

RECOMMENDATION ITU-R S.736-3*

**ESTIMATION OF POLARIZATION DISCRIMINATION IN CALCULATIONS
OF INTERFERENCE BETWEEN GEOSTATIONARY-SATELLITE
NETWORKS IN THE FIXED-SATELLITE SERVICE**

(Question ITU-R 42/4)

(1992-1994-1995-1997)

The ITU Radiocommunication Assembly,

considering

- a) that more than one geostationary-satellite network in the fixed-satellite service (FSS) operates in the same frequency band;
- b) that interference between networks in the FSS contributes to noise in each network;
- c) that it is necessary to protect a network in the FSS from interference by other such networks;
- d) that the detailed estimation of mutual interference between satellite networks, due to increased orbit occupancy requires more accurate values of polarization discrimination, resulting from the use of different or identical polarizations by wanted and interfering systems;
- e) that the use for actual coordination requirements of the values of polarization isolation factors in Appendix 29 to the Radio Regulations, would not provide a precise estimation of polarization discrimination in the calculation of actual interference margins,

recommends

- 1 that, to estimate the polarization discrimination between two satellite networks, the method described in Annex 1 should be used.

ANNEX 1

Estimation of polarization discrimination

1 Definition of the polarization of a wave

Polarization is defined as a vector of the electric field wave which is located in a plane orthogonal to the direction of the wave propagation.

Generally, this vector describes an ellipse. Two particular cases arise, firstly circular polarization where the two axes of the ellipse are equal, secondly linear polarization where one of the axes is zero.

If the radiated wave is linearly polarized, two orthogonal polarization planes exist, each polarization vector keeping a fixed direction. The polarization plane, for a linearly polarized wave, is the plane containing the direction of the wave propagation and the polarization vector.

If the radiated wave is circularly polarized, right- and left-hand rotations exist.

* This Recommendation should be brought to the attention of the Radiocommunication Working Party 10-11S.

2 Rec. ITU-R S.736-3

2 Definition of polarization angle and of relative alignment angle

The polarization angle ϵ is the angle between the vertical plane including the propagation direction (pointing of the earth station towards the satellite) and the polarization plane of the linearly polarized wave transmitted by the satellite or by the earth station pointed towards the satellite.

The relative alignment angle β is, in linear polarization, the angle between:

- the planes of polarization of the wanted and interfering signals ($\epsilon_1 - \epsilon_2$) (see Appendix 2);
- or the plane of polarization of the received signal and the plane of polarization of the receiving antenna (see Appendix 1).

In the co-polarized case, the angle β is given by:

$$\beta = |\epsilon_1 - \epsilon_2| + \delta$$

with:

δ : tolerances.

For calculation of the angles β and ϵ , see Appendices 1 and 2.

3 Definition of polarization decoupling ratio and polarization discrimination

The ratio of polarization decoupling $D_p(\varphi)$ of an earth station or a satellite antenna is the ratio of the field component in the wanted polarization to the field component in the orthogonal polarization. φ is the angle between the directions of wanted and interfering signals.

The polarization discrimination Y (factor of polarization/isolation) of a receive antenna is the ratio of the received power of the two waves of different direction and polarization.

It should be noted that, if the interfering or the wanted network (or both of them) operates a set of transponders on one polarization, and a set of co-frequency transponders on the orthogonal polarization, then it is not valid to include the full polarization discrimination in calculations of interference between the two networks. The degree of such discrimination will depend on the extent of the overlap of the pass-bands of transponders in one network with those of the other network. In the worst case, i.e., when the transponders of the two networks are exactly aligned in frequency and bandwidth, no inter-network polarization discrimination should be included in interference calculations between the two networks.

4 Calculation of polarization discrimination, Y , in linear polarization

4.1 Calculation of polarization discrimination, Y_d , in the down-link

The purpose of this calculation is to determine, in the case of a wanted receiving earth station, the discrimination with respect to an interfering wave. Earth-station radiation patterns have been established for co- and cross-polarization planes using experimental data.

The polarization angles are calculated for wanted and interfering signals using the coordinates of the two pointing directions of wanted and interfering satellite antennas and the coordinates of the reference earth station.

The derived value of discrimination Y_d takes into account the co-polarized wave coming from the interfering satellite, received by the earth-station receiver (co-polarized $A_1(\varphi)$ and cross-polarized $A_+(\varphi)$ patterns).

