for coverage of any one route.

There is an inherent assumption for communications that all beams will have the same power per channel, calculable from the worst case at a 10° aircraft elevation angle. This seems reasonable from payload construction, redundancy and reliability consideration and does not cause any major inefficiency in use of the satellite power.

Surveillance

Significant savings in satellite power for surveillance can be achieved if the eastern satellite provides the forward link for the northern and eastern Pacific routes and the western satellite provides the forward link for the west central and southern routes. Under these conditions Figure 1 shows that the forward link can always operate above 20° elevation angle. This will save the order of 4.7dB in required power (from Figure 3).

For an aircraft operating with a crossed slot antenna at a 20° elevation angle, Appendix A concludes that the forward surveillance channel will require the order of 29 watts RF through an earth coverage satellite antenna. Had a 10°

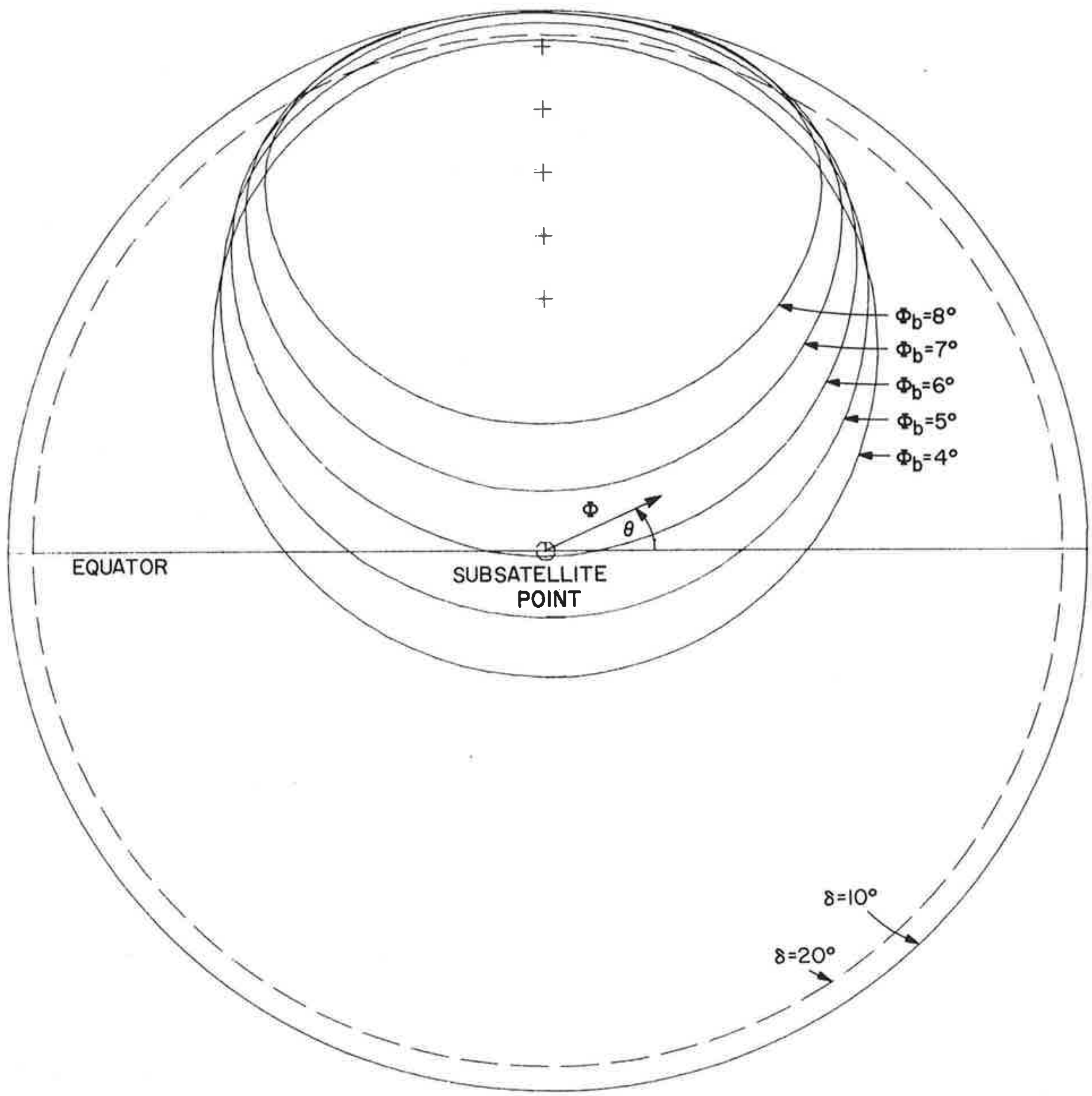


Figure 11. Constant Quality Contours K_k = 15dB

elevation angle been selected approximately 85 watts RF would be required.

Bisaga and Redisch (Reference 9) have used a linear model to describe the approximate relation between available daylight power and available eclipse power for a momentum wheel stabilized satellite. A calculation based on this model suggests that about 3 watts of increased daylight power can be achieved for each watt that the eclipse requirement is reduced. Since surveillance is required during the eclipse period, a reduction of 56 watts (85-29 w) through operation above a 20° elevation angle is accompanied by 168 watts of additional RF power during daylight for communications. This represents almost two additional voice channels. The cost of such an approach is rather modest: there is a requirement for a second frequency assignment, and the aircraft receiver must be capable of operating at one of two frequencies.

System capacity is estimated on this basis then: all communications are performed through the multibeam antenna down to an elevation angle of 10°. The forward surveillance link operates with an earth coverage satellite antenna above a 20° aircraft elevation angle. The eastern satellite provides the forward surveillance link for the northern and eastern Pacific routes at one frequency, and the western satellite provides for the balance of the Pacific at second frequency. The return surveillance links are above a 10° aircraft elevation angle and employ the high gain satellite antenna beams.

Channel Capacity Estimates

Several additional factors must be identified before making an estimate of channel capacity. Detailed link budgets are necessary in order to calculate RF power requirements in the satellite. These are developed in Appendix A. RF powers are translated into DC powers through an estimate of achievable efficiencies with state of the art L-band power amplifiers. Comparison of the DC power required per channel with available DC power for a typical satellite design allows an estimate of the number of channels to be made.

Power Budgets

It can be seen in Appendix A that the RF power required in the satellite for surveillance is 29 watts. Similarly the RF power required for a single channel of voice is 94 watts. For a multichannel beam, 118 watts per voice channel are necessary. These RF powers are based on a nominal signal to noise density ratio of 36.2 dB-Hz for the forward surveillance channel and 45dB-Hz for the voice channel.

