

## RECOMMENDATION ITU-R F.1108-2

**DETERMINATION OF THE CRITERIA TO PROTECT FIXED SERVICE  
RECEIVERS FROM THE EMISSIONS OF SPACE STATIONS  
OPERATING IN NON-GEOSTATIONARY ORBITS  
IN SHARED FREQUENCY BANDS**

(Questions ITU-R 118/9 and ITU-R 113/9)

(1994-1995-1997)

The ITU Radiocommunication Assembly,

*considering*

- a) that the World Administrative Radio Conference for Dealing with Frequency Allocations in Certain Parts of the Spectrum Malaga-Torremolinos, 1992 (WARC-92) has allocated to satellite services, on a co-primary basis, spectrum that is also allocated to the fixed service (FS);
- b) that the satellite services may wish to operate with space stations in non-geostationary orbits (non-GSOs);
- c) that emissions from space stations operating in non-GSOs and sharing the same spectrum may produce interference in receiving stations of the FS;
- d) that because of the wide geographic visibility of the emissions from space stations non-GSOs, frequency coordination with stations in the FS may not be practical;
- e) that FS systems must meet performance requirements on a worst-month basis;
- f) that the performance degradation for a FS system depends on the sum of the degradations due to emissions from all space stations that are visible to it;
- g) that studies of the power flux-density (pfd) at the surface of the Earth due to emissions from space stations non-GSO can be carried out by applying statistical methods to results from computer simulations,

*recommends*

- 1** that frequency sharing criteria for FS systems sharing spectrum with space stations in non-GSOs take into account the aggregate pfd resulting from the emissions of the total complement of space stations visible to FS stations at any point on the Earth;
- 1.1** that the tolerable interference be specified in terms of a pfd ( $W/m^2$ ) in an agreed bandwidth;
- 2** that pfd limits be determined on the basis of a statistical application of the principles of Recommendation ITU R F.758 in the case of digital radio-relay systems and Recommendation ITU-R SF.357 in the case of analogue radio-relay systems (method under study);
- 3** that due regard be taken of the fact that ITU-T Recommendation G.826 (from which Recommendations ITU-R F.1092 and ITU-R F.1189 are derived) imposes stricter error performance objectives for digital radio-relay systems;
- 4** that the pfd limits take into account the orbital parameters of space stations using the band;
- 4.1** that the methods in Annex 1 can be used for determining the visibility statistics of space stations operating in circular orbits;
- 4.2** that the degradation of the performance of analogue systems due to emissions from single or multiple space stations be determined using the methods described in Annex 2;
- 4.3** that the degradation of the performance of digital systems due to emissions from single or multiple space stations be determined using the methods described in Annex 3 (see Note 1);

- 4.4** that the effects on digital systems using diversity due to emissions from single or multiple space stations may be determined using the methods described in Annex 4 (see Note 2);
- 4.5** that the considerations in Annex 5 be used in assessing the non-uniformity of the interference in any month;
- 4.6** that the methodology given in Annex 6 can be used to develop the cumulative distribution of the ratio of received power to the sum of noise and interference powers and the associated fade margin loss due to emissions from single or multiple space stations (see Note 3).

NOTE 1 – The criterion of fractional degradation in performance (FDP) developed in this Recommendation is applicable to FS systems operating at frequencies where multipath fading is the principal cause of signal fading. For paths where rain attenuation is the principal cause of fading, further study is required. The assessment of the effect of short-term interference as described in § 4 of Annex 3 requires further study.

NOTE 2 – Diversity is not generally used at frequencies below 3 GHz. It is most often employed at frequencies where multipath fading is the principal cause of fading.

NOTE 3 – The methodology developed in Annex 6 may be used in assessing short-term interference or for evaluating interference potential in bilateral negotiations.

## ANNEX 1

### **Determination of the visibility statistics of space stations operating in circular non-geosynchronous orbits as seen by a terrestrial station**

#### **1 Introduction**

In order to develop sharing criteria between low-Earth orbiting (LEO) satellites and FS systems, it is necessary to determine how often a satellite will be visible in any direction for a particular terrestrial station or position and how strong will be the interference received from it. The purpose of this Annex is to develop the equations necessary to simulate the operation of a LEO satellite and thereby the necessary statistics. The development is sufficiently general that the results can be applied either for a random model or for a time evolutionary model.

Section 2 of this Annex provides a development of the equations of motion of a satellite, which is in a circular orbit, in an inertial coordinate system. In § 3, these equations are transformed to a coordinate system fixed on the Earth. The azimuth and distance of the sub-satellite point from a position on the surface of the Earth are determined in § 4. In § 5, the expressions for the elevation and off-boresight angle of the satellite are developed, and a simple criterion for testing for the visibility of a satellite that is above a particular position on the Earth is given.

A right-handed spherical coordinate system is used throughout this development for Earth-centred coordinates with  $(r, \theta, \lambda)$  where  $r$  is the distance from the origin,  $\theta$  is the angular distance from the North Pole, and  $\lambda$  is the angle around the Pole.

## 2 The satellite in the inertial frame

In order to determine the position of the satellite in the inertial frame, its position in the orbital plane must first be determined. For a body in a circular orbit around the Earth this description involves four Keplerian orbital parameters as follows:

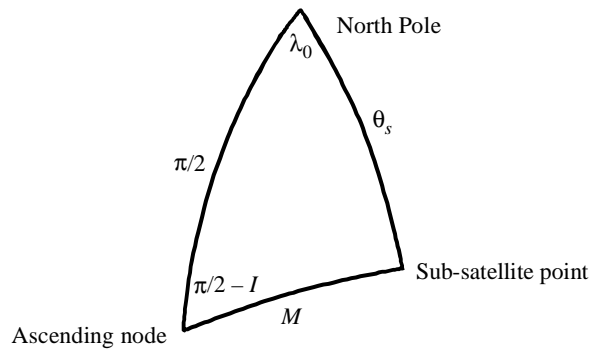
- $R_s$ : orbital radius, the distance from the centre of the Earth to the satellite
- $I$ : inclination angle (rad), the angle between the orbital plane and the Earth's equatorial plane. It is measured from 0 to  $\pi$  and is less than  $\pi/2$  if the satellite is headed eastward as it crosses the equatorial plane from South to North and greater than  $\pi/2$  if the satellite is headed westward as it crosses the equatorial plane from South to North
- $\Omega_s$ : angular distance (rad) along the equatorial plane from the zero reference to the position of the ascending node, the intersection where the plane of the satellite crosses the equatorial plane from South to North
- $M$ : mean anomaly (rad), the angular arc in the satellite orbital plane measured from the ascending node to the position of the satellite.

To determine the coordinates of the satellite in the inertial spherical coordinate system, one must first determine the position of the satellite referenced to  $\Omega_0$ , the angular position or longitude of the ascending node, measured East of the first point of Aries. The position of the sub-satellite point is denoted by  $\theta_s$  and  $\lambda_0$ .

These coordinates may be determined by spherical geometry with reference to Fig. 1. Applying the law of cosines to the arc  $\theta_s$  gives  $\cos \theta_s = \sin M \sin I$ . Since  $\theta$  is defined on the interval  $(0, \pi)$ :

$$\theta_s = \arccos(\sin M \sin I) \tag{1}$$

FIGURE 1  
Spherical triangle of satellite in the inertial frame



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Similarly, applying the law of cosines to the arc  $M$  gives  $\cos M = \sin \theta_s \cos \lambda_0$ . Equation (2) gives the values of  $\lambda_0$  for the entire range  $(\theta, 2\pi)$ .

$$\lambda_0 = \begin{cases} \arccos(\cos M / \sin \theta_s) & \text{for } \cos I \sin M \geq 0 \\ 2\pi - \arccos(\cos M / \sin \theta_s) & \text{for } \cos I \sin M < 0 \end{cases} \tag{2}$$

## 3 Transformation to Earth coordinates

These coordinates may be transformed simply to equivalent Earth coordinates. Since the Earth rotates eastward through  $2\pi$  rad in 23 h, 56 min, and 4.09 s, the East longitude of the sub-satellite point,  $\lambda_s$  is given by:

$$\lambda_s = \lambda_0 + \Omega_s - \Delta E t \tag{3}$$

where  $\Delta E = 7.292115856 \times 10^{-5}$  rad/s.

To complete a time description of the position of the sub-satellite point one needs to account for the position of the orbit as well as the position of the satellite on the orbit. The ascending node precesses westward at a rate of  $9.964 (R_E/R_S)^{3.5} \cos I$  degrees per day, where  $R_E (= 6378.14 \text{ km})$  is the equatorial radius of the Earth. Hence, the location of the ascending node evolves in time as:

$$\Omega_s = \Omega_0 - \Delta L t$$

where:

$$\Delta L = -2.0183 \times 10^{-6} (R_E/R_S)^{3.5} \cos I$$

Thus equation (3) becomes:

$$\lambda_s = \lambda_0 + \Omega_0 - (\Delta L + \Delta E) t \quad (4)$$

The orbital period (s) of a satellite in a circular orbit of radius  $R_s$  is given by  $T_s = 9.952004586 \times 10^{-3} R_s^{1.5}$ , where  $R_s$  is the radius of the satellite orbit (km). Hence:

$$M = M_0 + \Delta M t \quad (5)$$

where  $\Delta M = 2\pi/T_s$ .

#### 4 Distance and azimuth to a terrestrial station

The position of the terrestrial station must first be converted from standard coordinates of latitude and longitude into spherical coordinates. If  $L_T$  is the latitude and  $Lo_T$  is the longitude of the terrestrial station, both positive angles (degrees), the spherical coordinates of the station (rad),  $\theta_T$  and  $\lambda_T$ , may be obtained with the following two relations.

$$\theta_T = \begin{cases} (\pi/180) (90 - L_T) & \text{for } L_T \text{ North latitude} \\ (\pi/180) (90 + L_T) & \text{for } L_T \text{ South latitude} \end{cases} \quad (6)$$

$$\lambda_T = \begin{cases} (\pi/180) (Lo_T) & \text{for } Lo_T \text{ East longitude} \\ (\pi/180) (360 - Lo_T) & \text{for } Lo_T \text{ West longitude} \end{cases} \quad (7)$$

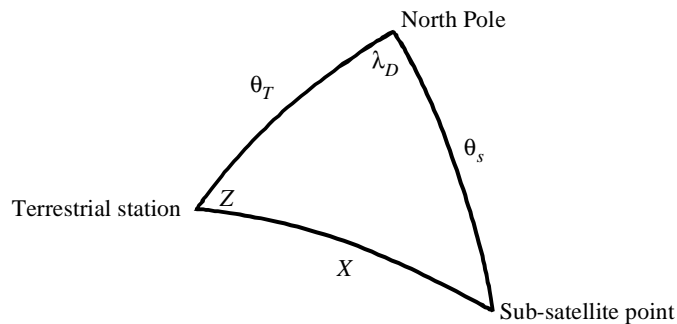
The difference in longitude from the terrestrial station to the sub-satellite point,  $\lambda_D$ , is just

$$\lambda_D = \lambda_S - \lambda_T \quad (8)$$

The distance  $X$  between the terrestrial station and the sub-satellite point in radians of arc may be determined by the law of cosines, referring to Fig. 2, as:

$$X = \text{arc cos} (\cos \theta_T \cos \theta_s + \sin \theta_T \sin \theta_s \cos \lambda_D) \quad (9)$$

FIGURE 2  
Spherical triangle for the distance between the sub-satellite point and the terrestrial station



The sub-satellite point is East of the terrestrial station if  $\sin \lambda_D$  is greater than zero and is West of the terrestrial station if  $\sin \lambda_D$  is less than zero. Hence the azimuth  $Z$  from the station to the sub-satellite point is obtained by applying the law of cosines to the arc  $\theta_s$  in Fig. 2:

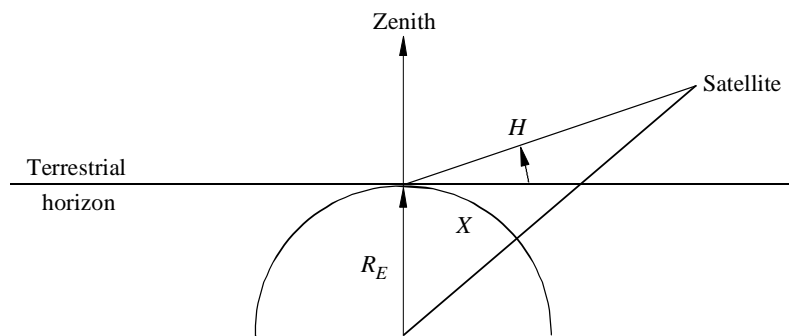
$$Z = \begin{cases} \text{arc cos} \left[ \frac{\cos \theta_s - \cos \theta_T \cos X}{\sin \theta_T \sin X} \right] & \text{for } \sin \lambda_D \geq 0 \\ 2\pi - \text{arc cos} \left[ \frac{\cos \theta_s - \cos \theta_T \cos X}{\sin \theta_T \sin X} \right] & \text{for } \sin \lambda_D < 0 \end{cases} \quad (10)$$

