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STUDY OF PERFORMANCE CHARACTERISTICS OF ANTENNAS FOR DIRECT BROADCASTING SATELLITE SYSTEMS AT 12 GHz.

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RCA Research & Development

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Phenomena affecting the design and operation of a broadcast satellite are analysed. We provide relations on attenuation and rain depolarization effects for incident linear and circular polarizations, allowing for imperfect antennas with finite isolation in clear weather and allowing for misalignment between transmitter and receiver polarizations. We then investigate interference due to an adjacent transmitter beam including the relevant antenna patterns and we deduce the net isolation. These results improve on several proposal reports submitted to CCIR by EBU. The relative advantages of linear and circular polarizations are outlined and we recommend the use of linear polarization at 12 GHz. We then comment on reference copolar and cross polar antenna patterns. The last chapter discusses system aspects of a broadcast satellite system. Included in the discussion are limitations to antenna reflector size, the apparent change in shape of ground area when the satellite is moved to different locations in the orbit, problems associated with channel assignment in a multibeam environment and the geometrical aspects of using linear polarization in communication satellite systems.

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ABSTRACT

Phenomena affecting the design and operation of a broadcast satellite are analysed. We provide relations on attenuation and rain depolarization effects for incident linear and circular polarizations, allowing for imperfect antennas with finite isolation in clear weather and allowing for misalignment between transmitter and receiver polarizations. We then investigate interference due to an adjacent transmitter beam including the relevant antenna patterns and we deduce the net isolation. These results improve on several proposal reports submitted to CCIR by EBU. The relative advantages of linear and circular polarizations are outlined and we recommend the use of linear polarization at 12 GHz. We then comment on reference copolar and cross polar antenna patterns. The last chapter discusses system aspects of a broadcast satellite system. Included in the discussion are limitations to antenna reflector size, the apparent change in shape of a ground area when the satellite is moved to different locations in the orbit, problems associated with channel assignment in a multibeam environment and the geometrical aspects of using linear polarization in communication satellite systems.

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CHAPTER I

INTRODUCTION

The European Broadcasting Union is proposing to launch a broadcast satellite, having a high power transmitter, beaming to individual home-type receivers. Various problem areas that arise are associated with interference problems caused by the satellite high power and by the relatively inexpensive receivers.

Neighbouring satellite transmitters will have to be designed such that their transmitted beams provide minimum interference within a single receiver on earth. Possibilities are spot beams directed to specific areas, frequency differences and differing polarizations between beams. Since rain depolarization effects are minimized for incident horizontal polarization and especially for polarization in the vertical plane, it is desirable to construct beams having one of these polarizations at the local spot on earth to where the beam is directed. The advantages of circular versus linear polarization also have to be considered before circular polarization is ruled out. To double the number of channels, each beam may be designed with two orthogonally polarized channels. Another problem is side-lobes, which can provide interfering signals at large off-axis angles unless their power envelope is minimized. Finally, satellite antennas having very small beam widths require large apertures.

The earth receivers will probably be inexpensive, unadjustable and small as compared to presently used earth stations. Their relative smallness means that the central beam width will be of the order of 1^{o} - 2^{o}, which is sufficiently broad that adjacent satellite beams, even through received off-axis, may interfere with the signal from the desired satellite. The fact that the receivers are unadjustable means that it will be difficult to correct for misalignment of polarization direction between that of the transmitted signal and that of the receiver. Misalignment can be caused by the wind, other weather conditions, mishandling and by Faraday rotation in the ionosphere. The latter is negligible for frequencies above 8 GHz. Misalignment introduces cross-polarization. Also attempting to construct cheap receivers may cause one to neglect means for bettering their inherent cross polarization isolation in clear weather. One can expect the receiver isolation to be worse than that of the satellite antenna. Another factor which may improperly be neglected is to provide protection against rain over the feed of the earth receiver. Rain dripping over the feed is known to greatly worsen the antenna isolation.

Chapter II discusses the theory of the rain depolarization phenomena and gives the results of measurements that have been reported in the literature. The contribution of the imperfections in the transmit and receive antennas to the coupling between the cross polarization channels is included. The decrease in antenna response away from the antenna axis is also included and standardized formulas for calculating this response are discussed.

Chapter III discusses system aspects of a broadcast satellite system. Included in the discussion are limitations to antenna reflector size, the apparent change in shape of a ground area when the satellite is moved to different locations in the orbit, problems associated with channel assignment in a multibeam environment, and the geometrical aspects of using linear polarization in communication satellite system.

Pertinent reports are reviewed and discussed in both Chapter II and Chapter III as appropriate depending upon the subject content of the report.

CHAPTER II

CROSS POLARIZATION EFFECTS

1. INTRODUCTION

In this chapter we consider the effects of rain on attenuation, cross polarization discrimination and isolation. In Section 2, we provide relations how to calculate attenuation and rain depolarization effects for incident linear and circular polarizations, for the case of perfect antennas and exact alignment. In Section 3, we extend these results to allow for imperfect antennas with finite isolation in clear weather and to allow for misalignment of the polarizations of the transmitter and receiver antennas. In Section 4, we investigate interference from neighbouring satellites or between adjacent beams. The antenna patterns are included and relations are given for the net isolation.

Various documents have been submitted to CCIR dealing with one or other of the above problems. The effects of rain have either not been analyzed properly or have been omitted altogether. The results in Sections 2,3 and 4 improve respectively on the reports EBU (K3) 162-E, CCIR 555 and EBU(K3) 135-rev.E.

In Section 5, we consider the relative advantages and disadvantages of linear versus circular polarization and we recommend the use of linear polarization at 12 GHz and higher frequencies. In Section 6, we comment on EBU report (K3) 139-rev.E, concerning reference antenna patterns. Considerations related to antenna design problems are given in Chaper III.

2. COMMENTS ON EBU PROPOSAL DRAFT REPORT (K3) 162-E, DEC(1975)

EBU draft report (K3) 162-E, Dec(1975), is an attempt to specify rainfall depolarization values to be adopted for system planning. Although useful for crude estimates, the formulas do not allow for linear polarizations and other effects. Only circular polarization is considered. Also Eq.(1) neither includes the important effect of the angle of incidence or the elevation angle, nor the equivalent path length through the rainfall. With the availability of calculated results by Oguchi and Hosoya (1974) and by Chu (1974), the better tabulated results should be used. Admittedly, the computer results are not available at 12 GHz, but rather at 11 GHz for various angles of incidence, but this difference is not great.

The "classical" formulation which we propose to follow uses the following quantities, assumed known.

(a) The slant path length distance through the rainfall, r' in km, between the satellite and earth receiver. This is usually deduced experimentally. Otherwise, the following theoretical formulas (Lee, 1975) are suggested as a good estimate for the vertical (V) and horizontal(H) extents of the rainfall.

$H(km) = 5.34 - 1.67 \log_{10} R$; $V(km) = 17.18 - 5.13 \log_{10} R$

where R is rainfall in mm/hr, assuming $R > 1$ and assuming that the values of R are available experimentally. Then the value of r' is given by the one of the following two expressions which is less than $(H^2 + V^2)^{\frac{1}{2}}$.

$r' = H/\sin\alpha$ or $r' = V/\cos\alpha$

Here $90^\circ - \alpha'$ is the elevation angle in degrees and $\alpha = \pi\alpha'/180$ in radians is the angle of incidence with respect to the vertical.

(b) The differential attenuation values per unit length, $\Delta A' = A'_H - A'_V$ in dB/km.

(c) The differential phase shift values per unit length, $\Delta\Phi'$ in degrees/km. Both $\Delta A'$ and $\Delta\Phi'$ are already averaged over the drop size distribution in space. Calculated values for them are available from Chu (1974) for $\alpha' = 90^\circ$ and these are given in Table I. Also calculated results from Oguchi and Hosoya (1974) are given here in Table II for $\alpha = 90^\circ, 70^\circ, 50^\circ$ and 30°. These values depend on rain rate and the tabulated values range over 0.25 to 150 mm/hr values for R.

(d) The canting angle, τ' in degrees. Consider the plane perpendicular to the propagation direction and project onto this plane the average image ellipse of the raindrop spheroids. The angle τ' is defined to be the angle between the electric field and the nearby axis of this ellipse. For an incident wave with horizontal or vertical polarization, the effective τ' can be taken to be between 2° to 4° (Watson and Arbabi, 1975). This approach is simpler than that of Chu (1974) who uses the averages $<|\tau'|> \approx 25^\circ$ and $<\sin^2 2\tau> \approx (0.14)^2 \sin^2(2<|\tau|>)$ in the equations.

Before we use the suggested formulas, we require the following changes in units:

$$\tau = \frac{\pi}{180}\tau' \quad , \quad \alpha = \frac{\pi}{180}\alpha' \quad , \quad r = 10^3 r'$$

$$\Delta A = \Delta A' \, 10^{-3}/8.686 \qquad \text{and} \qquad \Delta\Phi = \Delta\Phi' \, 10^{-3}\, \pi/180$$

Define the following quantities used by McCormick and Hendry (1973).

$$p^2 = \frac{\cosh(r\Delta A) - \cos(r\Delta\Phi)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)} \quad , \quad p\cos\chi = \frac{\sinh(r\Delta A)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)}$$

TABLE I (FROM CHU, 1974)

RAIN RATE	ATTENUATION (dB/km)			PHASE SHIFT (deg/km)		
mm/hr	Vertical Polarization A'_H	Horizontal Polarization A'_V	Difference $\Delta A'$ (Horiz.- Vert.)	Vertical Polarization	Horizontal Polarization	Difference $\Delta\Phi'$ (Horiz.- Vert.)
FREQUENCY : 11 GHz				ANGLE OF INCIDENCE α': 90°		
0.25	0.002428	0.002669	0.000241	0.3985	0.4195	0.021
1.25	0.01592	0.01820	0.00228	1.579	1.697	0.118
2.5	0.03787	0.04399	0.00612	2.880	3.127	0.247
5.0	0.09144	0.1076	0.01616	5.266	5.783	0.517
12.5	0.2907	0.3470	0.0563	11.69	13.06	1.37
25.0	0.6898	0.8293	0.1395	21.32	24.18	2.86
50.0	1.605	1.945	0.340	38.94	44.93	5.99
100.0	3.586	4.392	0.806	70.25	82.58	12.33
150.0	5.605	6.919	1.314	99.26	118.3	19.04

TABLE II (FROM OGUCHI AND HOSOYA, 1974)

Rain rate (mm hr)	Attenuation (dB/km) Vertical polarization	Attenuation (dB/km) Horizontal polarization	Attenuation (dB/km) Difference (Horizontal - Vertical)	Phase shift (deg. km) Vertical polarization	Phase shift (deg. km) Horizontal polarization	Phase shift (deg. km) Difference (Horizontal - Vertical)
	Frequency: 11 GHz,			Angle of incidence α': 90°		
0.25	0.002507	0.002731	0.000224	0.3962	0.4150	0.0188
1.25	0.01604	0.01809	0.00205	1.560	1.664	0.104
2.5	0.03781	0.04326	0.00545	2.844	3.064	0.220
12.5	0.2852	0.3349	0.0497	11.64	12.77	1.23
25.0	0.6745	0.7983	0.1238	21.09	23.66	2.57
50.0	1.554	1.855	0.301	38.47	43.85	5.38
100.0	3.504	4.230	0.726	69.95	81.13	11.18
150.0	5.467	6.637	1.17	98.99	116.1	17.11
	Frequency: 11 GHz,			Angle of incidence α': 70°		
0.25	0.002524	0.002721	0.000197	0.3983	0.4150	0.0167
1.25	0.01614	0.01796	0.00182	1.572	1.664	0.092
2.5	0.03805	0.04287	0.00482	2.869	3.063	0.194
12.5	0.2873	0.3312	0.0439	11.69	12.78	1.09
25.0	0.6801	0.7895	0.1094	21.42	23.69	2.27
50.0	1.569	1.835	0.266	39.18	43.93	4.75
100.0	3.547	4.189	0.642	71.52	81.40	9.88
150.0	5.543	6.580	1.037	101.4	116.6	15.2
	Frequency: 11 GHz,			Angle of incidence α': 50		
0.25	0.002567	0.002698	0.000131	0.4038	0.4148	0.011
1.25	0.01641	0.01762	0.00121	1.602	1.663	0.061
2.5	0.03868	0.04188	0.0032	2.93[illegible]	3.062	0.129
12.5	0.2925	0.3217	0.0292	12.07	12.79	0.72
25.0	0.6944	0.7673	0.0729	22.24	23.75	1.51
50.0	1.609	1.786	0.177	40.99	44.15	3.16
100.0	3.658	4.087	0.429	75.50	82.08	6.58
150.0	5.740	6.432	0.692	107.7	117.8	10.1
	Frequency: 11 GHz,			Angle of incidence α': 30°		
0.25	0.002616	0.002672	0.000056	0.4100	0.4147	0.0047
1.25	0.01672	0.01723	0.00051	1.636	1.662	0.026
2.5	0.03939	0.04076	0.00137	3.005	3.060	0.055
12.5	0.2985	0.3110	0.0125	12.49	12.80	0.31
25.0	0.7109	0.7420	0.0311	23.17	23.81	0.64
50.0	1.654	1.730	0.076	43.04	44.39	1.35
100.0	3.787	3.971	0.184	80.05	82.85	2.80
150.0	5.968	6.265	0.297	114.9	119.2	4.3

the cross polarization discrimination values ($XPD_{H,V}$) due to rain alone for linear polarizations in two orthogonal directions are given by

$$XPD_{H,V} = 10 \log_{10} \left[\frac{1 \mp 2p\cos\chi\cos 2\tau + p^2\cos^2 2\tau}{p^2\sin^2 2\tau} \right]$$

The upper sign applies to H and the lower sign to V polarization. For circular polarization, either right-hand or left-hand, the result is the same as letting $\tau = \pi/4$ in the above relation, yielding

$$XPD_C = -10 \log_{10} p^2$$

The attenuation in dB of the signals with respect to their clear weather values are given by

$$ATT_{H,V} = \left(A'_H + A'_V\right)\frac{F'}{2} + 5 \log_{10}\left[(1+p^2)^2 - 4p^2\cos^2\chi\right]$$

$$- 10 \log_{10}\left[1 \mp 2p\cos\chi\cos 2\tau + p^2\cos^2 2\tau\right]$$

for linear polarization where $A'_{H,V}$ are the attenuation values in dB/km given in Tables I and II for the respective two linear polarizations. For circular polarization

$$ATT_C = \left(A'_H + A'_V\right)\frac{F'}{2} + 5 \log_{10}\left[(1+p^2)^2 - 4p^2\cos^2\chi\right]$$

Obviously, even XPD_C is not simply related to ATT_C, so that the equation suggested in EBU draft report (K3) 162-E, Dec (1975), namely $XPD_C = 31 - 2(ATT_C)$ can at best be only approximate. The suggestion there is that it be used for $ATT_C \leq 6.1$ dB, valid for 99% of the worst month. However, fades greater than [illegible]B and in fact up to 20 dB do occur at 11 GHz (Watson and Arbabi, 1975) for the remaining time (1% of the worst month). Consequently for a more reliable system, better theoretical predictions should be applied. The relations given here can be applied to satisfy this requirement.