The cross-polarized wave coming from the interfering satellite intercepted by the co-polarized pattern of the station is also taken into account. However, the additional isolation afforded by the ratio of crossed polarization transmit-to-crossed polarization receive may be neglected.

$$Y_d = -10 \log (\cos^2 \beta + \sin^2 \beta \cdot 10^{-D_p(\varphi_b)/10} + \sin^2 \beta \cdot 10^{-D_{psat}/10}) \quad \text{dB} \quad (1)$$

where:

φ_b : topocentric separation between satellites

$D_p(\varphi_b)$: polarization decoupling of the wanted earth station:

$$D_p(\varphi_b) = A_1(\varphi_b) - A_+(\varphi_b) \quad \text{dB}$$

D_{psat} : polarization decoupling (dB) of the interfering satellite in the coverage area where the wanted station is located.

4.2 Calculation of the polarization discrimination, Y_u , in the up-link

The purpose of this calculation is to determine in a similar way to the preceding section, for a receive antenna of the wanted satellite, the discrimination Y_u with respect to an interfering wave.

$$Y_u = -10 \log (\cos^2 \beta + \sin^2 \beta \cdot 10^{-D_p(\psi_b)/10} + \sin^2 \beta \cdot 10^{-D_{pst}/10}) \quad \text{dB} \quad (2)$$

where:

ψ_b : angle between the main radiation direction and the direction of interfering earth station

$D_p(\psi_b)$: polarization decoupling of the wanted satellite:

$$D_p(\psi_b) = S_{//}(\psi_b) - S_{+}(\psi_b) \quad \text{dB}$$

$S_{//}$ and S_{+} : co-polarized and cross-polarized patterns of the wanted satellite antenna

D_{pst} : polarization decoupling (dB) of the interfering earth station.

5 Calculation of polarization discrimination, Y , in the case of two polarizations: one circular, the other linear

In the case of an interfering wave in linear polarization (the linear polarization vector can be derived from two circular polarization vectors, right- and left-hand rotation), the discrimination obtained at the receive wanted antenna operating in circular polarization can be expressed in a way similar to the above:

$$Y = -10 \log \frac{1}{2} (1 + 10^{-D_p(\varphi)/10}) \quad \text{dB} \quad (3)$$

where:

$D_p(\varphi)$: polarization decoupling of the receive antenna (dB).

Similarly, in the case of an interfering wave in circular polarization (the circular polarization vector can be composed of two orthogonal linear polarization vectors), the discrimination obtained at the receive wanted antenna operating in linear polarization is described by the same formula.

6 Application to actual cases

From the above relationships, the calculation of the polarization discrimination in various cases permits estimation of the improvement obtained in interference calculations. In particular the use of a polarization orthogonal to the one of the interference, may be considered. These relationships do not take into account the effects of propagation conditions on the signal polarization plane; these are included in Appendix 1.

7 Orientation of polarization planes

It is possible to orient the polarization plane of a receive (linearly polarized) satellite or earth-station antenna for two different optimum conditions, one to minimize clear-sky interference from an orthogonally polarized signal and the other to minimize the effects of depolarization due to rain. The means of calculating the optimum alignments in the two cases are described in Appendix 1.

8 Depolarization due to rain (see Appendix 3)

After atmospheric propagation, a wave in a given polarization (linear or circular) does not keep this polarization, because of the Faraday effect by the ionosphere and the cross-polarization effect by the troposphere. The area concerned is the radioelectric area from about some tens of megahertz to 50 GHz. Cross-polarization is the fact that part of the energy transmitted in a polarization is found in an orthogonal polarization after propagation.

The troposphere (non-ionized atmosphere) goes from the ground to about 15 km altitude and may create a cross-polarization of waves in the following cases:

- clear air effect (reflection phenomenon): the effect is small on oblique links;
- ice crystals effect: this effect becomes evident on satellite links and is due to the refraction of waves in altitude on the ice crystals, partially changed into liquid water (isotherm 0 °C). This cross-polarization can be very constricting because there is no attenuation;
- precipitation effect: the drops of rain can create, because of their non-spherical shape, a wave in the orthogonal polarization.

The effects of rain and ice crystals are dependent on the climate. The effects of drops of rain are studied for the satellite links in Appendix 3.

APPENDIX 1

TO ANNEX 1

Optimization of polarization orientation

1 Simple model of a satellite-to-Earth link

Depolarization effects on satellite-to-Earth (or Earth-to-satellite) links have been extensively analysed and mathematical procedures which take into account all known contributions to depolarization have been formulated. These procedures are, however, extremely complex and cumbersome. A simplified model, suitable for use in a first-order analysis of interference has therefore been devised which uses the concept of equivalent gain of a partial link (i.e. either the Earth-to-space or the space-to-Earth connection).