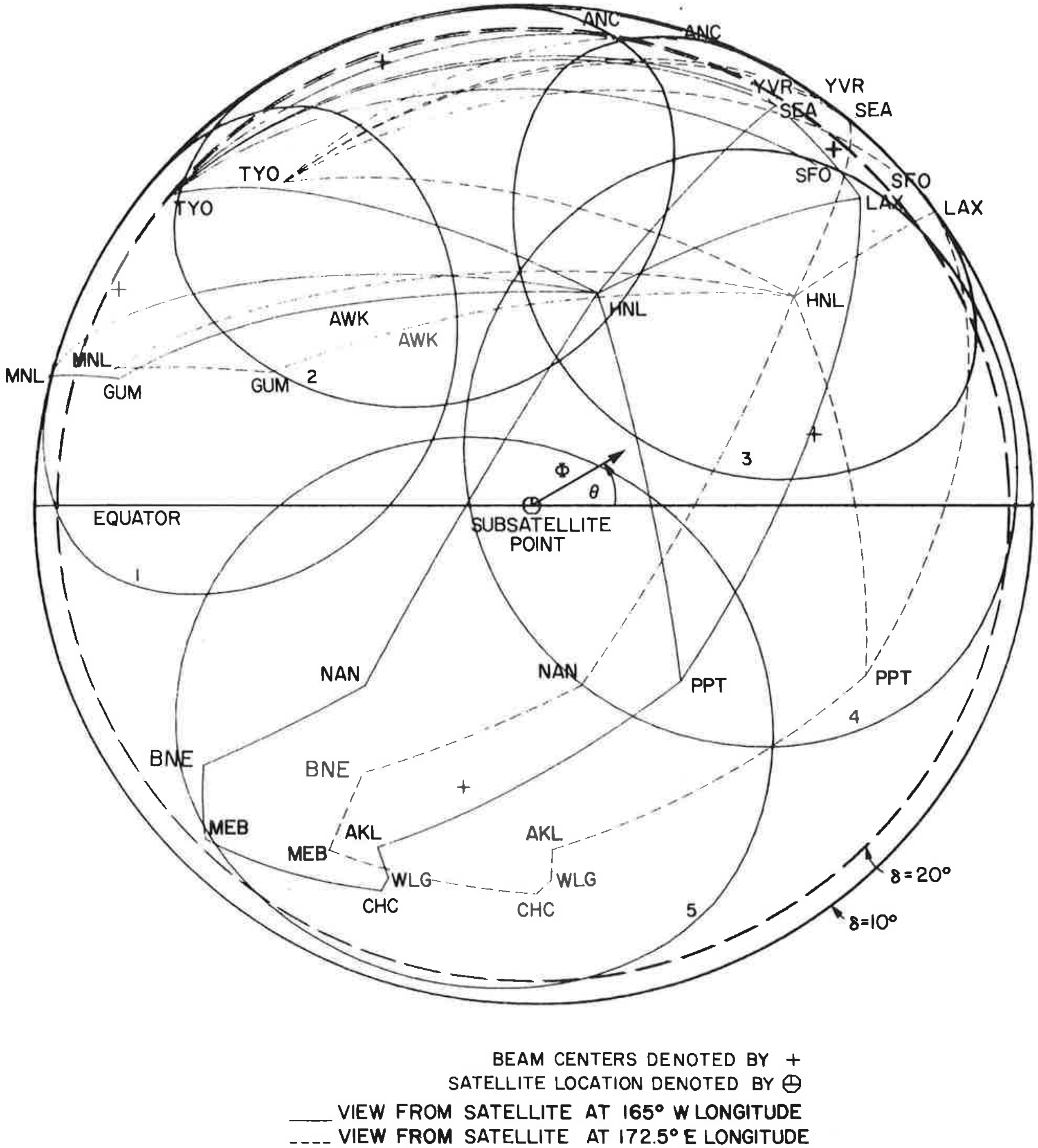


Figure 12. Configuration 1 Beam Coverage - Polar Projection

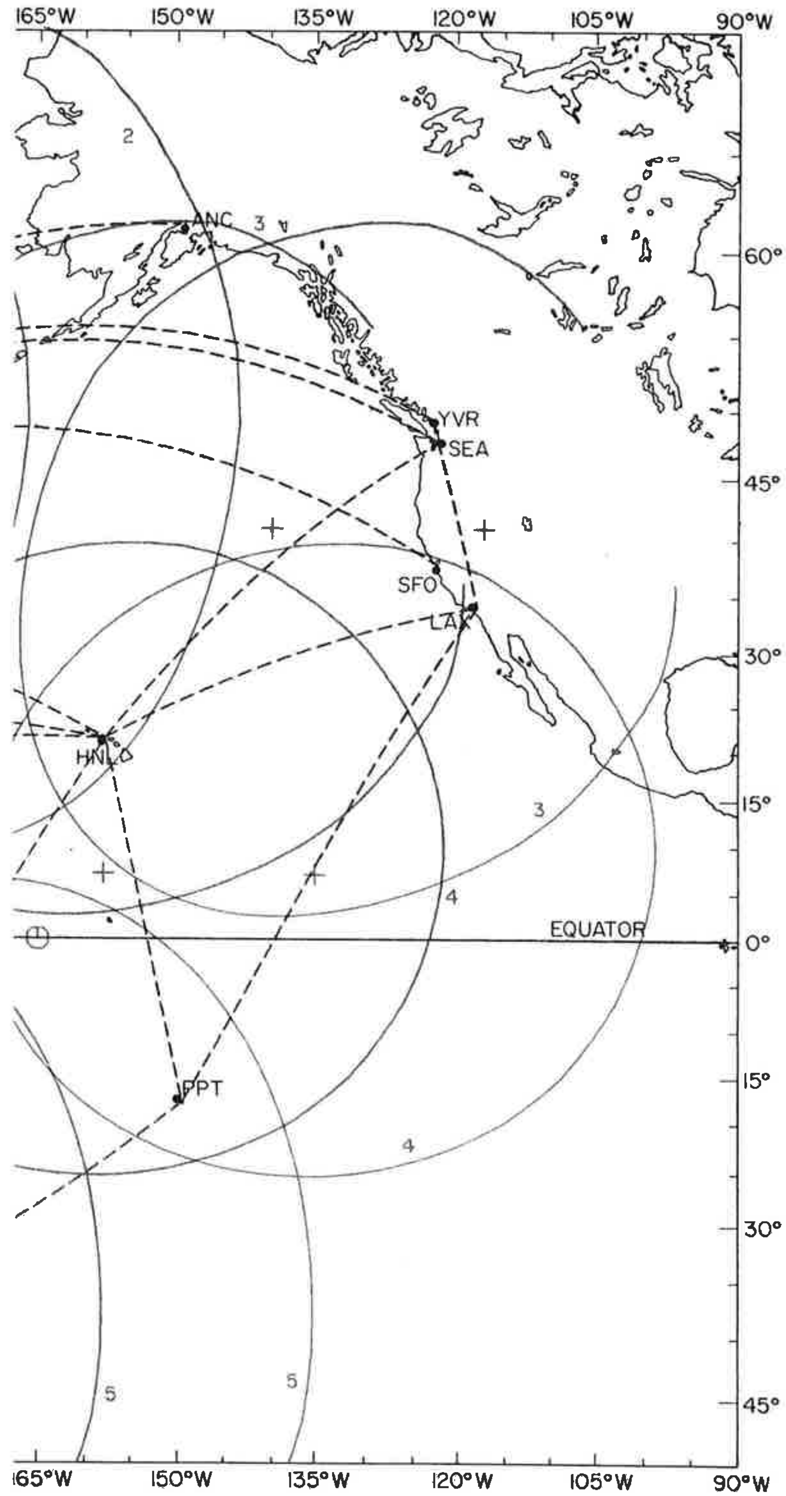


Figure 13. Configuration 1 Beam Coverage - Mercator Projection

The (average) RF power required for satellite to earth terminal communications is negligible, being of the order of .02 watts per channel for voice and .05 watts for the return surveillance link when the aircraft is at the edge of coverage.

Satellite DC Power

Redisch (Reference 10) has provided an estimate of combinations of daylight and eclipse powers that are achievable with a momentum wheel stabilized satellite suitable for aeronautical telecommunications. The values shown in Figure 4 represent end of life (5 yrs) DC power. Worst orbit geometry at summer solstice is assumed as well as expected worst satellite attitude. The 700-pound spacecraft can be launched into orbit by a Thor-Delta 904 with an 84" bulbous shroud and TE-M-422 apogee kick motor. Redisch's result and a linear approximation to it are shown in the figure. The level of the steps is a function of the quantization level of the battery units assumed. A linear approximation is felt to be more unbiased for this comparative analysis until a detailed power system design is completed.

Figure 14 assumes that 100 watts DC is available for housekeeping during daylight and eclipse, so only telecommunications eclipse requirements need be considered in selecting an operating point.

L-Band Power Amplifier Efficiencies

The number of channels that can be accommodated in the satellite is a function of their distribution in the beams. This is so because multiple channels in a single beam will require more than a proportionate share of DC power due to intermodulation losses and decreases in power amplifier efficiency at higher RF powers.

A recent study (Reference 11) of achievable power amplifier efficiencies at L-band has resulted in the diagram of Figure 15 relating total transistor amplifier efficiency to RF output power level. The plot is based on calculated overall power amplifier efficiencies using 10-watt transistors with collector efficiencies of 50% and 10dB gain. It is adopted for use in estimating channel capacities for all system configurations.

Numerical Channel Estimates

The only eclipse requirement of substance, besides housekeeping, is the forward surveillance link (29 watts RF). From Figure 15, this is achieved at approximately 48%