3. COMMENTS ON CCIR REPORT 555 (1974)

CCIR Report 555 (1974) illustrates remarkably well the co-polar and cross-polar patterns for various antennas and gives on-axis and off-axis cross-polarization discrimination values both for linear and circular polarizations. The patterns also show that in many cases there is no minimum on-axis for the cross-polar pattern.

Polarisers in the feed which are required to generate circular polarization are stated to be available with an ellipticity ratio of 0.2 dB giving 39 dB isolation at 4-6 GHz. Low ellipticity ratios (< 0.5 dB) can probably be obtained at 12 GHz.

Of the various antennas shown, we recommend for satellite use the off-set fed paraboloid, especially if multiple beams are to be used. An off-set feed provides (i) less return into the horn (ii) less blockage loss associated with the feed and support structures (iii) generally lighter weight and (iv) higher cross-polarization discrimination since a major degrader is the tower causing polarization changeover.

The state of the art on cross-polarization discrimination is about 33 dB for linear and 30 dB for circular polarization up to the 3 dB contour coverage area. Two methods for improvement that we propose are (i) to use a circular waveguide feeding the horn with the TE_{11} mode, which after reflection from the paraboloid gives a purer linear wave or (ii) use a longer focal length to diameter ratio of the order of 0.7 or larger. Extensions of method(i) are discussed by Tseng(1975).

CCIR Report 555 (1974) illustrates the effects of (i) misalignment of polarization, (ii) finite antenna ellipticity ratios for circular polarization and (iii) finite antenna isolations for linear polarization. The effect of rain is not included. The effects of rain in addition to the other factors are considered below.

In the following, we generalize the results in CCIR Report 555 (1974) in order to include propagation affects. The works of Oguchi, Chu, McCormick and others can be used to include the effect of rain along the propagation path. We consider first the case of linear polarization and then circular polarization.

Linear Polarization

We propose the following theoretical formulas to calculate the cross-polarization discrimination ($XPD_{H,V}$) for linearly polarized waves, either horizontal or vertical, along a one-way path. We provide results for the worst case where the clear weather phases of ellipticity of the transmitter and receiver antennas are of opposite sign.

We include the following effects:

(a) Off-beam center transmission and reception, where ϕ_T and ϕ_R are the the angles the line of sight propagation path makes with the respective normals to the antenna apertures.

(b) The clear weather finite polarization discrimination, $D'_T(\phi_T)$ in dB, of the satellite transmitter antenna between the co-polar antenna radiation pattern, $F'_T(\phi_T)$ in dB (negative quantity), and the cross-polar radiation pattern, $f''_T(\phi_T)$ in dB (negative quantity), with $D'_T(\phi_T) = F'_T(\phi_T) - f''_T(\phi_T)$.

(c) The clear weather finite polarization discriminations, $D'_R(\phi_R)$ and $D''_R(\phi_R)$ in dB, of the ground antenna. D'_R refers to discrimination in the co-polar receiver channel between reception of a co-polar radiation pattern, $F'_R(\phi_R)$ in dB, and a cross-polar pattern, $f'_R(\phi_R)$ in dB, with $D'_R(\phi_R) = F'_R(\phi_R) - f'_R(\phi_R)$. D''_R refers to discrimination in the cross-polar receiver channel between reception of the direct radiation pattern, $F''_R(\phi_R)$ in dB in the cross-direction, and the pattern $f''_R(\phi_R)$ in dB in the co-polar orthogonal direction, with $D''_R(\phi_R) = F''_R(\phi_R) - f''_R(\phi_R)$.

Also let the respective on-axis antenna gains be G'_R in dB and G''_R in dB.

(d) Angular difference of the polarization direction between the satellite and the earth antenna, θ' in degrees, and/or the Faraday rotation angle.

(e) Depolarization due to rain, assuming a constant or effective rainfall rate along the path. We use

i) the slant path length distance through the rainfall, r' in km, from the satellite to earth receiver

ii) the differential attenuation values per unit length, $\Delta A'$ in dB/km

iii) the differential phase shift values per unit length, $\Delta\Phi'$ in deg/km

iv) the effective canting angle of the raindrops, τ' in degrees.

Note that (i), (ii) and (iii) depend on elevation angle $(90^\circ - \alpha')$ in degrees, where α' is the angle of incidence with respect to the vertical. Also (i) to (iii) depend on the rain rate R in mm/hr, and on frequency f in GHz. For a transmitter using horizontal or vertical polarization, τ can be taken as a few degrees, say 4° as an example of a bad case (Watson and Arbabi, 1975). Values of (ii) and (iii) versus R, α' and f are obtainable from Chu(1974) and from Oguchi and Hosoya(1974). At 11 GHz, close to the frequencies of interest here, Oguchi and Hosoya give $\Delta A'$ and $\Delta\Phi'$ values for $\alpha' = 90^\circ$, 70°, 50°, 30°, (elevation angles $= 0^\circ$, 20°, 40° and 60° respectively) and for eight R values from 0.25 to 150 mm / hr.

Before we use the formulas, we require the following changes in units:

$$D_T = 10^{D_T'/20} \quad , \quad D_{R1} = 10^{D_R'/20} \quad , \quad D_{R2} = 10^{D_R''/20}$$

$$\theta = \frac{\pi}{180}\,\theta' \quad , \quad \tau = \frac{\pi}{180}\,\tau' \quad , \quad \alpha = \frac{\pi}{180}\,\alpha' \quad , \quad r = 10^3 r'$$

$$\Delta A = \Delta A'\, 10^{-3}/8.686 \quad , \quad \Delta\Phi = \Delta\Phi'\, 10^{-3}\pi / 180$$

Define the following quantities used by McCormick and Hendry (1973).

$$p^2 = \frac{\cosh(r\Delta A) - \cos(r\Delta\Phi)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)} \quad , \quad \tan\chi = \frac{\sin(r\Delta\Phi)}{\sinh(r\Delta A)}$$

$$p\cos\chi = \frac{\sinh(r\Delta A)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)} \quad , \quad p\sin\chi = \frac{\sin(r\Delta\Phi)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)}$$

Then the values of XPD for a one-way path are given by

$$XPD_{H,V} = 10 \log_{10} \frac{N_{\mp}}{D_{\mp}} + \left[f'_R(\phi_R) - f''_R(\phi_R)\right]_{H,V} + (G'_R - G''_R)_{H,V}$$

where

$$N_{\mp} = \left[(D_{R1} - D_T^{-1})\cos\theta \mp (D_{R1} + D_T^{-1})\, p\cos\chi\cos(2\tau + \theta) - (1 + D_{R1}D_T^{-1})\, p\sin\chi\sin(2\tau + \theta)\right]^2$$

$$+\left[(1 - D_{R1}D_T^{-1})\sin\theta + (D_{R1} + D_T^{-1})\, p\sin\chi\cos(2\tau + \theta) \mp (1 + D_{R1}D_T^{-1})\, p\cos\chi\sin(2\tau + \theta)\right]^2$$

and

$$D_{\mp} = \left[(1 + D_{R2}D_T^{-1})\cos\theta \mp (1 - D_{R2}D_T^{-1})\, p\cos\chi\cos(2\tau + \theta) + (D_{R2} - D_T^{-1})\, p\sin\chi\sin(2\tau + \theta)\right]^2$$

$$+\left[(D_{R2} + D_T^{-1})\sin\theta - (1 - D_{R2}D_T^{-1})\, p\sin\chi\cos(2\tau + \theta) \mp (D_{R2} - D_T^{-1})\, p\cos\chi\sin(2\tau + \theta)\right]^2$$

The top signs refer to XPD_H and horizontal is the co-polar channel and the bottom signs refer to XPD_V and vertical is the co-polar channel.

Examples are now given. In the absence of rain, $p = \chi = 0$, and for $F'_R = F''_R$, $f'_R = f''_R$, and $G'_R = G''_R$ the above reduces to

$$XPD = 10 \log_{10} \left[\frac{(D_R - D_T^{-1})^2 - (D_R^2 - 1)(1 - D_T^{-2})\sin^2\theta}{(1 + D_R D_T^{-1})^2 + (D_R^2 - 1)(1 - D_T^{-2})\sin^2\theta} \right]$$

which is the formula used to calculate Figure 9 in CCIR Report 555 (1974). This gives the reduction in XPD due to causes (a) to (d) above. Obviously as D_R and D_T go to infinity, we obtain

$$XPD = 10 \log_{10} \cot^2\theta$$

which is Figure 7 in Report 555. For the situation of perfect antennas, D_R and D_T infinite, and for exact alignment $\theta = 0$, we obtain

$$XPD_{H,V} = 10 \log_{10} \left[\frac{1 \mp 2p \cos\chi \cos 2\tau + p^2 \cos^2 2\tau}{p^2 \sin^2 2\tau} \right]$$

which is the relation given by McCormick and Hendry (1973) for linear polarization. This gives the reduction in XPD due to rain alone (cause (e) above). Another example again for D_R and D_T infinite but θ finite, so that effects (d) and (e) are included, yields

$$XPD_{H,V} = 10 \log_{10} \left[\frac{\cos^2\theta \mp 2p \cos\chi \cos\theta \cos(2\tau + \theta) + p^2 \cos^2(2\tau + \theta)}{\sin^2\theta \mp 2p \cos\chi \sin\theta \sin(2\tau + \theta) + p^2 \sin^2(2\tau + \theta)} \right]$$

The more general formula includes all causes (a) to (e).

Circular Polarization

We propose the following theoretical formulas to calculate the cross-polarization discrimination ($XPD_{R,L}$) for circular polarized waves, either right or left hand, along a one-way path. We consider the worst case where the respective clear weather ellipticity axes of the transmitter and receiver antennas are at right angles to each other. We include the following effects:

(a) Off-beam center transmission and reception, where ϕ_T and ϕ_R are the angles the line of sight propagation path makes with the respective normals to the antenna apertures.

(b) **The clear weather finite ellipticity, $E_T'(\phi_T)$ in dB, of the satellite transmitter antenna. This is related to the difference between the co-polar antenna radiation pattern, $F_T'(\phi_T)$ in dB, and the cross-polar radiation pattern, $f_T''(\phi_T)$ in dB, by**

$$F_T'(\phi_T) - f_T''(\phi_T) = 20 \log_{10} \left[(10^{E_T'/20} + 1) \Big/ (10^{E_T'/20} - 1) \right]$$

$$\approx 24.797 - 20 \log_{10} (E_T') + 0.009594 (E_T')^2$$

where the approximation holds for $E_T'/20 \ll 1$.

(c) The clear weather finite ellipticities, $E_R'(\phi_R)$ and $E_R''(\phi_R)$ in dB, of the ground antenna. $E_R'(\phi_R)$ refers to the co-polar receiver channel and is related (similar to the above formula) to the difference between the co-polar radiation pattern, $F_R'(\phi_R)$ in dB, and the cross-polar pattern, $f_R'(\phi_R)$ in dB. Similarly $E_R''(\phi_R)$ refers to the cross-polar receiver channel and is related to the difference between the direct radiation pattern, $F_R''(\phi_R)$ in dB in the cross-direction, and the pattern $f_R''(\phi_R)$ in dB in the co-polar orthogonal direction.

Because the axes of the receiver ellipticity are orthogonal to E_T', the E_R's are negative if E_T' is taken as positive. Also let the respective on-axis antenna gains be G_R' in dB and G_R'' in dB.

(d) Depolarization due to rain, similar to (e) above for linear polarization.

Before we use the formulas, we require the following:

$$E_T = 10^{E_T'/20}, \quad E_{R1} = 10^{-E_R'/20} = 10^{|E_R'|/20}, \quad E_{R2} = 10^{-E_R''/20} = 10^{|E_R''|/20}$$

$$\tau = \frac{\pi}{180}\tau', \quad \alpha = \frac{\pi}{180}\alpha', \quad r = 10^3 r'$$

$$\Delta A = \Delta A' \, 10^{-3}/8.686 \quad ; \quad \Delta\Phi = \Delta\phi' 10^{-3}\pi/180$$

$$p^2 = \frac{\cosh(r\Delta A) - \cos(r\Delta\Phi)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)} \quad , \quad p\cos\chi = \frac{\sinh(r\Delta A)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)}$$

$$p\sin\chi = \frac{\sin(r\Delta\Phi)}{\cosh(r\Delta A) + \cos(r\Delta\Phi)}$$ and the new quantities

$$\sin(\mu_T \pm \mu_{Rj}) = \frac{1 \pm E_T E_{Rj}}{\left[(1+E_T^2)(1+E_{Rj}^2)\right]^{\frac{1}{2}}} \quad \text{and} \quad \cos(\mu_T \pm \mu_{Rj}) = \frac{E_T \mp E_{Rj}}{\left[(1+E_T^2)(1+E_{Rj}^2)\right]^{\frac{1}{2}}}$$

Then the values of $XPD_{R,L}$ for a one-way path are given by

$$XPD_{R,L} = 10\log_{10}\frac{N^c_{\mp}}{D^c_{\mp}} + (G^c_R - G''_R)_{R,L} + 10\log_{10}\left[\frac{10^{F'_R/10} + 10^{f'_R/10}}{10^{F''_R/10} + 10^{f''_R/10}}\right]$$

where

$$N^c_{\mp} = \cos^2(\mu_T - \mu_{R1}) \mp 2p\cos\chi\cos2\tau\cos(\mu_T + \mu_{R1})\cos(\mu_T - \mu_{R1})$$
$$- \; 2p\sin\chi\sin2\tau\cos(\mu_T - \mu_{R1})\sin(\mu_T - \mu_{R1})$$
$$+ \; p^2\cos^2 2\tau\cos^2(\mu_T + \mu_{R1}) + p^2\sin^2 2\tau\sin^2(\mu_T - \mu_{R1})$$

and

$$D^c_{\mp} = \sin^2(\mu_T - \mu_{R2}) \pm 2p\cos\chi\cos2\tau\sin(\mu_T + \mu_{R2})\sin(\mu_T - \mu_{R2})$$
$$+ \; 2p\sin\chi\sin2\tau\cos(\mu_T - \mu_{R2})\sin(\mu_T - \mu_{R2})$$
$$+ \; p^2\cos^2 2\tau\sin^2(\mu_T + \mu_{R2}) + p^2\sin^2 2\tau\cos^2(\mu_T - \mu_{R2})$$

The top signs refers to XPD_R and right-hand circular is the co-polar channel and the bottom signs refer to XPD_L and left-hand circular is the co-polar channel.