### 5 Satellite elevation and angular distance from main beam

The elevation angle  $H$  of the satellite above the horizon of the terrestrial station, assuming a horizon angle of  $0^\circ$ , may be obtained by referring to Fig. 3.

$$H = \text{arc tan} \left[ \frac{\cos X - R_E / R_s}{\sin X} \right] \quad (11)$$

FIGURE 3  
Plane containing Earth centre, terrestrial station, and satellite



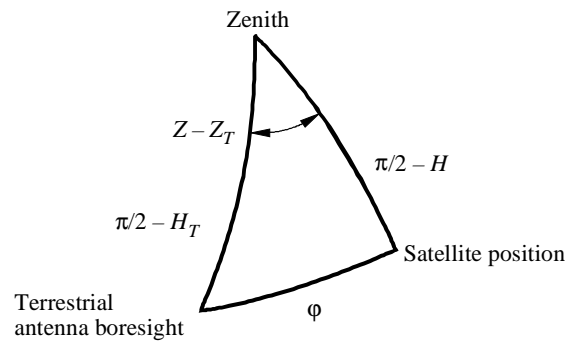
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Assume that the receiving antenna of the terrestrial antenna is aimed along the azimuth  $Z_T$  with an elevation angle of  $H_T$  rad above the local horizontal. The angular distance  $\phi$  from the main beam of this terrestrial station antenna to the satellite may be obtained by considering the spherical coordinate system centred on the terrestrial station with its axis in the zenith direction, as shown in Fig. 4. Applying the law of cosines to the side  $\phi$  gives:

$$\phi = \text{arc cos} (\sin H_T \sin H + \cos H_T \cos H \cos (Z - Z_T)) \quad (12)$$

FIGURE 4

**Spherical triangle for determination of the angle  
between the terrestrial beam and the satellite**



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Equations (1) to (12) provide a means for simulating the interference environment of a terrestrial station in the presence of a LEO satellite. Some simplifications are possible. For instance, only interference from satellites above the horizon is usually considered. From equation (11), the satellite is above the horizon for:

$$\cos X > R_E / R_s = \gamma \quad (13)$$

By using (13) in (9), it is possible to develop an expression for the range of longitudes that are within this circle of visibility for a particular sub-satellite point latitude or mean anomaly. Hence equations (10), (11) and (12) need only be evaluated under conditions that can be predetermined.

## ANNEX 2

**Simulation of interference into analogue  
radio-relay routes from LEO satellites**

## 1 Introduction

This Annex describes a computer program which implements the mathematical relationships developed in Annex 1. The resulting program can be used as an analysis tool for examining interference into simulated analogue radio-relay networks that share spectrum with LEO satellites representative of those that may operate in bands below 3 GHz. A number of example sharing scenario situations and their results are described.

## 2 Description of the model

The program mathematically simulates the path of a constellation of LEO taking into account the Earth's rotation and orbit precession effects. Interference is calculated for each 1/2 degree movement of the satellite in the constellation into each radio-relay receiver in a concentration randomly distributed radio-relay routes. The program accumulates interference density data for each radio-relay route for the period of the simulation. The program converts this data into a probability distribution for each route so that the performance of each route can be separately analysed. The results of the example scenarios described here are compared with the reference performance requirements described in Fig. 1 of Recommendation ITU-R SF.357. Recommendation ITU-R SF.357 proposes reference interference sharing criteria for analogue systems only.

## 2.1 Input

The simulation allows operator selection of the following parameters:

- frequency,
- latitude and longitude of the centre of the radio-relay route trendlines,
- radio-relay receive antenna gain,
- number of radio-routes to be analysed,
- satellite orbit altitude (same for each satellite),
- number of satellite orbital planes,
- longitude of the ascending node for each plane,
- orbit inclination (same for each plane),
- number of satellites per plane (same for each plane),
- high angle satellite pfd level,
- low angle satellite pfd level,
- length (in days) of the simulation.

The assumptions that are built into the model include:

- *For the radio-relay system model:*  
50 hop, 2 500 km routes, hop directions are selected by Monte Carlo methods.  
Receiver noise temperature of 1 750 K.  
Baseband 4 kHz bandwidth thermal noise per hop is 25 pW.  
Receive antenna characteristics per Recommendation ITU-R F.699.  
Losses (feeder, conversion) of 3 dB.
- *For the satellite system model:*  
Circular orbit only.  
pfd constrained to the following mask:

$$\begin{array}{ll}
 pfd_{low} & \text{for } 0 \leq \theta \leq 5^\circ \\
 pfd = pfd_{low} + 0.05 (pfd_{hi} - pfd_{low}) (\theta - 5) & \text{for } 5^\circ < \theta \leq 25^\circ \\
 pfd_{hi} & \text{for } 25^\circ < \theta \leq 90^\circ
 \end{array}$$

## 2.2 Output

The output of the program is a single data file named Leo.dat. Information is provided for each simulated radio-relay route. The output information is arranged to indicate the time duration of interference levels received by each route. Fifty sequential, 1 dB wide, interference ranges from 1 to 100 000 pW are supported. The program automatically increments the appropriate interference range for each route that is affected by a satellite for each 1/2° increment of orbit.

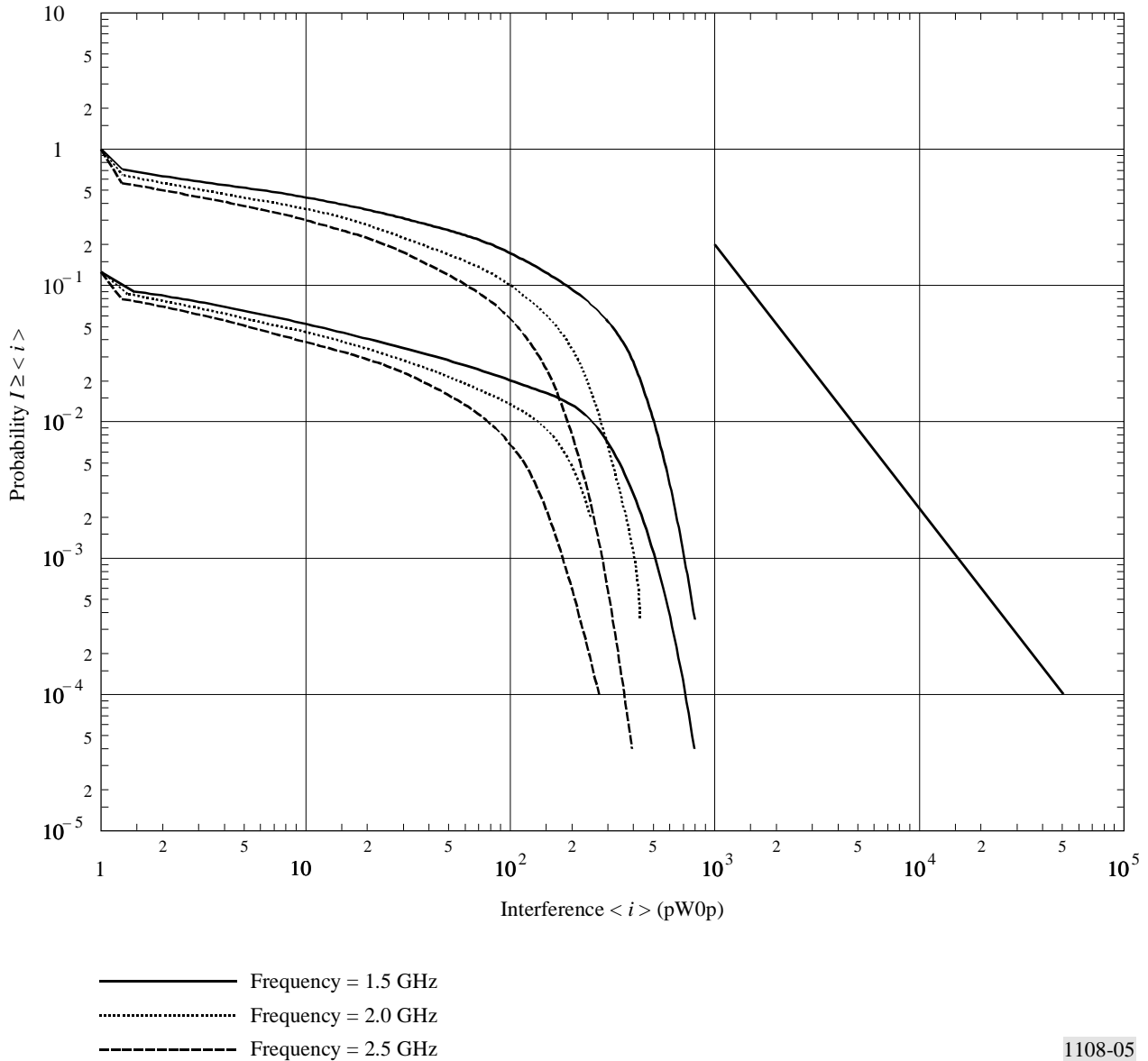
## 3 Simulation results

Recommendation ITU-R SF.357 defines both a short- and long-term limit of interference that is allowed into an angle modulated radio-relay system in bands shared with the fixed-satellite service. A linear form of interpolation is also indicated in the Recommendation for determining allowable interference levels for time durations between the long- and short-term period. Because the program calculates the interference data as a probability distribution, it is possible to evaluate each investigated sharing scenario by comparing program results with the limits of Recommendation ITU-R SF.357.

The interference limits defined in Recommendation ITU-R SF.357 are plotted on the right hand portion of the graphs of information appearing in Figs. 5 to 9 of this Annex. The curves to the left, in each figure, represent the interference into the most affected radio-relay route for the LEO/FS sharing scenario being considered.

For example, Fig. 5 presents an analysis of the effects of interference into the FS operating at 1.5 GHz, 2.0 GHz and 2.5 GHz where all other FS and LEO parameters are fixed. Two groups of scenarios were considered. The lower set of curves in the figure represents the interference effects into the FS from a single orbiting LEO. The second group of curves represent the interference effects when sufficient number of LEO are present in one orbit plane such that one satellite is constantly in view. A LEO system with only one satellite in constant view is a convenient reference for this comparison.

FIGURE 5  
**FS interference versus frequency**  
 (800 km, 50 hop routes, 33 dB antenna gain, 40° latitude, pfd = -154/-144 dB(W/(m<sup>2</sup> · 4 kHz)))



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Figure 6 demonstrates the effects of changes in orbit altitude and low angle of arrival pfd on the interference received by the FS from one LEO in continuous view. For this LEO scenario the pair of dashed curves shows (pfd = -144 dB(W/m<sup>2</sup>) (4 kHz bandwidth) for all angles of arrival), as might be expected, that orbit altitude, i.e. 800 km and 10330 km, is not a significant parameter.



The solid curve in Fig. 6 demonstrates that spot beams usage by LEO operating at either altitude will greatly reduce the level of interference into the FS.