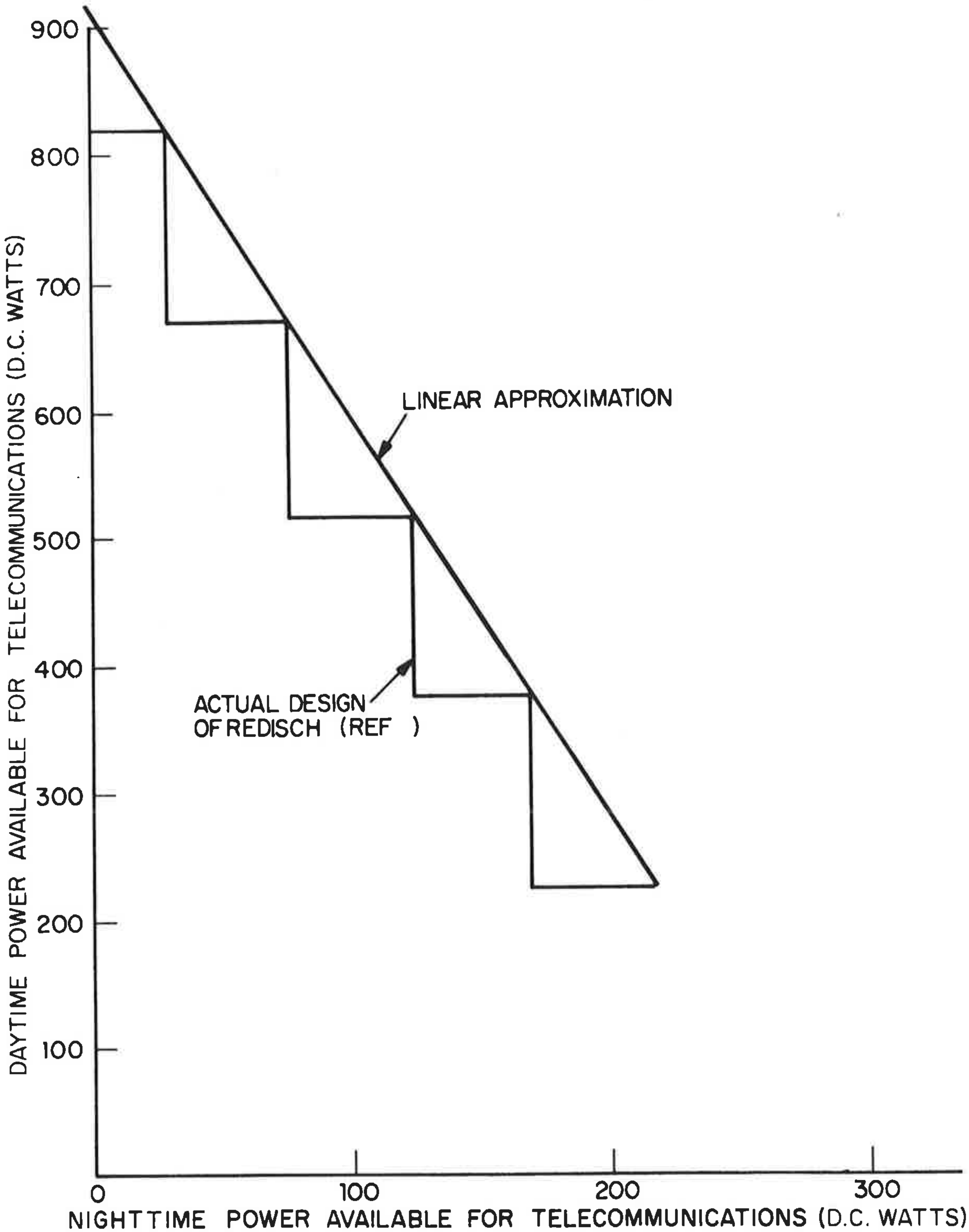


Figure 14. Eclipse Power Trade Offs for a Momentum Wheel Stabilized Satellite

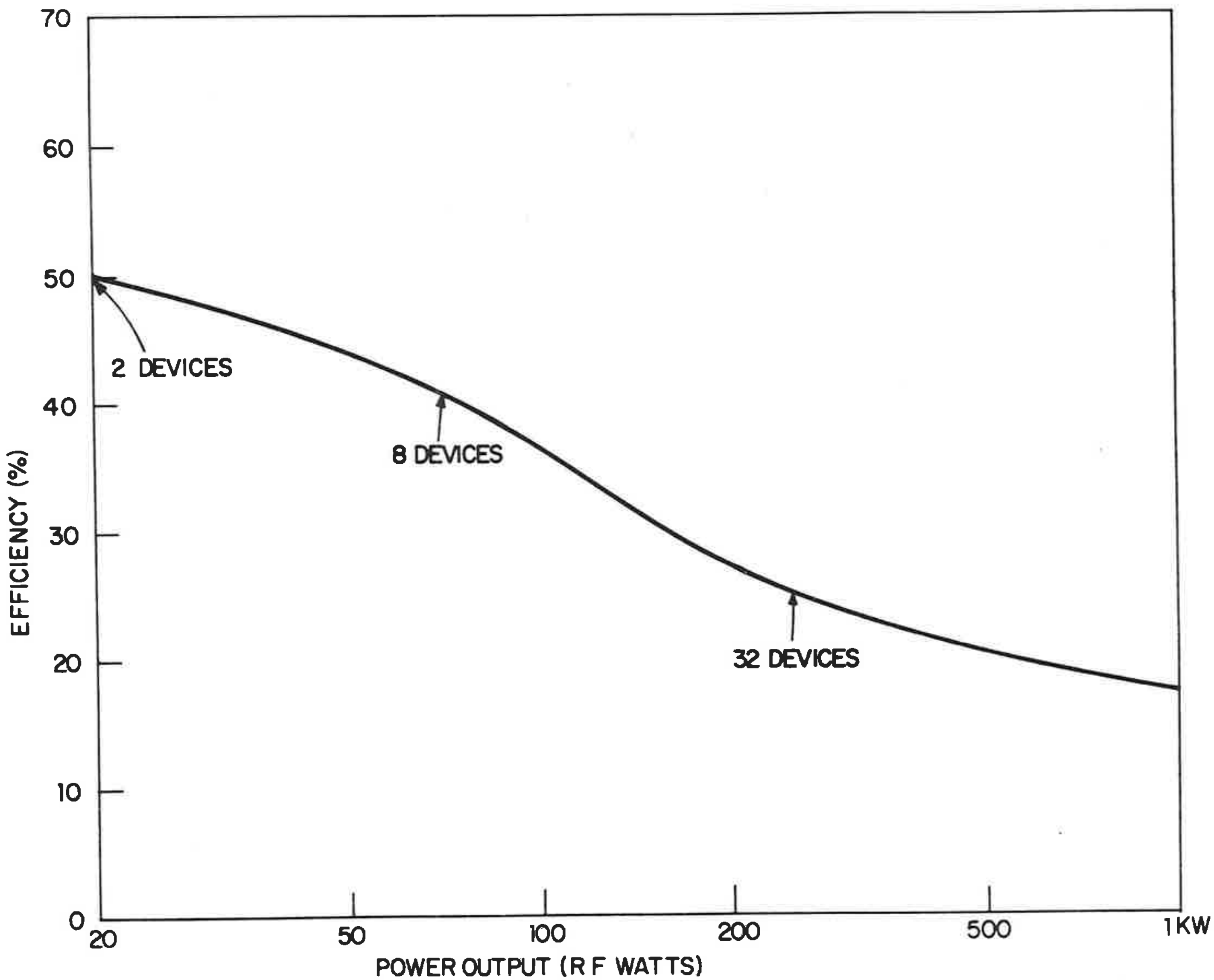


Figure 15. Locus of Efficiency Vs. Power, L-Band Transistor Amplifiers, Existing Technology

efficiency, resulting in a DC power requirement of 60 watts. From Figure 14, this leads to an end of life daylight DC power of 720 watts for communications and surveillance. Therefore, 660 watts are available for daylight communications.

A gross estimate of the voice channel capacity (based on 94 RF watts/channel and 37% efficiency) indicates that between 2 and 3 channels are achievable at the nominal signal to noise density ratio. Less than one channel per beam is, therefore, possible.

The best apparent method of utilizing this capacity is to provide a single channel transistor power amplifier in each beam and to limit the use of the five power amplifiers to two or three by procedural means. Channel activation would be under control of ATC. Since solid state amplifiers are envisioned operating in a class C configuration, those not in use would not cause a significant power drain. Appropriate preference could be given by ATC to priority provision of channels in the beams that cover the Principal Area in the Pacific. Somewhat more capacity would be available at the beginning of the satellites lifetime.

Further iterations allowing some variation in the voice quality but always using single channel amplification suggest that either 2 channels would be possible at a slightly increased carrier to noise density ratio (45.8dB-Hz) or 3 channels could be provided at slightly decreased carrier to noise density ratio (44.5dB-Hz). At 45dB-Hz, power for 2.6 channels is available. Although a choice would have to be made on an integral basis, the 2.6 channel figure is retained as a figure of merit for comparison with the other configuration explored.

TELECOMMUNICATION ANALYSIS - CONFIGURATION 2

Just as for the surveillance link, a power advantage can be demonstrated for voice if it is not required that both satellites cover the full Pacific region. Instead, if the eastern satellite provides communications for the eastern routes and western satellite covers the western routes, full communications coverage would be achieved operating at elevation angles above 20°. Since the link losses are changing very rapidly at this point, a savings of the order of 4.7dB is achieved per communications channel (from Figure 3). This reduces both the satellite and aircraft power required for a voice channel. Under these conditions, a 50% eclipse capacity must be included in each satellite to provide the nominal eclipse performance equivalent to configuration 1. Configuration 1 provided a 50% (system) eclipse capability since half of the total channel capacity available to any aircraft was derived from each satellite. Spacing was chosen to insure that only one satellite eclipsed at a time.

With the aid of Figure 14, it can be shown that an eclipse requirement for surveillance and 50% voice communications leads to a daylight DC power available for communications of 255 watts, a reduction of approximately 4.1dB in comparison with the satellite designed for minimum eclipse capability in configuration 1. The combined reduction in required power per channel and available power results in a slight comparative advantage (.6dB) to configuration 2. There are other factors that will influence the balance. Power amplifiers at lower RF powers will operate at higher efficiency. On the other hand, configuration 2 could require more multichannel amplification and therefore suffer to some extent from intermodulation losses.

Communications

If the high gain antenna beam locations are selected only on the basis of communications requirements, the surveillance backlink would not function, as each satellite would only cover part of the Pacific. Coverage by both satellites is required for surveillance on a full Pacific basis.

Therefore, it is necessary in configuration 2 to provide a beam arrangement in each satellite which has limited coverage for communications, operating above 20° elevation angle, but has full coverage for surveillance (on receive) down to a 10° elevation angle. Some beams will only be used for reception of ranging signals while others will transmit and receive voice and receive ranging data. Ranging channel transmission from satellite to the aircraft is again assumed to operate through an earth coverage L-band antenna.

A beam analysis has been done for configuration 2, with contours of constant link quality for communications being calculated at a link constant (K_k) of 20.0dB. For the Principal Area of the Pacific at a 20° elevation angle, the highest link constant that one could attain over the whole coverage area is when the beam centerpoint is directed at Φ of about 8.2°at a θ which is half way between YVR and LAX. Under this condition, the link constant at LAX or YVR would be approximately 20.5dB. (27.5 - 7.0dB). Contours of coverage for a K_k = 20.0dB are shown in Figure 16 for varying displacements of the beam, Φ_b. These are ultimately overlaid, in the coverage analysis, by the same link quality contours used for configuration 1, with a link constant of 15.0dB, to insure full Pacific coverage by both satellites for the return surveillance signal.