Examples are now given. In the absence of rain, $p = \chi = 0$, and for $E_{R1} = E_{R2}$ and $G'_R = G''_R$, the above reduces to

$$XPD = 10 \log_{10} \left[\cot^2(\mu_T - \mu_R) \right]$$

$$\approx 24.797 - 20 \log_{10} (E^\circ_T + |E^\circ_R|) + 0.009594 \left[(E^\circ_T)^2 + (E^\circ_R)^2 - 4E^\circ_T |E^\circ_R| \right]$$

where the approximation holds for $E^\circ_T/20 << 1$ and $|E^\circ_R|/20 << 1$.
Results based on this relation are plotted in Figure 8 of CCIR Report 555 (1974). For the situation of perfect antennas, E°_T, E°_R and $E^{\circ\prime}_R$ are zero, E_T, E_{R1} and E_{R2} are one, so that $XPD = 10 \log_{10} p^{-2} = -20 \log_{10} p$ which is the relation given by McCormick and Hendry (1973) for circular polarization. It is independent of τ and the same for right and left-hand circular. The more general formula includes all causes (a) to (d) and, as can be seen, it depends on τ.

4. COMMENTS ON EBU PROPOSAL REPORT (K3) 135- rev.E, DEC (1975)

This document suggests relations to calculate the interference arising from an unwanted satellite at an earth station, ordinarily receiving signals from a wanted closer satellite. The depolarisation induced by rain is included in the calculation and its effect is to change the polarization of the interfering radiation to the polarization of the receiver. The basic assumption, which is reasonable, is that the powers of the contributions to the interfering signal can be added since the relative phases are random with respect to each other. We however disagree with the analysis on two points. First the dependence of the cross polarization on the type of incident polarization (linear horizontal, linear vertical or circular) is omitted. Secondly, this report omits attenuation due to rain, which as we see below alters appreciably the relations. A revised analysis is given below.

The notation below follows that used in the previous two sections. The off-axis angle ϕ_T allows the radiation from the interfering satellite to reach the receiver, which detects it at its off-axis angle ϕ_R. We again include all the effects given in Section 3 for generality. In contrast to Section 3 where we aligned the phases of transmitter and receiver for the worst result, we now consider the phases to be random. We consider the two cases analysed in the EBU proposal, but we look separately at each subcase of linear and circular polarisation.

Case (1a) - Receiving Antenna with Nearly the Same Linear Polarization as Compared to that of the Interfering Satellite.

Define

$$P_{c\pm} = \cos^2\theta + p^2\cos^2(2\tau+\theta) \pm 2p\cos\theta\cos\chi\cos(2\tau+\theta)$$

$$P_{s\pm} = \sin^2\theta + p^2\sin^2(2\tau+\theta) \pm 2p\sin\theta\cos\chi\sin(2\tau+\theta)$$

Here θ is the misalignment angle between the transmitter and receiver polarisation directions, τ is the canting angle and the rain parameters, p and χ, are defined in Sections 2 and 3. These P_c and P_s factors allow for attenuation and cross-polarization due to rain.

The transmitter co-polar radiation pattern is denoted by $F_T'(\phi_T)$ in dB and its cross-polar radiation pattern is denoted by $f_T''(\phi_T)$ in dB. Later we also consider the transmitter radiating with orthogonal polarizations and then let $F_T''(\phi_T)$ in dB be the direct radiation pattern in the cross direction and let $f_T'(\phi_T)$ in dB be the cross-pattern in the co-polar orthogonal direction. For the receiver, we only use the co-polar radiation pattern $F_R'(\phi_R)$ in dB and its cross-polar pattern $f_R'(\phi_R)$ in dB, both for reception in the co-polar receiver channel. We also define

$$F_{T1} = 10^{F_T'/20}\ ,\ F_{T2} = 10^{F_T''/20}\ ,\ f_{T1} = 10^{f_T''/20}\ ,\ f_{T2} = 10^{f_T'/20}$$

$$F_R = 10^{F_R'/20} \quad \text{and} \quad f_R = 10^{f_R'/20}\ .$$

Here F_T' and f_T'' are normalized to $F_T'(0) = 0$.

Similarly F_T'' and f_T' are normalized to $F_T''(0) = 0$ and F_R' and f_R' are normalized to $F_R'(0) = 0$. For other off-axis angles, these quantities in dB are negative. The on-axis gains in dB are denoted respectively by G_T', G_T'' and G_R'.

Let P_R be the received power, P_T the transmitted power, λ the wavelength, and d the satellite to earth distance. As before r' in km is the propagation path through the rain. The other symbols below were defined previously in Sections 2 and 3.

For the case considered, the corrected result that we propose is given by

$$\left(P_R - P_T - G_T' - G_R'\right)_{H,V} + 20\ \log_{10}\ (4\pi d/\lambda)$$

$$+\ (A_H' + A_V')\ r'/2 + 5\ \log_{10}\ [(1 + p^2)^2 - 4\ p^2\cos^2\chi]$$

$$= 10\ \log_{10}\left(F_{T1}^2 F_R^2 P_{c\mp} + f_{T1}^2 f_R^2 P_{c\pm} + F_{T1}^2 f_R^2 P_{s\mp} + f_{T1}^2 F_R^2 P_{s\pm}\right)$$

$$= 10\ \log_{10}\left[10^{-(F_T' + F_R')/10} P_{c\mp} + 10^{-(f_T'' + f_R')/10} P_{c\pm} + 10^{-(F_T' + f_R')/10} P_{s\mp} + 10^{-(f_T'' + F_R')/10} P_{s\pm}\right]$$

The upper sign refers to H and the lower sign to V polarization.

In order to compare with the result in the EBU proposal, we let $\theta = 0$ so that $P_s = P_{s\pm} = p^2\sin^2 2\tau$ and we define the cross-polarization discrimination ratio

$$XPD_{H,V} = 10\log_{10}\frac{P_{c\mp}}{P_s} = 10\log_{10}\left[\frac{1+p^2\cos^2 2\tau \mp 2p\cos\chi\cos 2\tau}{p^2\sin^2 2\tau}\right]$$

Then the right hand side of the above expression for the received power becomes

$$(RHS)_{H,V} = 10\log_{10}P_{c\mp} + 10\log_{10}\Big[10^{-(F_T'+F_R')/10} + 10^{-(f_T''+f_R')/10}P_{c\pm}/P_{c\mp}$$

$$+\,10^{-(F_T'+f_R'+XPD_{H,V})/10} + 10^{-(F_R'+f_T''+XPD_{H,V})/10}\Big]$$

In the relation given in the EBU proposal, they omit attenuation so that $A_H' = A_V' = 0$, $P_{c\pm} = 1$ and $p = 0$ except in P_s . They also do not distinguish between incident polarizations. Their result then follows with their notation of $T = F_T'$, $R = F_R'$, $T_X = f_T''$, $R_X = f_R'$ and $D_X = XPD_{H,V}$. Obviously, such an expression is incorrect. The P_c factors introduce important corrections. Also $XPD_{H,V}$ and the double signs distinguish between linear H and linear V incident polarization.

Case (1b) - Same as Case (1a) but with Circular Polarization.

The result follows directly from the above upon setting $\theta = 0$ and $\tau = \pi/4$. We obtain the same expression for right and left-hand circular polarization upon using the assumption of random phases. The formula is

$$(P_R - P_T - G_T' - G_R')_c + 20\log_{10}(4\pi d/\lambda)$$

$$+\,(A_H' + A_V')\,r'/2 + 5\log_{10}\left[(1+p^2)^2 - 4p^2\cos^2\chi\right]$$

$$= 10\log_{10}\Big[10^{-(F_T'+F_R')/10} + 10^{-(f_T''+f_R')/10} + 10^{-(F_T'+f_R'+XPD_c)/10}$$

$$+\,10^{-(F_R'+f_T''+XPD_c)/10}\Big]$$

where $XPD_o = -10 \log_{10} p^2$. The right-hand side of this relation agrees with the form suggested in the EBU proposal. However, on the left-hand side, the attenuation factors, A_H', A_V' and the log argument involving p, are omitted in the proposal. They should be retained.

Case (2a) - Interfering Satellite with Nearly the Orthogonal Polarization as Compared to that of the Receiving Earth Antenna.

The result for this case is as follows:

$$(P_R - G_R')_{H,V} - (P_T + G_T'')_{V,H} + 20 \log_{10} (4\pi d/\lambda)$$

$$+ (A_H' + A_V')\, r/2 + 5 \log_{10}\left[(1+p^2)^2 - 4p^2\cos^2\chi\right]$$

$$= 10 \log_{10}\left(f_{T2}^2 F_R^2 P_{c\mp} + F_{T2}^2 f_R^2 P_{c\pm} + f_{T2}^2 f_R^2 P_{s\mp} + F_{T2}^2 F_R^2 P_{s\pm}\right)$$

$$= 10 \log_{10}\left[10^{-(f_T' + F_R')/10} P_{c\mp} + 10^{-(F_T'' + f_R')/10} P_{c\pm}\right.$$

$$\left. + 10^{-(f_T' + f_R')/10} P_{s\mp} + 10^{-(F_T'' + F_R')/10} P_{s\pm}\right]$$

Again, in order to compare with the expression in the EBU proposal, we let $\theta = 0$ and obtain for the right hand side

$$(RHS)_{H,V} = 10 \log_{10} P_{c\mp} + 10 \log_{10}\left[10^{-(f_T' + F_R')/10} + 10^{-(F_T'' + f_R')/10} P_{c\pm}/P_{c\mp}\right.$$

$$\left. + 10^{-(f_T' + f_R' + XPD_{H,V})/10} + 10^{-(F_T'' + F_R' + XPD_{H,V})/10}\right]$$

In the relation given in the EBU proposal, they set $A_H' = A_V' = 0$, $P_{c\pm} = 1$, $p = 0$ except in P_s, and $D_X = XPD_{H,V}$. They also do not distinguish between F_T'' and

F'_T and between f''_T and f'_T. Their result then follows with $T = F''_T$, $R = F'_R$, $T_X = f'_T$ and $R_X = f'_R$. As already mentioned for case (1a), such an expression is invalid.

Case (2b) - Same as (2a) but with Circular Polarization.

Again we obtain this result by letting $\theta = 0$ and $\tau = \pi/4$, yielding

$$(P_R - G'_R)_{R,L} - (P_T + G''_T)_{L,R} + 20 \log_{10} (4\pi d/\lambda)$$

$$+ (A'_H + A'_V)\, r'/2 + 5 \log_{10}\left[(1 + p^2)^2 - 4p^2 \cos^2 \chi\right]$$

$$= 10 \log_{10}\left[10^{-(f'_T + F'_R)/10} + 10^{-(F''_T + f'_R)/10} + 10^{-(f'_T + f'_R + XPD_c)/10} + 10^{-(F''_T + F'_R + XPD_c)/10}\right]$$

The right hand side agrees with the form suggested in the EBU proposal but the attenuation factors on the left hand side have not been included in the proposal and should be kept.

Cross-Polarization Isolation

The cross-polarization isolation of an antenna (XPI) against interfering signals can be derived by making use of the results for cases (1) and (2). XPI is simply the difference in dB between these two sets of results.

For linear polarization, we find from cases (1a) and (2a) that

$$(XPI)_{H,V} = G'_T - G''_T + 10 \log_{10}\left[\frac{F_{T1}^2 F_R^2 P_{c\mp} + f_{T1}^2 f_R^2 P_{c\pm} + F_{T1}^2 f_R^2 P_{s\mp} + f_{T1}^2 F_R^2 P_{s\pm}}{f_{T2}^2 F_R^2 P_{c\mp} + F_{T2}^2 f_R^2 P_{c\pm} + f_{T2}^2 f_R^2 P_{s\mp} + F_{T2}^2 F_R^2 P_{s\pm}}\right]$$

$$= G'_T - G''_T + F'_T - F''_T + 10 \log_{10}\left[\frac{D_R^2 P_{c\mp} + D_{T1}^{-2} P_{c\pm} + P_{s\mp} + D_R^2 D_{T1}^{-2} P_{s\pm}}{D_R^2 D_{T2}^{-2} P_{c\mp} + P_{c\pm} + D_{T2}^{-2} P_{s\mp} + D_R^2 P_{s\pm}}\right]$$

where $D_{T1} = F_{T1}/f_{T1}$, $D_{T2} = F_{T2}/f_{T2}$ and $D_R = F_R/f_R$ are the discrimination ratios of the antennas in clear weather.

To circular polarization, we find from cases (1b) and (2b) that

$$(XPI)_c = G'_T - G''_T + 10\log\left[\frac{F_{T1}^2 F_R^2 + f_{T1}^2 f_R^2 + p^2(F_{T1}^2 f_R^2 + f_{T1}^2 F_R^2)}{f_{T2}^2 F_R^2 + F_{T2}^2 f_R^2 + p^2(f_{T2}^2 f_R^2 + F_{T2}^2 F_R^2)}\right]$$

$$= G'_T - G''_T + 10\log_{10}\left[\frac{F_{T1}^2 + f_{T1}^2}{F_{T2}^2 + f_{T2}^2}\right] + 10\log_{10}\left[\frac{1 + \left(\frac{1-p^2}{1+p^2}\right)\frac{4E_{T1}E_R}{(1+E_{T1}^2)(1+E_R^2)}}{1 - \left(\frac{1-p^2}{1+p^2}\right)\frac{4E_{T2}E_R}{(1+E_{T2}^2)(1+E_R^2)}}\right]$$

$$= G'_T - G''_T + 10\log_{10}\left[\frac{F_{T1}^2 + f_{T1}^2}{F_{T2}^2 + f_{T2}^2}\right] + 10\log_{10}\left[\frac{1 + \left(\frac{1-p^2}{1+p^2}\right)[\sin^2(\mu_{T1}+\mu_R) - \sin^2(\mu_{T1}-\mu_R)]}{1 - \left(\frac{1-p^2}{1+p^2}\right)[\sin^2(\mu_{T2}+\mu_R) - \sin^2(\mu_{T2}-\mu_R)]}\right]$$

Similar to the definitions in Section 3, we introduce here E'_T, E''_T and E'_R, the clear weather ellipticity values in dB, of the circularly polarized antennas.