FIGURE 6  
Interference versus altitude and pfd  
(50 hop routes, 40° latitude, 2 GHz)

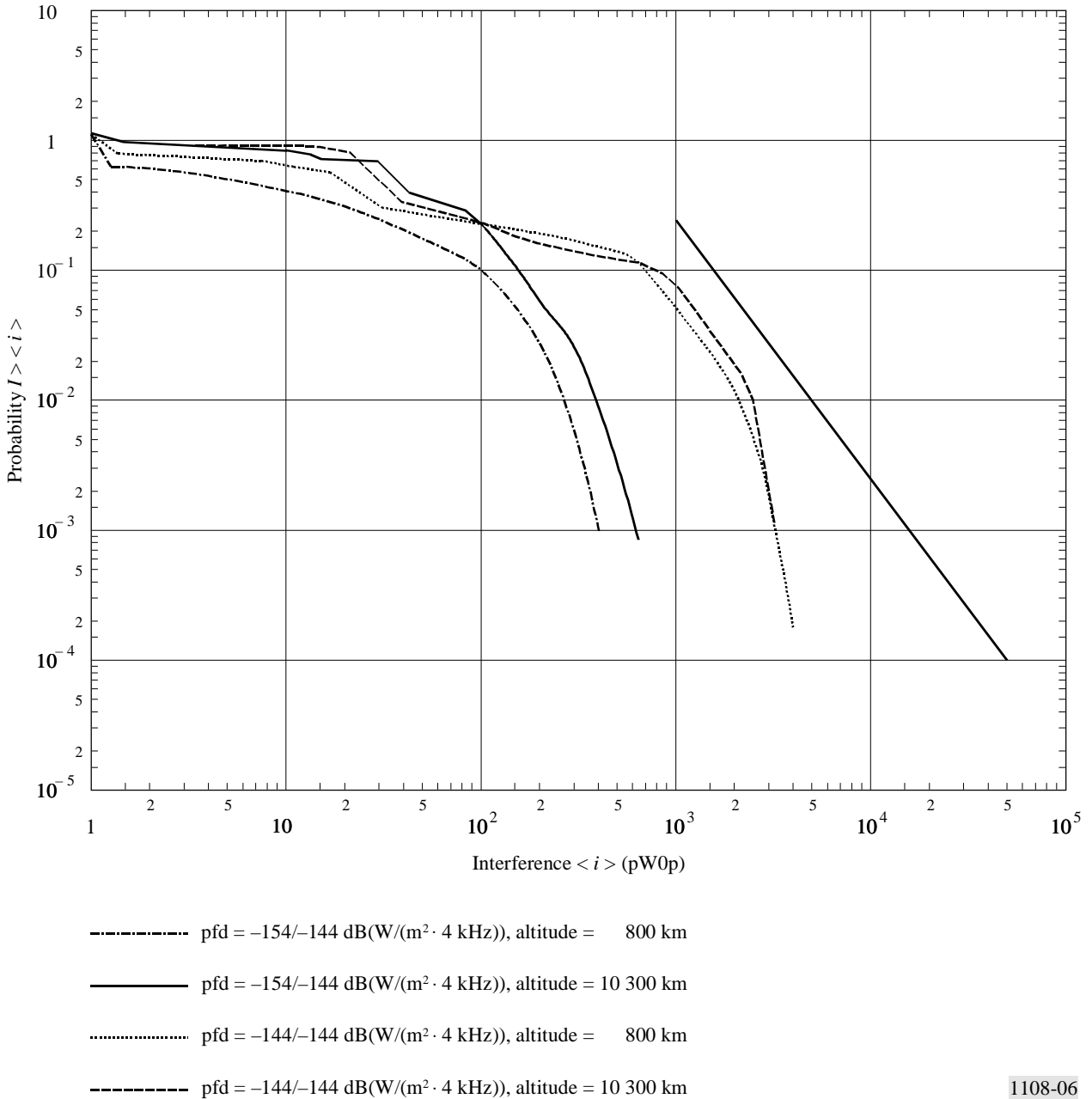
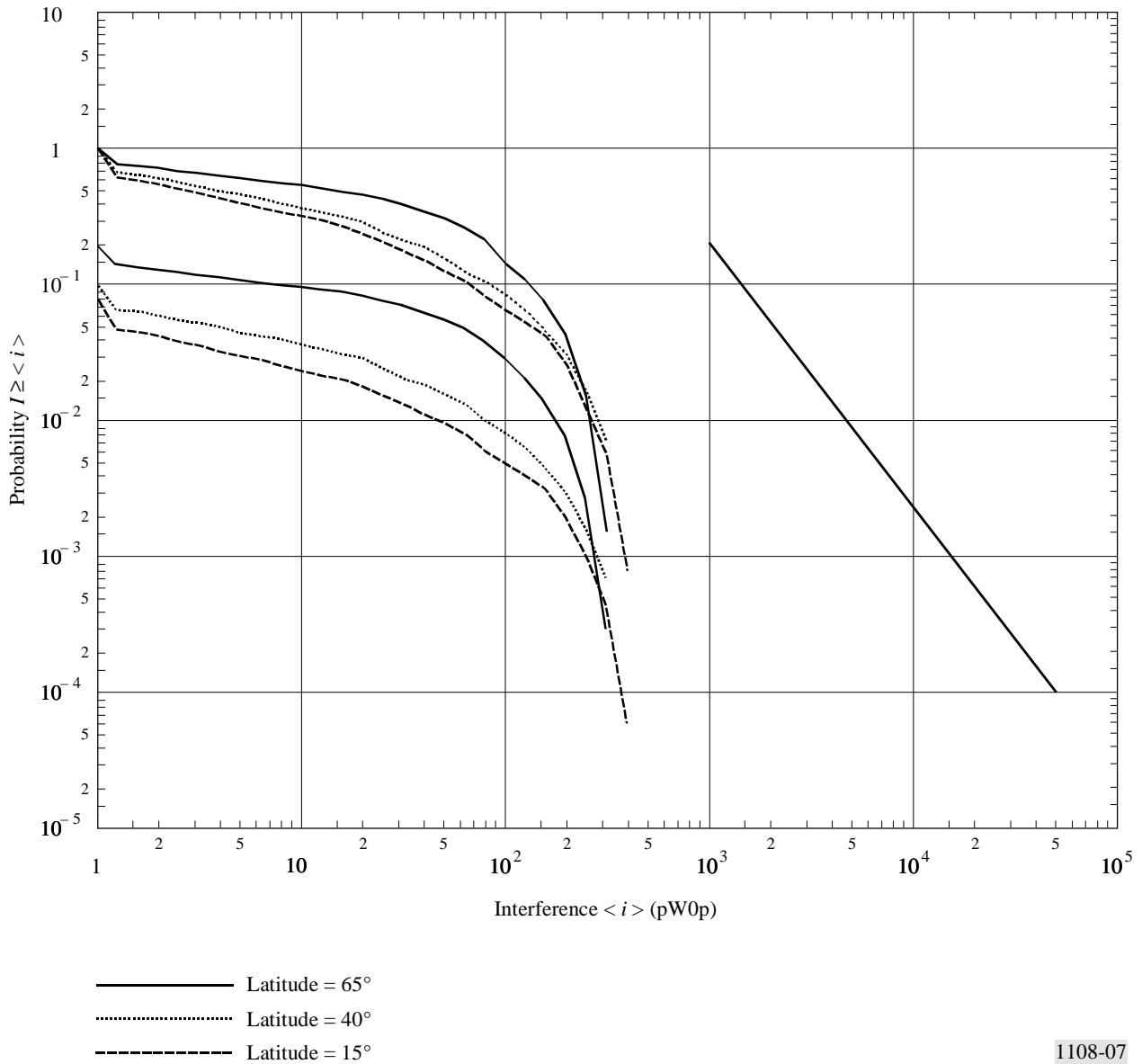


Figure 7 shows the results of an investigation of the effects of interference into the FS as a function of FS latitude. The upper three curves represent interference distributions into the FS at three different latitudes assuming the same single constant visible satellite constraint. It would appear that latitude is not a significant parameter with regard to the shape of the distributions as they are reasonably similar.

FIGURE 7

Interference ( $i$ ) pW in 4 kHz bandwidth

FS interference versus latitude  
 (50 hops, 33 dB antenna gain, pfd =  $-154/-144$  dB(W/(m<sup>2</sup> · 4 kHz)), 2 GHz)



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The lower group of three curves in Fig. 7 represent the distributions of received interference distributions at different latitudes from single orbiting satellites that have high orbit angles (80°). It is interesting to note here that if the curve plots were extrapolated back to the y axis for  $X=0$  it would approximately represent the percent of time that the satellites were visible to the FS systems at the indicated latitudes. Conversely the inverse of that number would also approximate the number of satellites needed to achieve constant single satellite visibility. It follows from a close observation of these curve plots in Fig. 7 that fewer satellites would be needed to continuously illuminate higher latitudes systems since the distribution for the 65° latitude radio-relay routes does appear to intercept the y axis at a much higher point.

This might be verified intuitively by considering that for every orbit of a highly inclined satellite system each satellite in the plane would be visible for a percentage of time to terrestrial sites at more northern or southern latitudes, whereas terrestrial sites at mid or lower latitudes may not be visible to any portion of some orbits. This would suggest that LEOs

optimized to serve medium and lower latitudes would cause more interference into higher latitude terrestrial systems since a larger percentage of the satellites in orbit would be visible to the higher latitude terrestrial sites.

Finally, Figs. 8 and 9 illustrate the interference effects into the FS from constellations of satellites that might represent practical operating systems. Both systems are arranged such that 3 to 6 satellites are continually visible to the terrestrial site requiring service. Figure 8 investigates a satellite constellation consisting of 6 circular orbit planes with 11 satellites per plane. All planes have the same inclination ( $86.5^\circ$ ) and the same satellite altitude (780 km). Figure 9 shows the interference distribution that might be expected from a 12 satellite constellation operating at an altitude of 10 370 km. The satellites are arranged in 3 orbit planes separated by  $120^\circ$  with inclinations of  $56^\circ$  and 4 satellites per plane.

