Bell Laboratories

subject: Interference Considerations for an Optimal Geostationary Orbit Utilization by the Iranian Satellite System

date: August 16, 1977

from: P. Stavroulakis

ABSTRACT

The major factors affecting interference between satellite systems have been reviewed and analyzed in this study. The procedure that must be followed in designing satellite systems for an optimal geostationary orbit utilization has been outlined with the necessary mathematical justification wherever applicable. Reference to the Iranian system has been made in relevant points.

TABLE OF CONTENTS

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MEMORANDUM FOR FILE

1. OVERVIEW AND OBJECTIVE

1.1 Introduction

The geostationary-satellite orbit is uniquely useful for communication satellites. There is, however, an ultimate limit to the number of communication satellites and consequently communication channels, which it can support in a given frequency range due to the effects of interferences between adjacent satellites. Efficient use of the geostationary satellite orbit and the frequency spectrum depends on good management principles as well as on thorough and objective evaluation of all the technical factors affecting orbit utilization. Procedures to that end have been established by the World Administrative Radio Conference for space telecommunications, 1971, for the coordination of frequencies assigned to space and associated earth stations. These procedures are contained as Article 7 and 9 of the Radio Regulations. The continuous increase of demand of satellite-provided communication service in the last few years and the speed and unpredictability of advances in technology tends to prevent efficient large-scale long-term planning of the fixed-satellite system, such as the one being planned for Iran. If the geostationary satellite orbit is to be used effectively for permanent communication facilities, systems must be designed and used, not only so that the objectives of individual systems are met, but also so that satellite networks using neighboring positions in the orbit do not interfere with each other without waste of the limited resource of orbit/spectrum. The optimal utilization of the geostationary orbit is sought in the middle way between excessive restriction that would cramp development and self-destructive freedom. Effective orbit utilization demands three things:

1) Engineering for an interference-limited environment. The basic characteristics of the equipment in the ground and in space and the techniques used for modulation and multiple access should be chosen to minimize the interference power level reached from and injected into other systems.

2) Effective intersystem coordination among neighboring satellites.

3) The avoidance of extreme inhomogeneity in orbit and spectrum sharing. There are two fundamental factors which govern inhomogeneity between satellite systems. The first factor results from relative differences between satellite systems in their potential for causing interference to other systems while the second

results from difference between satellite systems in their relative sensitivity to interference. Quantification of inhomogeneity of satellite systems can be used in the evaluation of interference based upon the concept that the noise temperature of the system receiving interference increases as the level of interference increases. This concept is discussed in Appendix A.

1.2 Objectives

The main objective of this study is to review the major interference problems that arise in satellite communication systems and give some analytical justification to the importance of each of the factors involved. The recommended procedures outlined for each case by CCIR is also discussed and some reference to the Iranian satellite system is made wherever it is applicable. The procedure followed has the following format: First, we present the major factors affecting interference and then analyze each one mathematically in simple forms whenever possible. The computer programs available at Bell Laboratories which deal directly with the interference problems have also been discussed. Finally, using the IFRB circulars available, as a reference, some brief discussion on the future 12/14 GHz geostationary satellite system characteristics has been included.

2. FACTORS AFFECTING INTERFERENCE

The major concern over the last few years in designing satellite systems has not necessarily been the limitation of interference between satellite networks because of two reasons. Firstly, the immediate need in designing for interference - limited environment has not been so urgent due to the plentiful capacity of the geostationary orbit and secondly, economic and technical reasons were the dominant factors in the design. These factors have led to designs which can be in conflict with stringent interference requirements. For example, satellite antenna radiation patterns have been optimized to provide maximum gain towards the earth stations within payload mass limits. Earth stations have been chosen to maximize performance only in the direction of the desired satellite without consideration of adjacent satellite. Modulation and multiple access techniques have been a compromise between a low-cost earth/space interference and high per-transponder traffic capacity. In the future, it will no longer be possible to ignore the need to design for limitation of interference between satellite networks. In this section, we shall discuss the basic factors that have to be considered in the design of geostationary satellite systems similar to that being designed for Iran. The discussion also includes those factors which are applicable to the Iranian system. The recommended procedure to be followed accepted by CCIR is outlined when applicable.

2.1 Satellite Station Keeping

Solar radiation pressure and irregularities in the earth's gravitational field are the cause for satellites to depart to east or west off its nominal longitudinal position, thus interfering with a neighboring satellite. Capacity is only slightly impaired by moderate orbital inclinations, but is greatly reduced when longitudinal positional drifts approach values comparable with the minimum permissible satellite spacing. The Radio Regulations require all satellites to be monitored within $\pm 1^\circ$ of the longitude of their nominal position but adjacent satellite system interference considerations reduce this outer limit significantly. This will be discussed later. To facilitate the discussion, we shall present the following example. Figure 1 shows satellites D, E, F, G, and H, part of an array of similar satellites all of which illuminate an earth station at the point Z served by satellite F. Each satellite is assumed to move $\pm\delta^\circ$ about its nominal orbital position and the angular separations between the nominal locations is θ°. If we make the assumption that the gain of the sidelobe envelope of the earth station antenna is approximated by

$$G(\theta) = 32 - 25 \log \theta \text{ (dBi)}$$

then using Figure 1 and the above equationk we can compute the <u>worst</u> possible interference contributions at Z from satellites D, E, G, H. It is easy to show, using the above relation and summing the contribution from all satellites, that interference at Z will be a function of

$$\theta^{-2.5}\left[1.18 + \left(1 - \frac{2\delta}{\theta}\right)^{-2.5} + 0.18\left(1 - \frac{\delta}{\theta}\right)^{-2.5}\right]$$

For a constant interference level, changing δ from $\pm 1.0°$ to $\pm 0.1°$, we can obtain an improvement of the orbit loading efficiency as much as 20 percent.[9] Clearly, an improvement in required satellite-spacing is obtained by keeping the east-west station keeping to within ±0.1 as is the case of the Iranian satellite.

2.2 Satellite Antenna Radiation Characteristics

Generally, there are two typical interference situations which arise from satellite antenna characteristics:

a) Two satellites may be well-separated in orbit but their service areas are close together and satellite antenna main lobe overspill is more than the directivity of the earth-station antennas can control.

b) Two satellites are relatively close together in orbit but their service areas are well-separated and interference arises via the sidelobe response of the satellite antennas.

These are obviously two different cases and require different treatment to reduce the interference between them. For the first case, the satellite antenna main lobe response must fall away rapidly in all directions outside the service area. This requirement, however, might have an undesirable effect on the orbital arc within which the satellite could be located and still serve its service arc. Due to the difficulty of controlling the second problem, it seems feasible to apply an internationally agreed limit to the satellite radiated power spectral density in directions well removed from the service area. This limit might take the following form. Let a contour A_0 (see Figure 2a) be drawn outside the service area of a beam so that there is a angular clearance between the contour and the nearest point in the service area as seen from the nominal location of the satellite. A family of contours are drawn separated by an angle B. The antenna might be required to fall below 20 dB relative to isotropic at contour A_0 and linearly to 0 at contour A_3. The actual values of these parameters depends on system economics, coordination with networks serving nearby areas and the provision of an adequate service arc. A similar limit is being designed for Zohreh 1 to reduce interference to systems outside of Iran.

2.3 Earth-Station Antenna Sidelobe Radiation

In 1965, CCIR adopted the expression:

$$G(\theta) = 32 - 25 \log \theta \text{ (dBi)}$$

as the reference radiation pattern for use in large-antenna interference calculations when specific antenna data are not available. Small and large scale inaccuracies of the profile of the main reflector and subreflector spillover are the most significant causes for sidelobe generating mechanisms over the angles where the sidelobes are likely to do most harm. An additional sidelobe performance of 3 dB for large earth station antennas could lead [5] to as much as 25 percent improvement of satellite spacings.

2.4 Polarization

The capacity of bandwidth-limited communication satellites may be increased by utilizing frequencies more than once by polarization - separation of two signals at the same frequency. The use of opposite-hand circular or crossed-linear polarizations may be used to effect an increase in the bandwidth by a factor as big as two. The degree of the polarization discrimination that can be achieved for the co-channel operation will determine the extent to which this increase of the bandwidth can be obtained. Linear orthogonal polarization gives better performance than circular but the tradeoff is that for the linear case, the satellite stabilization would need to be precise to within minutes of a degree and the earth station would be required to track the polarization. The main problem as far as the earth-station equipment is concerned is that of separating two orthogonally polarized signals received from an antenna feed and combining two high-power polarized signals into an orthogonal configuration for transmission to the feed. In general terms, the increase in channel capacity that can be achieved, given the necessary wanted-to-unwanted carrier ratios of the overall link can be summarized below [20].

For similar, co-channel FDM/FM emissions, wanted-to-unwanted carrier ratios in the range 23 to 31 dB would be sufficient to limit mutual interference to 1000 pWp. Given that ratio, the total channel capacity for a bandwidth-limited system would be increased by 60 [4] percent without increase in the total down-path power, and by 100 percent if the total down-path power were doubled. There would be no increase in capacity if the satellite system were power-limited. For similar co-channel 4-phase PCM/PSK emissions, and for a bit error rate of 10^{-4}, a wanted-to-unwanted carrier ratio of about 20 dB and an increase in the total down-path power of 4 dB would permit the total channel capacity to be doubled. For 8-phase PCM/PSK emissions, the corresponding carrier ratio would be about 25 dB.

2.5 Modulation Techniques and Spectral Energy Distribution

The choice of modulation techniques has a considerable effect upon the level of interference. The carrier power required for satisfactory reception of an emission is a function of the predemodulator bandwidth, but its potential for causing interference is a function of the power falling into the bandwidth of the link suffering interference and in many cases, to the spectral distribution of interference power within that bandwidth. Thus, a wideband unwanted signal may cause interference out of proportion to its mean flux density if the distributions of energy in the interfering spectrum is strongly nonuniform. In the absence of special arrangements (energy dispersal) the spectral energy distribution of emissions is usually concentrated about the carrier frequency for analogue emissions and about a series of discrete spectral lines in digital emissions, thus, increase the level of interference. Artificial spectral energy dispersal techniques, such as the addition of a low frequency sawtooth waveform to an FM baseband and the addition of a long cycle pseudo-random sequence to digital signals can improve the uniformity of the distribution of the spectral energy without significant degradation of the performance of wanted signal.

2.6 Intersystem Coordination

The coordination of one satellite system with its neighbors is as important a problem as the design of the system itself in achieving optimal orbital utilization. Interference between networks which might be severe can often be reduced to a tolerable or even negligible level by minor adjustments to technical characteristics if the need can be identified early enough. Procedures for the coordination of geostationary satellites wereagreed at an ITU conference in 1971. The whole process of coordination is based on a set of technical guidelines that have been developed over the years and their purpose is to yield solutions which satisfy the parties immediately involved while leaving opportunities for the entry into the orbit of yet more satellites. Some of the major aspects of these guidelines include:

a) Frequency Band Pairing

The problem of obtaining preferred frequency band pairings for each system seems not to have an easy solution due to the large number of degrees of freedom involved. This is also complicated by the fact that 1) many high capacity satellites use more than one pair, 2) national frequency allocations differ in different parts of the world.

b) Permissible Single-Entry Interference Noise Allocations

By international agreement, intersystem interference may account for up to 10 percent of all the noise degradations that are experienced in satellite link. The CCIR recommends that the allocation to any one interference source should not exceed 40 percent of the total intersystem interference budget. The level of interference corresponds roughly to the fractions of the total interference that would arise from the nearness of a hypothetical homogeneous array of equally spaced satellites of either sides in orbit of the wanted satellite. Clearly, this 40 percent maximum allocation needs to be elaborated into a scale of allocations taking account of orbital separation and the geographical relationships of the service areas involved.

c) Maximization of Service Arc

An attractive way of reducing intersystem interference is to move the satellites further apart. This presupposes that the service arc of the satellite is big enough. There are circumstances, however, that limit the service arc available to the particular satellite. The reasons may be economic, technical and operational. One of the technical reasons for example, may apply to satellite with multiple spot beams whose shape and relative sections are optimal only on a narrow orbital arc. The service arc for Zohreh 1 is 21°.