We then define

$$E_{T1} = 10^{E'_T/20}, \quad E_{T2} = 10^{E''_T/20}, \quad E_R = 10^{-E'_R/20},$$

$$\frac{F_{T1}}{f_{T1}} = \frac{E_{T1}+1}{E_{T1}-1}, \quad \frac{F_{T2}}{f_{T2}} = \frac{E_{T2}+1}{E_{T2}-1}, \quad \frac{F_R}{f_R} = \frac{1+E_R^{-1}}{1-E_R^{-1}}$$

and $$\sin(\mu_{Tj} \pm \mu_R) = \frac{1 \pm E_{Tj}E_R}{[(1+E_{Tj}^2)(1+E_R^2)]^{\frac{1}{2}}}.$$

The XPI ratios are of importance for this application related to interfering signals. Suggested expressions are given above.

5. CONSIDERATIONS ON LINEAR VERSUS CIRCULAR POLARIZATION

We first outline the advantages in the use of circular polarization and then those of linear polarization. Circular polarization is desirable for the following reasons:

(a) There is no need for polarization tracking in contrast to linear polarization where adequate alignment has to be maintained between the polarization directions of the satellite and earth antennas.

(b) Circular polarization is insensitive to Faraday rotation, whereas for linear polarization, rotation of the polarization angle introduces cross-polarization. This is an important consideration at frequencies below 6 GHz. However, at frequencies above 10 GHz, Faraday rotation is negligible and the above argument is no longer appropriate.

(c) Two adjacent areas serviced by separate satellites can maintain orthogonality using orthogonal right and left-hand circular polarizations, respectivity, for consecutive beam coverage. This is not so for linear polarization. This problem is discussed in Chapter III.

(d) The angle of polarization of the antenna may vary over its design bandwidth (CCIR Report 555 (1974)). This presents a possible disadvantage in a frequency reuse system employing linear polarization. In this case where the orthogonal polarization is also used, the overall isolation may not be maintained over its frequency bandwidth. This is not of concern if the isolation is still good enough throughout. However, methods have been proposed to cancel out cross polarization components induced by rain. Due to effect (d), these cancellation techniques may not be possible in the rf stage over the entire bandwidth, but will be limited to the if stage, separately for each transponder.

At the lower frequencies in the 4-6 GHz band, the advantages (a) and (b) are predominant in the choice of circular polarization. In the 12 GHz band, (a) and (c) are the main advantages what have to be taken into consideration.

The main reason in choosing linear polarization arises from considerations on propagation effects through rain. This first advantage is discussed at length below. We denote by XPD the cross-polarization discrimination or the ratio of direct to cross polarized received power in dB.

Depolarization due to rain is less and XPD is greater for all linear polarizations as compared to circular polarization, except for a canting angle of 45°, where circular and linear polarizations give about the same XPD. The theory, given in Section 2 above, indicates this fact. Since a distribution of canting angles exists, averaging over the canting angles favors linear polarization for most of the time (Watson and Arbabi, 1972). A vertically polarized electric field experiences better XPD and less attenuation than a horizontally polarized field and both provide better XPD than circular polarization. Experimental evidence substantiates the theory. Figure II.1 illustrates experimental results over terrestrial paths in the 17-19 GHz band. The top left hand side plots theory versus experiment using circular polarization (Semplak, 1973). The XPD value is plotted versus attenuation of the co-polar signal. The attenuation is that in excess of the clear weather value. The top right-hand side (from Hogg and Chu, 1975) compares the same experimental results with another experiment by Bostian et al (1973) using 45° linear polarization. We see that a 45° polarized wave is more or less equivalent to circular polarization, as theory (see Section 3) predicts for antennas with good clear weather isolation. The plot on the bottom left-side compares theory and experiment for an incident horizontally polarized wave for various path length (Chu, 1974). Finally, the bottom right-hand side plot shows the experimental XPD's for circular polarization

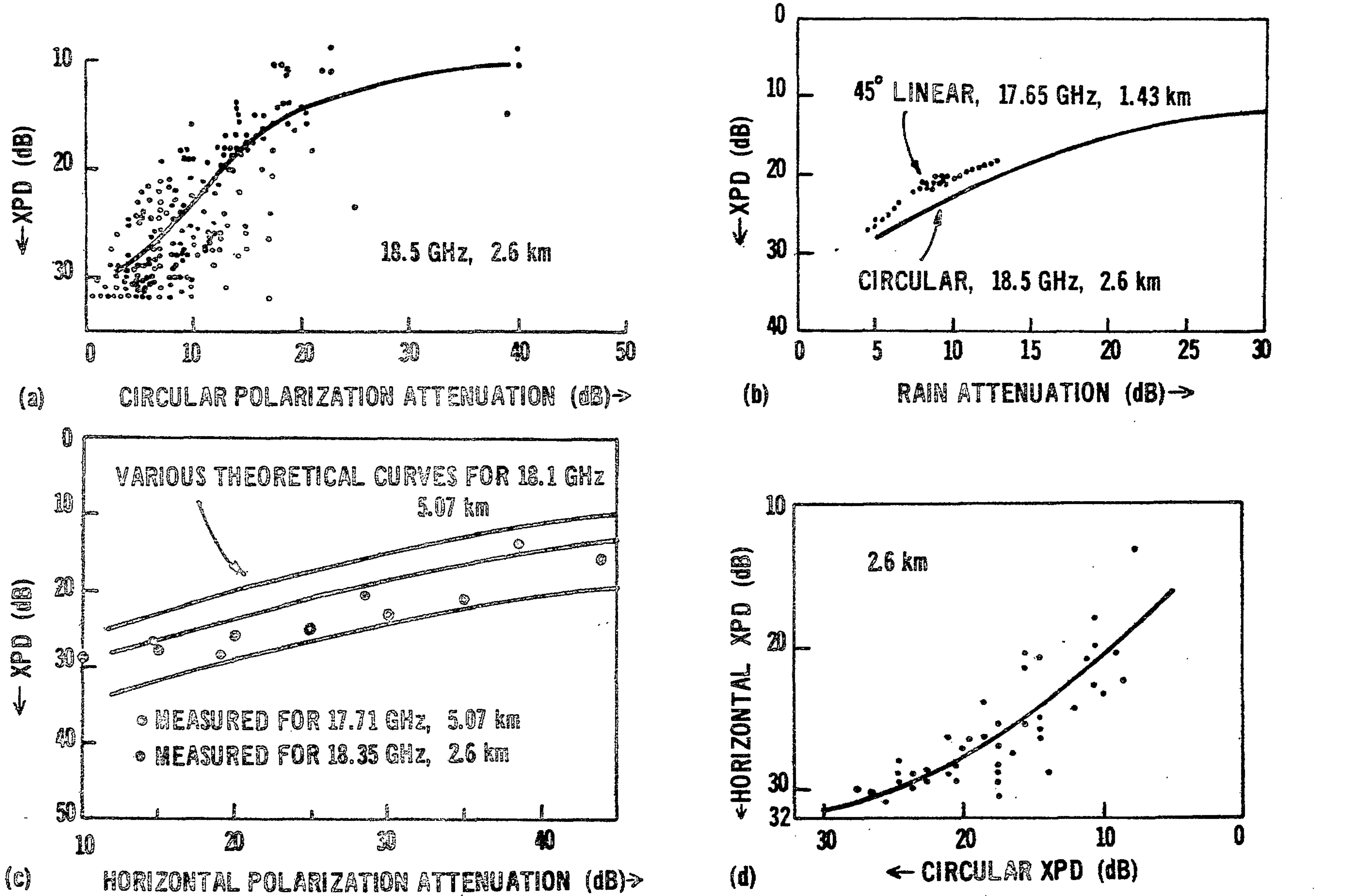

Figure II.1. COMPARISON OF LINEAR AND CIRCULAR INCIDENT POLARIZATIONS

(a) THEORY VERSUS EXPERIMENT FOR CIRCULAR POLARIZATION
(b) EXPERIMENTS WITH 45° LINEAR AND CIRCULAR POLARIZATIONS
(c) THEORY VERSUS EXPERIMENT FOR HORIZONTAL POLARIZATION
(d) EXPERIMENTS WITH HORIZONTAL AND CIRCULAR POLARIZATIONS WITH RESPECTIVE FREQUENCIES 18.35 AND 18.65 GHz

replotted against those for horizontal polarization, in the case of identical path lengths (Semplak, 1974). We clearly see that depolarization is worse for an incident circular polarization.

Figure II.2 illustrates experimental results obtained at 20 GHz with the ATS-6 satellite (Hogg and Chu, 1975). The polarization angle for these results is between 20°to 22° with respect to the vertical. For these polarization angles, the results lie as expected between theoretical predictions of XPD for vertical polarization (corresponding to 0°) and circular polarization (equivalent to 45°). This again indicates distinct advantages in the use of linear over circular polarization, even when the polarization angle is as large as 20°.

We already mentioned above that if the polarization angle at the beam center is vertical or horizontal, it is different at the beam edges and consequently, XPD is degrated there below that at beam center. In contrast for circular polarization, XPD doesn't change much in the east-west direction at a more or less constant elevation angle. One should not infer from this that circular polarization is better. In fact, as seen from Figure II.2, circular is worse and XPD for all finite polarization angles other than 45° using linear polarization is still better than circular polarization.

Figure II.3 gives theoretical predictions in relation to the planned European OTS satellite operating in the 11 to 12 GHz band (Watson and Soutter, 1975). This graph plots XPD versus attenuation using the Eurobeam A antenna on this particular satellite. The left-hand calculations are for circular polarization and the right-hand ones are for linear polarization, presumably horizontal. The canting angle on the beam axis is assumed to be 4°. Different curves result depending on the elevation angle and on the off-set of the earth station from beam center. The best XPD values occur for the largest elevation angle, with

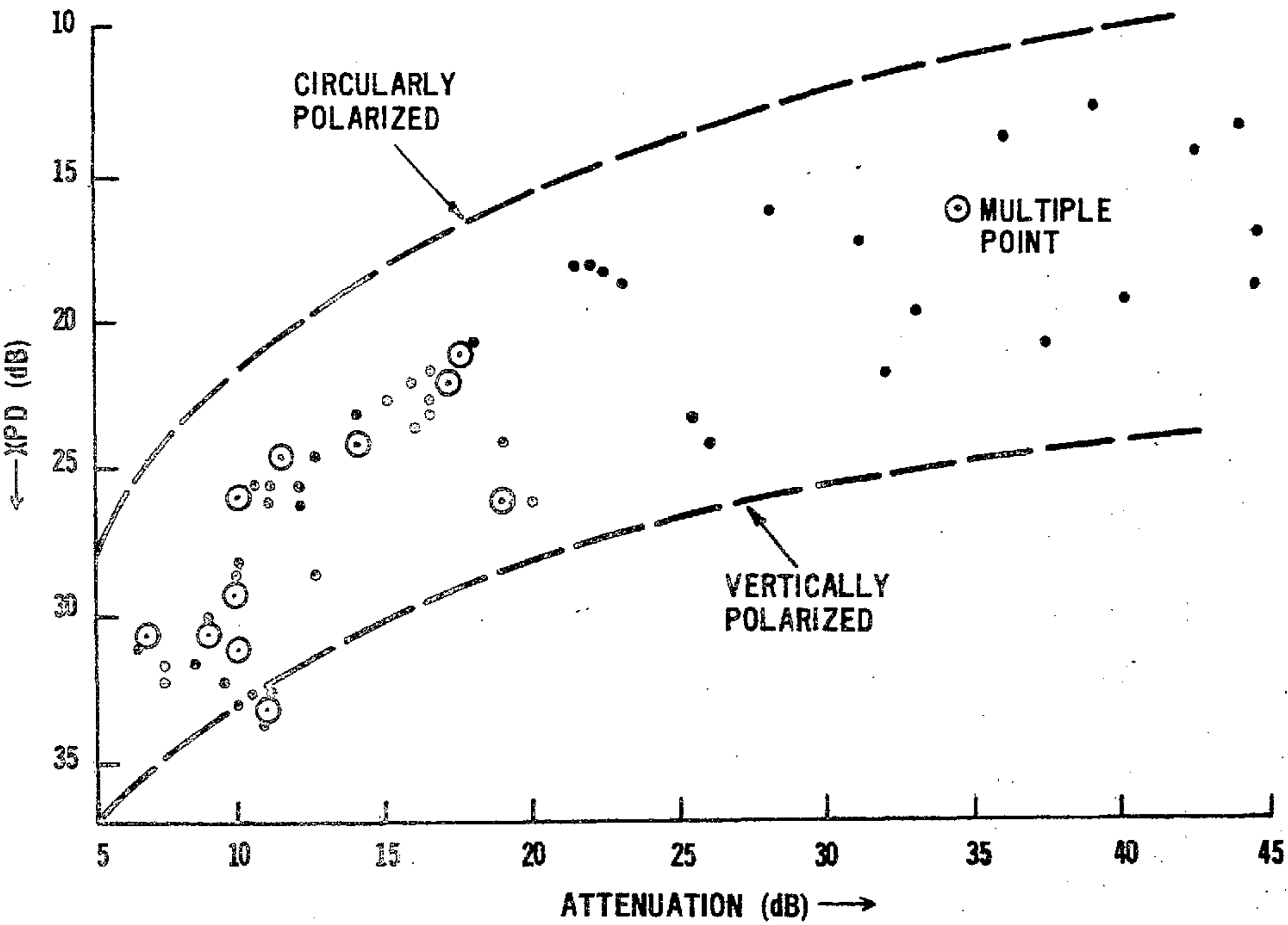

Figure II.2. BELL LAB MEASUREMENTS ON CROSS-POLARIZATION VERSUS ATTENUATION OF A 20 GHz SIGNAL FROM ATS-6. THE INCIDENT LINEAR POLARIZATION IS ORIENTED 20° FROM THE PLANE CONTAINING THE LOCAL VERTICAL. — — — — CALCULATED CURVES