FIGURE 8  
Interference (*i*) pW in 4 kHz bandwidth

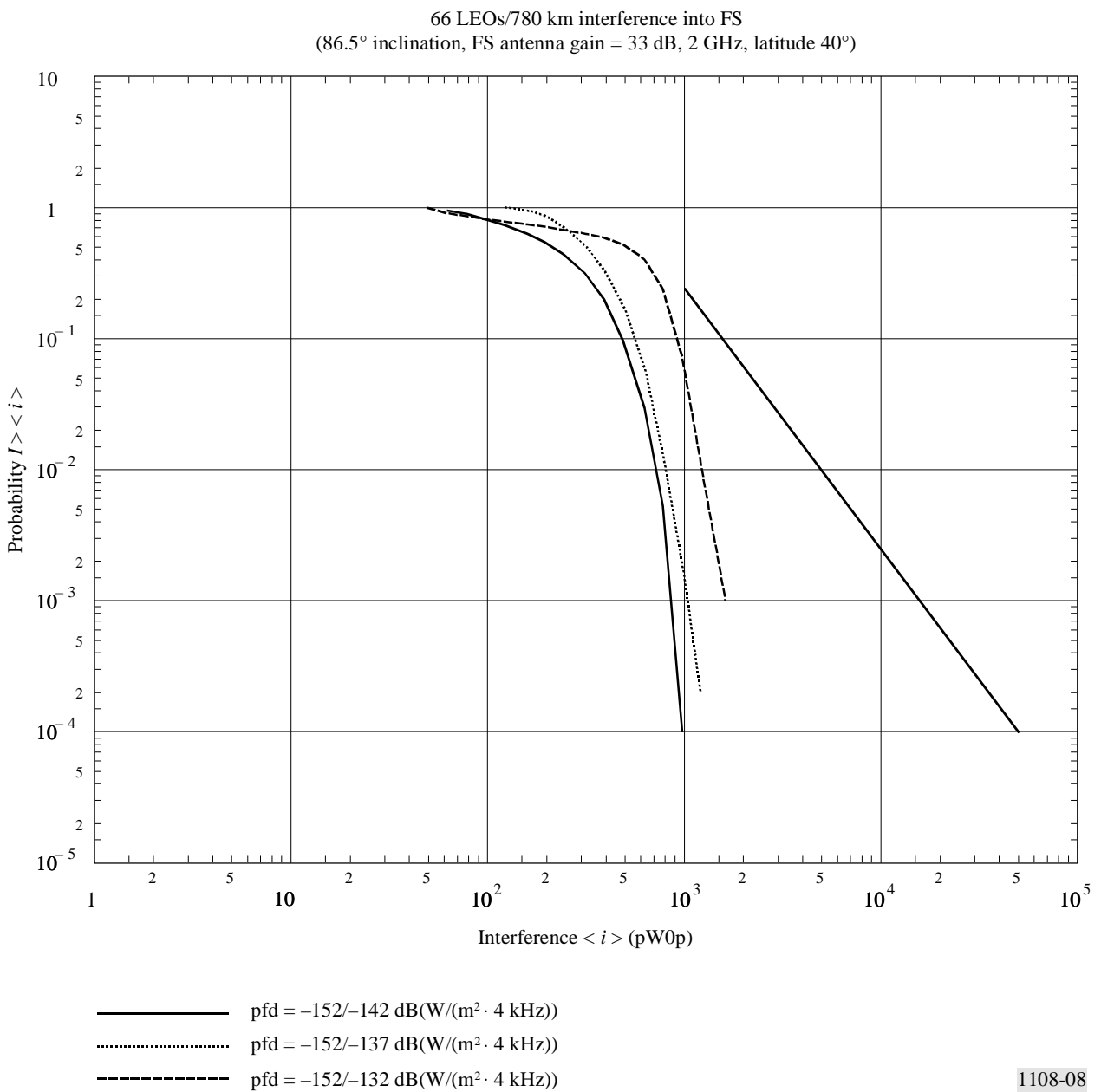
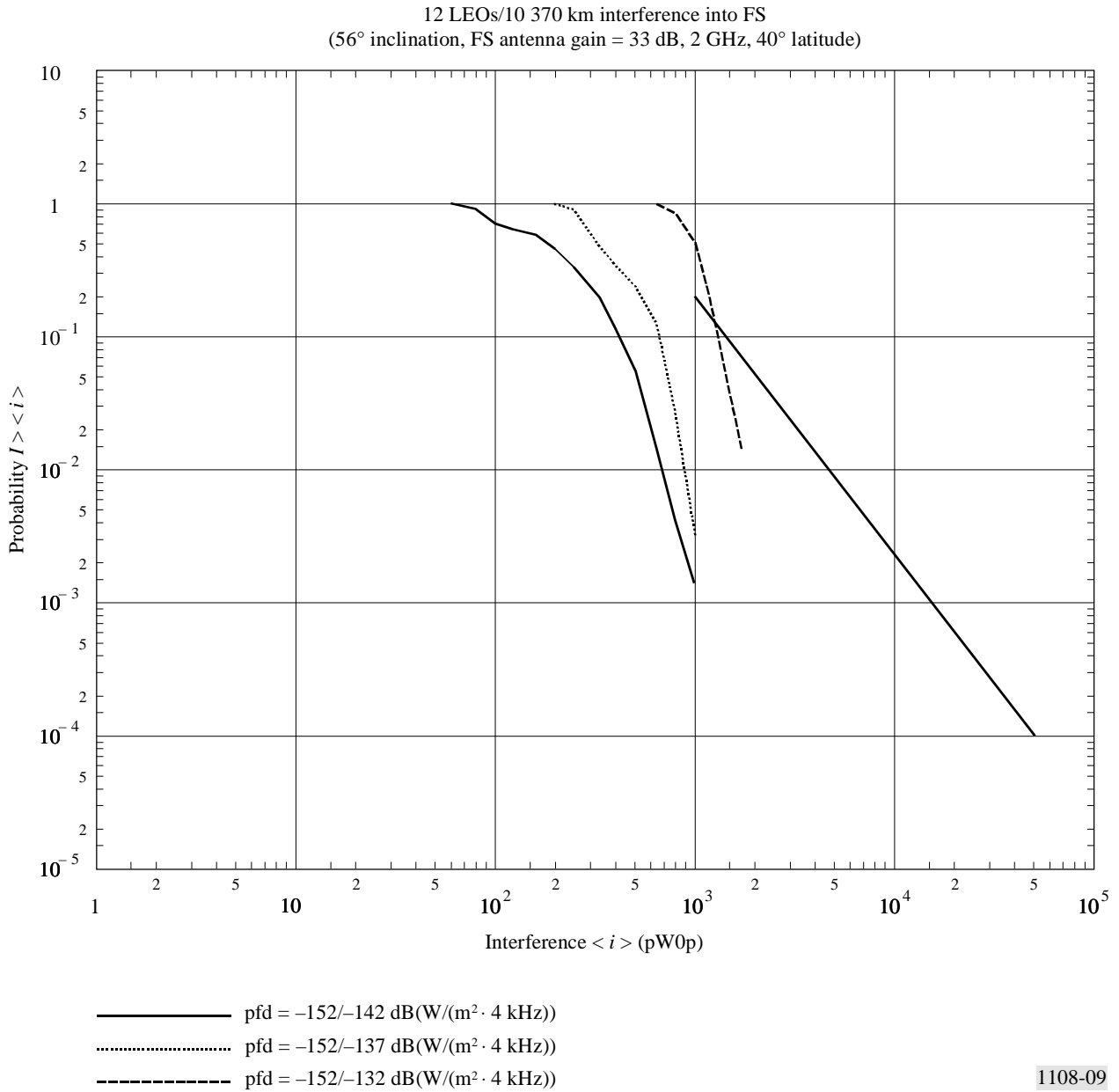


FIGURE 9  
Interference ( $i$ ) pW in 4 kHz bandwidth



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#### 4 Conclusions

Because of the time parameter introduced by LEOs, the analysis of sharing becomes very much more difficult; and, in important respects differs from sharing with GSO satellites. At this time there is no complete methodology for establishing protection requirements for the FS in a LEO environment. This is especially true when sharing with digital radio-relay systems. Recommendation ITU-R SF.357 provides a criteria which might be used for establishing pfd limits for sharing with analogue radio-relay routes. However, since the function of Recommendation ITU-R SF.357 is to establish sharing with GSO satellites, it may be appropriate to review it with respect to sharing with LEO satellite networks.

Assuming the validity of Recommendation ITU-R SF.357 then it would appear that, for situations where there are limited numbers of LEO visible to the FS that analogue radio-relay networks could share with LEO systems provided that low angles of arrival pfd emissions can be controlled. It is also apparent that, for high angles of arrival, pfd emission limits from LEO systems could exceed the levels currently established for the geostationary-satellite systems. Further study is clearly required and it is proposed that the development and use of simulation tools be encouraged to conduct such studies.

## ANNEX 3

### **Determination of the effects of emissions from space stations non-GSO on FS digital microwave receivers**

#### **1 Introduction**

The development of criteria for band sharing between the FS and space services using LEO satellites requires an understanding of the effects that the emissions from such satellites have on the performance of digital terrestrial receivers. The present Annex describes an approach to evaluating these effects on digital radios using a computer simulation. The simulation develops the statistics of interference power that would be received at a given location on a receiving antenna pointed in any one of a set of directions. It uses the orbital equations developed in Annex 1 and allows for either a single satellite or for a uniform constellation of satellites. Specific quantities developed include:

- the percentage of time that the received interference power exceeds a level; and
- the fractional increase in the probability of not meeting a performance criterion.

Detailed descriptions of the elements of the simulation are given in § 2 and 3 of the present Annex; the development of the expressions for performance degradation is given in § 4. Some representative results of interest are given in § 5.

#### **2 Statistical modelling**

The simulation develops interference statistics by considering the interference received from each of  $N_a$  equally spaced positions on an orbit. The total set of interferences is obtained by considering  $N_0$  orbits with their ascending nodes equally spaced around the equator. While this may not be representative in many cases, it is the most favourable or most permissive assumption for sharing in that it spreads out the interference most widely across the surface of the Earth. The consequences of this assumption need to be considered together with the assumption of circular orbits in further studies.

Clearly, for a single satellite, there are  $N_a \times N_0$  possible interference positions. Thus the probability associated with any one of them is  $1/(N_a N_0)$ .

The case of multiple satellites in a uniform constellation is also easily considered. A uniform constellation consists of a set of satellites spread over a set of identical uniformly spaced orbital planes. Each orbital plane contains the same number of satellites uniformly spaced on the orbit. The most uniform coverage and the most permissive sharing is obtained when the sets of satellites are equally phased. This means that when there is a satellite on one orbit crossing the equator, there will be a satellite on each of the orbital planes crossing the equator in the same direction.

In terms of the previously defined quantities, if  $N_a$  is an integral multiple of the number of satellites per orbit,  $N_{spo}$ , and  $N_0$  is an integral multiple of the number of orbital planes,  $N_{orb}$ , in the constellation, the number of unique states of the constellation is just  $(N_0/N_{orb})(N_a/N_{spo})$ .

### 3 Interference determination

Satellite emissions are assumed to be limited in the conventional manner: by a low level pfd for elevation angles, on the Earth, below a lower limit and by a higher pfd for elevation angles above a higher limit, with a linear escalation with elevation angle between the limits. The pfd is specified here in dB(W/(m<sup>2</sup> · MHz)).

The antenna gain,  $G_R(\varphi)$ , of the terrestrial receiver is that specified by Recommendation ITU-R F.699 for a gain, diameter, and frequency as independent inputs. The effective area applicable to determine the received interference power due to a pfd at an angle  $\varphi$  is given by:

$$A_{eff} = \frac{\lambda^2}{4\pi} G_R(\varphi)$$

where  $\lambda$  is expressed in m.

### 4 Modelling the effect of interference on digital systems

The outage probability of a digital system is often written in the following form:

$$P_0 = C \left[ 10^{-DFM/10} + 10^{-TFM/10} + 10^{-(C/I - CNC)/10} \right] \quad (14)$$

where:

$C$ : a constant depending on climate, terrain and link parameters

$DFM$ : dispersive fade margin (dB)

$TFM$ : thermal fade margin (dB)

$C/I$ : ratio of unfaded signal power to the noise-equivalent value of interference power (dB)

$CNC$ : value of carrier-to-noise ratio at which the performance criterion is just met (dB).

Modern digital systems usually have dispersive fade margins larger than their thermal fade margins, and are getting better. Hence, the first term in equation (14) can be ignored for interference considerations. While the noise-equivalent interference power of a specific interferer into a specific receiver may be less than the measured power, for general sharing considerations, particularly where there are multiple interferers, it can be conservatively assumed that the interference has the same effect as thermal noise with the same power. Since the difference in decibels between the unfaded carrier-to-noise ratio and the critical carrier-to-noise ratio (CNC) is the thermal noise fade margin (TFM), the fractional increase in  $P_0$ , the probability of exceeding the performance objective, is equal to the ratio of the interference power  $I$  to the noise power  $N_T$ , where both are measured at the detector in Watts or in Watts per unit bandwidth. That is, the fractional increase is equal to  $I/N_T$ , for a constant interference power  $I$ . To simplify discussion such an increase in  $P_0$  will be designated as a fractional degradation in performance (FDP) or a percentage degradation in performance.

If an interferer caused an interference power  $I_i$  for a fraction of a month,  $f_i$ , and was absent for the remainder of the month, the incremental FDP due to this interference would be given by:

$$\Delta P_{0,i} = \frac{I_i f_i}{N_T}$$

The FDP due to a set of events, where the  $i$ th event consists of the fraction of time that the interference had a power  $I_i$ , is given as:

$$FDP = \sum \Delta P_{0,i} = \sum \frac{I_i f_i}{N_T} \quad (15)$$

where the summation is taken over all interference events. The summation over  $I_i f_i$  is the discrete equivalent to the first moment of the probability distribution of the interference power into the receiver since  $f_i$  is the probability that the interference power has a value between  $I_i$  and  $I_i + \Delta I_i$ .

The FDP may also be expressed as a fade margin loss (FML) (dB), where:

$$FML = 10 \log (1 + FDP) \quad (16)$$

whereas, the mean interference level above thermal noise is given in dB as  $10 \log FDP$ .

Although equation (14) has been used primarily with reference to the occurrence of outage, the probability of the bit error ratio of the receiver exceeding  $1 \times 10^{-3}$ , most measures of digital radio performance scale with the outage. Hence, equation (15) may be used as a measure of the FDP. While the expressions in (15) and (16) provide reasonable bounds on the degradation of performance for moderate interference levels, they may underestimate the effects for interference levels, say, 20 dB higher than the thermal noise, because the dispersive effects included in the first term in (14) begin to become important and because shallow fading may not follow the Rayleigh fading law implicit in (14).

The effects of high levels of interference may best be assessed through separate considerations with respect to short-term interference criteria or through an examination of the cumulative distribution of the ratio of received signal power to the sum of the noise and interference powers (see Annex 6). Development of the most appropriate method is currently under study in Radiocommunication Study Group 9.

The other consideration of high interference levels is whether they are high enough to degrade the error performance of a link in the absence of fading. Performance criteria such as residual bit-error ratio in Recommendation ITU-R F.634, or others required to meet ITU-T Recommendation G.826, which are being developed, may need to be considered. Only if such high interference events occur sufficiently rarely or not at all, can their effect be neglected.

The form of (15) makes it eminently suited for interference studies because it allows large constellations of satellites to be treated simply regardless of whether or not they are uniform. Also the effects of multiple constellations can be easily assessed since the FDP produced by each can be added to determine the total or composite FDP.

## 5 An alternative derivation of FDP

Assume that the performance of a digital radio operating on a hop is controlled by the occurrence of deep fading due to multipath propagation on the hop. For systems with effective adaptive transversal equalizers or for sufficiently narrow-band systems, such as those typically found at frequencies below 3 GHz, this is a reasonable assumption.

If  $C$  is the unfaded received signal level,  $N_T$  is the thermal noise level, and  $k$  is the minimum value of  $C/N_T$  needed to meet the controlling performance requirement, the conditions for meeting the requirement will not be met when:

$$\frac{rC}{N_T} < k \quad (17)$$

where:

$r$ : fading factor

$$= 10^{-A/10}$$

$A$ : fade depth (dB).