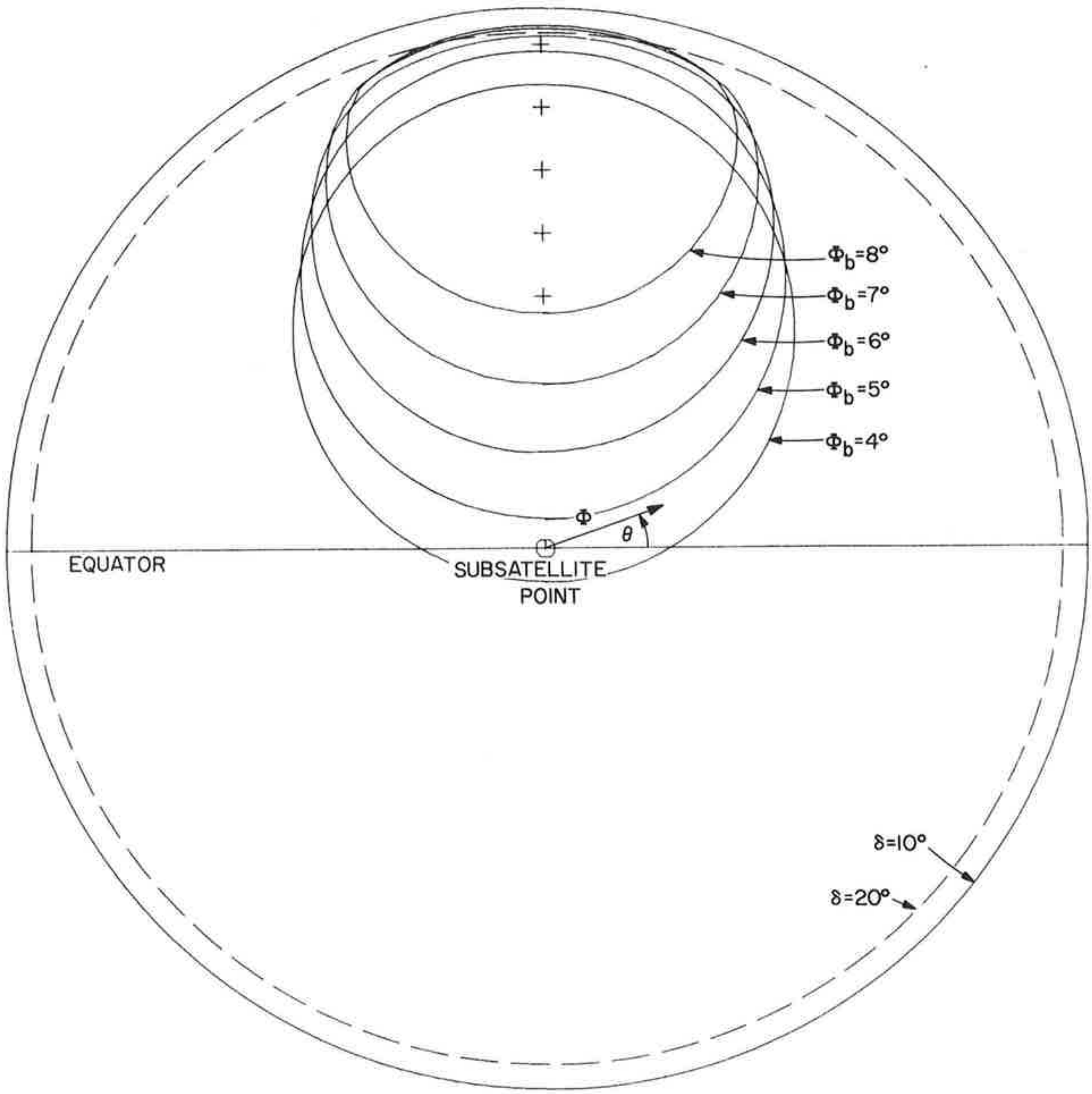


Figure 16. Constant Quality Contours, K_k = 20dB

Beam Location

The link quality contours are obviously smaller in dimension than those generated for configuration 1 due to the exclusion, in this case, of the fast fall off region in the terminal contour between 10° and 20° aircraft elevation angles. A favored communications beam distribution for configuration 2 is shown in polar projection in Figure 17. Figure 18 demonstrates the equivalent contours in Mercator projection. Only the beams which are used for communications are shown for the eastern satellite. Similar factors were considered as were in configuration 1 with the additional complication that, after communications beams were selected, an overlay of the 15dB link quality contours was required to provide full Pacific coverage for surveillance. This added constraint and the smaller dimension of the link quality contours increased the required number of beams to six. The western satellite has six beams which are all used for both communications and surveillance return. The eastern satellite uses only two of its six beams for communications; all provide return links for surveillance. Beam coverage for the return surveillance link is shown in Figures 19 and 20.

Channel Capacity Estimates

The link analysis of Appendix A results in satellite communications power requirements, when links operate above 20°, of 37 watts for a multichannel beam and 29 watts for a single channel beam. An upper bound on voice channel capacity (based on 29 watts per channel at 48% efficiency and 255 watts DC available) indicates that 4.2 channels are achievable per satellite. Of course, there are a wide variety of ways in which the channels can be distributed in the beams. One reasonable distribution, somewhat consistent with present traffic densities in the Pacific, would be to provide a single channel power amplifier in each of the six beams of the western satellite, any four of which could operate simultaneously. The eastern satellite would have two channels permanently in beam 4 covering the Principal Area of the Pacific and one or two channels in the other active beam (3). Dual channel beams would have to operate at a level of 74 watts at an efficiency of about 40%. This selection provides between two and five channels to Principal Area traffic. In addition to the two always available in beam 4 of the eastern satellite, most of the Principal Area is covered by beam 3 of the eastern satellite and beam 4 of the western satellite.

Assuming this allocation of channels to beams is reasonable, a second numerical channel estimate can be made allowing some variation in the nominal signal to noise

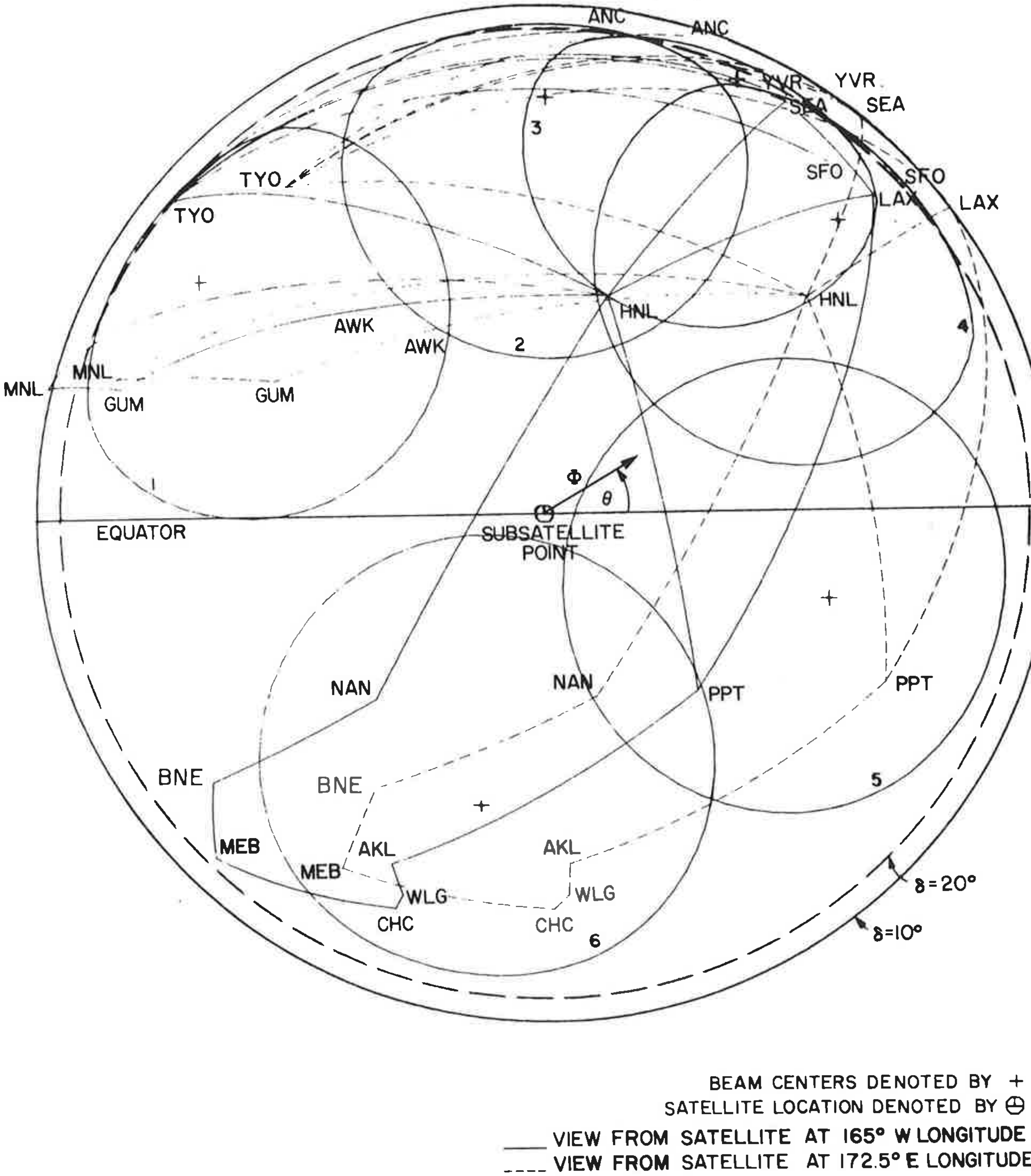


Figure 17. Configuration 2 -- Communications Beam Coverage -- Polar Projection

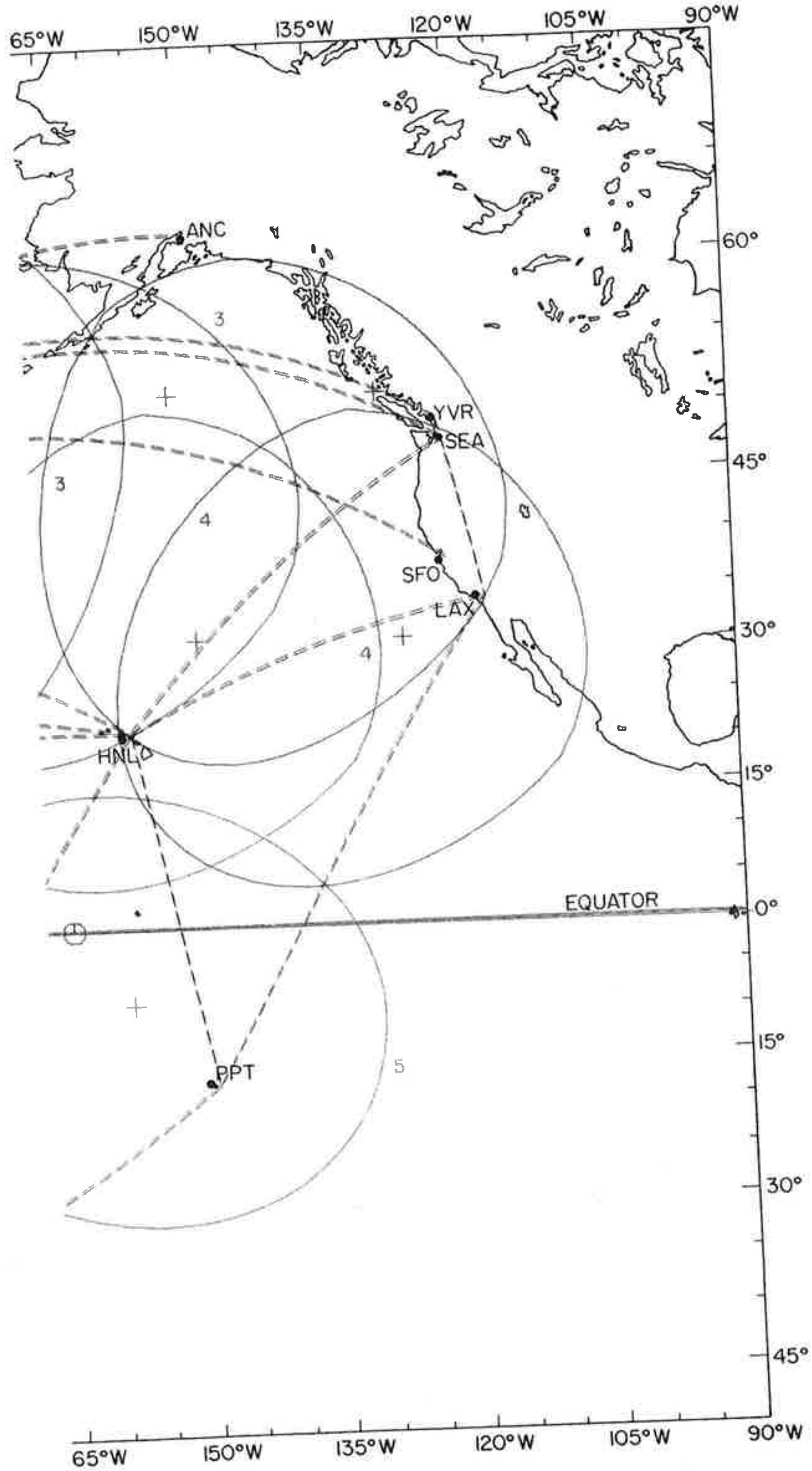


Figure 18. Configuration 2 -- Communications Beam Coverage -- Mercator Projection

density requirement. From this, four channels can be shown to be available in the western satellite at a signal to noise density ratio of 45.1dB-Hz. Two channels can be made available in beam 4 of the eastern satellite and one channel in beam 3, all at a signal to noise density ratio of 45.1dB-Hz.