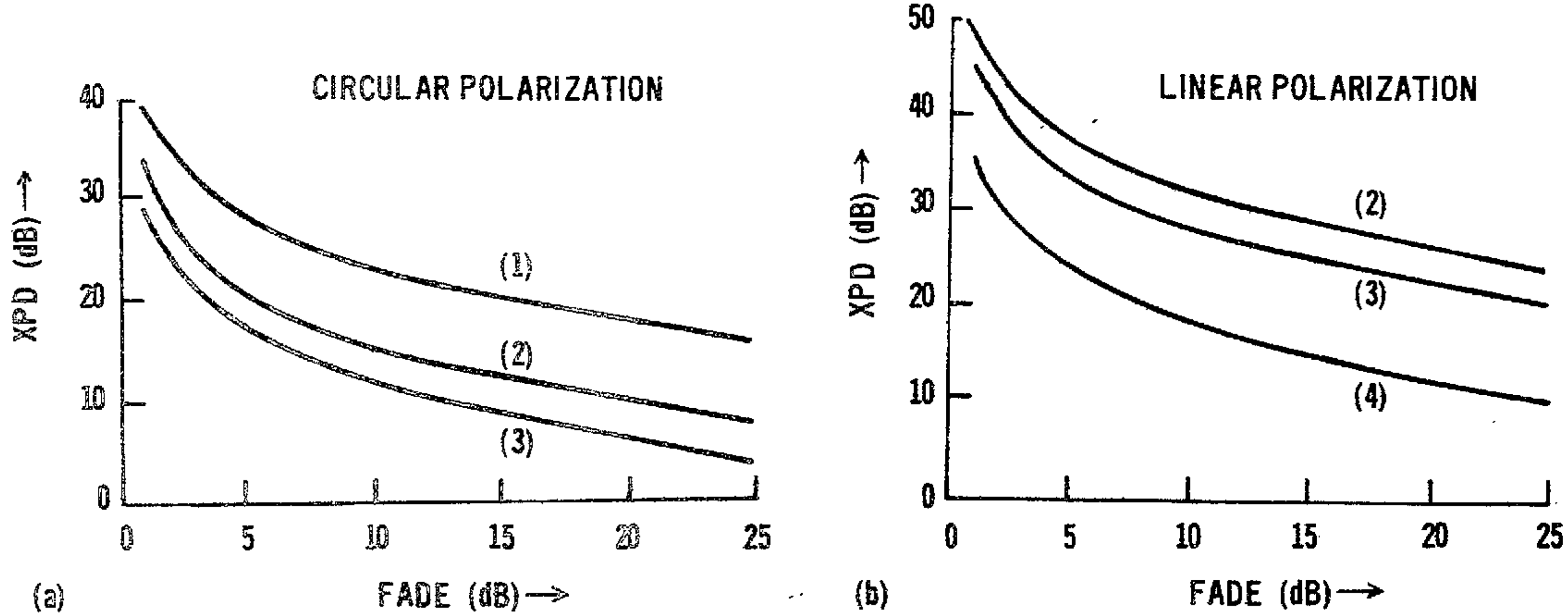

Figure II.3. CALCULATED XPD VERSUS FADE FOR A SATELLITE TO EARTH LINK AT 11 GHz

SATELLITE ELEVATION ANGLE FOR (1) 60°
(2) 40° (BEAM CENTER)
(3) 20° (BEAM EDGE, NORTH)
(4) 40° (BEAM EDGE, EAST-WEST AND POLARIZATION ANGLE = 17°)

receiver on beam axis and with the beam using linear polarization. Curve (1) shows results for an elevation angle of 60° with circular polarization. Curves (2) for a 40° elevation angle compare linear to circular and show that circular is worse than linear polarization. The same would be true for 60° or any other angle. Curves (3) are for a 20° elevation angle which occurs towards the beam edge in the north and the XPD values are now lower for both polarizations. At 40° elevation, the polarization angle at the receiver changes from linear horizontal at beam center to 17° with respect to horizontal as one moves in the east-west direction to the 3 dB beam edge. This decreases further XPD for linear polarization as indicated by curve (4). For circular polarization, curve (2) still applies in this case, but this curve (2) is still worse than curve (4) for linear polarization. This fact was already mentioned at the end of the previous paragraph.

Consider the following example for Canada. Let a satellite be situated at about 100°W longitude, radiating vertically polarized waves in the meridian plane. The polarization angle covering all of Canada with a single beam would vary by about $\pm 30^{\circ}$ with respect to the plane on earth containing the local vertical. With several spot beams, this variation in polarization angle can be greatly reduced and in all cases, it is below the 45° equivalent of circular polarization.

For reference, the following formula can be used with good accuracy to calculate the polarization angle ξ. Let the satellite be situated at longitude L_{os}. Let the on-axis beam from the satellite antenna intersect the earth at latitude L_{aa} and longitude L_{oa}. Define $L_{da} = L_{oa} - L_{os}$. Also let the off-axis ray intersect the earth at latitude L_a and longitude L_o and define $L_d = L_o - L_{os}$. The polarization angle ξ, as measured from that at beam center, is then given by

$$\tan \xi = \frac{\sin L_{aa} \cos L_a \sin L_d - \cos L_{aa} \sin L_{da} \sin L_a}{\sin L_{aa} \sin L_a - \cos L_{aa} \sin L_{da} \cos L_a \sin L_d}$$

In particular when $L_{da} = 0$, we obtain $\tan \xi = \cot L_a \sin L_d$.

We now summarize our first advantage.

(a) Both from terrestrial links and satellite to earth links and both from theoretical predictions and experimental data, linearly polarized systems perform better than circular ones in the presence of rain and provide better XPD. Other advantages of linear polarization are as follows:

(b) A polarizer is required to generate circular polarization and this device introduces ellipticity. The isolation for the antenna cannot be made better than say 33 dB if the polarizer ellipticity is 0.4 dB. This advantage is however not appreciable since 33 dB isolation is sufficient in many cases. The design of high performance polarizers is given by Soma et al (1974). Furthermore, even linearly polarized ground antennas may want to insert an adjustable polarizer (instead of using mechanical means) in order to align the receiver electric field direction to that of the incoming wave.

(c) In the off-axis directions and in the side-lobes, the antenna clear weather isolation is better for linear than for circular polarization, provided alignment can be maintained (CCIR Report 555, 1974). Also, cross-polarization for linear polarization is usually concentrated in four lobes in the 45° off-axis planes, whereas for circular polarization, circular symmetry is maintained and the depolarization covers a larger area (Watson and Soutter, 1975; Ghobrial, 1975).

Let us reconsider the previously mentioned disadvantages of linear polarization. Misalignment remains a problem as far as the earth station is concerned, where it can be caused by winds or mishandling. A misalignment of 2° decreases XPD to 29 dB and 8° decreases it to 17 dB. Occasional checking of the earth antenna alignment may be necessary. As far as the satellite is concerned, it is generally maintained that its attitude control can be kept to within 0.25°, so that a variable polarization should not occur. If problems arise due to improper station keeping, then the plane of polarization will change as well, presenting problems both to linear and circular polarization systems.

In order to overcome the cross-talk problem mentioned in (c) under advantages of circular polarization, one of the proposed solutions (see Chap. III) is to use alternate frequency channels as well as orthogonal polarizations in adjacent beams. By the use of different frequencies, discrimination can be maintained even at the beam edges.

The OTS is being designed with several antenna systems (EBU Report Com.T.(N) 86-E, 1974). Two are the Eurobeam A beam and the steerable spot beam, both of which use two orthogonally polarized linear waves and another is the Eurobeam B beam which uses a single circularly polarized wave. The reason for including the latter is the uncertainty presented by polarization misaligmment with linear polarization. One of the purposes of OTS is to enable a comparison between the two types of polarization.

As discussed above, at frequencies above 10 GHz, propagation effects favor linear polarization. Misalignment problems favor circular polarization. We feel that the advantages of linear polarization outweigh the disadvantages if the number of earth stations that have to be serviced occasionally for alignment are not too many. Watson and Soutter (1975) also show that linearly polarized systems perform significantly better at 12 GHz in the presence of rain and offer greater capacity with multi-level PSK modulation. Our recommendation, however, has to be qualified. In the future, the situation may arise where ground stations may proliferate greatly with a multitude of individual home receivers. Proper alignment cannot be expected to be performed or maintained by all the operators. Then the economics of servicing all these stations will be a determining consideration. Circular polarization may be the easy way out of this problem, even at the expense of fading and depolarization occuring during precipitation. However, a better solution is to use linear polarization and insert easily adjustable polarizers to align the polarizations.

6. REFERENCE ANTENNA PATTERNS AND COMMENTS ON EBU PROPOSAL (K3) 139-rev-E, Jan (1976)

The EBU proposal (K3) 139-rev-E(1976) proposes two sets of reference pattern envelopes both for the co-polar and cross-polar components. One set is applicable to satellite transmitting antennas and the other set to individual receiver antennas.

It is difficult to suggest reference envelopes that apply to all different situations and types of antennas, which encompass central horn fed reflectors, off-set fed reflectors, Cassegrain reflectors, horn reflectors feeding Cassegrain, etc., since each class has a somewhat different envelope decay. The co-polar pattern envelope also depends on whether methods are used for side-lobe control, such as special designs of the aperture edges. The cross-polar pattern envelope also differs on the means taken to suppress or filter the cross polarization component, such as grid reflectors, long focal length paraboloids, or optimum modes for feeding the dish which cancel out the cross-pattern. Blockage obstacles and antenna supportsalter the envelope shapes and cause spurious side-lobes. Furthermore, the envelopes can differ in the two E-and H-planes, so that any reference has to include both. There is also a dependence of the pattern envelopes on frequency within the bandwidth.

In view of all these variables, at best one can only propose reference envelopes for the average type of antenna and require actual ones to surpass these requirements by being below the envelopes. Even so, it is conceivable for the actual cross-polar pattern in the side-lobes to be above the co-polar pattern, for example at null points in the co-polar pattern.

Satellite Co-Polar Pattern Envelope

The suggestion in the EBU proposal for the co-polar pattern envelope of satellite antennas has evolved through various stages. CCIR Report 558(1974) suggests the following for fixed satellite antennas.

$$
\begin{aligned}
F'_T(\phi) &= -3(2\phi/\phi_0)^2 && \text{for} \quad 0 \le \phi/\phi_0 \le 1.29 \\
&= -20 && \text{for} \quad 1.29 \le \phi/\phi_0 \le 3.15 \\
&= -25 \log_{10}(2\phi/\phi_0) && \text{for} \quad 3.15 \le \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. In the above, $F'_T(\phi)$ is the gain in dB relative to its on-axis value, namely $F'_T(0) = 0$. Also, ϕ is the angle away from the beam axis and ϕ_0 is the total beamwidth so that $F'_T(\pm\phi_0/2) = -3$ dB.

In another report (CCIR Report 215-3(1974)), referring to broadcast satellites, a different reference envelope is proposed, namely

$$
\begin{aligned}
F'_T(\phi) &= -12(\phi/\phi_0)^2 && \text{for} \quad 0 \le \phi/\phi_0 \le 0.50 \\
&= -10.5 - 25 \log_{10}(\phi/\phi_0) && \text{for} \quad 0.50 \le \phi/\phi_0 \le 0.82 \\
&= -20 - 135 \log_{10}(\phi/\phi_0) && \text{for} \quad 0.82 \le \phi/\phi_0 \le 1.09 \\
&= -25 && \text{for} \quad 1.09 \le \phi/\phi_0 \le 3.80 \\
&= -10.5 - 25 \log_{10}(\phi/\phi_0) && \text{for} \quad 3.80 \le \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. This envelope, representative of normal designs with lobe control, includes the curve B modification in Figure 3 of CCIR Report 215-3 (1974) and also a Gaussian pattern for near zero angles. This same reference pattern was proposed in the original preview documents of EBU proposals (K3) 135-E (1975) and (K3) 139-E (1975).

In the latest proposal EBU (K3) 139-rev E (1976), the suggestion is to have a single reference envelope which includes satellite antennas for both fixed and broadcast satellites. Towards this end, the following simple envelope is proposed for the co-polar pattern.

$$
\begin{aligned}
F'_T(\phi) &= -12(\phi/\phi_0)^2 && \text{for} \quad 0 \leq \phi/\phi_0 \leq 1.44 \\
&= -25 && \text{for} \quad 1.44 \leq \phi/\phi_0 \leq 3.80 \\
&= -10.5 - 25 \log_{10}(\phi/\phi_0) && \text{for} \quad 3.80 \leq \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. It is seen that the fixed satellite envelope is adopted up to ϕ/ϕ_0 beyond one and the previous broadcast satellite envelope is adopted for ϕ/ϕ_0 greater than 1.44. In many cases, one can do better than required by this envelope, especially if precautions are taken to reduce side lobes. This final suggestion nonetheless looks reasonable for average types of antennas.

Satellite Cross-Polar Pattern Envelope

Different reference envelopes apply depending on whether special care is taken for increasing the antenna isolation. If some special effort is exercised, the following reference envelope is proposed in all three EBU documents, namely preview ones (K3) 135-E(1975) and (K3) 139-E(1975) and the later one (K3) 139 – rev.E (1976). The satellite cross-polar envelope in dB, denoted by $f'_T(\phi)$, is given relative to $F'_T(0) = 0$, by

$$
\begin{aligned}
f'_T(\phi) &= -36 - 25 \log_{10}\left|\frac{\phi}{\phi_0} - 1\right| && \text{for} \quad 0 \leq \phi/\phi_0 \leq 0.42 \\
&= -30 && \text{for} \quad 0.42 \leq \phi/\phi_0 \leq 1.58 \\
&= -36 - 25 \log_{10}\left|\frac{\phi}{\phi_0} - 1\right| && \text{for} \quad 1.58 \leq \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. If no special effort is taken to minimize the cross-component, the documents suggest that the 25 in front of the log be changed to 40, and the corresponding ϕ/ϕ_0 limits would then be 0.29 and 1.71.

Our opinion is that there is a greater difference in the envelopes between the two cases where care is taken or not to suppress cross-polarization. With a solid dish, it is difficult to obtain 30 dB isolation up to the 3 dB points ($\phi/\phi_0 = 0.5$) over the whole frequency bandwidth, although it may be available at specific frequencies. A gridded reflector can make a big difference, even though the number of reflectors have to be doubled in a dual-polarized system since one reflector can only be used per polarization. With grids, one can filter the cross-polarization level, theoretically to 50 dB isolation, but practically to about 36 dB up to the 3 dB points. We thus feel that with gridded systems one can do better than the reference envelope shown. Without special care, the cross-polar envelope is usually worse than the modified expressions suggested above.

A possible modification that we suggest is to alter the middle equation from -30 to -33 dB and change the corresponding ϕ/ϕ_0 limits to 0.24 and 1.76. This applies to a proper design minimizing cross-polarization.

A good antenna should display a deep minimum in cross polarization on axis. This is not always observed (see CCIR Report 555, 1974). Sometimes, this is not inherent in the antenna but due to the imperfect measuring antenna used to derive the cross-polar pattern of the test antenna. Otherwise, scatter from supporting structures may actually fill in the minimum. Both the magnitude in dB of the minimum and its position in space may also vary as the frequency is changed. Nonetheless, we agree with the reference even though it shows only a relatively small increase in cross polarization from on-axis to $\phi/\phi_0 = 0.5$. Such a reference incorporates even lower on-axis minimum values and indicates to the designer the desire to obtain a deep on-axis minimum.