If there is interference, which is approximately Gaussian-noise-like, with an average power  $I$  at the detector, then the controlling performance criterion would not be met if:

$$\frac{rC}{N_T + I} < k \tag{18}$$

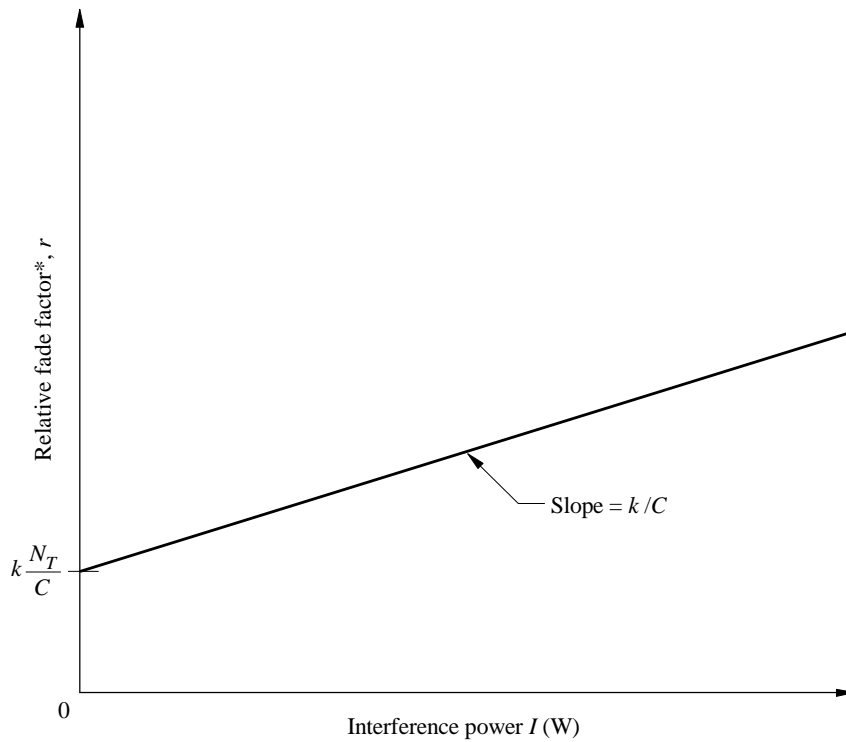
Clearly the performance criterion is not met when:

$$r \leq k \left( \frac{N_T}{C} + \frac{I}{C} \right) \tag{19}$$

Figure 10 shows the boundary of the region where the inequality in equation (18) is just met. When the interference power is not constant, the satisfaction of the controlling performance objective requires an appropriately small probability of the joint occurrence of fading and interference with values below the dividing line in Fig. 10. Specifically, if  $p_r(r)$  is the probability density function for the fading factor,  $p_I(I)$  is the probability density function for the interference power, and these processes are independent, the fraction of a month that the critical performance criterion will not be met,  $P_{0i}$ , is given by:

$$P_{0i} = \int_0^{\infty} dI \int_0^{(k/C)(N_T + I)} p_r(r) p_I(I) dr \tag{20}$$

FIGURE 10  
Boundary of region where critical performance criterion is met



\* Ratio of faded to unfaded power.



In most cases of interest the value of equation (20) is controlled by the occurrence of deep multipath fading, and its evaluation can be simplified. Recommendation ITU-R P.530 predicts that in the deep fading regime the probability of a fade factor less than  $r$  is proportional to  $r$ . Thus the probability density function for the fade factor must be a constant.

$$p_r(r) = \beta \quad r \ll 1 \quad (21)$$

where  $\beta$  is the constant of proportionality, which may be described as a fade occurrence factor. Hence, the fraction of a month, during which the critical performance criterion will not be met is determined by using equation (21) in (20).

$$P_{0i} = \frac{\beta k}{C} (N_T + I_{av}) \quad (22)$$

where  $I_{av}$  is the average interference power, or

$$I_{av} = \int_0^{\infty} I p_I(I) dI \quad (23)$$

The FDP is the fractional increase in the percentage of time that the controlling performance criterion will not be met because of the presence of interference. Denoting the value of equation (22) in the absence of interference by  $P_{0o}$ , the FDP could be expressed as  $FDP = (P_{0i}/P_{0o}) - 1$ , or

$$FDP = \frac{I_{av}}{N_T} \quad (24)$$

which is equivalent to equation (15).

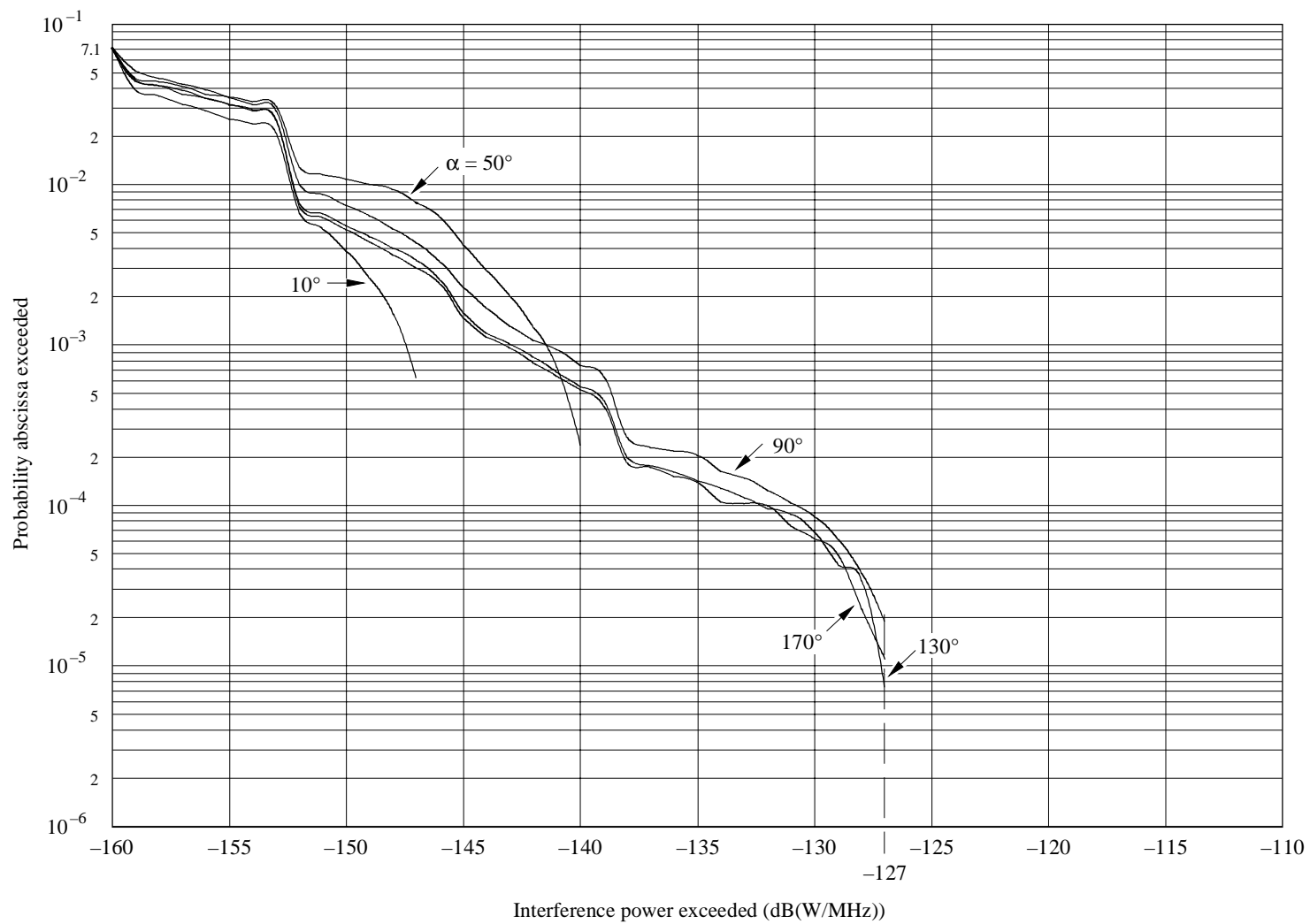
## 6 Sample results of simulation

This section presents some results from a number of test runs of the simulation. The objective was to identify some basic trends and problem areas. Unless otherwise specified, the terrestrial station is assumed to be at a latitude of 40° N operating at 2.000 GHz with a 2.76 m diameter antenna with 33 dB gain and that the waveguide losses are 2 dB. In accordance with Recommendation ITU-R F.759, the noise figure of the receiver is taken as 4 dB. The satellite emissions fall on the pfd limit of -130 dB(W/(m<sup>2</sup> · MHz)) for elevation angles of 5° or less and increase by 0.5 dB per degree from 5° to 25°, beyond which they attain the value of -120 dB(W/(m<sup>2</sup> · MHz)). The satellite interference is sampled at 0.5° increments around the orbit for 720 orbits uniformly spaced around the equator.

Figure 11 shows the cumulative distribution of the interference power received by antennas with different pointing azimuths from a satellite in an orbit with an altitude of 800 km and an inclination of 50°. Because of the limited inclination of the orbit, the satellite is never observed near the northern horizon. Hence the antennas pointed at azimuths within 50° of the North Pole never receive interference at boresight and have truncated distributions. As a consequence, there is a correspondingly larger probability of boresight observances at somewhat larger azimuth angles. Figure 12 shows this clearly in a plot of the percentage degradation in performance for a set of angles for this case.

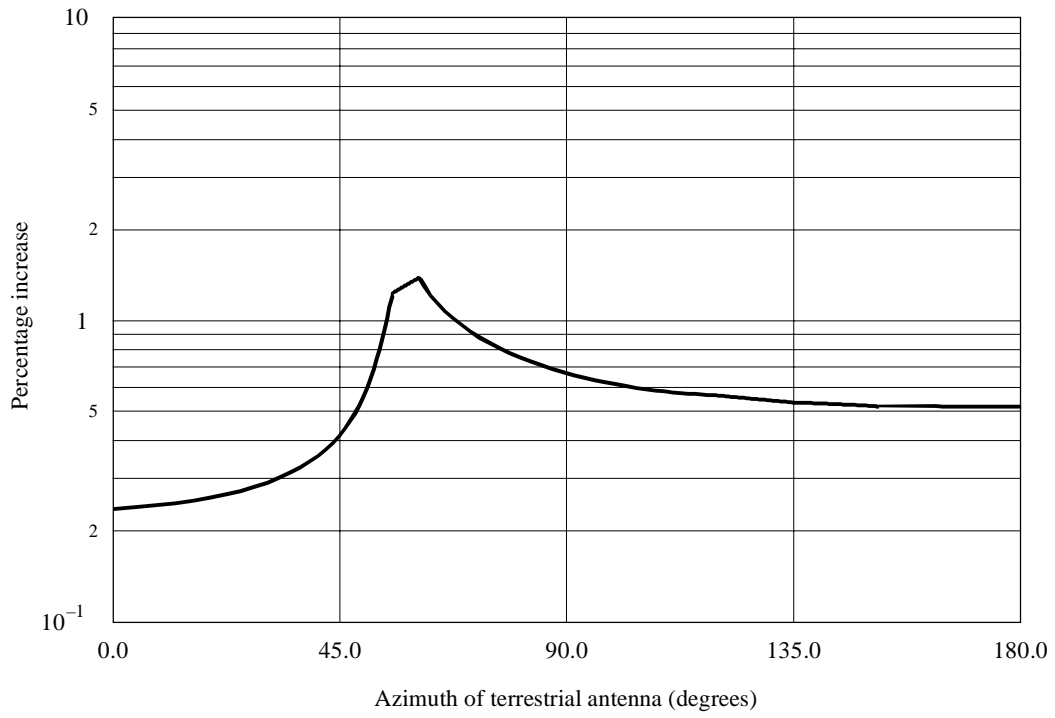
Figure 13 shows the cumulative distribution of received interference power for the same situation except for the orbital inclination which is 89.5°. Clearly the effect of azimuth is much less pronounced in this case.