3. GENERAL INTERFERENCE MODEL

3.1 Introduction

In the following discussion, we shall present the problem of interference as a fundamental limitation in the utilization of the geostationary orbit. The inevitability of interference is as physically fundamental as that of noise within a communication system. In the case of satellite networks, as we discussed in the previous section, they necessarily operate in a interference environment. In communication systems design, it has been customary to quantify the performance of the network (in the case of satellite, the performance of the link) in terms of the signal-to-noise, S/N, ratio and/or bit error probability at a point where such a measure can give some indication as to the quality of the link and/or the degree of the interference from other networks. In general, if we define by Q the quality of wanted signals which can either refer to the S/N or the bit error probability of the communication channel, then we can write in a functional form :

$$Q = f(S_W, S_I, L_W, L_I) \tag{1}$$

where

Q = wanted signal quality in terms of S/N or error probability, P_e.

S_W = modulation characteristics of the wanted signal, i.e., signal type, modulations index, baseband bandwidth; subscripts W and I refer to wanted and interfering signal respectively.

L_W = network link parameters i.e., EIRP, frequency and antenna size.

We observe that the evaluation of the interference effects depends on the nature of both wanted and interfering signals and on the characteristics of the communication link under consideration. From the countless combinations of these factors that might arise in practice, we shall only discuss three cases which are important to satellite communications: FDM/FM multichannel telephony, FM Television and Coherent phase shift keyed (CPSK) signals.

3.2 Interference Between FDM/FM Telephony Signals

Let the wanted signal $S_W(t)$ be given by

$$S_W(t) = A\cos\left(\omega_{1c}t+\phi(t)\right) \tag{2}$$

and the interfering signal $S_I(t)$ be given by

$$S_I(t) = rA \cos\left(\omega_{2c} t + \psi(t) + \mu\right) \quad , \quad r < 1 \qquad (3)$$

where

$\phi(t), \psi(t)$ are assumed to be Gaussian signals.

μ is assumed to be uniformly distributed over the interval $(0, 2\pi)$.

The sum of these two signals can be written:

$$S(t) = ARe\left\{e^{j(\omega_{1c} t + \phi(t)}\right\} + rAR_e\left\{e^{j\psi(t)} e^{j(\omega_{2c} t+\mu)}\right\} \qquad (4)$$

$$= AR_e\left\{e^{j(\omega_{1c} t + \phi(t))}\left[1 + re^{j\psi(t)} e^{j[(\omega_{2c} - \omega_{1c})t + \phi(t) + \mu]}\right]\right\} \qquad (5)$$

if we set

$$\alpha(t) e^{\lambda(t)} \equiv 1 + re^{j\psi(t)} e^{j[(\omega_{2c} - \omega_{1c})t - \phi(t) + \mu]} \qquad (6)$$

equations (5) can be written

$$S(t) = AR_e\left\{e^{j(\omega_1 t + \phi(t))}\alpha(t)e^{j\lambda(t)}\right\}$$

$$= AR_e\left\{\alpha(t)\varepsilon^{j(\omega_1 t + \phi(t) + \lambda(t))}\right\} \tag{7}$$

An ideal phase detector operating on (7) would produce the following output

$$S_o(t) = (\phi(t) + \lambda(t))$$

From (6) it is seen that

$$\lambda(t) = \mathrm{Im}\ell n\left[1 + re^{j\psi(t)}e^{j[(\omega_{2c}-\omega_{1c})t - \phi(t) + \mu]}\right] \tag{8}$$

Hence the effect of interference is embodied in the excess angle $\lambda(t)$. For small interference i.e., $r \ll 1$ it can be shown[9] that the power spectral density of $\lambda(t)$ is given by

$$S_\lambda(f) = \frac{1}{4A^2}\left\{S_I(f-f_d)*S_W(f) + S_I(-f-f_d)*S_W(-f)\right\} \quad (9)$$

where

$$f_d \equiv f_{2c} - f_{1c} \quad (10)$$

$*$ indicates the convolution operator.

$$S_W(f) \equiv \int_{-\infty}^{\infty} e^{-\left(R_\phi(0) - R_\phi(\tau)\right) - j2\pi f\tau} d\tau \quad (11)$$

$$S_I(f) = \int_{-\infty}^{\infty} \left\{r^2 e^{-\left(R_\psi(0) - R_\psi(\tau)\right)}\right\} e^{-j2\pi f\tau} d\tau \quad (12)$$

and $R_\phi(\tau)$, $R_\psi(\tau)$ are the autocorrelations for $\phi(t)$ and $\psi(t)$ respectively.

It can be shown [11] that for FM signals with preemphasis, the power transfer function of the preemphasis network being G(f), the ratio, NPR, of signal power (model by noise) in a particular telephone channel to that produced by the interference is given by

$$\mathrm{NPR} = \frac{M_1^2\ f_{max} b}{r^2(1-\varepsilon)} \left\{ \int_{f_c-b/2}^{f_c+b/2} f^2 G(f) S_\lambda(f) df \right\}^{-1} \tag{13}$$

where

f_c = center frequency of channel under consideration

b = telephone channel bandwidth (3.1 kHz)

f_{max} = top baseband frequency of wanted signal

M_1 = rms modulation index of wanted multichannel baseband

ε = ratio of lowest to highest frequency of multichannel baseband

In decibels,equation (13) can be written

$$10 \log \mathrm{NPR} = 10 \log \frac{1}{r^2} + 10 \log \left(\frac{M_1^2\ f_{max} b}{1-\varepsilon} \right) \left\{ \int_{f_c-b/2}^{f_c+b/2} f^2 G(f) S_\lambda(f) df \right\}^{-1} \tag{14}$$

The second term has been given the name interference reduction factor (IRF) and equation (14) can be written

$$\left.\frac{\text{Power of wanted signal}}{\text{Power of unwanted signal}}(\text{dB})\right|_{\substack{\text{in a telephone}\\ \text{channel}}} = \frac{\text{wanted carrier power}}{\text{unwanted carrier power}}(\text{dB}) + (\text{IRF}) \qquad (15)$$

Hence

$$\left(\frac{S}{I}\right) = \left(\frac{C}{I}\right) + (\text{IRF})^{+} \qquad (16)$$

where

$\left(\frac{S}{I}\right)$ is the signal to interference ratio in dB

$\left(\frac{C}{I}\right)$ is the carrier to interference ratio in dB

(IRF) is the interference reduction factor in dB

In simple numeric units, equation (16) can be written

$$\frac{S}{I} = \frac{C}{I} \times \text{IRF} \qquad (17)$$

For the case of high index, FDM/FM signals, as is the case of satellite systems, equation (11) can be approximated by a Gaussian shape, i.e.,

+ wherever applicable, we have defined $\left(\frac{A}{B}\right) = 10 \log \frac{A}{B}$

$$S_w(f) = \frac{1}{\sqrt{2\pi}\Delta f} e^{-\frac{f^2}{2\Delta f^2}}$$

where

Δf is the rms frequency deviation for the wanted multi-channel baseband.

If we assume a similar shape for the interference spectrum, then the expression (17) becomes

$$\frac{S}{I} = \frac{C}{I} \times \text{IRF} \tag{18}$$

where

$$\text{IRF} = \frac{2\sqrt{2\pi}\; M_1^2\; M}{(1-\varepsilon)u^2 \left[e^{-\frac{(u+v)^2}{2M^2}} + e^{-\frac{(u-v)^2}{2M^2}} \right] G(f_G)} \tag{19}$$

$$M \equiv \sqrt{M_1^2 + M_2^2}$$

$$M_2 \equiv \frac{\Delta f_I}{f_{max}}$$

Δf_I = rms frequency deviation of interference signal

$$u \equiv \frac{f}{f_{max}}$$

$$v \equiv \frac{f_{2c}-f_{1c}}{f_{max}}$$

A more commonly used measure of the effect of interference at the output of a telephone channel is the interference noise power in pwop. From equation (16) we obtain

$$N_I = \begin{matrix}\text{Interference noise}\\ \text{power is pwop}\end{matrix} = 10^{\left(90 - \left[\frac{C}{I}\right] - (IRF)\right)/10} \qquad (20)$$

Thus, for a link carrying an FDM/FM signal, the problem of interference prediction reduces to the computation of the interference reduction factor (IRF) and the wanted to unwanted signal ratio at the receiver input. The former shows the dependence of output interference on the parameters of the wanted and unwanted signals, the latter the dependence on equipment and propagation parameters. For the simple interference model shown in Figure 3, we can break up the relative carrier power between the wanted and unwanted signals into an up-link component and down-link component as follows.

$$\left(\frac{C}{I}\right)(\text{up}) = (\text{EIRP-Path Loss})\Big|_{\substack{\text{wanted}\\\text{signal}}} - (\text{EIRP-Path Loss})\Big|_{\substack{\text{unwanted}\\\text{signal}}} \tag{21}$$

where

$$(\text{EIRP-Path Loss})\Big|_{\substack{\text{unwanted}\\\text{signal}}} = \left(\text{EIRP(on axis)} - [G_I(0) - G_I(\theta)] - \text{path loss}\right)\Big|_{\substack{\text{unwanted}\\\text{signal}}}$$

Equation (21) then becomes

$$\left(\frac{C}{I}\right)(\text{up}) = (\text{EIRP-Path Loss})_{\substack{\text{wanted}\\\text{signal}}} - \left(\text{EIRP(on axis)} - \text{Path Loss}\right)_{\substack{\text{unwanted}\\\text{signal}}}$$

$$+ \left(G_I(0) - G_I(\theta)\right)\Big|_{\substack{\text{unwanted}\\\text{signal}}} \tag{22}$$

where $G_I(0)$, $G_I(\theta)$ refers to on-axis and off-axis gain (in dB) of the unwanted signal respectively.

The carrier to interference ratio of the up-link is equal to the difference in illuminations of the wanted and adjacent satellites and the earth station antenna suppression,, $(G_I(0) - G_I(\theta))$. We saw in Section 2.3 that the adopted expression for $G(\theta)$ by CCIR is of the form

$$G(\theta) = 32 - 25 \log \theta (\text{in dB})$$

For the down path, the expression equivalent to (22) has the following form:

$$\left(\frac{C}{I}\right)(\text{down}) = \text{EIRP} - \text{Path Loss} + \text{Gain(on axis)}\Big|_{\substack{\text{wanted}\\ \text{signal}}} -$$

$$- \text{EIRP} - \text{Path Loss} + \text{Gain (off-axis)}\Big|_{\substack{\text{unwanted}\\ \text{signal}}} .$$

Hence,

$$\left(\frac{C}{I}\right)(\text{down}) = \text{EIRP(wanted)} - \text{EIRP(unwanted)} + \text{Gain(on axis,wanted)}$$
$$- \text{Gain(off axis, unwanted)} \quad (23)$$

When the interfering signal is crosspolarized with respect to wanted signal and the polarization discrimination of the receiving antenna is Y_D(dB), equation (23) becomes

$$\left(\frac{C}{I}\right)(\text{down})\Big|_{\text{crosspolarization}} = \left(\frac{C}{I}\right)(\text{down})\Big|_{\substack{\text{without}\\ \text{crosspolarization}}} + Y_D \tag{24}$$

In actuality, the geostationary orbit is and will be occupied by satellites possessing a wide range of parameters, fulfilling a variety of functions. To make the problem tractable, certain simplifying assumptions can be made in order to reduce the dimensionality of the problem. One particular set of assumptions that renders the problem amenable to formulation has been referred to as the homogeneous model. In [8], an attempt has been made to study <u>inhomogeneous</u> systems. The main objective of the paper is to define a measure of inhomogeneity and assess the magnitude of the measure of inhomogeneity is the impact of this inhomogeneity on satellite spacing requirements. Some discussion on this is given in Appendix A.

<u>Orbit-Spectrum Utilization Measure</u>

If the carrier-to-noise and carrier-to-interference ratios are sufficiently high (above threshold) the total baseband noise may be obtained by simple addition of the individual contributions. Hence,

$$N_T = N_t + N_I \tag{25}$$

where

N_t is the thermal noise

N_I is the interference noise

Using the same procedure as in equation (18), we obtain

$$N_T = \left\{\frac{10^9}{S/N} + \frac{10^9}{S/I}\right\}(\text{pwop})$$

thus

$$N_T = 10^9\left\{\left[\frac{C}{N} \times \text{NRF}\right]^{-1} + \left[\frac{C}{I} \times \text{IRF}\right]^{-1}\right\} \tag{26}$$

where

NRF is the noise reduction factor of the system .