COMPARISON OF THE TWO CONFIGURATIONS

There are two main factors which can be quantified that give an indication of the relative performance of the two configurations. The first is the number of aircraft per available channel averaged over all aircraft. This is directly related to the average voice channel access time incurred by aircraft. Secondly, the aircraft RF power requirements are easily compared.

Average Number of Aircraft Per Channel

From the numerical channel estimates for the two configurations, configuration 2 appears to have a slight advantage over configuration 1 measured by the number of aircraft per available channel averaged over all aircraft in the Pacific. If 50% of the peak instantaneous traffic is assumed to exist in the West Coast to Hawaii routes and 50% simultaneously in other areas of the Pacific, a rough estimate can be made of the improvement that is achieved. Retaining partial channels for comparative purposes, in configuration 1, we assume 2 channels are available for West Coast to Hawaii traffic with the balance of 3.2 available for the rest of the Pacific. The average number of aircraft per channel is therefore

$$M_1 = 1/2 \left[\frac{.5N}{2} + \frac{.5N}{3.2} \right] = .203N \quad \text{aircraft/channel}$$

where N is the total number of aircraft.

For configuration 2 we will assume that 2 channels are available for West Coast to Hawaii traffic and 5.2 for the balance of the Pacific. Therefore

$$M_2 = 1/2 \left[\frac{.5N}{2} + \frac{.5N}{5.2} \right] = .173N \quad \text{aircraft/channel}$$

Had we assumed that four channels were available for Principal Area traffic and 3.2 channels available for the balance of the Pacific,

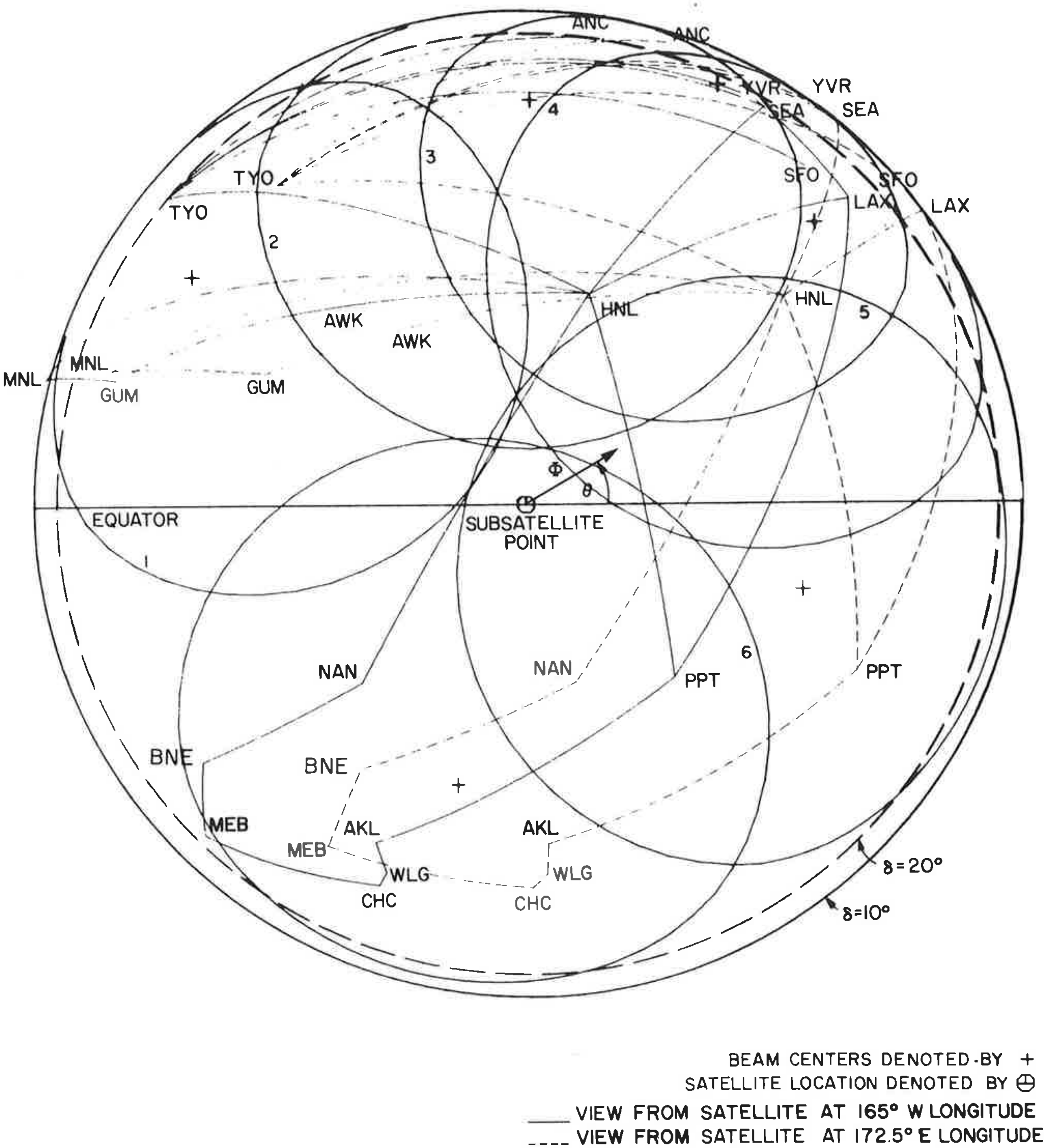


Figure 19. Configuration 2 -- Surveillance Beam Coverage -- Polar Projection

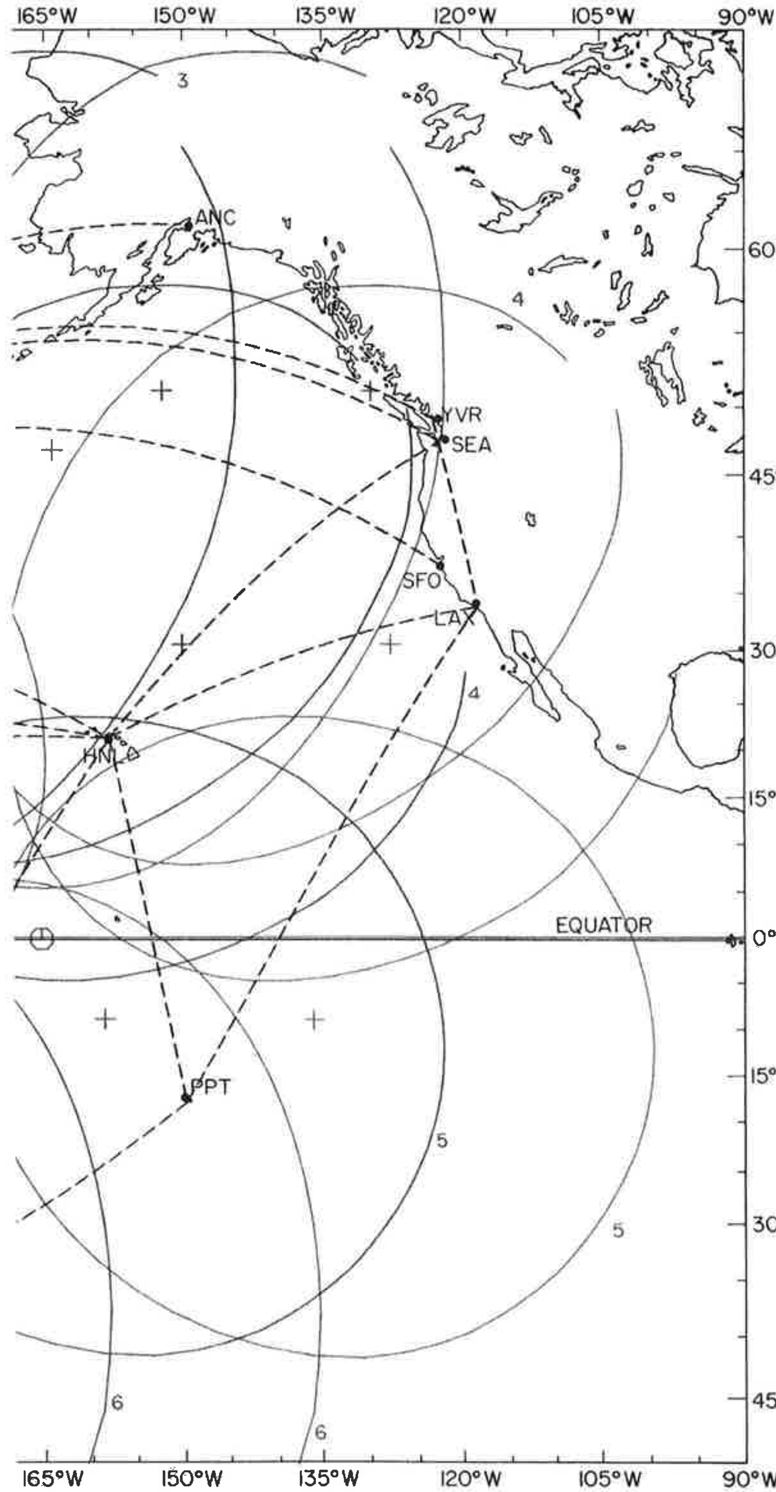


Figure 20. Configuration 2 --
Surveillance Beam Coverage --
Mercator Projection

$$M_2' = 1/2 \left[\frac{.5N}{4} + \frac{.5N}{3.2} \right] = .141N \quad \text{aircraft/channel}$$

Under this range of assumptions the average number of aircraft per channel is reduced from 15 to 30% in configuration 2. Note that this comparison is sensitive to the distribution of traffic assumed as well as to the aircraft antenna employed. If higher gain aircraft antennas allow a larger number of channels, a better match of the channels to traffic might be made for both configurations.