FIGURE 11  
Cumulative distribution of interference power for a terrestrial station at 40° latitude  
from a satellite in an orbit with 50° inclination and 800 km altitude



1108-11

FIGURE 12  
 Percentage performance degradation for the case in Fig. 11



1108-12

FIGURE 13

Cumulative distribution of interference power for a terrestrial station at 40° latitude  
from a satellite in an orbit with 89.5° inclination and 800 km altitude

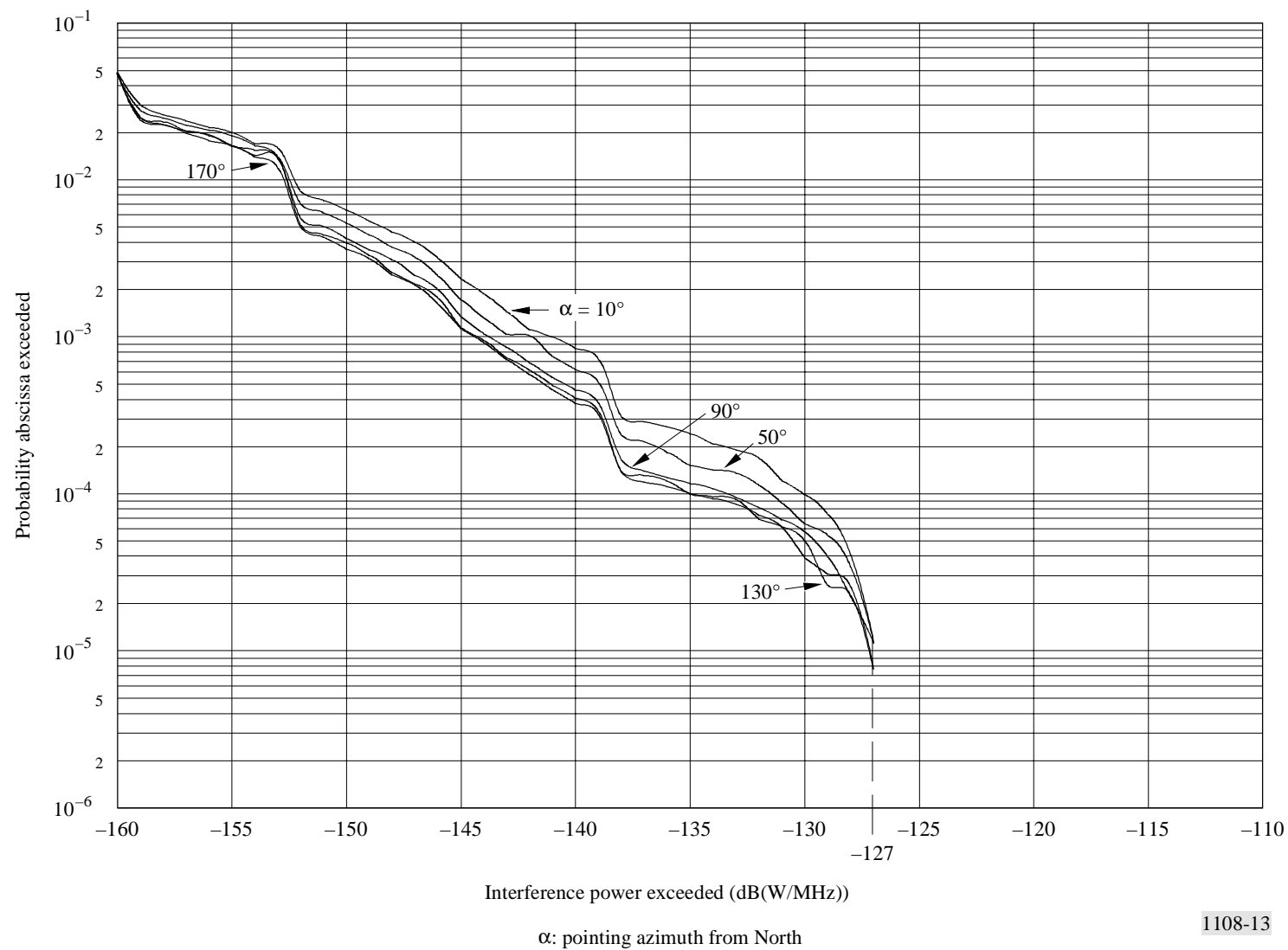
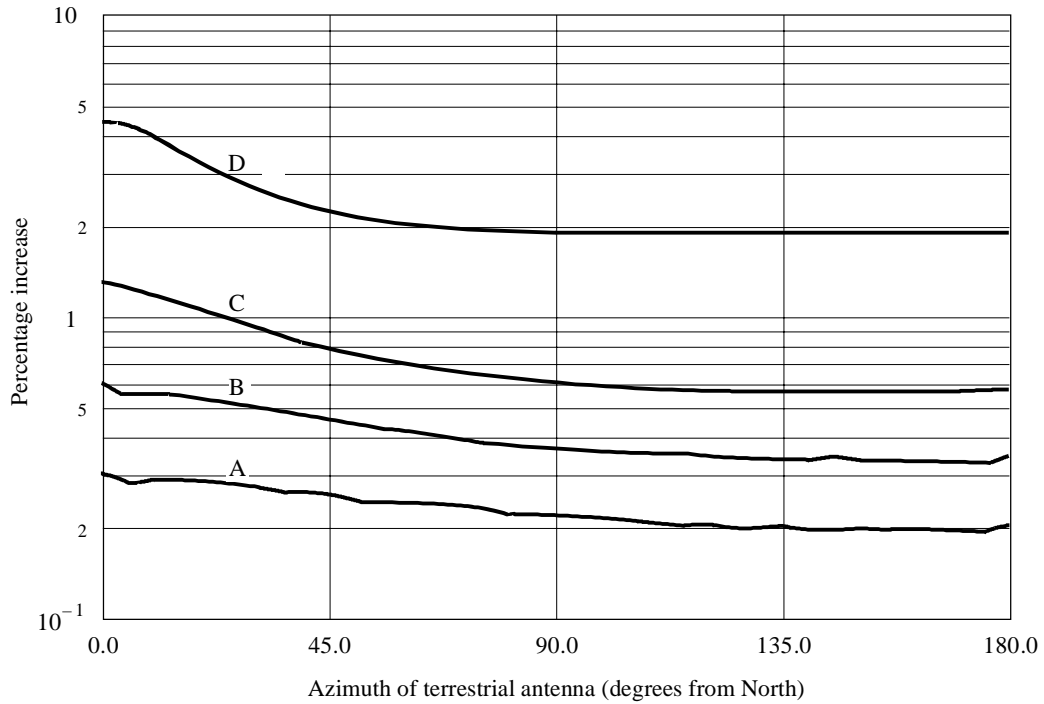


Figure 14 illustrates the effect of satellite altitude through a plot of percentage degradation in performance versus azimuth angle. The performance degradation caused by a satellite increases linearly with orbital altitude up to nearly 10 000 km as does the area of the Earth visible to the satellite at any instant.

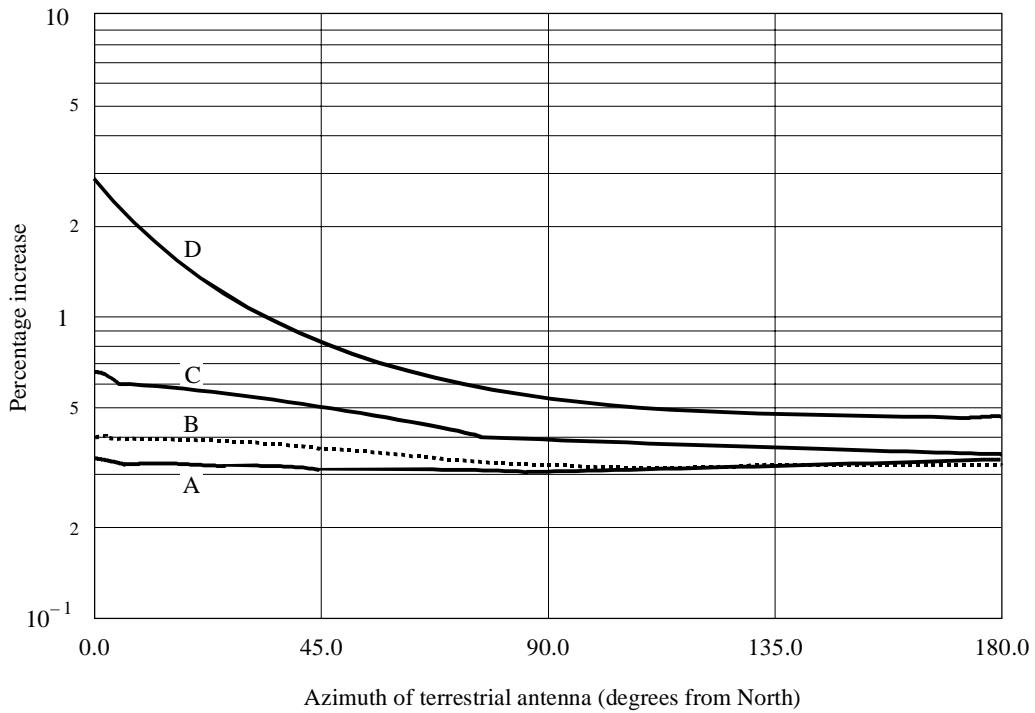
FIGURE 14  
**Percentage degradation in performance for a terrestrial station at 40° latitude due to interference from a satellite with 89.5° inclination and various altitudes**



Curves A: altitude = 400 km  
 B: altitude = 800 km  
 C: altitude = 1 600 km  
 D: altitude = 10 000 km

The effect of the latitude of the earth station on the performance degradation is illustrated by Fig. 15. While the effects are not severe, they are increasingly important closer to the poles for near polar pointing angles.

FIGURE 15  
**Percentage degradation in performance for terrestrial stations  
 at various latitudes due to interference from a satellite  
 in an orbit with 89.5° inclination at 800 km altitude**



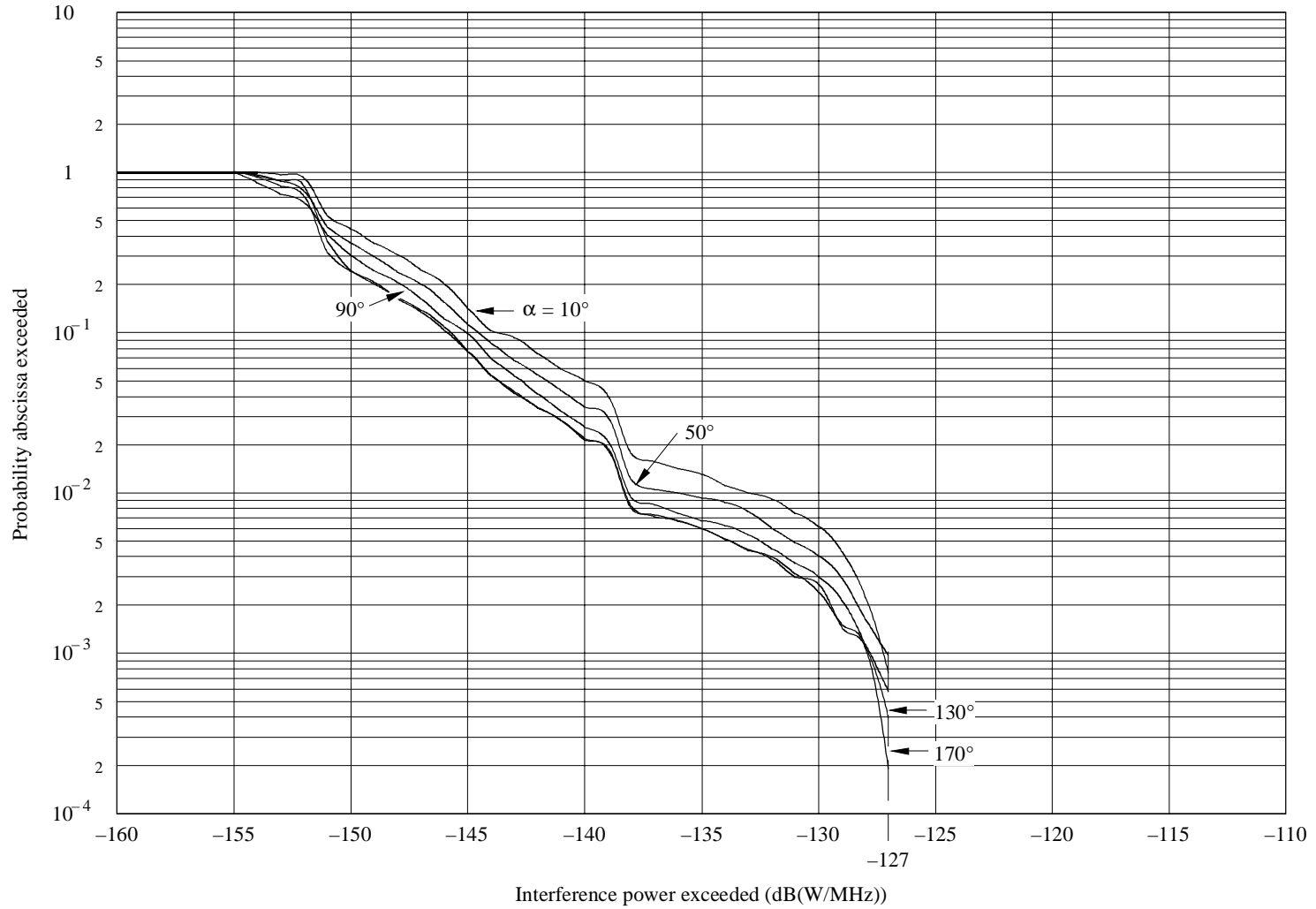
Curves A: latitude = 0°  
 B: latitude = 20°  
 C: latitude = 40°  
 D: latitude = 60°

1108-15

Figures 16 and 17 show the effect of a uniform constellation of 55 satellites operating on a co-channel basis as they would if they were employing code division multiple access (CDMA). Comparing Figs. 13 and 16, one finds the interference distributions for the single satellite and multiple satellite cases to be quite similar. The comparison is more obvious in Fig. 17 where the performance degradation caused by 55 satellites is seen to be 55 times worse than that caused by a single satellite.