For large off-axis angles beyond the second side-lobe, it is questionable whether the envelopes for direct and cross have any meaning. First the symmetry about the axis is not maintained. Secondly, in relation to isolation considerations, the power in cross-polarization may surpass the co-polar power at minimum points in the co-polar pattern. Nonetheless, the reference pattern envelopes serve to indicate the need to decrease the envelopes of the side-lobes for both direct and cross to be sufficiently below their values at $\phi/\phi_0 = 0.5$. These references should be kept for this reason but perhaps made constant at their values attained at about the position of the third side-lobe.

Individual Receiver Co-Polar Pattern Envelope

For individual reception, CCIR Report 215-3(1974) and EBU preview report (K3)139-E(1975) suggest the following co-polar pattern envelope for $F'_R(\phi)$, the receiver gain in dB, relative to its on-axis value of $F'_R(\phi) = 0$.

$$F'_R(\phi) = -9 - 20 \log_{10}(\phi/\phi_0) \qquad \text{for } 0.5 \leq \phi/\phi_0 \leq 11.22$$
$$= -30 \qquad \text{for } 11.22 \leq \phi/\phi_0$$

with a limit at the isotropic gain. This envelope is drawn as curve B in Figure 6 of CCIR Report 215-3 (1974) for individual reception. For community reception where the antenna is designed with better side-lobe suppression, CCIR Report 215-3 (1974) suggests replacing the above by $F'_R(\phi) = -10.5 - 25 \log_{10}(\phi/\phi_0)$ for $0.5 \leq \phi/\phi_0$.

In a later proposal, EBU (K3) 139-revE (1976), it is suggested that the above relations for individual receivers should be retained only for $\phi/\phi_0 \geq 0.707$. For small off-axis angles, a flat-top is allowed up to $\phi/\phi_0 = 0.25$ in order to account for possible pointing errors of $\pm 0.5^\circ$ and a Gaussian is adopted for ϕ/ϕ_0 between 0.25 and 0.707. This gives the following for the reference envelope:

$$
\begin{aligned}
F_R^{!}(\phi) &= 0 && \text{for} \quad 0 \leq \phi/\phi_0 < 0.25 \\
&= -12\,(\phi/\phi_0)^2 && \text{for} \quad 0.25 < \phi/\phi_0 \leq 0.707 \\
&= -9 - 20 \log_{10} (\phi/\phi_0) && \text{for} \quad 0.707 \leq \phi/\phi_0 \leq 11.22 \\
&= -30 && \text{for} \quad 11.22 \leq \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain.

It seems to us that the proposed envelope which decreases as $-9 - 20 \log_{10} \phi/\phi_0$ is more representative of an antenna having a specially designed uniform illumination over the aperture. Usual antennas have side-lobes somewhat lower than the envelope and the envelope is then more rapidly falling. We would suggest consideration of the following modification replacing the last two dependences.

$$
\begin{aligned}
F_R^{!}(\phi) &= -9.52 - 23.4 \log_{10} \phi/\phi_0 && \text{for} \quad 0.707 \leq \phi/\phi_0 \leq 7.5 \\
&= -30 && \text{for} \quad 7.5 \leq \phi/\phi_0
\end{aligned}
$$

<u>Individual Receiver Cross-Polar Pattern Envelope</u>

In EBU preview proposals EBU (K3)135-E(1975) and (K3) 139-E(1975), it is proposed to have $f_R^{!}(\phi)$, the cross-polar pattern envelope in dB relative to $F_R^{!}(0) = 0$, vary as

$$
\begin{aligned}
f_R^{!}(\phi) &= -30 - 40 \log_{10} |\phi/\phi_0 - 1| && \text{for} \quad 0 \leq \phi/\phi_0 \leq 0.44 \\
&= -20 && \text{for} \quad 0.44 \leq \phi/\phi_0 \leq 1.40 \\
&= -30 - 25 \log_{10} |\phi/\phi_0 - 1| && \text{for} \quad 1.40 \leq \phi/\phi_0 \leq 2.0 \\
&= -30 && \text{for} \quad 2.0 \leq \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. If the later document, EBU proposal (K3) 139-revE (1976), it is correctly argued that the minimum on-axis value of -30 dB may be difficult to obtain in view of possible pointing errors. We also pointed out above that the minimum that occurs on-axis may be partly filled in if no special care is taken. The modified envelope is now suggested by EBU to be

$$
\begin{aligned}
f'_R(\phi) &= -25 && \text{for} \quad 0 \leq \phi/\phi_0 \leq 0.25 \\
&= -30 - 40 \log_{10} |\phi/\phi_0 - 1| && \text{for} \quad 0.25 \leq \phi/\phi_0 \leq 0.44 \\
&= -20 && \text{for} \quad 0.44 \leq \phi/\phi_0 \leq 1.40 \\
&= -30 - 25 \log_{10} |\phi/\phi_0 - 1| && \text{for} \quad 1.40 \leq \phi/\phi_0 \leq 2.0 \\
&= -30 && \text{for} \quad 2.0 \leq \phi/\phi_0
\end{aligned}
$$

with a limit at the isotropic gain. We generally agree with this pattern.

Our previous remarks for satellites on the far off-axis patterns also apply here. In order to improve on the cross-polarization pattern for linear polarization up to $\phi/\phi_0 = 1.4$, one should use a long focal length paraboloid. With good design, both the co-polar and cross-polar envelopes can be surpassed.

A final suggestion that we make is to require that the reference envelopes be met throughout the frequency bandwidth and for both E- and H-planes. This should be explicitely stated.

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CHAPTER III

SYSTEMS AND IMPLEMENTATION PROBLEMS

1.0 REVIEW OF ANTENNA AND SYSTEM REPORTS

Report 215-3 Broadcasting Satellite service: Sound and Television. This is a very good overall review of all aspects of the broadcast satellite service. No significant omissions were noted and very little fault could be found with the report. A few general comments follow.

There is some ambiguity in the nomenclature used to distinguish between a satellite system intended for direct reception by home receivers and a system intended for reception by a central earth terminal. Both types of satellite broadcast their signals uniformly over a large area and both are received by fixed (rather than mobile) earth stations.

The magnitude of receiver thermal noise is omitted from Figure 1. An estimate for 10 log (T/300) would be about 5 dB at 12 GHz and 1 to 2 at 700 MHz. When this noise source is included, the lowest noise would be observed at about 3 GHz in an urban environment and at about 700 MHz in a rural environment.

The advantages of the geostationary orbit are such that the choice always seems to go that way unless the mission requires the extension of service to the polar regions (latitude greater than 75°). In this latter case a polar or near polar orbit is generally selected.

The numbers presented for the antenna pointing errors appear to be somewhat optimistic though the confidence level of the errors are not given. When all sources of pointing error are considered, including thermal distortion and initial misalignment of the attitude sensor and the antenna, worst case analysis on 3-axis systems(considered equivalent to the 3σ level)shows an antenna beam pointing error of the order of 0.2 to 0.25 degrees.

Figure 2a in report 215-3 appears to be a reasonable estimate of the RF power capability of a single generating source however the EIRP estimate given in figure 2b appears to be about 6-10 dB too high at the low end of the frequency scale. In addition the advent of beam pointing errors and surface tolerance errors should occur at lower frequencies. In particular it is not considered technically feasible to maintain accuracies on a 12 meter deployed mesh reflector out to a frequency of 10 GHz. A smaller size reflector should be assumed for the higher frequencies. Figures 4 and 5 of the report are very useful for initial budgetary estimates of overall system parameters but they should not be relied on for detailed budgeting or subsequent design work.

Report 558 "Satellite Antenna Patterns in the Fixed Satellite Service".

The report quotes a maximum satellite antenna gain of about 50 dB on axis limited by the spacecraft antenna pointing errors of $\pm 0.2^{\circ}$. This gain figure is probably attainable when the destination on the ground is a single earth terminal. However, in the broadcast mode, where it is necessary to service large areas on the ground, the satellite antenna gain will be limited to a much lower value by the specified pointing accuracy. A gain of about 40 dB is probably the upper limit unless the pointing errors are reduced.

2.0 LIMITATION TO ANTENNA BEAM SIZES

In designing a spacecraft antenna, allowance must be made for antenna beam pointing errors. That is, the antenna beam must be made larger, by an amount of $\pm \Delta\theta$, than the minimum required to illuminate the desired ground area. This allows the antenna to be misdirected by the amount $\Delta\theta$ and still keep the ground coverage area within the edge contour of the antenna beam.

Because the beam dimensions are larger than the minimum the gain at the edge contour will be reduced due to the presence of the pointing errors.

If it is desired to cover a large ground area with a series of adjacent spot beams then the parameter that must be maximized is the product of coverage area and antenna gain. For a circular beam it can be shown that the gain is inversely proportional to the beam width squared. The coverage area, reduced by the pointing errors, is proportional to $(\theta_3 - 2\Delta\theta)^2$ as shown in the insert in Figure III-1.

Thus

$$\text{product} \propto \frac{1}{\theta_3^2}(\theta_3 - 2\Delta\theta)^2$$

$$= 1 - 4\frac{\Delta\theta}{\theta_3} + 4\left(\frac{\Delta\theta}{\theta_3}\right)^2 ; 0 < \Delta\theta < \frac{\theta_3}{2}$$

In the limits $\Delta\theta$ can not be less than zero and must not be greater than $\theta_3/2$.

A plot of the above equation is shown in Figure III-1. It shows that in the case of zero pointing errors the limit is unity. If the pointing errors increase to one tenth the beam width there is already a loss in coverage area (or gain) of 36% or about 2 dB. This is probably the largest ratio of $\Delta\theta/\theta_3$ that can be tolerated. That is, for a pointing error of ±0.2 the minimum beam width should not be smaller than 2 degrees. Since this is approximately the state of the art in spacecraft attitude control, any smaller beam size must be accompanied by antenna fine steering capabilities to remove the attitude errors of the spacecraft. The actual trade-off point between fixed antennas and steerable antennas must be determined by detailed trade-off studies in each case. Since some of the antenna pointing errors are a result of thermal distortion in the antenna itself, an appropriate means of antenna pointing is RF tracking of a ground beacon using a monopulse feed incorporated into the actual antenna. The dominant source of pointing error should then be the

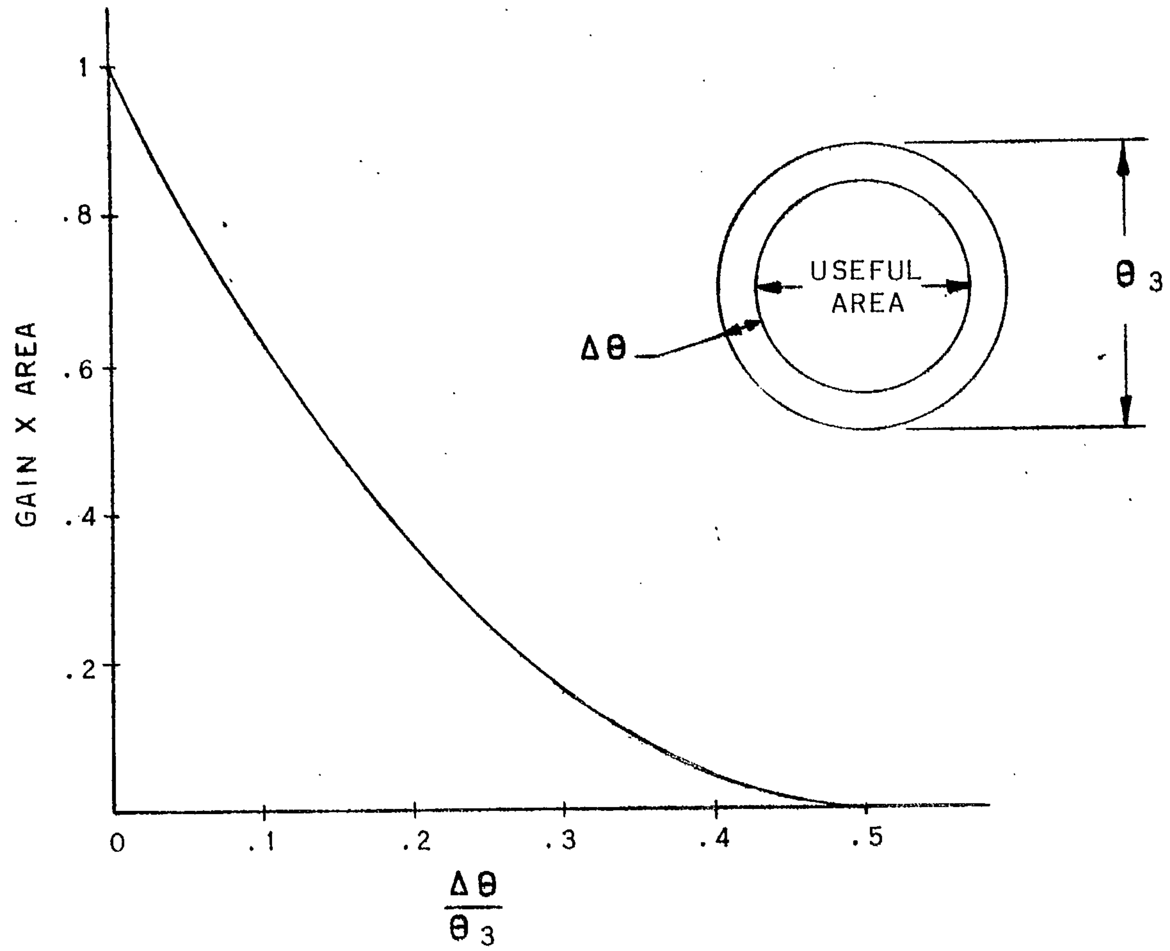

FIGURE III-1. GAIN-COVERAGE PRODUCT VERSUS ANTENNA POINTING ERRORS NORMALIZED TO THE 3 dB BEAM WIDTH signal to noise ratio of the beacon and a considerable reduction in pointing error should result. There should be no intractable technical problems in implementing a tracking antenna with the possible exception of the reliability of the steering mechanism for a seven year mission. There is also a logistics problem associated with placing a ground beacon in an appropriate location. This problem would be solved if the tracking system could be designed with an electronically steerable axis. However, this would introduce some additional pointing errors which may be intolerable.