Aircraft Power Requirements

It is straight forward to assess the relative aircraft power requirements for the two configurations. Results of the link analyses of Appendix A are reproduced in Table 1 below. A peak RF power requirement has been added under the assumption that both voice and surveillance operate through the same linear power amplifier on the aircraft. The peak power requirement is the square of the sum of the square roots of the individual powers, since voltages of the two channels can add directly. Note that these peak powers can be avoided if separate antennas and transmitters are employed for communications and surveillance or if the voice signal is blanked out during a surveillance burst.

TABLE 1. AIRCRAFT RF POWER REQUIREMENTS

	Voice	Surveillance	Peak Simultaneous Power
Configuration 1	200w	85w	545w
Configuration 2	63w	85w	294w

Both relative and absolute values of RF powers are important. If a switched antenna achieves a 3dB reduction in power for either configuration the absolute level of power (150W) for configuration 1 may be approaching a point where the further reduction achieved in configuration 2 (to 31 watts) does not lead to significant cost savings. If this is true, however, the back link quality for configuration 2 can be significantly improved over configuration 1 through use of a 100 watt amplifier. Its signal to noise density ratio will be approximately 5dB higher, resulting in a nominal 50 dB-Hz channel.

Cost and System Reliability Factors

Configuration 1 has an advantage over configuration 2 in that both satellites have identical design. This will minimize development costs and provide a level of failure protection that may not exist in configuration 2. Configuration 2 will have basically identical satellite and antenna designs but will have a different transponder design in each satellite. Further effort is necessary to quantify the marginal development costs and to assess operational reliability and redundancy strategies before an overall cost benefit position can be taken for either configuration. These factors will likely have different value in different stages of implementation, i.e., preoperational vs operational.

It is conceivable that a single transponder design could be developed for configuration 2 which is tailored to the specific channel allocation requirements of the different satellites by switching on the ground or in orbit by ground command. This would allow all the benefits of configuration 2 to be achieved with a single satellite design. In addition, with such a design, channels could be redistributed to accommodate unanticipated traffic densities if routes change or to optimize satellite utilization on a seasonal or daily basis.

Surveillance Performance

The surveillance accuracy of the system is essentially independent of the configuration chosen since satellite locations and link parameters are indentical for both. A digital computer program was used to estimate the surveillance system accuracy over the Pacific. This program appropriately sums all of the error contributors with the exception of multipath. The results should be regarded as optimistic, therefore, until adequate measurements or analyses are available to assess the relative effect of multipath.

The total radiolocation error on the earth's surface due to many independent error contributors will approach a bivariate normal distribution. Such a distribution will project onto the earth in elliptical form. The half major and half minor axes of the ellipses in Figure 21 represent the 1σ values of the sum error in the directions indicated.

For the outer ellipses, the two way ranging error due to receiver noise has been taken at $1066m(1\sigma)$. This is consistent with the signal to noise densities employed in the surveillance link analysis. In addition, it is assumed that (1σ)

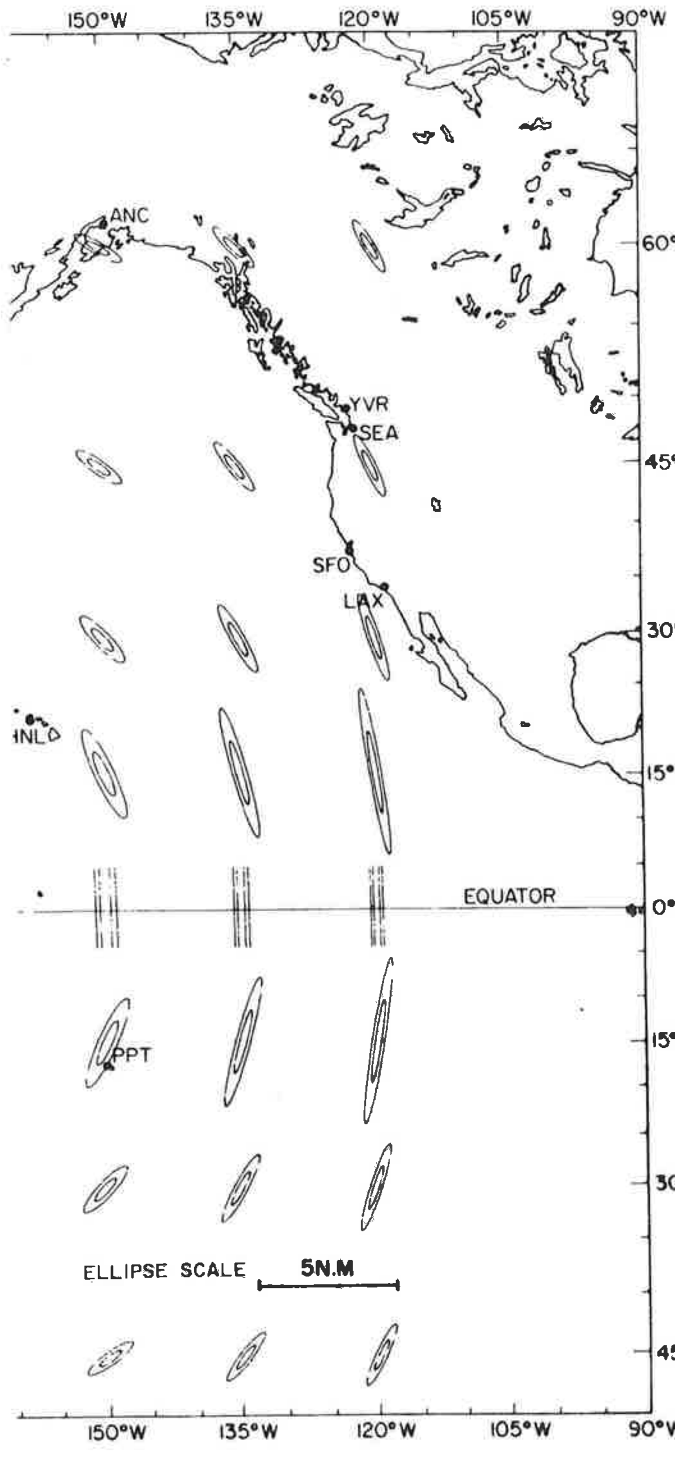


Figure 21. Surveillance Errors

satellite tracking errors of 20 meters exist radially and of 100 meters along and across track. An altimeter error of 50 meters and a residual uncertainty in the columnar electron density of the ionosphere of $2X10^{17}$ electrons/ M^2 are assumed, all on a 1σ basis. All errors are taken to be independent.

Note that in the West Coast to Hawaii area, absolute errors of up to 1.8 nm (1σ) exist; in other areas of the Pacific, errors of up to 3.5nm (1σ) occur at 15° latitudes. Errors are very large in a north-south direction on the Equator.

The inner ellipses result from identical error inputs, except the two way ranging error due to receiver noise has been reduced by a factor of two to 532 meters (1σ). Note that the dimensions of the ellipses all are approximately halved; indicating that receiver noise errors are a dominant error source in the sum. In order to achieve this accuracy, assuming the same phase measurement accuracy at the ground station, the high tone frequency on the surveillance channel would have to be doubled to 20kHz. This would require broadening the bandwidth of the transponder to approximately 67kHz and would increase the aircraft power for surveillance by approximately 1.5dB, to 121 watts.

Note that the major error source is uncorrelated from aircraft to aircraft and, hence, relative position errors will be larger by the order of $\sqrt{2}$ over absolute position error. This will be true whether multipath is a significant additional error or not, as it will likely be uncorrelated from aircraft to aircraft.

SYSTEM PERFORMANCE IMPROVEMENT POTENTIAL

There are two design changes apparent that could improve the performance of a Pacific telecommunications satellite system significantly: (1) the use of moderately higher gain aircraft antennas and (2) addition of a third satellite. The former has not been assessed fully because of the lack of full 4π steradian patterns on the more promising aircraft antennas of this sort. The latter has not been explored simply for lack of time.

Switched Aircraft Antennas

Link improvements are shown in Table 2 for the DICO two element slot dipole and the Boeing two and three element slot dipoles. These improvements are achieved because of higher $(G_a-M)_{95}$ for these antennas from Figures 5, 6, and 7.

All values are referenced to the value calculated at the same elevation angle for the Boeing Crossed Slot Antenna.

TABLE 2. LINK IMPROVEMENTS ANTICIPATED WITH SWITCHED AIRCRAFT ANTENNAS

Antenna \ Elevation Angle	$\delta=10°$	$\delta=20°$
Boeing Crossed Slot	0(ref)	0(ref)
DICO Slot Dipole (2 elements)	+.2dB	+.4dB
Boeing Slot Dipole (2 elements)	+ 3.3dB	data unavailable
Boeing Slot Dipole (3 elements)	+4.1dB	+1.7dB

It is clear that configuration 1 will benefit more from use of these antennas than configuration 2. This is because the gain and rejection ratios of the crossed slot antenna are improving rapidly at a 10° elevation angle.

The DICO slot dipole shows little improvement at either elevation angle over the crossed slot antenna. In addition, Figure 6 shows that G_a-M (100%) for the DICO slot dipole will be lower than G_a-M (100%) for the crossed slot antenna. This would lead to (very infrequent) fades with the DICO antenna that are deeper by 2.4dB than those encountered with the crossed slot. On balance, the crossed slot antenna appears superior, as it achieves essentially equivalent performance without requiring switching by the pilot.

The Boeing two element slot dipole shows a rather substantial improvement when used with configuration 1. This could double the number of channels available, if all users were equipped uniformly with an equivalent antenna. Notice that the additional improvement achieved by going to the more complex three element Boeing slot dipole is very small (.8dB). All things considered, the Boeing two element slot dipole appears to achieve the greatest improvement for the smallest increase in complexity.

An antenna system which appears very promising is the combination of two: one equivalent to the Boeing two element slot dipole, the other equivalent to the crossed slot. Nominally, the crossed slot would be used for surveillance and the slot dipole for communications. This combination would have the following features:

1. Significant performance improvement is achieved for the communication function with the simplest switched antenna.
2. Difficulties associated with maintaining the satellite in the beam of a switched antenna for independent surveillance are avoided. This becomes a more difficult task as the routes approach a north-south direction.
3. Separation of the surveillance and communication systems allows an easy evolution of the functions to occur with provision of communications first, automatic INS position feedback next and independent surveillance later, if tests demonstrate its operational necessity. Avionics and aircraft antennas could be implemented in phases.
4. A degree of redundancy will exist in the antenna system that will not if one antenna or the other were employed. It is conceivable that the total avionics implementation could be built to operate, under emergency conditions, on either antenna perhaps at slightly degraded quality at the worst elevation angles. Separation of the communications and surveillance transponders also has inherent redundancy advantages.