It can be shown[11] that for homogeneous satellite systems

$$\text{IRF} = \begin{cases} 76\left(1 + 9.5M_0^3\right), & n \geq 240 \text{ channels} \\ 3n^{0.6}\left(1 + 9.5M_0^3\right), & 12 \leq n < 240 \end{cases} \tag{27}$$

which includes a 4 dB factor due to preemphasis and 2.5 dB of psophometric weighting. In the case of thermal noise

$$\text{NRF} = \begin{cases} 380\left(\alpha M_0^3 + M_0^2\right), & n \geq 240 \text{ channels} \\ 15n^{0.6}\left(\alpha M_0^3 + M_0^2\right), & 12 \leq n < 240 \end{cases} \tag{28}$$

where M_0 is the multichannel modulation index, α^2 is the peak-to-average baseband power ratio.

For a homogeneous system, equations (22) and (23) become:

$$\left(\frac{C}{I}\right)_{up}(\text{dB}) = G_I(0) - G_I(\theta) \tag{29}$$

$$\left(\frac{C}{I}\right)_{down}(\text{dB}) = \text{Gain(on axis,wanted)} - \text{Gain(off axis, unwanted)} \tag{30}$$

According to the CCIR recommendation 465-17, we can use the following expression for the off-axis gain

$$G(\theta) = 32 - 25 \log \theta$$

If we define by α_1, the ratio of down-link to up-link C/N ratio, we write

$$\frac{C}{N}_{total} = \frac{C}{N}\Big|_{down} \frac{1}{1+\alpha_1} \qquad (31)$$

Using the same technique for interference, we obtain,

$$\frac{C}{I}_{total} = \frac{C}{I}\Big|_{down} \left(\frac{1}{1+\alpha_2}\right) \qquad (32)$$

where

α_2 is the ratio of down-link to up-link $\frac{C}{I}$ ratio

Expression (25) then becomes

$$N_T = 10^9 \left\{ \left[\frac{C}{N}\Big|_{down} \frac{NRF}{1+\alpha_1} \right]^{-1} + \left[\frac{C}{I}\Big|_{down} \frac{IRF}{1+\alpha_2} \right]^{-1} \right\} \qquad (33)$$

Using equation (30) we can write

$$\left.\frac{C}{I}\right|_{down} = \frac{\text{Gain(on axis, wanted)}}{\text{Gain(off axis, unwanted)}} \begin{pmatrix}\text{numeric}\\ \text{ratio}\end{pmatrix}$$

The above ratio can also be written as

$$\left.\frac{C}{I}\right|_{down} = \frac{\varepsilon\left(\frac{\pi D}{\lambda}\right)^2}{10^{3.2}\theta^{2.5}} = \frac{\varepsilon\pi^2}{10^{3.2}} D^2\lambda^{-2}\theta^{-2.5} \qquad (34)$$

where $g(0) = \varepsilon\left(\frac{\pi D}{\lambda}\right)^2$, ε is the efficiency of the antenna. Thus, we have

$$\left.\frac{C}{I}\right|_{total} = \frac{\varepsilon\pi^2}{10^{3.2}} 0^2\lambda^{-2}\theta^{-2.5} \frac{1}{1+\alpha_2} \qquad (35)$$

Substitution of (35) into (33) yields

$$N_T = 10^9 \left\{ \left[\frac{C}{N}\Big|_{down} \cdot \frac{NRF}{1+\alpha_1} \right]^{-1} + \left[\frac{\varepsilon\pi^2}{10^{3.2}} D^2 \lambda^{-2} \theta^{-2.5} \frac{IRF}{1+\alpha_2} \right]^{-1} \right\} \quad (36)$$

We observe that the total noise power of the satellite link is a function of all the parameters contained in equation (36). Normally, N_T is fixed as a performance objective and there is a tradeoff among the parameter within the constraint. One of the most useful measures for orbit/spectrum utilization is the number of channels per MHz per degree of orbital spacing. From the Carson's rule bandwidth $W = 8400n(\alpha M_0+1)$, we obtain [9]

$$n' \equiv \text{Number of channels per MHz} = \frac{n\times 10^6}{8400\times n(\alpha M_0+1)}$$

$$n' = \frac{119}{\alpha M_0+1}$$

The number of channels per MHz per degree, n'', is then given by

$$n'' \equiv \frac{119}{\alpha M_0+1} \cdot \frac{1}{\theta} \quad (37)$$

Substituting θ from equation (36) into equation (37), we obtain

$$n'' = \frac{119}{\alpha M_0+1}\left\{\left(\frac{N_T}{10^9} - \frac{1+\alpha_1}{\left.\frac{C}{N}\right|_{down}\text{NRF}}\right)\cdot\frac{\varepsilon\pi^2D^2\lambda^{-2}\cdot\text{IRF}}{10^{3.2}(1+\alpha_2)}\right\}^{-\frac{1}{2.5}} \tag{38}$$

If we set:

$$N_T = 7500 \text{ pwop}$$

$$\alpha_1 = \alpha_2 = 0$$

$$\alpha = \sqrt{10}$$

$$D/\lambda = 300$$

We can obtain a relationship between n' and n'' for various levels of $\frac{N_t}{N_I}$ and(C/N). This relationship is shown graphically in Figure 4.

There are a number of interesting points to be made from Figure 4. First, it will be recalled that the abscissa is the number of channels/MHz (per satellite). If every satellite is allowed the same bandwidth, the abscissa gives the relative number of channels per satellite. Hence, for fixed n'', the relative number of satellites is inversely proportional to the abscissa. At the same time, the relative E.I.R.P. is given by cutting across at constant n'' if the link parameters are assumed the same. For example, suppose $n'' = 19$. From the figure,[4] this can be achieved for $n' = 64$

and (C/N) = 39 dB and also for n′ = 30 and (C/N) = 24 dB. Thus, in the latter case over twice as many satellites are required but the E.I.R.P. can be 15 dB lower. The case which is preferable will depend on many factors including cost and possible limitation on the power flux-density. Another fact evident from Figure 4 is that the larger n′ is, the more sensitive n″ is to E.I.R.P. variations. This fact is worth noting in light of the various factors which may cause the E.I.R.P. of a satellite to degrade during its lifetime. Another feature worth noting is that as the (C/N) decreases the possible range of n′ decreases. This is explained by the fact that, for each (C/N) there is an n′ for which $N_t = N_T$, and hence permits no interference noise. This accounts for the downward bend and asymptotic appearance of the curves. The inference is that as the(C/N) is decreased one is automatically forced to satellites with higher modulation indices and hence lower capacity per unit bandwidth. Thus Eq. (34) and Fig. 4 provide useful tools for trading off orbit/spectrum utilization with satellite capacity, as a function of the link parameters and the composition of the noise budget.

3.2 Interference Into FM Television Signals (TV/FM)

When the link carries a television signal, the effect of rf interference on the quality of the television picture is not easily described in terms of a signal to interference ratio at the channel output unless the interference can be represented as gaussian noise. Even in the case of noise-like interference, the correspondence between the output signal-to-interference ratio and subjective evaluations of picture quality can only be established by experimental measurements with groups of television viewers. It is common to express the results of such measurements by relating grades of picture quality directly to the wanted-to-unwanted signal ratio C/I at the receiver input. In particular, the value of C/I corresponding to a specified picture grade and a specific kind of unwanted signal is called the interference protection ratio for that picture quality and type of interference. For a link carrying a television channel, it is thus sufficient to evaluate the effective wanted-to-unwanted signal ratio at the input to the down link receiver and to compare it with the protection ratio C/I data to infer the resultant picture quality on the link. When there are several unwanted signals affecting the wanted signal, it is necessary to take into account the fact that they are likely to differ in the amount of picture degradation they cause not only because the interfering signals differ in strength but also in their ability to affect the wanted signal. For cases like these, a useful concept has been developed namely the <u>interference sensitivity factor Q_{ij}</u>, which is defined as the ratio of the protection ratio for the wanted signal against interference from an identical reference signal to its protection ratio against interference from the actual unwanted signal. If we denote the protection ratio against an identical interference signal i by

$$\frac{C}{I}\,(M_i, M_i, 0) \equiv \rho_{TV,TV}(M_i, M_i, 0)$$

and the protection ratio against the actual unwanted signal,

$$\frac{C}{I}\,(M_i, M_j, f_d) \equiv \rho_{TV,TV}(M_i, M_j, f_d)$$

where

M_i, M_j are the peak modulation indices for the wanted and unwanted signals

$f_d = f_j - f_i$, f_j, f_i being the carrier frequencies of the unwanted and wanted signals respectively

from the definition of the interference sensitivity factor, we obtain:

$$Q_{ij} \equiv \frac{\rho_{TV,TV}(M_i, M_i, 0)}{\rho_{TV,TV}(M_i, M_j, f_d)} \tag{39}$$

If the number of interfering signals is N, the total protection ratio can be written as

$$\left[\frac{C}{I}\right]^{-1} = \sum_j \left[\frac{C}{I}\right]_{ij}^{-1} \frac{1}{Q_{ij}}$$

In the following discussion, we shall present three types of interference possibilities that are possible in satellite communications. These are: 1) Interference into a TV/FM channel from a TV/FM interfering signal, 2) Interference into a TV/FM channel from a FDM/FM signal and 3) Interference into an FDM/FM channel from a TV/FM channel. The efforts towards quantifying the relationship between the subjective experimental measurements on the picture quality and the ratio of the wanted to unwanted signal at the receiver input have resulted into empirical formulas standardized by CCIR.

a) TV/FM into TV/FM

When both the wanted and unwanted signals are TV/FM, the experimental data can be best fitted by the equation [20].

$$10 \log \rho_{TV,TV}(M_i,M_j,f_d) = 29.5 - 20 \log M_i - f_d M_i^{-0.85} - 0.475\, \mu^{-2.5} f_d^{0.645\mu} \log \mu \tag{40}$$

where

$$\mu \equiv M_i/M_j$$

$$M_i = \frac{W_i}{2f_{max,TV}} - 1 = \frac{\Delta f_{pp}}{2f_{max,TV}}$$

and

W_i = Carson's rule bandwidth of TV/FM signal

Δf_{pp} = peak-peak deviation caused by television baseband

$f_{max,TV}$ = max. frequency of video signal (4.2 MHz).

Substituting equation (40) into (39), we obtain

$$10 \log Q_{TV,TV} = f_d M_i^{-0.85} + 0.475\ \mu^{-2.5}\ f_d^{0.645\mu} \log \mu \qquad (41)$$

b) FDM/FM into TV/FM signal

When the unwanted signal is an FDM/FM telephony signal, the empirical equation equivalent to that given by (40) has the form

$$10\ \rho_{FDM/TV}(M_i, M_j, f_d) = 24.1 - 20 \log M_i - f_d M_i^{-1.15} - 0.85\ \mu^{-3} f_d^{\ 0.5\mu} \log \mu \qquad (42)$$

The sensitivity factor for interference into a TV/FM signal from an FDM/FM signal is given by

$$10 \log Q_{TV,(FDM/FM)} = 10 \log \rho_{TV,TV}(M_i,M_i,0) - 10 \log \rho_{TV,FDM}(M_i,M_j,f_d) \tag{43}$$

Substituting equation (39) and (41) into (43), we obtain

$$10 \log Q_{TV,FDM} = 5.4 + f_d M^{-1.15} + 0.85\mu^{-3} f_d^{0.5\mu} \log \mu$$

Note that in no case does the interference sensitivity depend on the modulation index of the unwanted signal when the carrier frequency offset is zero (f_d=0). Also note that, for zero-frequency offset, a TV/FM signal is about 5.4 dB less susceptible to interference from an FDM/FM signal than to interference from another TV/FM signal.

c) TV/FM into FDM/FM Signal

When the interfered with signal is an FDM/FM telephone signal, experimental results have shown that an equation similar to that given in (19) for $f_d > 0$ can be obtained, i.e.,

$$\mathrm{IRF} = \frac{\left(0.2 + 8m_i^3\right) w_n w_p f(n_i)}{e^{-\frac{(1+v)^2}{h(m_i)}} + e^{-\frac{(1-v)^2}{h(m_i)}}}$$

where

$$h(m_i) = 1.7\left(1.85 + m_i^2\right)$$

$10 \log w_n$ = 2.5 dB psophometric weighting factor

$10 \log w_p$ = 4 dB preemphasis improvement factor

m_i = rms modulation index of FDM/FM baseband

$$f(n_i) \equiv \begin{cases} 1.7\, n_i^{0.6} , & 12 \le n < 240 \\ 42.8 , & n_i \ge 240 \end{cases}$$

$$v = \frac{f_d}{f_{max}}$$

Having obtained the proper protection ratios or IRF for the interference of the links under consideration, we can follow a procedure similar to that given by equation (21), (22) for the cases which involve TV/FM signals and (36) for the cases which the interfered with signal is an FDM/FM telephony signal to determine the proper spacing of the satellite on the geostationary orbit.