The equivalent gain (as a power ratio) for one partial link can be represented by the following approximation:

$$\begin{aligned}
 G &= G_1 \cdot \cos^2 \beta + G_2 \cdot \sin^2 \beta \\
 G_1 &= G_{tp} \cdot G_{rp} \cdot A + G_{tc} \cdot G_{rc} \cdot A + G_{tp} \cdot G_{rc} \cdot A \cdot X + G_{tc} \cdot G_{rp} \cdot A \cdot X \\
 G_2 &= \left(\sqrt{G_{tc} \cdot G_{rc} \cdot A} + \sqrt{G_{tp} \cdot G_{rp} \cdot A} \right)^2 + G_{tp} \cdot G_{rp} \cdot A \cdot X + G_{tc} \cdot G_{rc} \cdot A \cdot X \quad (4)
 \end{aligned}$$

where:

- β : relative alignment angle, for linear polarization, between the received signal polarization plane and the plane of polarization of the receive antenna
- G_{tp} : co-polar gain characteristic of the transmit antenna expressed as a power ratio (Recommendations ITU-R S.465, ITU-R S.580 for earth stations and Recommendation ITU-R S.672 for satellites)
- G_{tc} : cross-polar gain characteristic of the transmit antenna expressed as a power ratio (Recommendation ITU-R S.731 for earth stations)
- G_{rp} : co-polar gain characteristic of the receive antenna expressed as a power ratio (Recommendations ITU-R S.465, ITU-R S.580 and ITU-R S.672)
- G_{rc} : cross-polar gain characteristics of the receive antenna expressed as a power ratio (Recommendation ITU-R S.731 for earth stations)
- A : rain fade as a power ratio ≤ 1
- X : rain depolarization as a power ratio $\ll 1$.

The following sections give derivations for the angle, β , for the two scenarios:

- polarization aligned to minimize effects of rain fade, and
- polarization aligned to minimize interference.

Using the equivalent gain concept, the wanted carrier power, C , or the single-entry interfering power, I , on each partial link is simply given by:

$$C \text{ (or } I) = P_T - L_{FS} - L_{CA} + 10 \log G \quad \text{dBW} \quad (5)$$

where:

- P_T : wanted (interfering) transmitting antenna power (dBW)
- L_{FS} : free-space loss on the wanted (interfering) link (dB)
- L_{CA} : clear-air absorption on the wanted (interfering) link (dB)
- G : equivalent gain on the wanted (interfering) link (dBi).

2 Polarization orientation to minimize interference due to rain depolarization

As illustrated in Fig. 1, the apparent polarization plane at the Earth's surface is a function of the geographical coordinates of the boresight, the test point under consideration, and the satellite. The following formula for this polarization angle ε can be used:

$$\tan \varepsilon = \frac{\sin \psi_b \cdot \cos \psi_p \cdot \sin (\lambda_p - \lambda_s) - \cos \psi_b \cdot \sin \psi_p \cdot \sin (\lambda_b - \lambda_s)}{\sin \psi_b \cdot \sin \psi_p + \cos \psi_b \cdot \cos \psi_p \cdot \sin (\lambda_b - \lambda_s) \cdot \sin (\lambda_p - \lambda_s)} \quad (6)$$

where:

- ψ : latitude
- λ : longitude
- b : boresight
- p : test point
- s : satellite.

In the above, it is assumed that the polarization plane is optimized for minimum rain fade at the boresight, i.e. aligning with either the local horizontal or the local vertical. In functional form, equation (6) may be rewritten:

$$\varepsilon = f(\psi_b, \lambda_b, \psi_p, \lambda_p, \lambda_s)$$

To determine the interference component at test point, p , the difference in polarization angles is required.

Thus, if the wanted and interfering signals are "co-polar", the angle, β , in equation (4) may be expressed as:

$$\beta = |\varepsilon_1 - \varepsilon_2| + \delta \quad (7)$$

where:

- $\varepsilon_1 = f(\psi_{b_1}, \lambda_{b_1}, \psi_p, \lambda_p, \lambda_{s_1})$
- $\varepsilon_2 = f(\psi_{b_2}, \lambda_{b_2}, \psi_p, \lambda_p, \lambda_{s_2})$
- b_1 : boresight of wanted satellite s_1
- b_2 : boresight of interfering satellite s_2
- δ : allowance for mis-alignment of earth-station antenna and rotational tolerances of satellite beams.