Channel Capacity Improvement

A rough estimate can be made of the improvement possible with this antenna system operating in configuration 1 on the assumption that the satellite RF power can be reduced by 3.3dB per channel (to 44 watts/channel). Figure 15 suggests that between six and seven channels could be achieved at an efficiency of about 44%. If five beams are employed, a reasonable disposition of channels might be to provide one channel in each of four beams and two in the West Coast to Hawaii beam. Intermodulation losses and lower efficiencies at the higher power required for the dual channel beam will reduce the improvement factor, however. A second iteration indicates that two channels could be achieved in the West Coast to Hawaii beam but less than four channels (3.4) in the other four beams.

Without full 4π steradian patterns on the aircraft antenna a satellite antenna beam configuration cannot be identified. Just as for the case of configuration 2, lowering the power required per channel will be accompanied by a reduction in the size of the coverage area per beam. This occurs because the inner portion (near $\Phi = 0$) of the constant quality contours is a strong function of the satellite antenna pattern. If the power at edge of coverage is reduced by 3dB, the inner boundaries of the contours will displace to a point of 3dB higher gain on the satellite antenna pattern. This results in a reduction in the extent of the contours by about .9° in Φ. If a greater number of beams is required to give full coverage, then increased coupling losses could occur, further reducing the improvement. In summary, although adequate data is not available to do a full design, it appears that an improvement of the order of 3dB is practically achievable using an aircraft antenna similar to the Boeing Slot dipole operating in configuration 1.

Three Satellite Implementation

Another system configuration which appears to exhibit significant potential requires the use of 3 geostationary satellites. The central and eastern satellites would provide for routes in the Eastern Pacific and the central and western satellites for the Western Pacific. In addition to further reductions in channel power available from operation generally at higher elevation angles than 20°, coverage by two satellites at every point in the Pacific will likely allow a drastic reduction in the eclipse power requirement. This factor alone could increase the power available in each satellite for communications by 4.1dB. Combined with the additional capacity inherent in three rather than two satellites, it is reasonable to anticipate a factor of three or four increase in channel capacity at a relatively small (∿25%) increment in the establishment costs. This approach bears further detailed evaluation.

SUMMARY REMARKS

The analyses which are contained in this report can only be regarded as first steps toward a favorable system solution. The sensitivity of the results to many of the assumptions must be emphasized. This is true on both an absolute and relative basis.

MULTIPATH

The characterization of the multipath channel as totally diffuse at L-band with an effective reflection coefficient of Γ = -6dB requires confirmation through extensive flight experiments. While the values chosen were selected so as not to be inconsistent with available data, substantially more experimental effort is necessary to allow resolution of this question with a high degree of confidence.

Even if the surface is totally diffuse, there may be other effects of multipath that constrain the system design more strongly than the simple requirement for additional satellite power to combat fading. It is conceivable, under combined conditions of high surface reflectivity and low antenna rejection ratio, that multipath noise could exceed receiver noise levels. If this condition occurs, the effect may be to limit the achievable signal to noise ratio on the link. Increases in satellite power to offset multipath will be accompanied by proportionate increases in (multipath) noise power. This could lead to a condition of limited link quality - peculiar to L-band and higher frequencies because of the diffuse nature of the reflecting surface.

A rather simple model has been used to explore this effect. Under the assumption that multipath noise can be represented by a white noise which is band limited by the I.F. of the receiver, and that the total multipath power in the I.F. is K times the signal power ($K \leq 1$), the margin M' required in the satellite to achieve a required signal to noise density ratio can be shown to be

$$M' = \frac{1}{1 - \left(\frac{S}{N_O}\right)\left(\frac{K}{B}\right)}$$

In the above equation, M' is the multipath margin.
S/N_O is the required signal to noise

density ratio.
K is the ratio of multipath signal power to direct signal power.
B is the I.F. bandwidth.

This function is plotted in Figure 22 for a bandwidth of 10kHz, typically what will be required for a narrow band FM voice link. Equivalent values of voice link intelligibility are shown, measured with a list of 256 phonetically balanced words. Note, for instance, that the model suggests that voice intelligibility is limited to 92.5% if multipath signal attenuation (K) due to surface reflectivity polarization isolation and antenna rejection ratio is of the order of -6dB. Similar limiting effects may occur for both data link and surveillance. The model is not felt to be adequate to deal with this factor with high confidence, and so the quantitative results must be viewed with suspicion. Nevertheless, it indicates a possible limitation that ought to be dealt with carefully by experiment. This factor has not been accounted for in the system designs developed herein.

IONOSPHERIC SCINTILLATION

Not much can be said about the statistics of ionospheric scintillation at L-band because so little data exists. Recent measurements by Comsat Corp. (Ref. 12) at C-band suggest that scintillation levels at L-band may be much higher than anticipated, particularly at low geomagnetic latitudes during certain times of the year. Further measurements are certainly required to develop a worldwide scintillation model as well as to evaluate the operational significance of the fading depths, rates and durations encountered at L-band for voice data and surveillance systems.

SATELLITE ANTENNA CHARACTERISTICS

Another simplifying assumption which has been made is that the loss (1dB) associated with coupling between feed elements for all multibeam antennas is the same. This value is not inconsistent with measurements available to date. Yet the true value is very dependent on the feed system. Coupling losses will be a function of the number of beams employed and their relative spacing. A systematic measurement program is felt necessary here to refine the relationship between this loss factor and the beam configuration chosen. Some of the beam spacings for configuration 2 result in rather close spacings (-2dB points on adjacent patterns). In particular, it would appear worthwhile to consider replacement of beams in close proximity by single elliptically shaped beams. The more promising beam configurations require further review, both on the basis of physical realizability and from the viewpoint of achieving acceptable coupling losses.

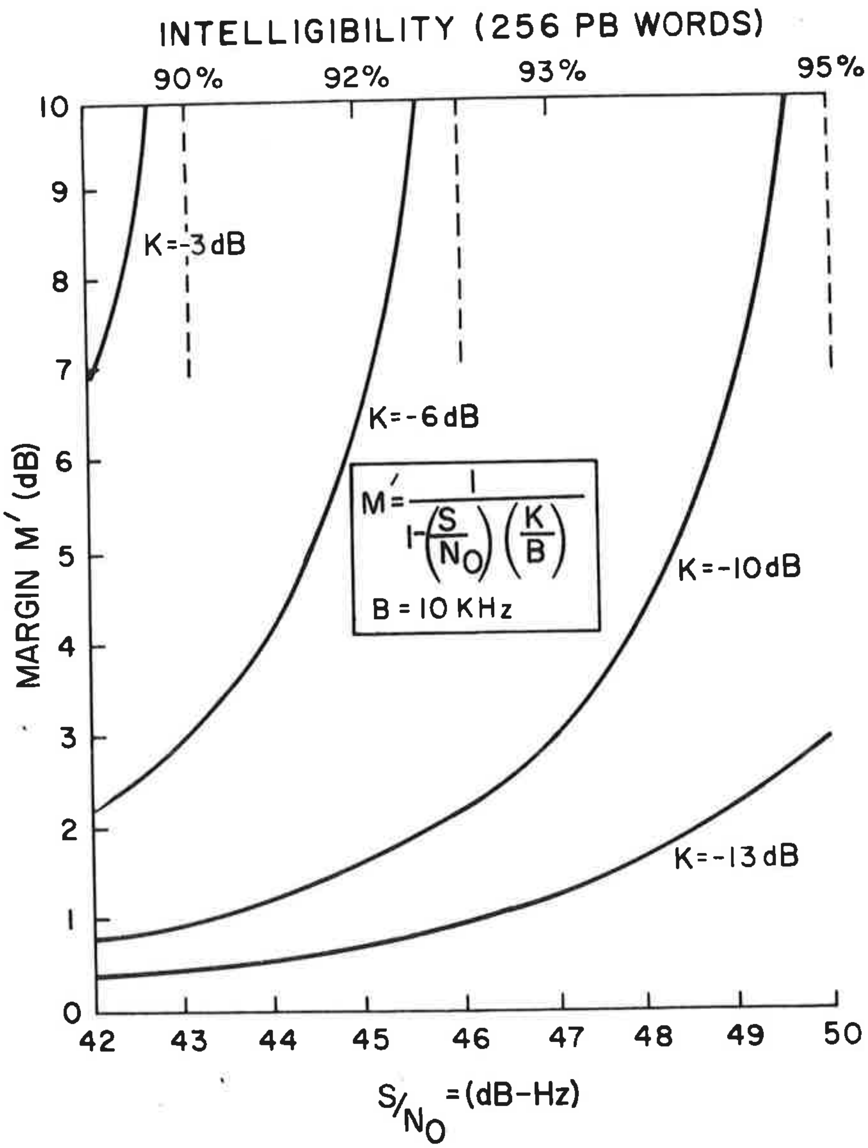


Figure 22. Margin Requirements for Diffuse Multipath

A second iteration based on the use of narrower satellite antenna beams for configuration 1 could show some improvement over the result achieved. It was rather easy to cover the main routes with 5 beams in configuration 1. This implies that it may be achieved with 5 beams with narrower beamwidth and higher gain. On the other hand, in configuration 2, it was difficult to achieve full coverage with six beams. Further attempts should be made in all configurations to generate feed tapers that will produce a slow fall off of the secondary pattern on the side of the beam toward the nadir of the satellite. While this will reduce gain on axis somewhat, it can increase coverage rapidly and reduce stabilization losses in this area.

AIRCRAFT ANTENNA CHARACTERISTICS

Sutton (Ref. 13) has pointed out the possible sensitivity of L-band aircraft antenna patterns to dynamic effects of an aircraft in flight. Wing tip motion can be larger than a wavelength at L-band and could lead to time varying interference effects occurring throughout a flight which would disturb the nulls of the antenna. This suggests a possible limitation in our ability to model the aircraft antenna properly with static patterns and also casts suspicion on our ability to predict the effects of ocean multipath, even if a perfect multipath characterization of the ocean surface is available.