3.3 Interference into Digital Signals

Due to the inherent nonlinear nature of digital systems, there is no formal solutions to the interference problem of digital systems analogous to equation (9) for FDM/FM signals. The effect of interference cannot be explicitly defined as is true for analog systems. The problem becomes more difficult when many sources of impairment are included. The main difficulty lies in extracting the individual effects and in the numerical evaluations involved. Exact solutions have been obtained only in simplified cases. For more general cases, satisfactory bounds have been obtained for design purposes. In the following discussion, we shall consider only coherent phase-shift keyed CPSK systems as they currently represent the most practical implementations for communications satellites.

Let us consider an M-phase CPSK system. If we assume that each signal transmitted has a duration T, the received signal waveform in the absence of noise during the N^{th} interval can be represented as

$$S_N(t) = (2S)^{\frac{1}{2}} \cos(\omega_0 t+\theta) \quad , \quad NT \leq t \leq (N+1)T \qquad (44)$$

where

$$\theta = \frac{2\pi n}{M} \quad , \quad n = 0,1,2,\ldots,M - 1$$

Suppose the functional form of the j^{th} interferer is of the form

$$S_j(t) = (2I_j)^{\frac{1}{2}} \cos(\omega_j t+\theta_j+\mu_j) \quad , \quad NT < t \leq (N+1)T \quad (45)$$

where

$$\theta_j = \frac{2\pi n}{M} \quad , \quad n = 0,1,2,\ldots,M - 1 \ .$$

μ_j = random variable uniformly distributed over the interval $(0,2\pi)$.

If there are K interferers entering the receiver, the total received signal during the N^{th} interval can be written

$$r_N(t) = (2S)^{\frac{1}{2}} \cos(\omega_0 t+\theta) + \sum_{j=1}^{k} (2I_j)^{\frac{1}{2}} \cos(\omega_i t+\theta_j+\mu_j) + n(t) \quad (46)$$

where $n(t)$ is zero mean noise with variance σ^2. Assuming that the receiver detects only the phase angle ϕ of the resultant signal, we can write [12]

$$\phi = \tan^{-1} \frac{\hat{r}_N(t)}{r_N(t)} - \omega_0 t \tag{47}$$

where $\hat{r}_n(t)$ is the Hilbert transform of $r_n(t)$ and is given by

$$\hat{r}_N(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{r_N(\tau)}{t-\tau} \, d\tau \tag{48}$$

The noise term can be written analytically

$$n(t) = I_c \cos(\omega_0 t+\theta) - I_s \sin(\omega_0 t+\theta)$$

Equation (46)-(48) yield

$$\phi = \theta + \tan^{-1} \frac{I_s + \sum_{j=1}^{k} (2I_j)^{\frac{1}{2}} \sin[(\omega_j-\omega_0)t + \theta_j - \theta + \mu_j]}{(2S)^{\frac{1}{2}} + I_c + \sum_{j=1}^{k} (2I_j)^{\frac{1}{2}} \cos[(\omega_j-\omega_0)t + \theta_j - \theta + \mu_j]} \tag{49}$$

If we make the following definitions

$$R_j \equiv \sqrt{\frac{I_j}{S}} \tag{50}$$

$$\left.\begin{aligned} \delta &\equiv \sum_{j=1}^{K} \sqrt{\frac{I_j}{S}} \sin \lambda_j = \sum_{j=1}^{k} R_j \sin \lambda_j \\ \eta &\equiv \sum_{j=1}^{K} \sqrt{\frac{I_j}{S}} \cos \lambda_j = \sum_{j=1}^{k} R_j \cos \lambda_j \end{aligned}\right\} \tag{51}$$

$$\lambda_j \equiv (\omega_j - \omega_0)t + \theta_j - \theta + \mu_j \tag{52}$$

$$\left.\begin{aligned} \rho &\equiv \frac{\sqrt{S}}{\sigma} \\ v &\equiv \frac{I_s}{\sqrt{2S}} \quad , \quad u = \frac{I_c}{\sqrt{2S}} \end{aligned}\right\} \tag{53}$$

we can now write

$$\phi = \theta + \tan^{-1} \frac{v+\delta}{1+u+\eta} \tag{54}$$

where δ and η are functions of the random variables λ_j. For a binary CPSK system, a received signal (phasor diagram) in the presence of noise and interference is shown in Figure 5. It can be shown [11] that the probability of symbol error is given by

$$P_e = \frac{1}{2} E\{efc(\rho+\rho\eta)\} \tag{55}$$

The evaluation of expression (55) presents a computational challenge becasue it entails the evaluation of the expected value of the function erfc($\rho+\rho\eta$) i.e.,

$$P_e = \int_{-\infty}^{\infty} efc(\rho+\rho\eta)f(\eta)d\eta \; . \tag{56}$$

and the knowledge of the probability density function of η, $f(\eta)$. Using various approximation methods (series expansion and bounding techniques), many results in the form of graphical illustrations have been published which lend good deal of insight into digital system performance in the presence of interference. In Figure 6, we observe that the error probability increases as the level of interference increases. When the S/I is of the order of (or smaller than) the S/N ratio, the effect of interference is not as severe as an equal amount of thermal noise power. The opposite is true, however, for values of S/I larger than S/N.

Using the same procedure as that described by equation (22) we obtain

$$\left.\frac{S}{I_j}\right|_{down} = \frac{G(0)}{G(\theta)} \qquad (57)$$

Equation (57) facility assumes that the satellites have equal EIRP, earth coverage and their path loss is the same. Previously (45) we made the definition:

$$R_j = \sqrt{\frac{I_j}{S}} \qquad (58)$$

Hence

$$R_j = \sqrt{\frac{G(\theta)}{G(0)}} = \sqrt{\frac{10^{3.2}\theta^{-2.5}}{\pi^2 \varepsilon (D/\lambda)^2}}$$

$$R_j = \frac{18}{\theta^{1.25} D/\lambda} \qquad (59)$$

where

$G(\theta) = 10^{32-25 \log \theta}$

$G(0) = \pi^2 \varepsilon (D/\lambda)^2$

ε = efficiency of the antenna.

We observe from that equation (56) that the bit error probability is a function of θ through equations 51 and (59). Numerical results are presented in Figure 7 which show bit error probability as a function of (S/N) with satellite spacing as a parameter. It can also be shown [11] that the error probability is slightly sensitive on the number of interferers K when $K \geq 10$. Many times it is computationally advantageous to consider the interference as additional Gaussian noise. For a given S/I ratio (determined by D/λ and θ) the Gaussian assumption becomes progressively better as the S/N becomes smaller [17]. In general, it can be used as a conservative upper bound when the characteristics of the interference signal are not completely known. Usually, in a particular application, the error probability is given as a basic requirement. The trade between (S/N) and satellite spacing can be simply obtained by cutting across the Figure 7 at constant error probability. As an example of these trade-offs, suppose that a bit error probability of 10^{-5} is required. The satellite spacing is plotted in Figure 8 as a function of (S/N). We observe that, in general, the satellite spacing is quite sensitive to (S/N) for a fixed error probability. This indicates that, in practice, station keeping will have to be accurate or that appropriate margin for satellite drift will have to be provided. A better measure of the orbit-spectrum utilization is the number of channels per MHz per degree as we discussed in Section 3.1 eq. (34). It can be shown [21] that for digital signals, the bandwidth is determined by the equation (digitally modulated carrier bandwidth)

$$W = \frac{2\ R_b}{\log_2 M} \tag{60}$$

where

R_b is the bit rate (bps)

M is the number of different phase levels

The baseband bit rate as a function of the baseband bandwidth is given by

$$R_b = 2kB$$

where

k = number of bits per sample

B = baseband bandwidth (3=4000n, n number of channels)

Equation (60) then becomes

$$W = \frac{2(2k\times 4000xn)}{\log_{2M}} = \frac{.112\times 10^6 n}{\log_2 M} \tag{61}$$

where we used $k = 7$.

If $W = 10^6$, then we have from (61)

$$n' = \frac{\text{channels}}{\text{MHz}} = 8.93 \log_2 M \tag{62}$$

Consequently, the number of channels per MHz per degree takes the form

$$n'' = \frac{8.93 \log_2 M}{\theta} \text{ channels/MHz/degree .} \tag{63}$$

For general digital signals other than telephony, we can directly solve for R_b'', which denotes the bps per MHz per degree directly from equation (60). Hence,

$$R_b'' = \frac{10^6 \log_2 M}{2\theta} \text{ bps/degree/MHz} \tag{64}$$

W/n

Having determined the spacing of the satellites for a given $\left(\frac{S}{N}\right)$ from Figure 8, we can determine the number of channels or bps per MHz degree available in that particular arrangement of the geostationary orbit. This measure (63) allows us to make direct comparison between analog and digital systems on the basis of their orbit spectrum utilization.

3.4 Computerized Interference Analysis

Bell Laboratories has developed computer programs which are now available for the computation of the interference into analog and digital signals. These programs have the acronyms: FMSPCTR, ANINTREV, ARBINTP, GENINT and CJOIN and can be accessed and utilized in batch form using a few control cards and the appropriate input data. These programs are explained in memoranda [21]-[26] as far as the input-output requirements are concerned.

Rand corporation has developed a computer program for NASA which specifically deals with the interference of satellite system and it is included in the report of reference [7]. The input data of this program constitute a detailed description of the systems, their geographical deployment, the links they provide and the signals carried on these links. For each station, the description includes the transmitter power, the dimensions, efficiency, co-and cross-polarized envelopes of the transmitting and receiving antennas and the receiving system noise temperatures. The description of each link includes the identity of the satellite and the two earth stations involved, the uplink and downlink carrier frequencies, rf bandwidth and the number and type of message channels. The output data include a summary of the system description, the interference in picowatts as a point of zero relative level for fixed satellite systems and the carrier to interference ratio at the receiver input for broadcasting satellites. In addition to the individual contributions, the output includes the wanted signal power, the unwanted signal power, IRF and protection ratios along the interference path and the values of carrier to noise ratio. A limitation of the program is that it is applicable only to analog signals.

To return to the programs available within the Bell System, we shall briefly describe the capabilities of each one of them mentioned before:

1) FMSPCTR

This program computes the analog FM spectrum with a modulating signal of multichannel telephony. Part of the output is a microfilm graph of the continuous spectrum. Three choices of preemphasis are available - a power series approximation, CCIR, and no preemphasis, but other baseband spectrum shapes can easily be included.

2) ANINTREV:

This program computes the baseband noise due to interference of one analog system into another. The basic mathematical tool used is to convolve two RF spectra with each other and thus arriving at the baseband spectrum of the interference. The spectrum arrived at is compared with the baseband multiplex signal and, given the tolerable noise, the necessary RF discrimination is found, (C/I).

3) ARBINTP:

A program similar to the previous one in substance but with more general capabilities is available for the computations of interference noise for the case when a signal of known but arbitrary shape is interfering into an analog FDM/FM system.

4) GENINT:

This program extends the computational capacity of the previous programs by allowing the direct computations of interference from an arbitrary signal of known RF spectrum into an FM signal of arbitrary type. Both spectra are supplied by the user and both can have discrete and/or continuous parts.

5) CJOIN:

This is a program that computes tight upper and lower bounds on the expected probability of error of a multi-level CPSK signal corrupted by multiple co-channel angle modulated interferers. The program is valid over a wide range of carrier-to-noise ratio values as well as most practical carrier to interference ratios for an arbitrary number of interferers of various amplitudes.

These programs can be used in conjunction with the results and analysis of the previous sections to determine the satellite spacing for acceptable interference levels. A simple description of the input-output data of these programs is given in Appendix B.

4. PRESENT AND FUTURE 12/14 GHz SATELLITE SYSTEMS

Table I contains the characteristics of the 12/14 GHz satellites that members of the ITU have to file with the International Frequency Registration Board (IFRB) as a part of the Advance Publications required by the union. This table is not complete yet but efforts are being made to obtain the same information for all present and future 12/14 GHz geostationary satellite systems. Their position on the geostationary orbit is given in Figure 10. The main reason for this information is that each Telecommunication Administration of the union has the right to know what level of interference, if any, other systems of other administrations cause to its satellite or terrestrial system and vice versa. In case of unacceptable interference, CCIR provides the mechanism, the major parts of which have been outlined in this memorandum, for coordination between the parties in dispute. This procedure is necessary in order to prevent wasteful use of the geostationary orbit and provide some kind of privacy to individual communication networks. As seen in Table I, the relevant information for interference consideration provided by each administration includes the following: 1) Position of the satellite in the geostationary orbit, frequency band for up-link and down-link, classes of stations and nature of service, maximum spectral power density for both up-link and down-link and gains of both earth stations and satellite antenna in the transmitting and receiving mode. The information given in Table I for each satellite system can be used as an input to the procedure described in the previous sections to determine the interference levels of each system into any other system desirable. To determine whether or not an administration should demand coordination at all with interfering adjacent systems, use of the 'ΔT' criterion given in the Appendix C should be made first. If such an evaluation reveals that coordination should be sought, the procedure is outlined in the Radio Regulations published by ITU.