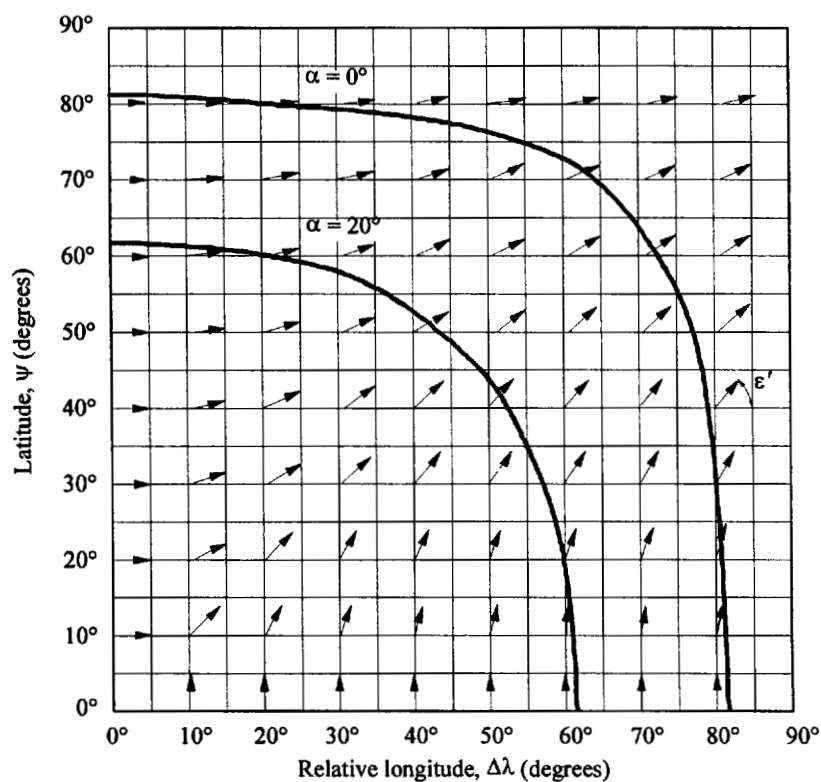
If the wanted and interfering signals are "cross-polar" the angle β_χ in the worst case, is:

$$\beta_\chi = \frac{\pi}{2} - |\varepsilon_1 - \varepsilon_2| - \delta \quad (8)$$

Under some circumstances the distinction between co-polar and cross-polar may be academic. Thus for the purposes of this analysis the following definition will be assumed:

- if both wanted signals are aligned to the respective local horizontals or both are aligned to the respective local verticals, they will be considered co-polar.

FIGURE 1
Variation of received angle of polarization on the Earth



α : angle of elevation

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3 Polarization orientation to minimize clear-sky interference

Minimum interference occurs when the polarization planes at the satellite orbit are orthogonal, i.e. when the polarization planes are either in the equatorial plane or in the plane of the Earth's North-South axis. The following formula for the angle of polarization, ε' , can be used when the polarization vector of the transmitted wave is parallel to the equatorial plane:

$$\tan \varepsilon' = \frac{\sin(\lambda_p - \lambda_s)}{\tan \psi} \sqrt{1 + \left(\frac{\alpha' \sin \xi}{1 - \alpha' \cos \xi} \right)^2} \quad (9)$$

$$\cos \xi = \cos(\lambda_p - \lambda_s) \cdot \cos \psi_p$$

α' : radius of earth divided by radius of orbit ≈ 0.151 .

Thus, in functional form:

$$\epsilon' = g(\psi_p, \lambda_p, \lambda_s)$$

When the wanted and interfering signals are "co-polar", i.e. when both have polarization planes parallel to the equatorial plane or when both are perpendicular to the equatorial plane, the relative angle, β , between wanted and interfering polarization planes is given by:

$$\beta = |\epsilon'_1 - \epsilon'_2| + \delta \quad (10)$$

where:

$$\epsilon'_1 = g(\psi_p, \lambda_p, \lambda_{s_1})$$

$$\epsilon'_2 = g(\psi_p, \lambda_p, \lambda_{s_2})$$

s_1 : wanted satellite

s_2 : interfering satellite.

Similarly when the two signals are cross-polar, the relative angle β_χ is given by:

$$\beta_\chi = \frac{\pi}{2} - |\epsilon'_1 - \epsilon'_2| - \delta \quad (11)$$

The variation of ϵ' is given in Fig. 1.