FIGURE 16

Cumulative distribution of interference for a terrestrial station at 40° latitude  
due to a uniform constellation of 55 satellites in orbits with 89.5° inclination and 800 km altitude

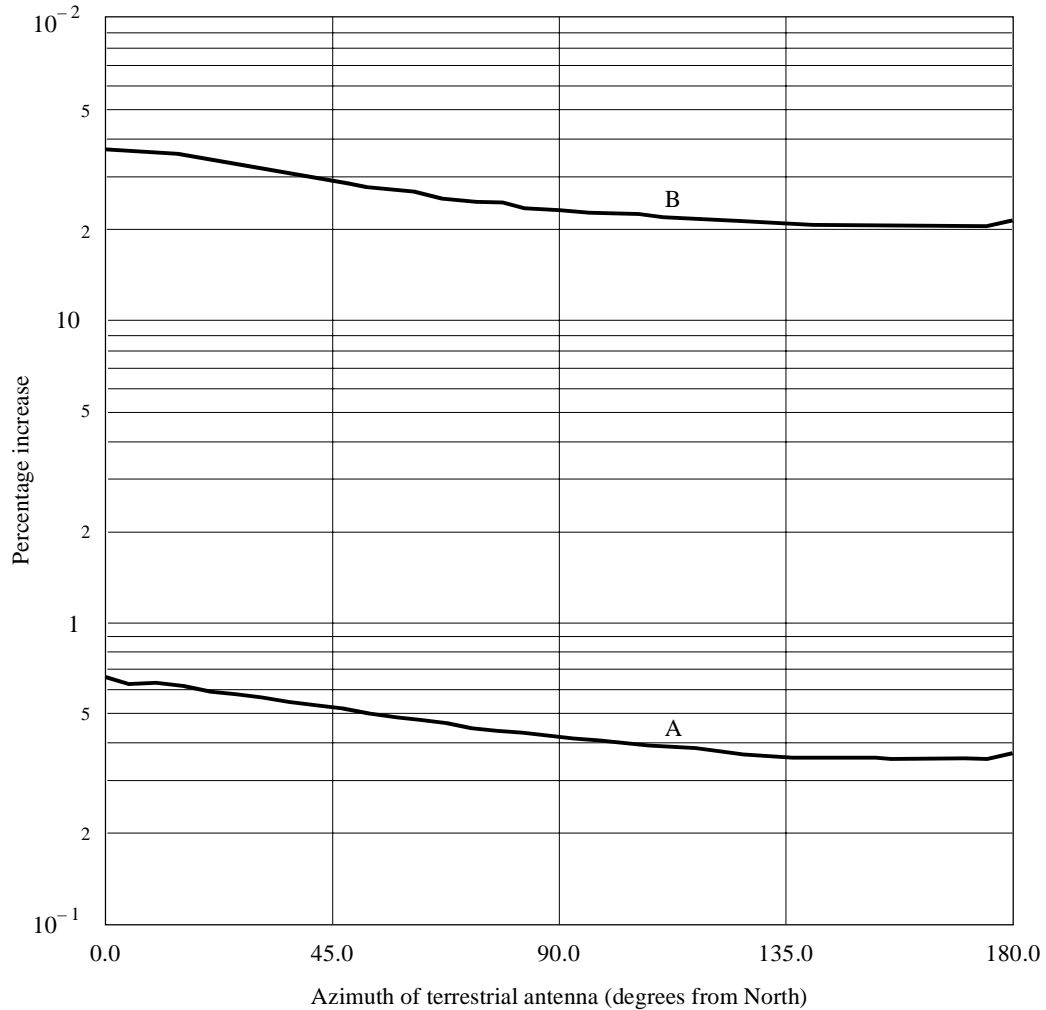


$\alpha$ : pointing azimuth from North

1108-16

FIGURE 17

Percentage degradation in performance for a terrestrial station at 40° latitude due to a single satellite and a uniform constellation of 55 satellites in orbits with 89.5° inclination and 800 km altitude



Curves A: 1 satellite  
B: 55 satellites

1108-17

## 7 Interim conclusions

The degradation in performance was shown to be linearly dependent on the number of satellites for satellites in a uniform constellation. In general, the degradation is additive over all satellites interfering into the pass band of a receiver.

For satellites in non-geosynchronous orbits using the same escalation in pfd with elevation angle, the FDP experienced by terrestrial receivers at moderate latitudes has limited variation with:

- pointing angle – within a factor of three for latitudes up to 60° and altitudes up to 800 km;
- satellite altitude – increases approximately linearly with altitude;
- station latitude – increases by an amount that is within a factor of about two from 20° to 60° latitude.



These conclusions could vary for different pfd escalations. Stations at high latitudes may experience greater variation in the FDP with respect to azimuth angle for satellites in near polar orbits. Sharing may be facilitated by coupling the escalation or the pfd limit itself to orbit altitude and inclination. These possibilities merit further study.

These conclusions depend on the use of nearly circular orbits that are not geosynchronous. The use of highly elliptical orbits requires further information and further study particularly because the interference statistics may not be stable over the one-month periods during which performance criteria must be met. The means to accommodate such operation requires further study.

The use of geosynchronous orbits would increase the variations of the percentage degradation in performance with respect to both pointing angle and location of the terrestrial station. These are the types of considerations that are normally part of a detailed coordination procedure. Since coordination with every terrestrial station would seem to be impractical, the alternative would be to decrease the allowed satellite emissions (pfd). While such limits could be devised simply, further study is needed.

If both GSO and non-GSO satellites were used in the same frequency band the sharing considerations would become increasingly complex, especially since the interference effects of the two types of satellites are additive.

This Annex has considered the interference from satellite constellations which occupy the spectrum uniformly on a co-frequency basis and assumes that the satellite emissions are constrained by a fixed pfd mask at the surface of the Earth. Specific systems may employ frequency re-use within the constellation which might improve the prospects for sharing. If this methodology were applied to a detailed consideration of specific systems, the evaluation of interference effects could make use of the antenna beams and frequency re-use plans implemented in the satellites.

## ANNEX 4

### Methodology to determine the effect of interference on digital receivers employing diversity

#### 1 Introduction

In frequency bands where multipath fading is the dominant cause of performance degradations, in the absence of interference, various forms of frequency diversity are often implemented. The performance improvements achieved, in the absence of interference, and the degradation of the diversity performance due to interference will depend somewhat on the particular diversity implementation chosen. Some systems may use an antenna with characteristics different than those of the main antenna in obtaining a diversity signal. Different systems may use different combining/switching arrangements in obtaining a combined signal. All other things being equal, a system that uses identical antennas in the main and diversity signal paths will achieve the greatest performance improvements compared to the non-diversity system, such a diversity system also appears to be the least affected by interference.

For the purpose of developing the FDP of a diversity system, it will be assumed that the digital system uses identical antennas in both diversity branches, and is sufficiently narrow-banded or well equalized that its performance requirements are dominated by signal loss. In this case, the fraction of a month that the critical performance criterion is not met,  $P_{0i}$ , can be developed in the same manner as equation (20), except that one needs to distinguish between diversity and non-diversity quantities. Thus:

$$P_{0i} = \int_0^{\infty} dI p_I(I) \int_0^{(k/C)(N_T+I_C)} dr p_r(r) \quad (25)$$

The interference power  $I$  and its distribution are characterized, as in the non-diversity case, in the branch containing the main antenna, relative to  $N_T$ , the effective system noise power attributed to that branch. The interference power after processing,  $I_C$ , relative to the noise after processing is used to determine interference degradation. Because there is sufficient system gain ahead of the diversity, processing the output can be rescaled so that the noise component has the value  $N_T$  again. The interference power in this rescaled output is  $I_C$ . Thus, in the diversity case, one would redraw Fig. 10 with  $I_C$  as the abscissa to derive equation (25).

Where deep multipath fading is the primary cause of performance degradation of a diversity FS system, Recommendation ITU-R P.530 provides a method of predicting the diversity receive levels of narrow-band signals in the deep fading regime. From this, one can determine that the probability of a fade factor less than  $r$  is proportional to  $r^2$ . Thus, the probability density function for the fade factor must be proportional to  $r$ , and:

$$p_r(r) = \gamma r \quad r \ll 1 \quad (26)$$

where the parameter  $\gamma$  includes the effects of diversity implementation.

Equation (26) has been found to be generally appropriate for describing the diversity operation of FS systems in the presence of multipath fading. Substituting equation (26) into (25) and integrating gives:

$$P_{0i} = \frac{\gamma k^2}{2C^2} \int_0^{\infty} (N_T + I_C)^2 p_I(I) dI \quad (27)$$

or the diversity fractional degradation in performance (DFDP) as:

$$DFDP = \int_0^{\infty} \left( \frac{2I_C}{N_T} + \frac{I_C^2}{N_T^2} \right) p_I(I) dI \quad (28)$$

Equation (28) can be evaluated easily for two important cases: ideal switched diversity and equal gain maximum power combining diversity. Both types will be considered for the case where the antenna in the diversity branch has the same gain as that in the main branch, and the two branches are otherwise identical.

## 2 Switched diversity

In this case, diversity operation is achieved through the operation of a switch that chooses the least faded signal. Hence the interference and effective noise power in either antenna appears at the output, unscaled, and:

$$DFDP = \int_0^{\infty} \left( \frac{2I}{N_T} + \frac{I^2}{N_T^2} \right) p_I(I) dI \quad (29)$$

or:

$$DFDP = 2 \frac{I_{av}}{N_T} + \frac{I_2}{N_T^2} \quad (30)$$

where  $I_{av}$  is as defined in equation (23) and  $I_2$ , the second moment of the interference power, is given as:

$$I_2 = \int_0^{\infty} I^2 p_I(I) dI \quad (31)$$

Equation (30) can also be written in the same form as (15) for use in simulations:

$$DFDP = \sum f_i \left[ \frac{2I_i}{N_T} + \left( \frac{I_i}{N_T} \right)^2 \right] \quad (32)$$

### 3 Maximum power combining

A maximum power combiner shifts the relative phase between the two diversity branches so that the replicas of the desired signal in the two branches will be in phase. Since the interference contribution from the two antennas is coherent, the  $I/N$  would be twice as high at the combiner output as at the input if the interference had the same relative phase as the desired signal. If the branch-to-branch phase shift of the interference is different from that of the desired signal by  $\phi$  radians, the interference power at the combiner output,  $I_C$ , would be given as:

$$I_C = 2I \cos^2 (\phi/2) \quad (33)$$

This result may be substituted into equation (28). Assuming that the phase  $\phi$  is uniformly distributed over the interval 0 to  $2\phi$ , one can determine its average effect. This gives the following:

$$DFDP_{mpc} = \int_0^\infty \left( \frac{2I}{N_T} + \frac{3I^2}{2N_T^2} \right) p_I(I) dI \quad (34)$$

or:

$$DFDP_{mpc} = 2 \frac{I_{av}}{N_T} + \frac{3I_2}{2N_T^2} \quad (35)$$

This may also be written in the form as equation (15) for use in simulations.

$$DFDP_{mpc} = \sum f_i \left[ \frac{2I_i}{N_T} + \frac{3}{2} \left( \frac{I_i}{N_T} \right)^2 \right] \quad (36)$$

### 4 Diversity fade margin loss (DFML)

From the preceding developments, the FDP of a diversity system may be expected to be at least twice as great as that of an otherwise identical non-diversity system in the same interference environment. Conversely, using equation (26), it is easily established that the loss of DFML system for a given DFDP is half of that of a non-diversity system for a like value of FDP. That is:

$$DFML = 5 \log (1 + DFDP) \quad (37)$$

If the variance of the interference power into a FS receiver,  $\sigma^2$ , is defined in the usual way:

$$\sigma_I^2 = I_2 - I_{av}^2 \quad (38)$$

and the DFML may be written in terms of the non-diversity FDP as:

$$DFML = 10 \log \sqrt{(1 + FDP)^2 + (FDP \sigma_I / I_{av})^2} \quad (39)$$

## 5 Summary

In environments where the interference power into a FS receiving system is constant, or does not vary strongly in time, the loss of fade margin experienced by that system will not depend on whether or not it employs diversity. In most cases interference variations are considered not to be strong when the variance of the interference power is comparable to the square of the average interference power.