5. CONCLUSION

The major factors affecting interference between satellite systems have been analyzed for future use in interference calculations. The purpose of this study is to analyze the problem of interference and provide the framework for calculating the interference level in the specific satellite systems. This memorandum can also be considered as a source document for a literature survey of work done in the past. The depth of the analysis of the interference problem is consistent with the limited time allotted to this study. Many of the points discussed will be investigated in detail during the course of the Zohreh satellite system development.

Peter Stavroulakis

HO-4375-PS-mk P. Stavroulakis

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References
Table 1
Figures 1-10
Appendices A, B, C

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J. M. Sipress
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TABLE I

		UPLINK CHARACTERISTICS			DOWNLINK CHARACTERISTICS		
	POSITION	CLASS*	FREQUENCY	MAX. SPECTRAL DENSITY	CLASS*	FREQUENCY	MAX. SPECTRAL DENSITY
LOUTCH 1	346°E	TC,CO	14.0-14.5 GHz	dBw/Hz -25 (F5) +5 (FO) Antenna Gain=63 dB	EC,CO	10.95-11.20 GHz 11.45-11.7 GHz	dBw/Hz -53 (F5) -18 (FO) Antenna Gain 30 dB
LOUTCH 2	58°E	TC,CO	14.0-14.5 GHz	-25 (F5) +5 (FO) Gain 63 dB	EC,CO	10.95-11.2 GHz 11.45-11.7 GHz	-53 (F5) -18 (FO)w/no modulation. Gain 30 dB
LOUTCH 3	90°E	TC,CO	14.0-14.5 GHz	-25 (F5) +5 (FO) Gain 63 dB	EC,CO	10.95-11.2 GHz 11.45-11.7 GHz	-53 (F5) -18 (FO) Gain 30 dB
LOUTCH 4	140°E	TC,CO	14.0-14.5 GHz	-25 (F5) +5 (FO) Gain 63 dB	EC,CO	10.95-11.2 GHz 11.45-11.7 GHz	-53 (F5) -18 (FO) Gain 30 dB
MAROTS-B	347.5°E	TK,TR,TC TD,TG,CP	1.6 GHz 14.4 GHz	-42 Gain 60 dB	EC,ED,EG EK,ER,CP	1.54 GHz 11.69 GHz	-55 dB/Hz
USASAT	254°E	TK,TD,TC CV,CR	14.0-14.5 GHz	-38 Gain 55 dB	EC,ER	11.7 12.2 GHz	-57 dBw/Hz
C-1 TELESAT	247.5°E	TD,TK,TR, TC,CV,CD	14.0-14.5 GHz	-30 dBw/Hz	ED,EK,ER CV,CP	11.7-12.2 GHz	-46 dBw/Hz
INTELSAT	63°E	TD,TK,TC CV,CR	5.925-6.425 GHz 14.0-14.5 GHz	-34 dBw/Hz	EK,ER,EL CV,CR	10.95-11.2 GHz 11.45-11.70 GHz	-60 dBw/Hz -63 dBw/Hz
ZOHREH 1 2 3	34°E 26°E 47°E	TC,TD,TK TR,TE	14.0-14.5 GHz	-32 dBw/Hz -32 dBw/Hz -32 dBw/Hz	EC,ER	10.95-11.2 GHz 11.45-11.7 GHz	-33 dBw/Hz -46 dBw/Hz -46 dBw/Hz

* Symbols indicate the class of station and nature of service. Explanations are given in Appendix 10 of Radio Regulations, e.g., TC Earth Station in fixed satellite service.

APPENDIX A

Inhomogeneous Systems Interference

The utilization of the geostationary orbit in the case of dissimilar satellites and earth stations is of special interest. When two satellites operate adjacently in the geostationary orbit, there are, in general, two "minimum spacings." One spacing is determined by the protection requirements of the one system and the other spacing is determined by the protection requirements of the adjacent system. If these two spacings are not equal, then the largest of the two must be used.

If a high E.I.R.P. satellite is used in conjunction with high-temperature earth-station receivers and a neighboring satellite system operates with both low E.I.R.P. and earth station receiver temperature, it can be shown that the inter-satellite spacing is generally determined by the sensitive system. It should be noted tha this will be the case even if the sensitive system is operating with the larger earth station antenna. It is expected that by judiciously arranging the satellite systems in the orbit, the efficiency of utilization of the orbit can be increased. In general, clustering similar satellite systems and minimizing the number of dissimilar satellites in adjacent orbital "slots" promotes an efficient use of the orbit. On the other hand, there are certain cases where separating in the orbit the various satellites of a given system seems to be indicated. Satellite systems equipped with narrow "spot" beams and illuminating the same areas on the surface of the earth should, whenever possible, not be placed adjacently in the geostationary orbit to alleviate interference problems. In the following discussion, we will try to quantify one measure of inhomogeneity and then examine the impact of the inhomogeneity on the satellite spacings. There are two fundamental factors which govern inhomogeneity between satellite systems. The first factor results from relative differences between satellite systems in their potential for causing interference to other systems, while the second results from difference between satellite systems in their relative sensitivity to interference. Following the "ΔT" approach given in the Appendix 29 of the Radio Regulations [18], the following four inhomogeneity factors can be defined:

1) Up-link interferences potential, I_u

$$I_u \equiv 10 \log P_e \text{(dBw/Hz)}$$

2) Down-link interference potential, I_d

$$I_d \equiv 10 \log P_s g_s \text{ (dBw/Hz)}$$

3) Up-link interference sensitivity, S_u

$$S_u \equiv 10 \log \frac{g_r \gamma}{T} \text{ dB/}^\circ\text{k}$$

4) Down-link interference sensitivity, S_d

$$S_d \equiv 10 \log \frac{1}{T} \text{ (dB/°k)}$$

where

P_e = Maximum power density per hertz delivered to the antenna of the interfering earth station (watts/Hz)

P_s = Maximum power density per hertz delivered to the antenna of the interfering satellite

g_s = Transmitting antenna gains of the interfering satellite

g_r = Receiving antenna gain of the interfered with satellite

γ = Transmission gain of the interfered with satellite link evaluated from the output of the receiving antenna of the space station to the output of the receiving antenna of the earth station.

T = The equivalent link noise temperature.

Based upon the concept of calculating the increase in the equivalent link noise temperature, the orbit spacing required for meeting a specific criterion can be determined. Since the calculation does not take into account actual modulation characteristics or carrier frequencies, the orbit spacings which are obtained might be larger than those needed in actual cases. It is worth noting, however, that these separations do represent the <u>minimum</u> orbital separations required to eliminate the need for <u>coordination</u> between satellite systems.

The fractional increase in noise temperature is given by [18]

$$\frac{\Delta T}{T} = \frac{i_u s_u g_e(\theta)}{k\ell n} + \frac{i_d s_d g_{e'}(\theta)}{k\ell_d}$$

where

$g_e(\theta)$ = Sidelobe gain of the interfering transmitting earth station

$g_{e'}(\theta)$= Sidelobe gain of the interfered with receiving earth station antenna

θ = Angular separation between two satellites

k = Boltzman's Constant (1.3810^{-23} J/K)

ℓ_u = Uplink pathloss (numeric ratio)

ℓ_d = Downlink pathloss (numeric ratio)

i = antilog I

s = antilog S

In Figure 9, the satellite spacing required to meet the 2 percent "ΔT" criterion is plotted for the downlink contribution for the hypothetical case of interfering satellite with I_d = -32 dBw/Hz and S_d = -20.4 dBw/K then $I_d + \rho_d$ = -52.4.

From Figure 9, we see that a separation of 15° the system will meet the 2 percent limit of temperature increase so the system needs no coordination.

APPENDIX B

Input-Output Data of Bell System Interference Computer Programs

In the following, we shall present the input-output data of the Bell computer programs we discussed in Section 3.4.

1) FMSPCTR.

Input Data

a) Number of talkers

b) Top baseband frequency in Hz

c) Bottom baseband frequency in Hz

d) RMS frequency deviation in Hz

e) Preemphasis; one of 'NONE,' 'CCIR' and 'BELL'

Output Data

a) Numeric data in the form of columns of frequency versus baseband and modulated power spectrum

b) Microfilm graph of the plot of spectra versus frequency

2) ANINTREV

Input Data

a) Frequency band

b) Interference requirement

c) Nominal frequency difference

d) System characteristics

e) Number of talkers

f) Top baseband frequency

g) Bottom baseband frequency

h) Frequency deviation

i) Frequency tolerance

j) Preemphasis (NONE, CCIR, BELL)

Output Data

Tabulated data of the baseband frequency, signal to interference ratio, interference allowed and the necessary C/I.

3) ARBINTP

This program has inputs and outputs similar to the previous program except that the user is required to insert the spectrum of the unwanted signal in tabular form.

4) GENINT

For this program, the user must also supply the wanted signal spectrum in tabular form, otherwise it is similar to ARBINTP.

5) CJOIN

Input Data

a) Level of desired CPSK signal

b) Carrier to noise ratio of wanted signal

c) Number of interferers

d) Relative amplitude of interferers

e) Carrier to total interference power ratio

Output Data

The output lists the value of the upper bound, P_e^u on the error probability for multilevel CPSK and the actual value for binary CPSK.

APPENDIX C

Coordination Procedures with Terrestrial Systems

In the following discussion, the coordination area around an earth station transmitter or receiver in frequency bands between 1-40 GHz shared between space and terrestrial services will be briefly outlined. The operation of earth stations and terrestrial stations in the shared frequency bands between 1-40 GHz may give rise to interference when the distance between the stations of the two services is below a certain value. For such uses, a coordination area is determined by calculating, in all directions from an earth station, the coordination distances and drawing on an appropriate map the coordination contour. For the determination of the coordination area, two cases may have to be considered: a) the earth station is receiving b) the earth station is transmitting. To obtain the distance from an earth station beyond which harmful interferences from or into a terrestrial station may be considered to be negligible, we assume that the attenuation of an unwanted signal is a monotonically increasing function of distance.

The amount of attenuation required between an interfering transmitter and an interfered-with receiver is given by the relations [27].

$$L(p) = (P_t) + (G_t) + (G_r) - P_r(p)$$

where

$L(p)$ is the minimum permissible basic transmission loss (in dB) for p percent of the time.

P_t is the maximum available transmitting power level (in dBw) in the reference bandwidth at the input of the antenna of an interfering station

G_t gain of the transmitting antenna

G_r gain of the receiving antenna

and $P_r(p)$ is given by

$$P_r(p) = 10 \log(KT_rB) + J + M(p) - W$$

where

$P_r(p)$ is the maximum permissible interference power level in (dBw) in the reference bandwidth to be exceeded for no more than p percent of the time at the receiver input of an interfered with station.

$J^{(dB)}$ the ratio of permissible long term (20 percent of the time) interfering power to the thermal noise power in the receiving system, e.g., if the total interference power is 1000 pwop and the thermal noise power 25 pwop, then J = 16 dB

M(p) is the ratio between the maximum permissible interference power during p percent of the time for one entry of interference and during 20 percent of the time for all entries of interference.

W equivalence factor relating interferences and thermal noise.