APPENDIX 2

TO ANNEX 1

Calculation of polarization angle and relative alignment angle

1 Calculation of polarization angle ϵ of a wave in linear polarization

1.1 Definition of orthonormal coordinate systems (see Fig. 2)

The orthonormal coordinate systems used are the following:

- the base Earth-centre coordinate system R_g : $(\vec{X}_g, \vec{Y}_g, \vec{Z}_g)$: $\vec{Z}_g$ is directed to the North and $\vec{X}_g$ in the equatorial plane is determined by the direction $\vec{GS}$, G is the Earth centre and the origin of the system and S the satellite;
- the coordinate system R_s connected with the satellite S: $(\vec{X}_s, \vec{Y}_s, \vec{Z}_s)$: $\vec{Z}_s = -\vec{X}_g$ and $\vec{Y}_s$ is directed to the East in the equatorial plane;
- the coordinate system R_a connected with the antenna A of satellite S: $(\vec{X}_a, \vec{Y}_a, \vec{Z}_a)$: $\vec{Z}_a$ is directed to boresight Pv and $\vec{Y}_a$ is directed to the East in the equatorial plane;

and the system $R_a(\gamma)$ linked with the polarization vector of the antenna A of satellite S: $(\vec{X}_a(\gamma), \vec{Y}_a(\gamma), \vec{Z}_a)$: the transformation from coordinate system R_a into coordinate system $R_a(\gamma)$ is made by a rotation $(-\gamma)$ around $\vec{Z}_a$. That axis $\vec{Y}_a(\gamma)$ is located in the plane of symmetry of the reflector of antenna A and defines the direction of the linear main polarization of antenna A for a propagation direction $\vec{Z}_a$ i.e. towards the boresight Pv of the antenna A of satellite S;

- the coordinate system R_p connected with earth station P and satellite S on which is connected the earth station: $(\vec{X}_p, \vec{Y}_p, \vec{Z}_p)$: $\vec{Z}_p$ is directed to satellite S and $\vec{X}_p$ is directed to the left of an observer who, placed at station P , faces at satellite S : direction $\vec{X}_p$ is $\vec{Vert}(P) \wedge \vec{Z}_p$;

$\vec{Vert}(P) = \vec{GP}$ gives the direction of the local vertical on the Earth at earth station P

$$\vec{Vert}(P) = \left[R_t \cos \psi_p \cos (\lambda_p - \lambda_s); R_t \cos \psi_p \sin (\lambda_p - \lambda_s); R_t \sin \psi_p \right] \text{ in system } R_g$$

hence:

$$\vec{X}_p = (\vec{Vert}(P) \wedge \vec{Z}_p) / \|\vec{Vert}(P) \wedge \vec{Z}_p\| = (\vec{GP} \wedge \vec{PS}) / \|\vec{GP} \wedge \vec{PS}\|$$

$$\vec{Y}_p = \vec{Z}_p \wedge \vec{X}_p$$

$$\vec{Z}_p = \vec{PS} / \|\vec{PS}\| \text{ with } \vec{PS} = h \vec{X}_g - \vec{GP}$$

Parameters and notations are as follows:

index 1: wanted satellite S_1 and earth station P_1

index 2: interfering satellite S_2 and earth station P_2

index d : down-link

index m : up-link

P_v : boresight of the antenna A of satellite S

P : any point on the Earth

R_t : radius of the Earth: 6 378 km

h : radius of the geostationary-satellite orbit (GSO): 42 164 km

k : GSO radius divided by radius of the Earth
 $= 6.62 = h / R_t$

ψ_p : latitude of earth station P

λ_p : longitude of earth station P

ψ_{pv} : latitude of boresight P_v

λ_{pv} : longitude of boresight P_v

λ_s : longitude of satellite S

θ_p : geocentric angle $\hat{SGP}$: angle at the centre of the Earth between the sub-satellite point and earth station P

γ : inclination angle of the ellipse of the satellite antenna coverage pattern: angle between the equatorial plane and the polarization vector (or direction of the ellipse major axis), in the plane perpendicular to the main radio axis, and is chosen to be positive for the trigonometric direction from the equator towards the ellipse major axis

δ : allowance for mis-alignment of earth station antenna and rotational tolerance of satellite beams

$(\psi, \theta, (\varphi - \gamma))$: Euler angles appearing in the transformation matrix M from system R_s to system $R_a(\gamma)$

$\wedge$: cross product

$\|\vec{Z}\|$: magnitude of vector $\vec{Z}$.

1.1.1 Vectors

1.1.1.1 The direction of the local vertical of an earth station at any point P is expressed in the base earth-centre coordinate system R_g by:

$$\vec{Vert}(P) = \left[R_t \cos \psi_p \cos (\lambda_p - \lambda_s); R_t \cos \psi_p \sin (\lambda_p - \lambda_s); R_t \sin \psi_p \right]$$