Another limitation on the antenna beam size is the shroud dimensions. The 8 foot Thor-Delta shroud has an inside clear diameter of approximately 7 feet. An antenna aperture limited to this diameter will have a beam width of just under one degree at 12 GHz. The 10 foot Atlas Centaur shroud would contain an antenna with a beam width of about 3/4 degrees at 12 GHz. To obtain narrower beam widths it would be necessary to build the antenna with fold out sections. The usual type of deployable antenna used in space is a fold out mesh reflector suitable for low frequencies. The mesh stretches straight between the ribs introducing a surface error. To make the errors tolerable at 12 GHz, the number of ribs must be increased, and it is anticipated that the surface errors introduced by the mesh would limit the beam size to approximately 0.5 degrees. Only one such reflector could be carried but it could be used for a number of spot beams by means of more than one feed horn.

3.0 SYSTEMS IMPLICATIONS

Before considering the different antenna types and making recommendations about those types which are most suitable, it is necessary first to consider the overall system in order to establish the antenna requirements.

The discussion that follows is not intended to be fully definitive but to indicate what direction a broadcast satellite system might take. In addition, it will outline the context in which the antenna discussion must be viewed.

We will assume that the broadcast satellite system requires an EIRP at 12 GHz of 58 dBW equivalent to that of CTS with the 200 watt TWTA. CTS uses a steerable 2.5° beam width antenna. The equivalent EIRP can be obtained with higher gain antennas and lower power TWTAs as indicated in the following table.

BW deg	GAIN dB	Power (watts)	EIRP dBW
2.5°	36	200	58
2.1°	37.5	142	58
1.75	39	100	58
1.5	40.4	72	58
1.0	44	32	58
.75	46.5	18	58
.5	50	8	58

To avoid the complication of antenna steering a beam width of about 2 deg is chosen with a corresponding TWTA power of 120 watts. This matches the power of the Hughes TWT being built for the Japanese Broadcast satellite. Using a 3914 Thor-Delta with 2000 lbs launch capability the transponder would consist of two active TWTAs each with a redundant unit.

Two TWTAs would operate in daylight and one during eclipse. It requires four 2° antenna beams to cover Canada and the problem is to cover the country with a spacecraft with only 2 active TWTAs and taking into consideration the sparing problem.

Assume that it is necessary to provide service uniformly to the whole country rather than only to the populous areas. It is necessary therefore to launch two active spacecraft plus a spare, all of which must be identical. The two active satellites can be placed in the same slot (so that a single uplink antenna may be used) with a negligible probability of interference. Each spacecraft must carry antenna feeds for all four beams with facilities for switching the TWTA to the desired beam. There is space within the Thor-Delta shroud to provide two reflectors of the required size so that beams 1 and 3 could be provided by one reflector and beams 2 and 4 by the other. The minimum weight solution is to use one reflector for all four beam using four adjacent feed horns. The single reflector approach would probably be followed in spite of a problem overlapping the beams sufficiently close to provide continuous coverage.

One of the problems associated with fixed beam antennas is that of operating from different orbital locations. When the satellite is moved from one orbital location to another the shape and size of the ground coverage area changes as viewed from the satellite. In addition the ground area moves from west to east as the satellite is moved from east to west and vice-versa. This latter effect is accommodated by biasing the attitude of the satellite to point the antenna axis at the apparent center of the coverage area. To accommodate the change in size and shape it is customary to oversize the antenna beam to include the whole coverage area for all expected orbit locations. This would be done also in the case of multibeam antenna system but an additional problem appears at the boundary between adjacent beams. Figure III-2 shows the outline of Canada as it appears when viewed from two different slot locations. The spacecraft attitude has been biased in both cases to optimize the coverage at the east and west extremities of the

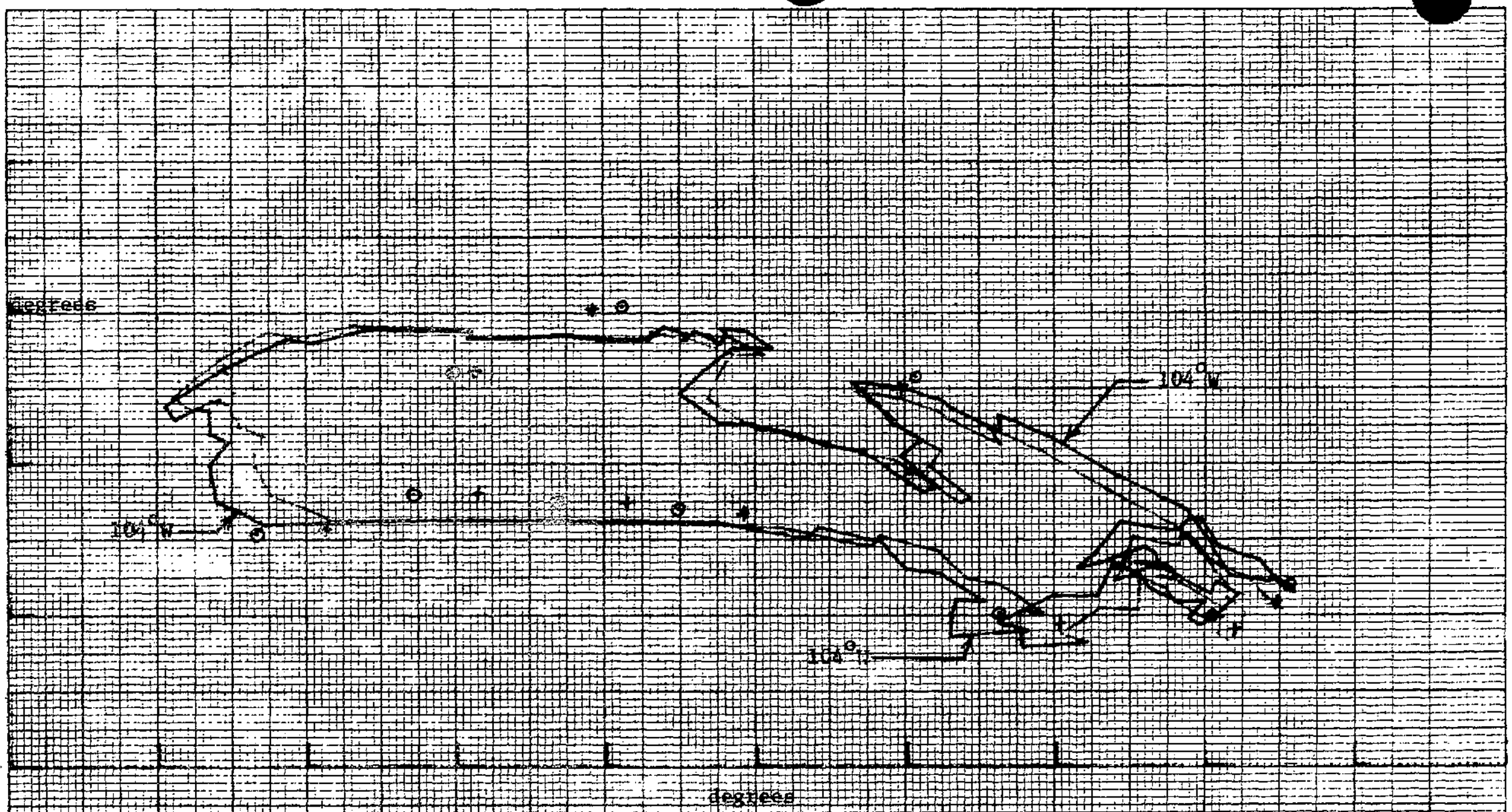

Figure III-2 The apparent size and shape of Canada as viewed from 104 and 114 degrees west including an attitude bias to optimize antenna gain. Antenna contours not shown.

⊙ Location of cities for 104°W
+ Location of cities for

country as specified by the city locations. For this reason the biasing is sensitive to the antenna beam shape and would change slightly for a different antenna beam configuration. The trend is very obvious however. The southern part of the country has a larger apparent shift than the northern part. The change in attitude bias approximately compoensates for the shift at the northern continental coast and more than compensates for the shift in the arctic islands. Individual cities in the south move by nearly 0.5° in spacecraft coordinates. This is sufficient so that a large fraction of the country would move from one spot beam to an adjacent spot beam when switching to an alternate satellite located 10 deg away in the orbital arc. This would mean that the ground station and would have to switch channel numbers if the alternate spacecraft is to be used, implying additional cost in the ground terminal. An obvious solution is to keep the operational spacecraft close together in the orbital arc thus keeping this effect to a minimum.

4.0 POLARIZATION ALIGNMENT OF ADJACENT SATELLITES

Assume that it is required by mutual agreement that all the spacecraft at 12 GHz have linear polarization aligned with the north-south spin axis of the earth. In the case of pencil beams such as we are considering it is permitted to tilt the beam axis towards the north or the south so as to optimally cover the desired ground area. In this case the polarization vector is not precisely aligned with the earth's axis but it tilted by the same amount the antenna is tilted. Different spacecraft around the orbital arc all pointing at the same latitude have polarization vectors which appear as on the surface of a cone with half angle equal to the tile angle. Thus two satellites at different locations in the orbital arc but illuminating the same ground area will have a polarization misalignment due to the tilt angle. This misalignment is calculated and presented in Figure III-3 as a function of angular separation

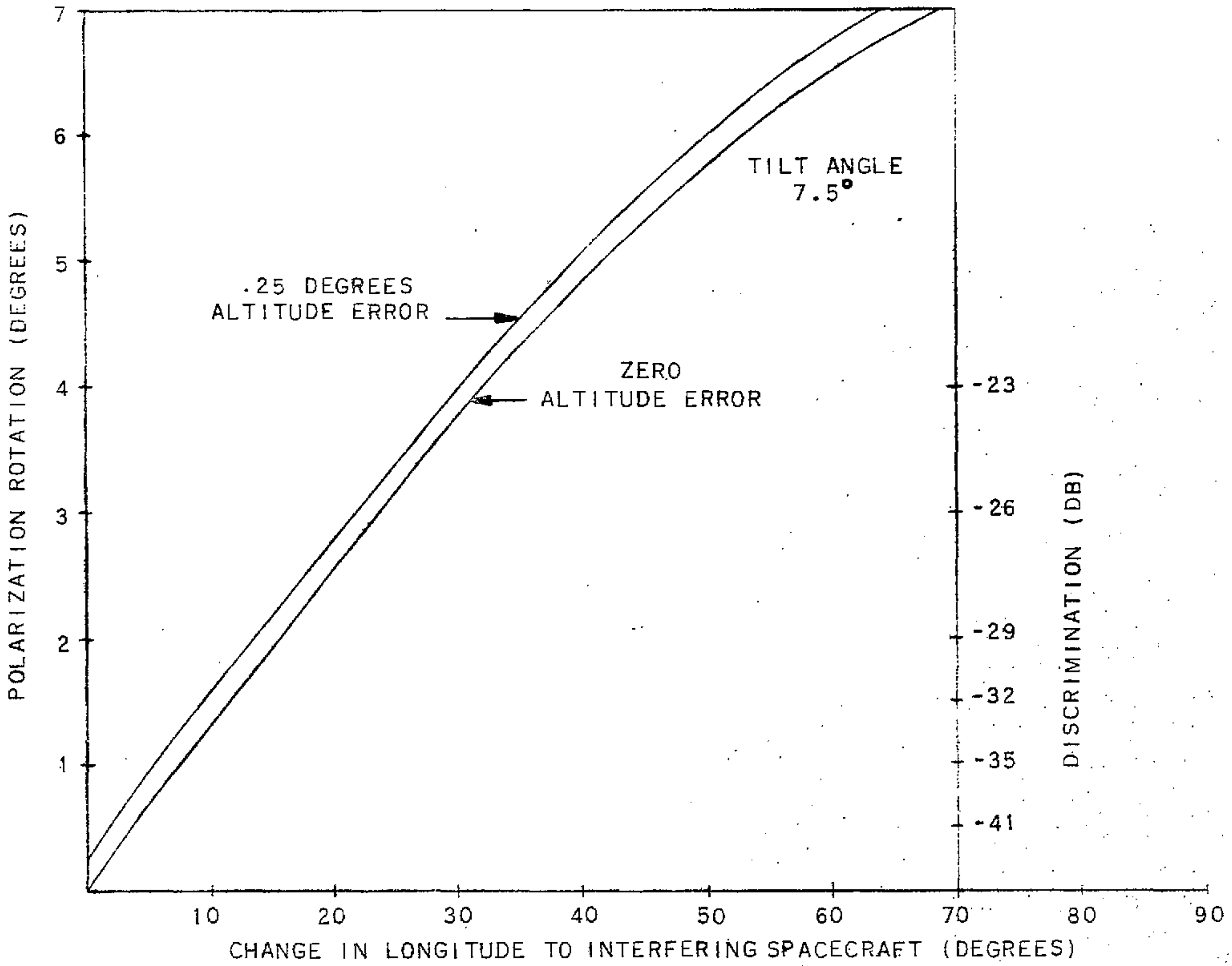

FIGURE III - 3. - DISCRIMINATION LEVEL DUE TO ANTENNA TILT ANGLE.
NOT INCLUDING EARTH ANTENNA DISCRIMINATION

between the cooperating satellite and the interfering satellite. The lower curve is for zero attitude error and the upper curve for an attitude error, for the interfering satellite, of 0.25 degrees.

Also shown in figure is the level of interference (in dB) resulting polarization error. This isolation is in addition to that offered by the off axis response of the ground antenna. Since all the satellites illuminating the same ground area would normally be located within 10 degrees of arc the polarization isolation is 32 dB plus the off axis response of the ground antenna to cross-polarized radiation. This is considered to be a negligible source of interference provided the polarization vector on the spacecraft is nominally aligned with the earth's spin axis.

5.0 OTHER SPACECRAFT ANTENNAS

Cassegrain Reflector;

The standard center fed Cassegrain geometry is very good for large antennas. For smaller antennas with beam widths of one degree or more the subreflector is either too small to form a good reflecting surface or too large such that the blockage effects are excessive. This geometry has never been used on a spacecraft.

Cassegrain Horn Feed:

This geometry eliminates the blockage by offsetting the reflector. At the same time the size of the subreflector is increased till it has satisfactory beam forming properties. However, the geometry has two drawbacks. First, the total area of precision reflecting surface is considerably increased with a corresponding increase in weight. Second, the geometry is such that the center of gravity of the antenna is pushed farther away from the spacecraft upper deck thus increasing the mechanical design and fabrication problems of the antenna and magnifying the dynamic stability problem of the spacecraft.

Conical Horn Reflector:

Because of the large size of the conical horn this type of antenna is considered to be too large and heavy for application on a satellite. For earth coverage beams at microwave frequencies a simple horn without the reflector is frequently used but for beam sizes of the order of one degree the horn would become excessive in size and weight.