To expedite calculations the transmission loss can be normalized to 0.01 percent and 4 GHz [27], hence

$$L(0.01) = L(p) - F(p) - 20 \log f/4$$

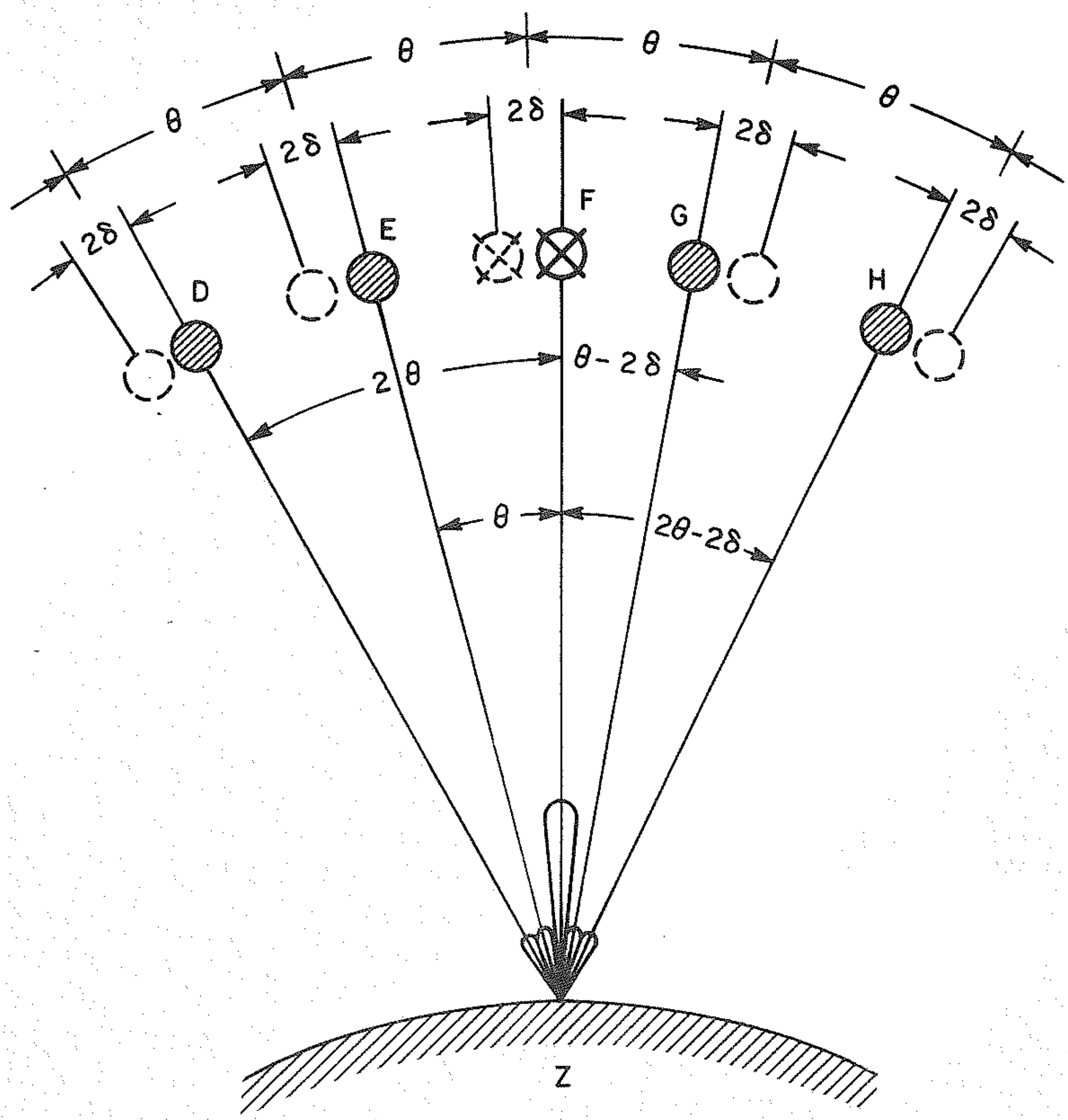
where

F(p) is the correction factor in dB to relate the effective percentage of the time p to 0.01 percent. This factor is given graphically in [24]. f is frequency in GHz.

Having determined the loss L(0.01) we need to correct it by a factor ΔL which accounts for the difference in transmission loss over paths that have different horizon elevation angles at the earth station. This factor is given in [22] as a plot of ΔL versus elevation angle. Thus, we have for the corrected transmission loss

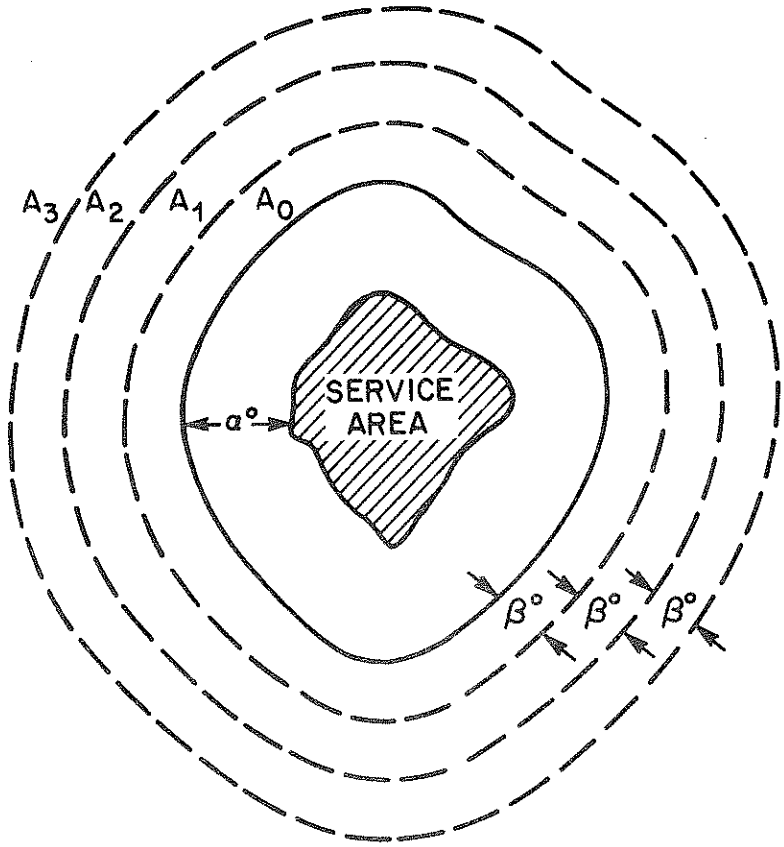
$$L = L(0.01) - \Delta L$$

The corrected loss L can then be used to determine the coordination distance around the earth station. This has to be repeated for all azimuths to complete the contour. A graphical procedure is also outlined in [27] in the case when the coordination area involves more than one zone.



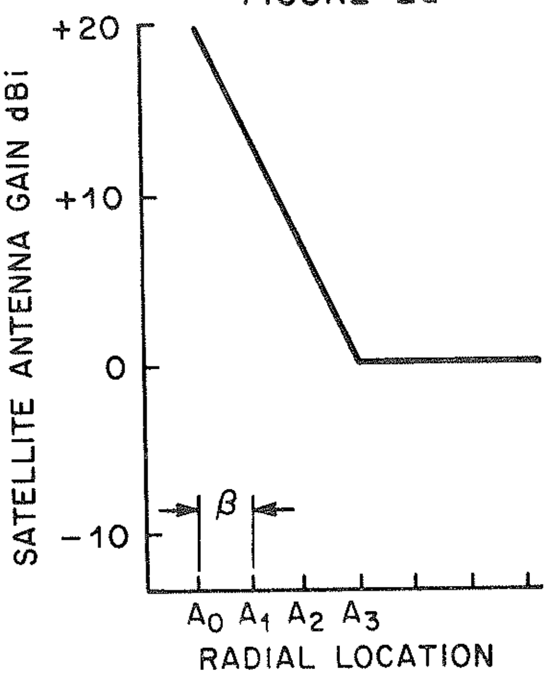
INTERFERENCE DUE TO SATELLITE DEPARTURES
FROM NOMINAL POSITION

FIGURE 1



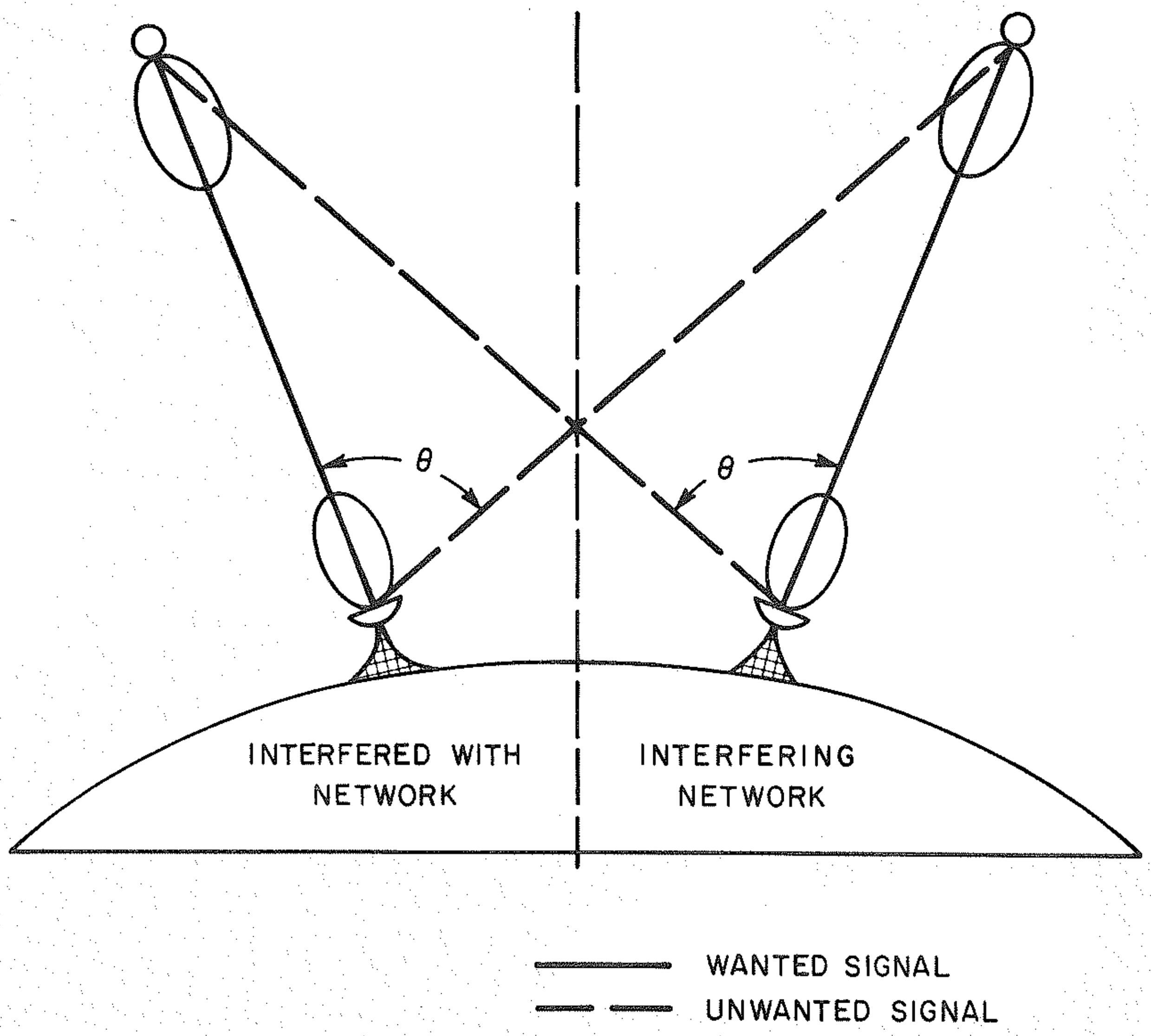
LIMITATION OF SATELLITE ANTENNA SIDELOBE RADIATION
(SERVICE AREA)