Most of the existing antenna patterns at L-band have been made on scaled aircraft with the antennas mounted in the vicinity of the wings. This has been partly motivated by an attempt to improve the rejection characteristics of the antenna through wing shielding. A rather simple ray path analysis, however, suggests that the wing will not block the ocean reflection except over a very limited range of azimuth angles. This fact combined with the desirability of avoiding dynamic effects of the wings tends to suggest the need for further antenna pattern measurements with the antenna mounted in other areas of the aircraft. The most promising location appears to be in the vicinity of the cockpit, considering the desirability of short cable runs between the antenna, power amplifier and transceiver and accessibility of the equipment for maintenance.

SURVEILLANCE

The surveillance technique assumed in the system analysis is a simple tone turn around system. Boeing's analysis (Ref. 14) suggests that the acquisition time of the aircraft receiver will be of the order of 1 1/2 minutes if lock is lost on the surveillance carrier. Loss of lock could occur during unexpectedly high scintillation or if abrupt changes in the direction of the aircraft were to take place (similar to those that would if a pilot were implementing emergency procedures in the principal routes). The adequacy of such long acquisition times for the surveillance signal in the forward direction should be reviewed, particularly in light of the increased value of surveillance during emergencies. Techniques which would allow more rapid acquisition of the surveillance signal without serious power penalties in the satellite need further identification.

In order to acquire the surveillance signal at the earth terminal rapidly enough to allow one aircraft per second to be located, a doppler tracking procedure must be implemented on the ground. On a second by second basis, the receiver local oscillator frequency is reset based on the past doppler history of aircraft under surveillance. Abrupt changes in the course or speed of an aircraft in the several minute interval between consecutive fixes could result in loss of track on the aircraft by ATC.

In both directions the surveillance system appears most susceptible to losing contact between aircraft and ATC during a time when it may be particularly needed. Most surveillance approaches identified to date will suffer from this problem. A full assessment of the operational acceptability of these limitations if felt necessary.

NEED FOR A PREOPERATIONAL SATELLITE

Many of the uncertainties identified in the previous paragraphs tend to be of such a nature that they can only be fully resolved by extended measurements and experience in the true environment of the operational system. Significant information should continue to be drawn from the more limited experimental facilities available, i.e. high altitude balloons or NASA's ATS Satellites. In any case, these questions and others dealing with definition of operational procedures must be carefully and systematically resolved before final identification of the characteristics of an operational system can be expected. The preoperational satellite development program which has been given support by the Office of Telecommunications Policy is the first major step in that direction.

APPENDIX A

LINK DESIGN

TABLE A-2. FORWARD SURVEILLANCE LINK ANALYSIS SATELLITE TO AIRCRAFT - 10° AND 20° ELEVATION ANGLES - 1560 MHz

Factor	Value (10°)	Value (20°)	Remarks
Transmitter Power	19.4dBW(87 watts)	14.6dBW(29 watts)	
Transmitting Circuit Loss	-1.5dB	-1.5dB	
Transmitting Antenna Gain	16.0dB	16.0dB	31" aperture at -3dB point
Transmitting Antenna Pointing Loss	-.4dB	-.4dB	$\pm$.5° attitude stability
Space Attenuation	-188.5dB	-188.3dB	21800nm/21200nm Ref. Fig.5
Receiving $(G_a-M)_{95}$	-7.0dB	-2.4dB	
Supplemental Fading Loss	-1dB	-1dB	To account for ionospheric scintillation and normal aircraft pitch and roll.
Receiving Circuit Loss	-2.0dB	-2.0dB	
Net Circuit Loss	-184.4dB	-179.6dB	
Total Received Power	-165.0dBW	-165.0dBW	
Signal Power Degradation (D_1)	-.3dB	-.3dB	12.0dB S/N at output of satellite repeater
Noise Power Degradation (D_2)	-0.0dB	-0.0dB	12.0dB S/N at output of satellite repeater
Effective Received Power	-165.3dBW	-165.3dBW	3.5dB NF, 2dB Loss, Ta=75°K
Receiver Noise Density	-201.5dBW/Hz	-201.5dBW/Hz	
Detection - Carrier			
Received Modulation Loss	-4.6dB	-4.6dB	
Received Carrier Power	-169.9dBW	-169.9dBW	
Carrier Tracking Noise Bandwidth(2BL)	17.4dB	17.4dB	55Hz PLL demodulator BW
Threshold C/N in $2B_L$	10.0dB	10.0dB	
Threshold Carrier Power	-174.1dB	-174.1dB	
Performance Margin	4.2dB	4.2dB	

TABLE A-2. (CONTINUED)

Factor	Value (10°)	Value (20°)	Remarks
Detection - Data Channel			
Modulation Loss	-8.4dB	-8.4dB	
Received Data Subcarrier Power	-173.7dBW	-173.7dBW	
Bit Rate	17.4dB	17.4dB	55bps
Required Bit Energy to Noise Density Ratio	10.4dB	10.4dB	CPSK, 10^{-4} B.E.R.
Threshold Subcarrier Power	-173.7dBW	-173.7dBW	
Performance Margin	0dB	0dB	
Detection - Tone Channel			
Modulation Loss	-15.4dB	-15.4dB	
Received Tone Subcarrier Power	-180.7dBW	-180.7dBW	
Tone Filter Noise BW	33.8dB	33.8dB	2.4kHz tone transponder BW
Noise Power in Filter BW	-167.7dBW	-167.7dBW	
S/N in Filter BW	-13.0dB	-13.0dB	

TABLE A-3. RETURN SURVEILLANCE LINK ANALYSIS
AIRCRAFT TO SATELLITE - 10° ELEVATION ANGLE - 1660 MHz

Factor	Value	Remarks
Transmitter Power	19.3dBW	85 watts
Transmitting Circuit Loss	-2.0dB	
Transmitting $(G_a - M)_{95}$	-7.0dB	Ref. Fig.5
Supplemental Fading Margin	-1dB	To account for ionospheric scintillation and normal aircraft pitch and roll.
Space Attenuation	-189.0dB	21800nm
Satellite Antenna Gain	27.2dBW	Link constant taken as 15.5dB to account for operation at 1660 MHz
Receiving Antenna - Feed Coupling Loss	-1.0dB	
Receiving Antenna - Pointing Loss	-1.6dB	±.5° Attitude stability
Receiving Circuit Losses	-1.5dB	
Net Circuit Loss	-175.9dB	
Total Received Power	-156.6dBW	
Signal Power Degradation D_1	-	
Noise Power Degradation D_2	-	
Effective Received Power	-156.6dBW	
Receiver Noise Density	-199.1dBW/Hz	5.0dB NF, 1.5dB Loss, Ta=290°K
Repeater		
Repeater BW at IF	46.7dB	47kHz BW
Noise Power in IF BW	-152.4dBW	
S/N at Power Amplifier Output	-4.2dB	

TABLE A-4. RETURN SURVEILLANCE LINK ANALYSIS
SATELLITE TO EARTH TERMINAL - 10° ELEVATION ANGLE - 1560 MHz

Factor	Value	Remarks
Transmitter Power	-12.9dBW	.051 watts
Transmitting Circuit Loss	-1.5dB	
Transmitting Antenna Gain	16.0dB	31" aperture at -3dB point
Transmitting Antenna Pointing Loss	-.4dB	±.5° attitude stability
Space Attenuation	-188.5dB	21800nm
Propagation Margin	-1.7dB	
Receiving Antenna Gain	42.5dB	40 ft. aperture
Receiving Antenna Pointing Loss	-1.0dB	
Receiving Circuit Loss	-1.5dB	
Net Circuit Loss	-136.1dB	
Total Received Power	-149.0dBW	
Signal Power Degradation D_1	-5.6dB	-4.2dB S/N at satellite repeater
Receiver Noise Degradation D_2	-8.9dB	-4.2dB S/N at satellite repeater
Effective Received Power	-163.5dBW	
Receiver Noise Density	-205.4dBW/Hz	Ta=50°K, Tr=90°K, 1.5dB loss
Detection - Carrier		
Carrier Modulation Loss	-5.0dB	
Received Carrier Power	-168.5dB	
Carrier Tracking Noise Bandwidth ($2B_L$)	25.4dB	350Hz
Threshold C/N in $2B_L$	10dB	
Threshold Carrier Power	-170.0dBW	
Performance Margin	1.5dB	

TABLE A-4. (CONTINUED)

Factor	Value	Remarks
Detection - Data Channel		
Modulation Loss	-8.3dB	
Received Data Subcarrier Power	-171.8dB	
Bit Rate	23.2dB	210bps
Required Bit Energy to Noise Density Ratio	10.4dB	CPSK, 10^{-4} BER
Threshold Subcarrier Power	-171.8dB	
Performance Margin	0dB	
Detection - Tone Channel		
Modulation Loss	-15.5dB	
Received Tone Plus Noise Power	-179.0dBW	
Signal Power Degradation D_1'	-7.0dB	-13dB S/N at output of aircraft repeater
Receiver Noise Degradation D_2'	-2.4dBW	-13dB S/N at output of aircraft repeater
Effective Received Tone Power	-188.4dBW	
Tracking Loop Noise BW ($2B_L$)	7.0dB	5Hz PLL demodulator BW
Threshold T/N in $2B_L$	10.0dB	
Threshold Tone Power	-188.4dBW	
Performance Margin	0dB	

TABLE A-5. FORWARD VOICE/DATA LINK ANALYSIS
EARTH TERMINAL TO SATELLITE - 10° ELEVATION ANGLE - 1660 MHz

Factor	Value	Remarks
Transmitter Power	-2.8dBW	.525 watts
Transmitting Circuit Loss	-1.5dB	
Transmitting Antenna Gain	43.0dB	40 ft. aperture
Transmitting Antenna Pointing Loss	-1.0dB	
Space Attenuation	-189.0dB	21800nm
Propagation Margin	-1.7dB	
Receiving Antenna Gain	16.5dB	31" aperture at -3dB point
Receiving Antenna Pointing Loss	-.4dB	±.5° attitude stability
Receiving Circuit Loss	-1.5dB	
Net Circuit Loss	-135.6dB	
Total Received Power	-138.4dBW	
Signal Degradation D_1	-	
Receiver Noise Degradation D_2	-	
Effective Received Power	-138.4dBW	
Receiver Noise Density	-199.1dBW/Hz	5.0dB NF, 1.5dB Loss, Ta=290°K
Repeater		
Repeater BW at IF	45.2dB	33.2kHz
Noise Power in IF	-153.9dBW	
S/N into IF Limiter	15.5dB	
S/N out of IF Limiter	18.4dB	
S/N out of Power Amplifier	18.4dB	

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