Results from many simulations of the interference from uniform constellations of satellites indicate that the variance of the interference power is frequently orders of magnitude higher than the square of the mean interference power. In these cases, the contribution of the variance in the interference, as evidenced by the second term in equations (30) and (39), becomes the dominant effect, which will limit the acceptable interference power levels, regardless of whether one is using performance degradation or fade margin loss.

For purposes of evaluating the effects of interference in diversity systems, the FML of an ideal switched diversity system provides the simplest basis for comparisons.

### ANNEX 5

#### **Considerations of the uniformity of the interference environment in a month**

As time evolves, the sub-satellite point of a non-GSO satellite in a circular orbit traces out a path on the surface of the Earth. After some number of complete orbits, this path will return to the same, or almost the same, point on the surface of the Earth. The elapsed time for this occurrence is the repeat period of the satellite. Satellite constellations that have short repeat periods of several days or very long periods, such as many months, may require special consideration because FS systems must meet performance requirements in any month.

The period chosen for simulating non-GSO constellation interference into FS receivers should be chosen to satisfy two conditions. One is that the simulation period be equal to the repeat period of the constellation, which is the time between successive passes of a specific satellite over a given spot on the surface of the Earth. The second condition relates to the uniformity in longitude of the interference environment produced by the constellation. The statistics of the interference received by identical FS receivers at the same latitude may also depend on the station longitude. An assessment of this variation with longitude can be made by considering the distribution in longitude of the South-to-North Equatorial crossings of every satellite in the constellation over its repeat period.

Since FS systems must meet their performance requirements in any month, satellite interference assessments should be based on the worst month, nominally a 30-day period. Simulation runs to determine the FML in the fading regime, both for diversity and non-diversity FS receivers, show that the FDP or FML is sensitive to the constellation orbital parameters and the initial conditions of the constellation, parameters which control the uniformity of the interference environment in a month.

There may be a number of ways the longitudinal uniformity of interference can be achieved in planning a non-GSO constellation, for example, changing the altitude of the satellites, changing the angle between the orbital planes and/or introducing a plane-to-plane shift in the phase of the satellites within the planes. The practical viability of such approaches would need further study. The method chosen is not important to the FS. However, it should be recognized that inability to achieve uniformity could subject a significant number of FS stations to a worse interference environment. This would need to be taken into account in any detailed assessment of the effects of interference on real systems.

## ANNEX 6

**The methodology for developing the cumulative distribution of the ratio of received power to the sum of noise and interference powers from results of simulations of the emissions from constellations of non-GSO space stations**

## 1 Relationship between $C/I$ and $C/(N + I)$

The FDP and the FML for digital systems with performance thresholds in the deep multipath fading regime can be determined using the methods developed in Annex 3. The approach used in § 5 of that Annex can be extended to less deeply faded conditions where the shape of the cumulative distribution of fade depth may be important. The following distributions may be defined for this purpose:

$F_M(A)$ : probability that the received signal on a path fades to a level of  $A$  (dB) or more below the nominal, or unfaded receive level

$F_{C/(N+I)}(Z)$ : probability that the ratio of carrier power to noise-plus-interference power (dB), is  $Z$  (dB) or more below the unfaded carrier-to-noise power ratio.

The integral over the variable  $r$  in equation (20) is  $F_M(Z - 10 \log(1 + I/N_T))$ , and the left hand side of equation (20) is  $F_{C/(N+I)}(Z)$ . Thus:

$$F_{C/(N+I)}(Z) = \int_0^{\infty} p_I(I) F_M(Z - 10 \log(1 + I/N_T)) dI \quad (40)$$

For any distribution of multipath fading and probability density function of received interference power, equation (40) provides the means of developing the cumulative distribution of the ratio of carrier to noise-plus-interference power. The probability density of the interference power in a FS receiver, due to a constellation of non-GSO satellites is usually obtained by computer simulation. If this distribution is saved, it may be used in equation (40) afterwards in a separate calculation for evaluating the effects of fading on performance at moderate fade depths.

## 2 Modelling the cumulative distribution of fade depth

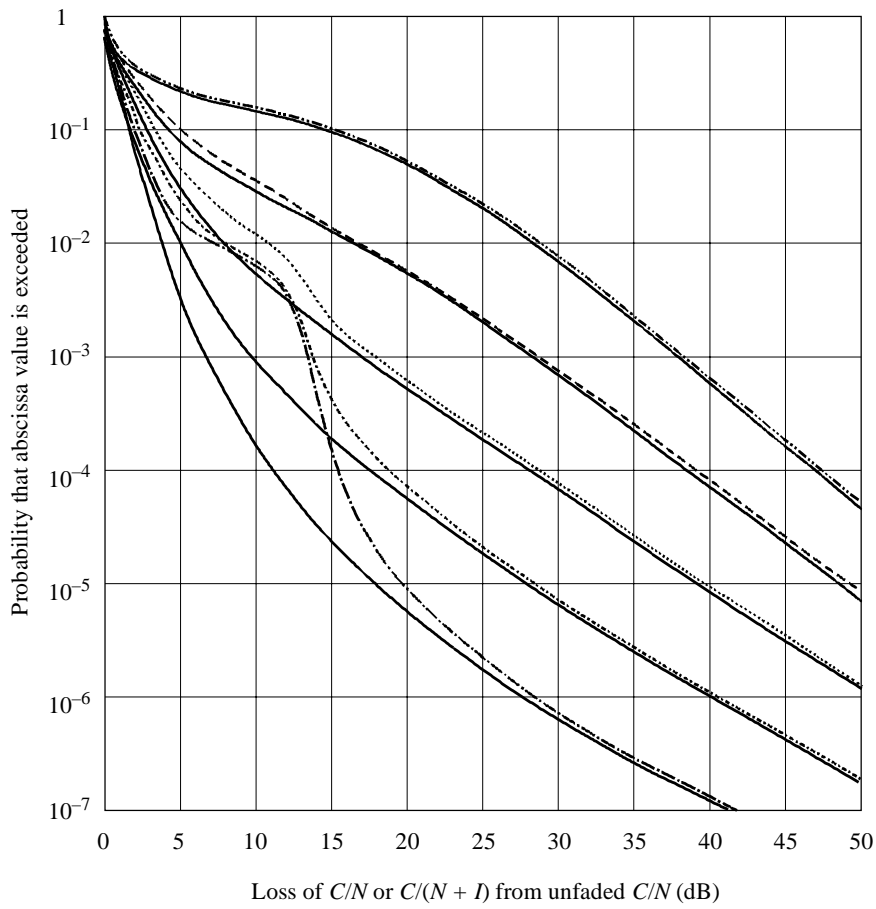
ITU-R has developed a mathematical model given in Recommendation ITU-R P.530 consisting of a family of multipath fading distributions, where the family is characterized by a parameter  $qt$ . This model can be used to define the function  $F_M(A)$  over all values of  $A$ , both positive and negative. The model provides a useful basis for clarifying procedures and illustrating results. It is used for this purpose in the following paragraphs.

## 3 An example

Figure 18 shows five pairs of distributions of the loss of  $C/I$  and  $C/(N + I)$ , one pair for each of five values of the  $qt$  parameter using the interference probability density developed for the case of a sample LEO-F constellation operating at pfd levels given in Recommendation ITU-R M.1141 at a frequency of 2180 MHz to a FS receiving station at 40° latitude and at a worst-case azimuth angle of 50°. For a given FS path of a given length and location in a geo-climatic area only a single  $qt$  value is applicable. At any point on one of the  $C/N$  distributions the vertical distance to the corresponding  $C/(N + I)$  distribution corresponds to a performance degradation, and the horizontal separation corresponds to a FML. The separations between the  $C/N$  and  $C/(N + I)$  distributions can be determined precisely with a carefully written computer program. The results of such a calculation are given in Fig. 19 for the distributions shown in Fig. 18.

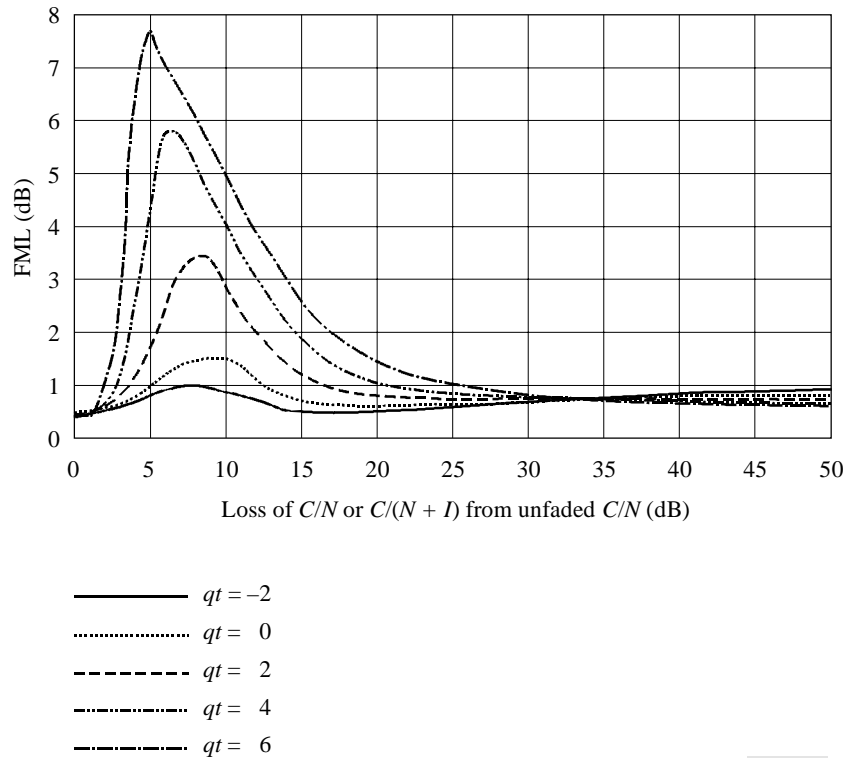
The loss of  $C/N$  with respect to the unfaded  $C/N$  is identical to fade depth. Although the FML decreases slightly at shallower fade depths for the case of  $qt$  equal to  $-2$ , for the positive values of  $qt$ , which are more typical of fading below 3 GHz, the FML increases significantly at shallower fade depths.

FIGURE 18  
**Cumulative probability distributions of the loss  $C/N$  and  $C/(N + I)$  from unfaded  $C/N$  from a simulation of a LEO-F constellation for non-diversity operation for a FS receiving antenna at  $50^\circ$  azimuth from North with several values of parameter  $qt$**



- |                       |                      |
|-----------------------|----------------------|
| ————— $qt = -2$       | ————— $qt = 4$       |
| - - - - - $I:qt = -2$ | - - - - - $I:qt = 4$ |
| ————— $qt = 0$        | ————— $qt = 6$       |
| - - - - - $I:qt = 0$  | - - - - - $I:qt = 6$ |
| ————— $qt = 2$        |                      |
| ..... $I:qt = 2$      |                      |

FIGURE 19  
**Non-diversity FML at a specified fade depth derived from simulation**  
**results used in Fig. 18**  
 (Azimut = 50°)



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#### 4 Conclusions

FML at intermediate fade levels can be significantly larger, larger by many decibels, than the loss at deep fading levels. The larger values of FML are associated with the slope of the cumulative distribution of fading. This association is apparent from comparing Figs. 18 and 19, for instance. Here it is seen that the largest loss occurs for the fading distributions that have the largest slope and near the fade levels where these large slopes occur. Clearly, the FML at intermediate depths is sensitive to the detailed shape of the cumulative distribution of fade levels on a path.

Nevertheless, the methodology developed in this Annex can be applied to any fade depth distribution. It will need to be exercised with real fading distributions or the Recommendation ITU-R P.530 model. The detailed assessment of the actual impact of the FML on the performance of a given FS system would require detailed knowledge of the system characteristics or of its error performance at a specified fading level along with its performance criteria.