FIGURE 2a



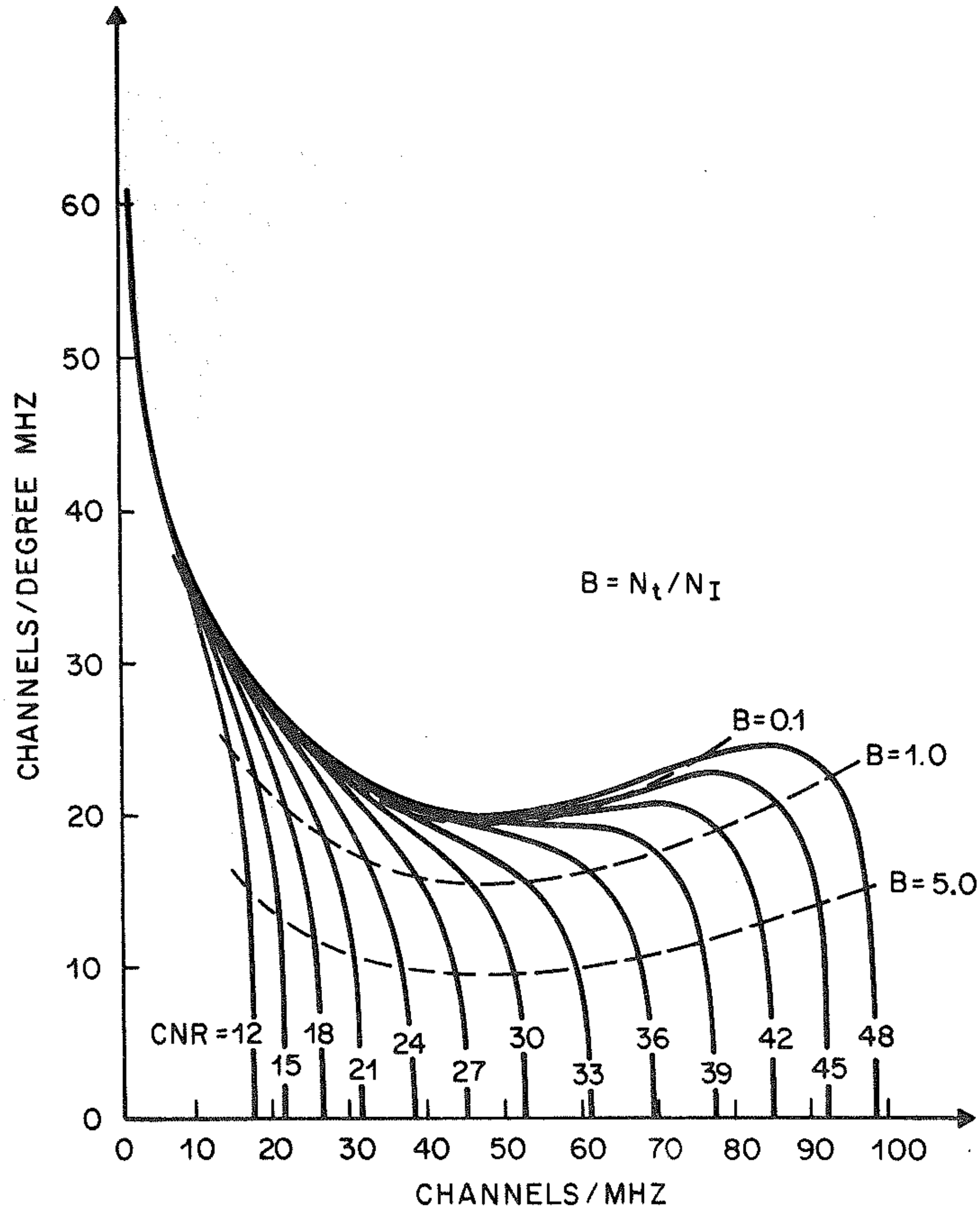
LIMITATION OF SATELLITE ANTENNA SIDELOBE RADIATION
(AT CONTOURS)

FIGURE 2b



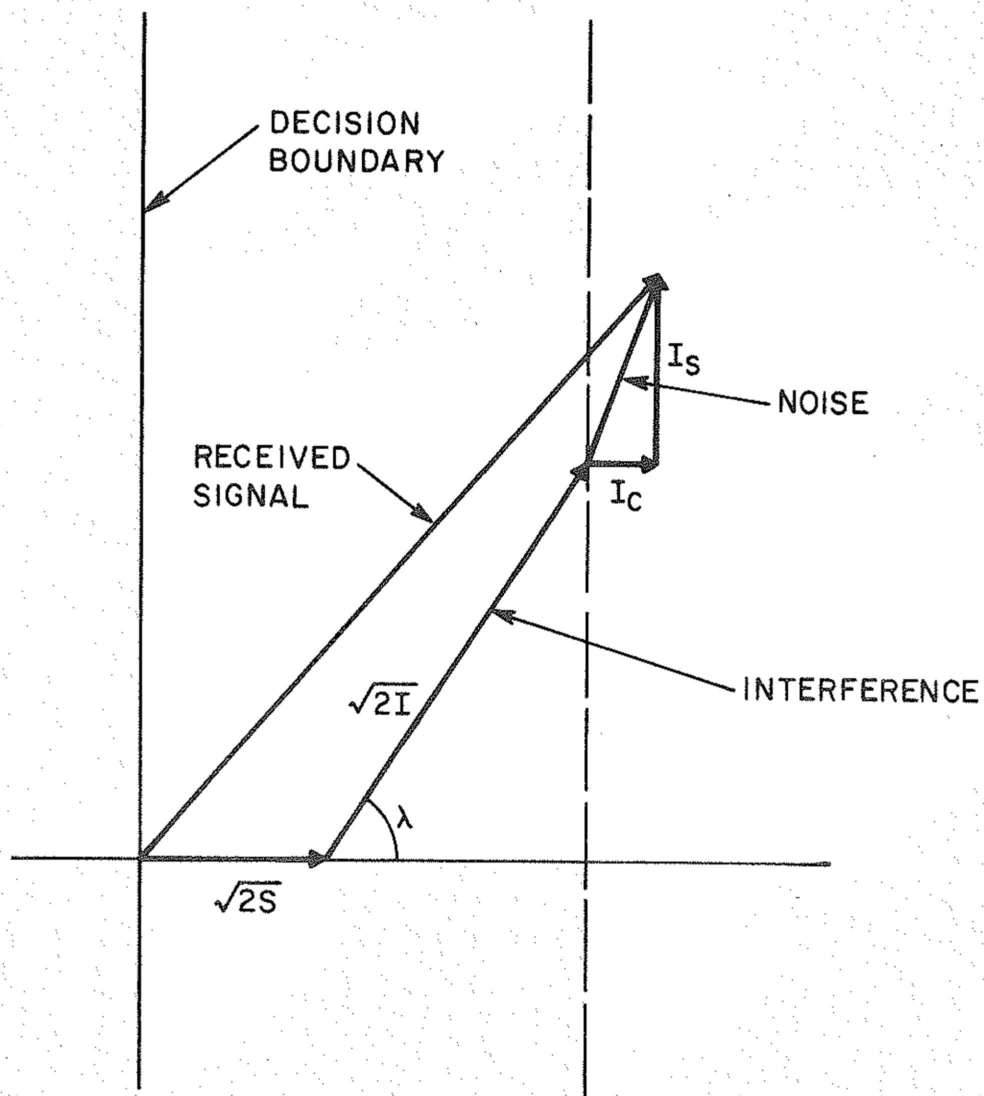
INTERFERENCE MODEL

FIGURE 3



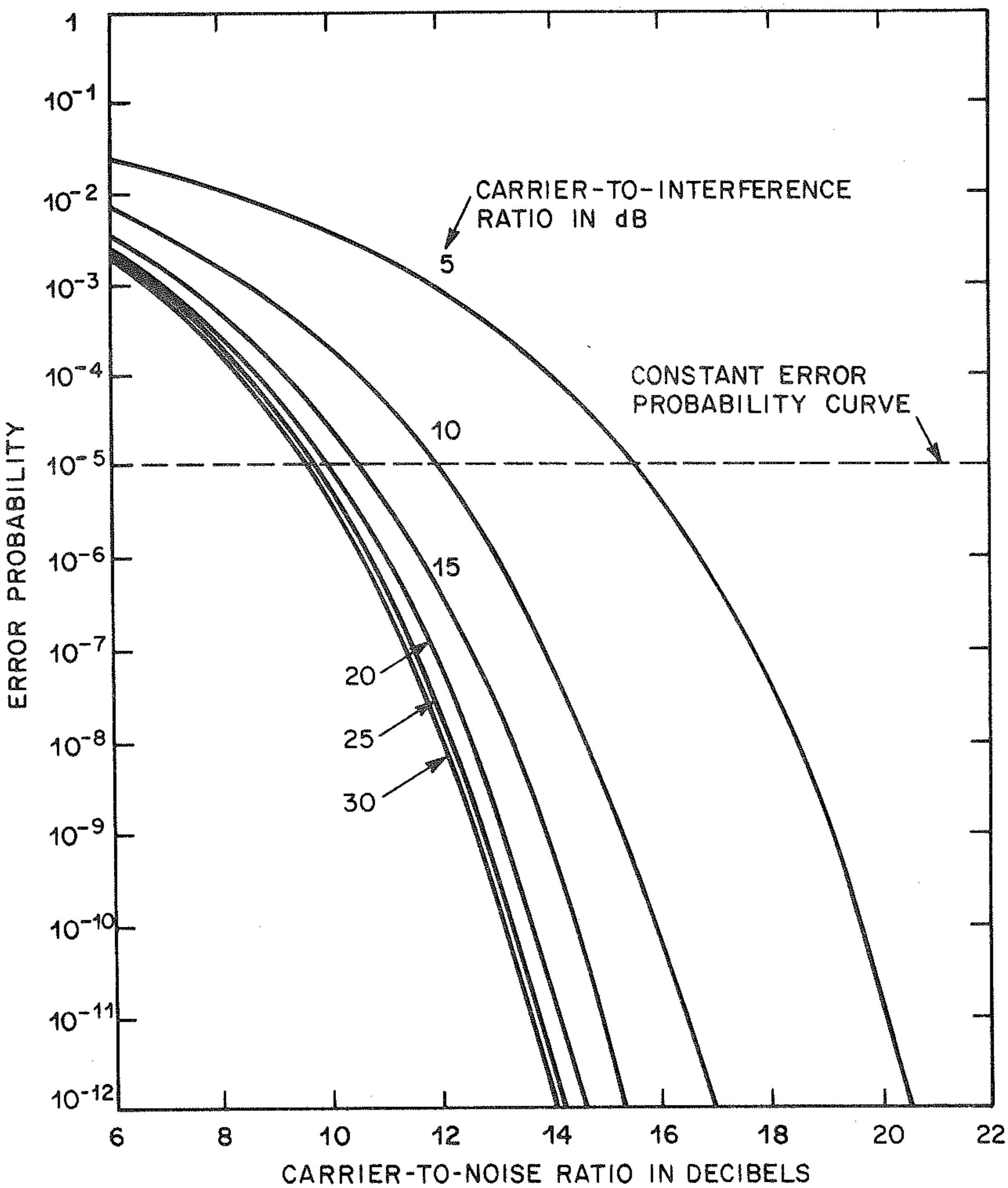
ORBIT/SPECTRUM UTILIZATION MEASURE FOR FDM/FM TELEPHONY SIGNALS

FIGURE 4



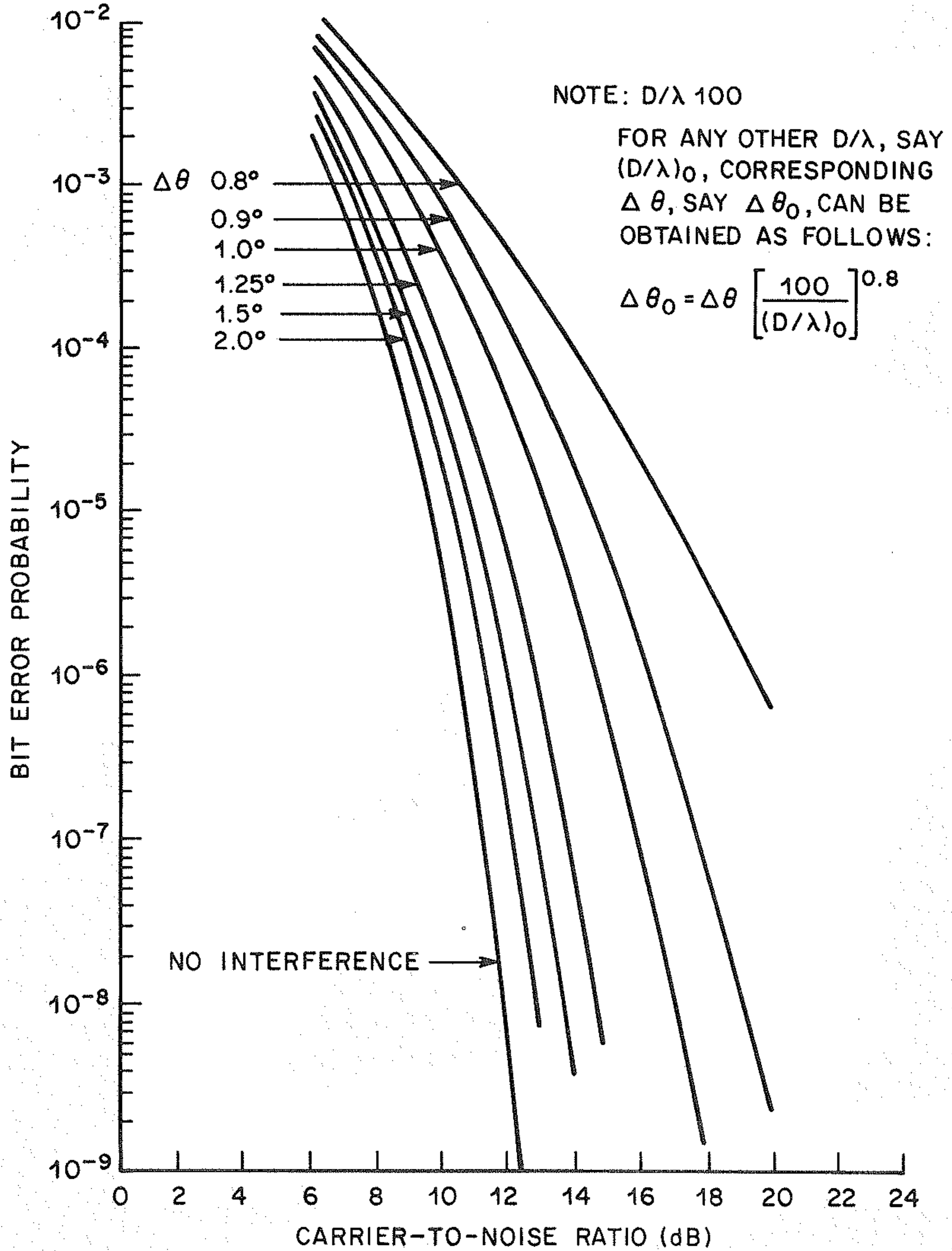
PHASOR REPRESENTATION OF M-CPSK SIGNAL FOR M=2