Prime Focus Reflector:

This simple geometry generally has minimum weight and size and is simple from both an electrical and mechanical design standpoint. It suffers from a loss of gain due to blockage of the horn and a decrease in cross polarization due to scattering from the horn and horn support structure.

Off-Set Fed Reflector:

This configuration is generally used for spacecraft antennas. It removes all, or nearly all, blockage from the antenna aperture giving maximum antenna gain. In addition it reduces the scattering from the horn and support structure into the cross-polarized component.

Modifications to the basic configuration include circular aperture feed horns, multi-horn feeds, gridded reflectors, and gridded screens.

Circular feed horns are used to reduce the cross-polarization isolation of the antenna. At the appropriate F/d ratio, the cross-polarized component introduced by the horn can be used to cancel the component introduced by the reflector thus effecting an improvement in cross-polarization isolation. Multiple feed horns are used to provide a carefully contoured far field antenna beam to match the desired ground coverage area. This is accomplished by using a large aperture giving a pencil beam for each of the feed horns. By driving an appropriately selected subset of the feed horns with equal amplitude and phase, the desired antenna beam shape can be built up. Other shapes of antenna beams can

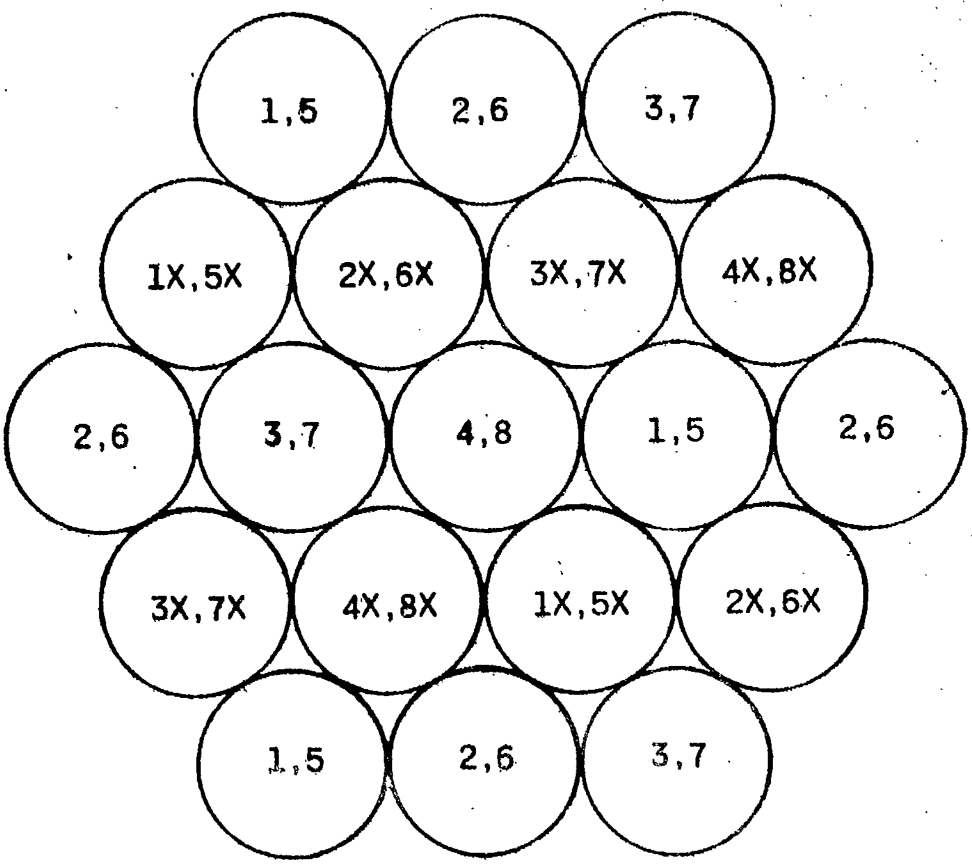

FIGURE III - 4. A POSSIBLE CHANNEL ASSIGNMENT SCHEME FOR A MULTIPLE BEAM ANTENNA SYSTEM be obtained by selecting another subset of the feed horns. This antenna design optimizes the antenna gain over the coverage area for a number of reasons. First, the gain of the antenna is fairly uniform across the beam. The energy maximum normally appearing at the beam center has been spread uniformly over the beam increasing the gain above that which would be obtained from a diffraction limited beam. Second, the antenna beam has a sharp fall off outside the coverage area. Third, by contouring the antenna beam to match the desired coverage area a large amount of energy that would normally be directed toward unpopulated areas can be directed into the main beam to increase the gain in the desired direction. The magnitude of the gain increase will depend upon the complexity of the desired coverage area and the number of spot beam used to make up the antenna beam.

In another application of multiple feed horns, the horns are not paralleled but are used individually to carry different signals to adjacent areas on the ground by connecting the singals to adjacent feed horns on the satellite. Because adjacent spot beams overlap on the ground it is necessary to provide isolation by using different frequencies or crossed-polarization or both. As an example, consider an antenna with sidelobes such that a given frequency can be used on beams 1 and 4 with an acceptably low level of interference. If the band is divided into eight 60 MHz channels, then the channels can be assigned to the spot beams in the grid as indicated in Figure III-4. Two 60 MHz channels can be assigned to each beam and each beam can carry different information than any other beam. In this way the full antenna gain of the spot beam is maintained for each channel but many power amplifiers are required to feed all the spot beams. To cover a country such as Canada from the geostationary orbit, only four beams 2^{o} in diameter are required.

6.0 APPARENT POLARIZATION ROTATION OF SATELLITE SIGNALS

A problem associated with rain depolarization occurs when a single satellite is used to illuminate large areas of the ground. If a single large antenna beam is used to illuminate the whole area the field vectors are everywhere essentially parallel in the beam. However, when viewed from the ground the apparent polarization orientation is not the same everywhere. If the satellite polarization is such that it appears vertical on the subsatellite longitude then it will not appear vertical in other locations. This is because of a change in the local vertical rather than a rotation of the polarization vector. This effect has been calculated using the formula.

$$\tan \xi = \sin \text{Long} \div \tan \text{Lat}$$

where Lat is the latitude of the earth station, Long is the longitude of the earth station relative to the subsatellite longitude and § is the apparent rotation of the polarization vector with reference to the local vertical compared to the orientation on the subsatellite longitude. This formula does not include the contribution due to the fact that the field vectors are not precisely parallel everywhere. This latter contribution is very small and has been neglected for beam widths of a few degrees as considered here.

Results of the calculation are shown in Figure III-6. It is seen that, for a single beam covering Canada and polarized vertical on the subsatellite longitude, the polarization vector near the edges of the country are rotated from the local vertical by as much as 25-30 degrees. Thus, while vertical polarization shows minimum rain depolarization, at the edges of the country the polarization is no longer vertical and rain depolarization is considerably worse.

In the multibeam situation there are two alternatives:

1) Each individual beam can have its polarization vector rotated so that it appears parallel to the local vertical at the beam center.

2) The polarization vectors of every beam are made parallel (or perpendicular) at the satellite, irrespective of the apparent orientation at the earth stations.

In the first case the rain depolarization is minimized everywhere and the resulting cross-coupling between polarizations is acceptable. In the second case the cross-coupling between beams is minimized and then the rain depolarization effect is accepted. The channel assignments shown in Figure III-4 have been made under the assumption of case 2 (polarization vectors are parallel at the spacecraft). A suitable channel assignment scheme for case 1 (polarization vectors locally vertical or horizontal at beam center) is shown in Figure III-5. A detailed analysis would be required in any particular case to minimize cross-coupling between beams including all factors such as the fact that deliberate polarization rotation (as in case 1) gives a continuous coupling factor while rain depolarization only occurs for a fraction of the total time.

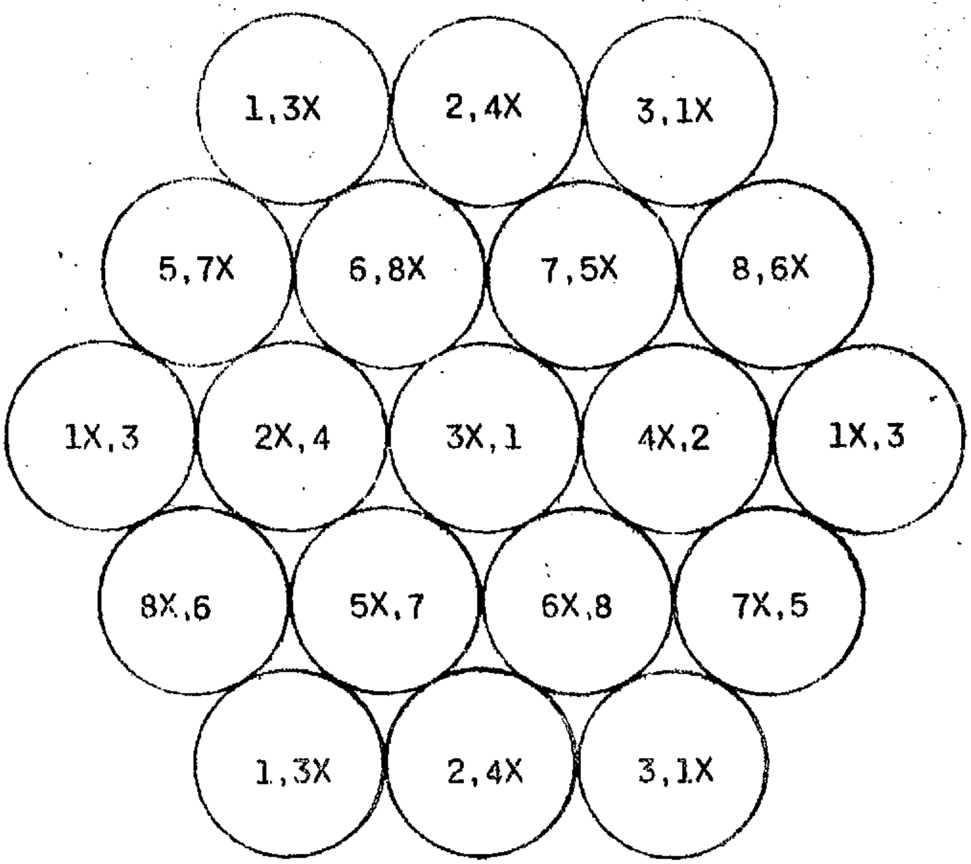

FIGURE III - 5. A CHANNEL ASSIGNMENT SCHEME SUITABLE FOR A SYSTEM MAINTAINING THE POLARIZATION AT EACH BEAM CENTER TO BE LOCALLY VERTICAL AND HORIZONTAL

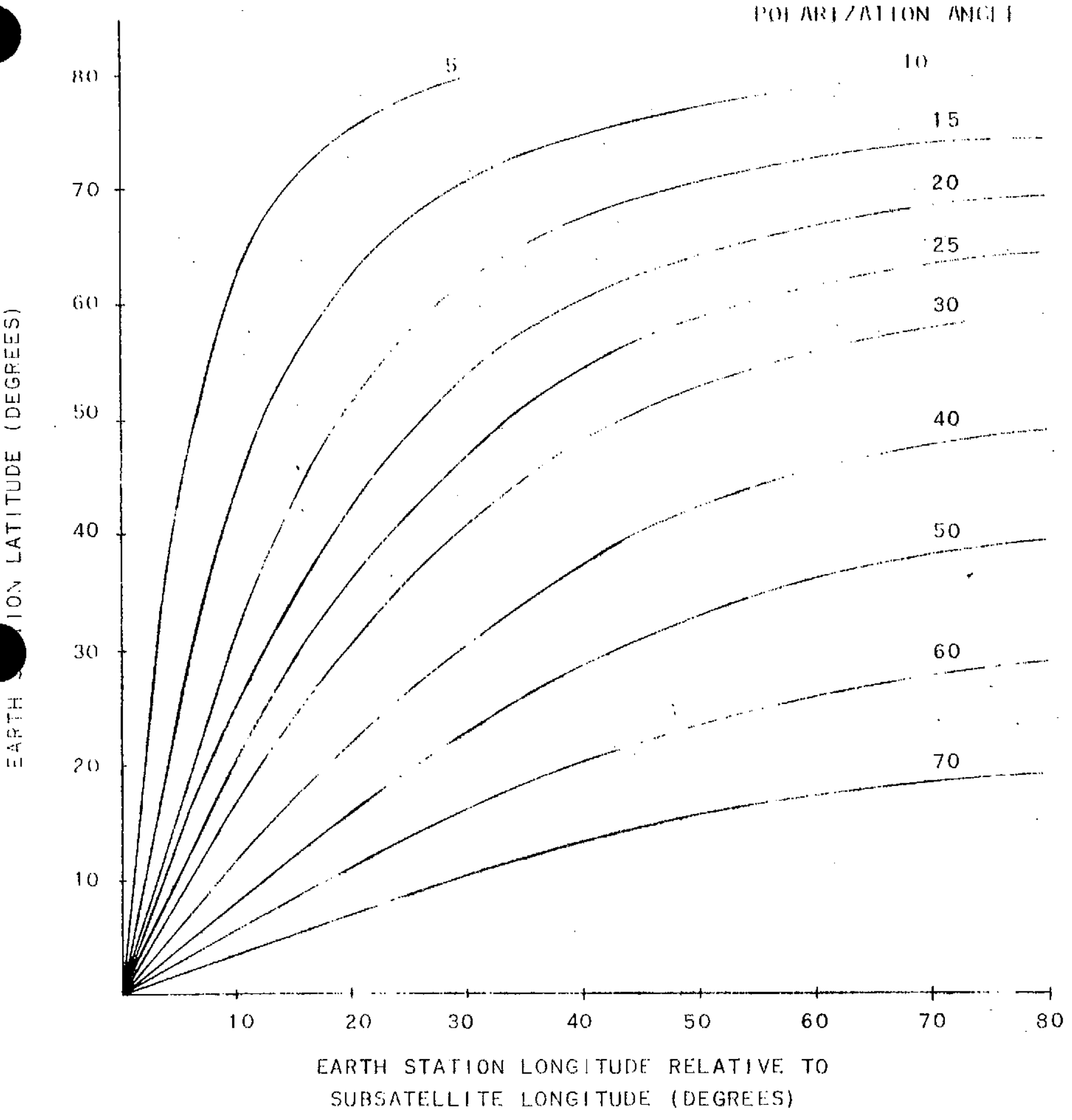

FIGURE III-6. CHANGE IN APPARENT POLARIZATION ANGLE RELATIVE TO AN EARTH STATION LOCATED ON THE SUBSATELLITE LONGITUDE

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