FIGURE 5



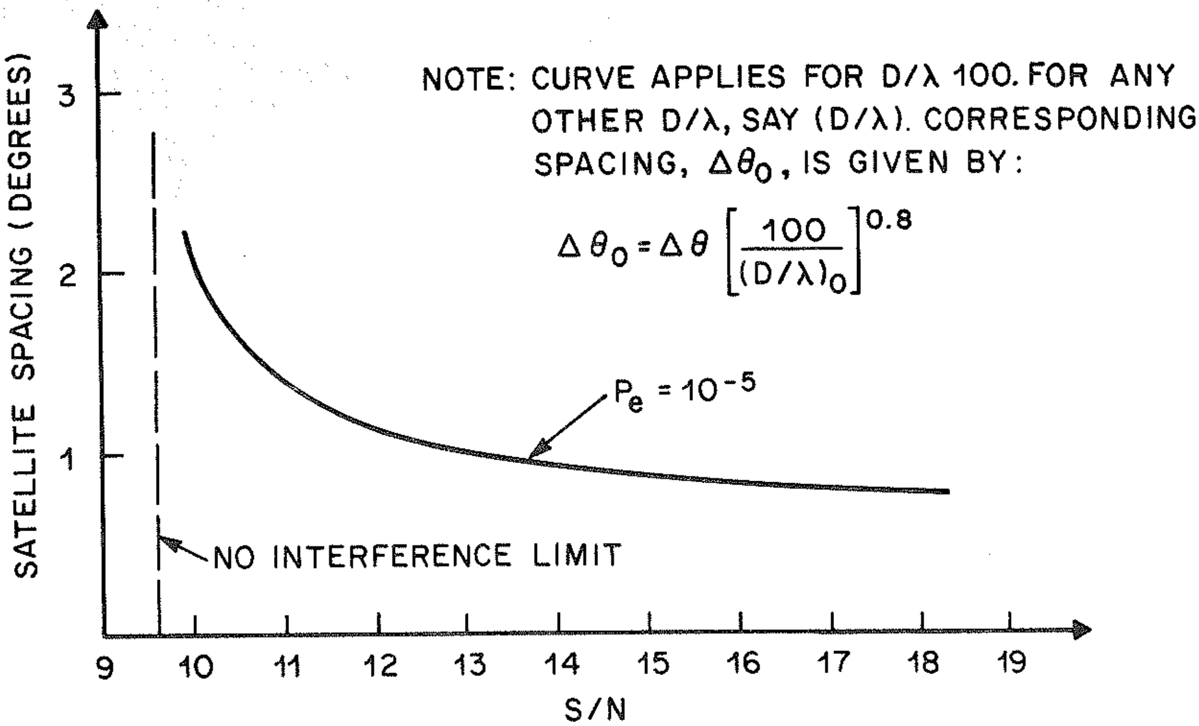
BIT ERROR PROBABILITY VERSUS S/N FOR DIFFERENT LEVELS OF INTERFERENCE

FIGURE 6



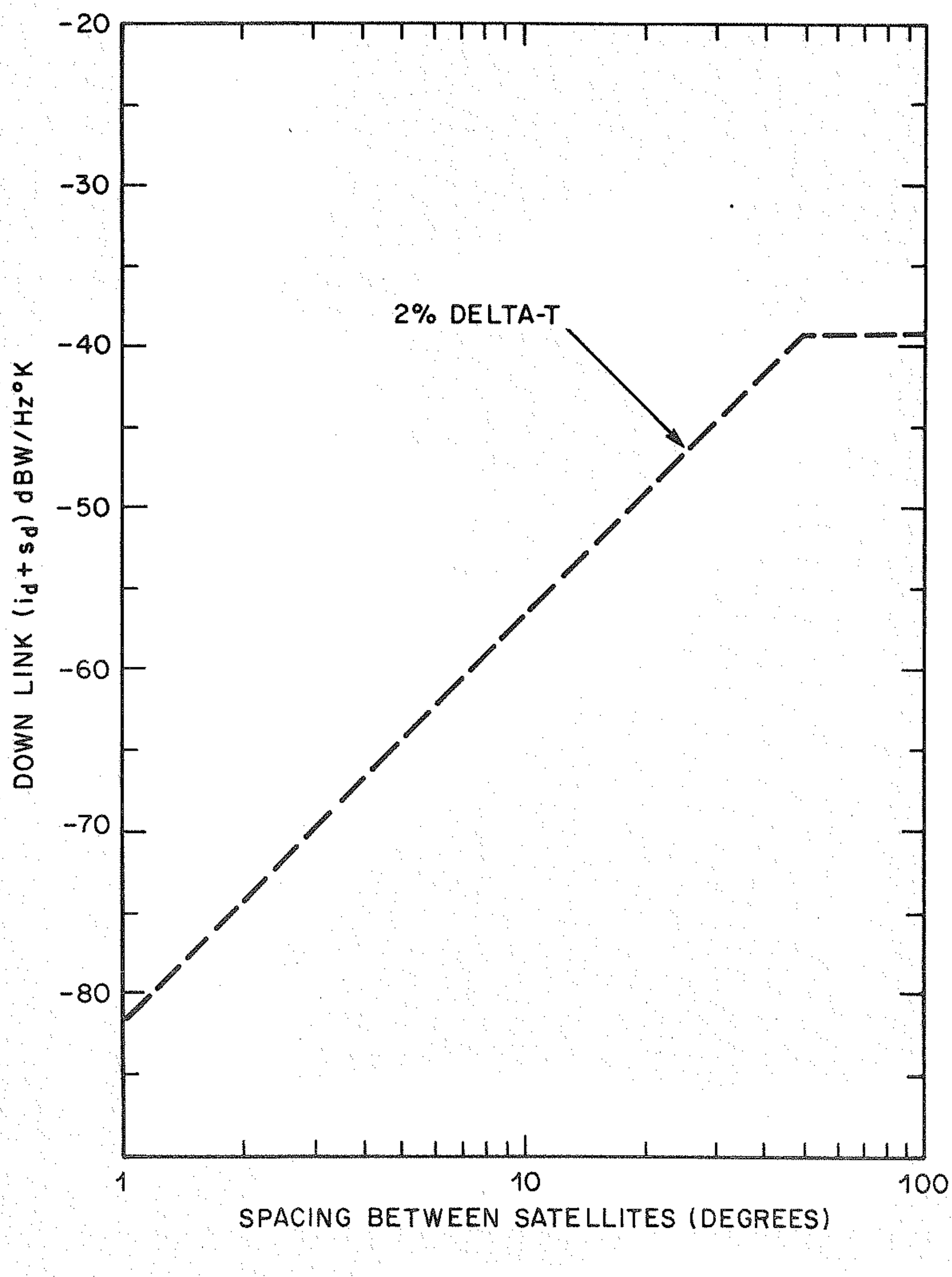
BIT ERROR PROBABILITY VERSUS S/N PARAMETERIZED BY θ

FIGURE 7



SATELLITE SPACING VERSUS (S/N) FOR BINARY CPSK

FIGURE 8



ORBITAL SPACING REQUIREMENTS

FIGURE 9

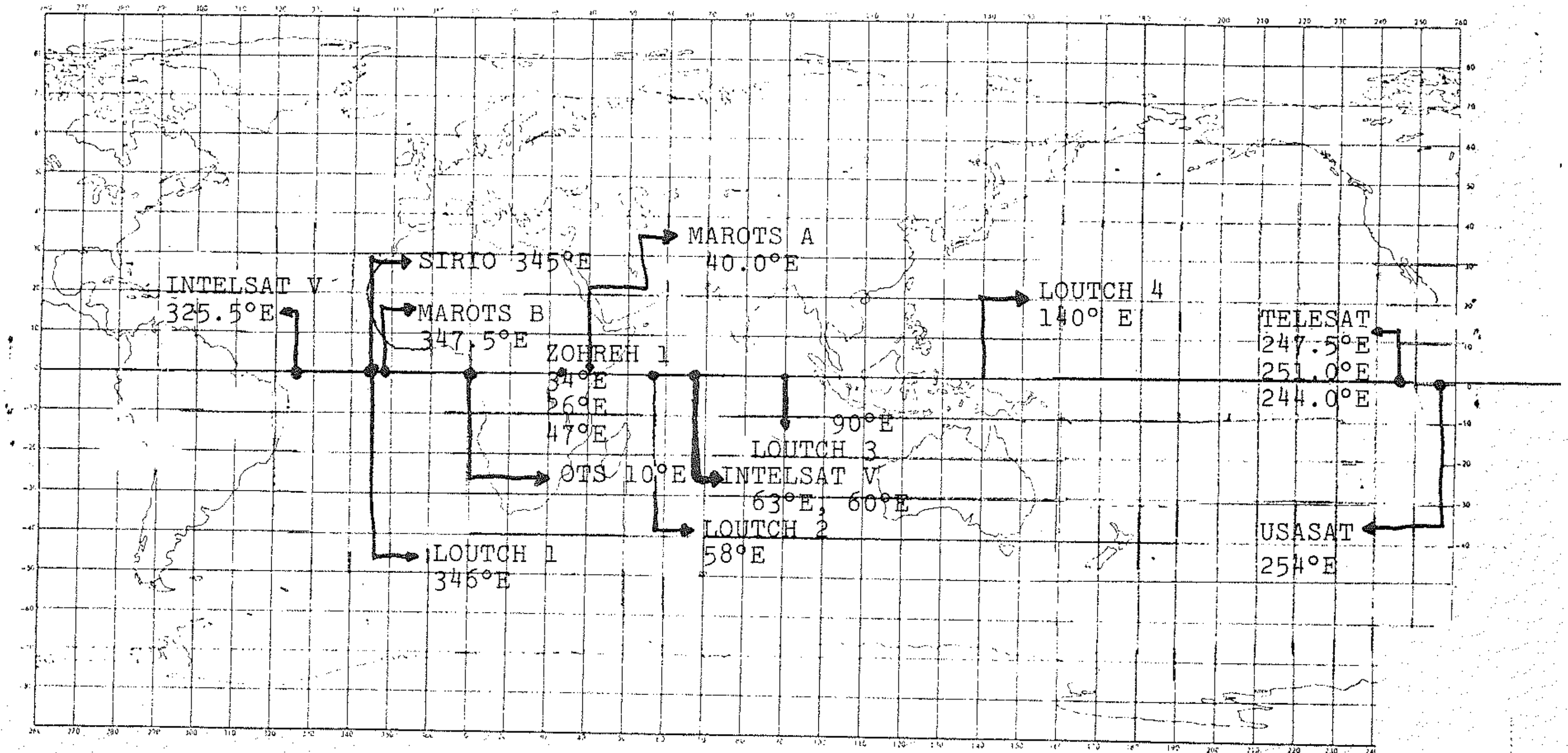


Figure 10. Position of 12/14 GHz Satellites on the Geostationary Orbit