RECOMMENDATION ITU-R F.1108-4

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)

(1994-1995-1997-2002-2005)

Scope

This Recommendation contains various methodologies to determine the criteria to protect fixed service receivers from emissions of space stations operating in non-geostationary orbits in shared frequency bands, including highly elliptical orbits (HEOs).

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 fixed wireless systems and Recommendation ITU-R SF.357 in the case of analogue fixed wireless 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.1397 and ITU-R F.1491 are derived) imposes stricter error performance objectives for digital fixed wireless 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);

4.7 that Annex 7 provides an example methodology that could be used to evaluate the interference to a station in the FS from a non-GSO satellite constellation using circular or elliptical orbits, including highly elliptical orbits (HEOs).

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, θ, λ) where r is the distance from the origin, θ is the angular distance from the North Pole, and λ 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 π 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

Ω_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.

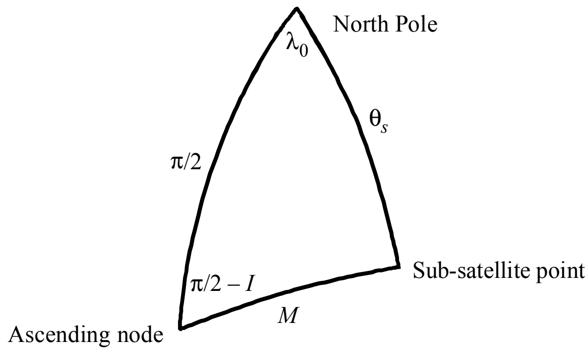
To determine the coordinates of the satellite in the inertial spherical coordinate system, one must first determine the position of the satellite referenced to Ω_0, the angular position or longitude of the ascending node, measured East of the first point of Aries. The position of the sub-satellite point is denoted by θ_s and λ_0.

These coordinates may be determined by spherical geometry with reference to Fig. 1. Applying the law of cosines to the arc θ_s gives $\cos \theta_s = \sin M \sin I$. Since θ 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



1108-01

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 λ_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 2π rad in 23 h, 56 min, and 4.09 s, the East longitude of the sub-satellite point, λ_s is given by:

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

where $\Delta E = 7.292115856 \times 1^{-5}$ 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 (= 6 378.14 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:

$$\lambda_s = \lambda_0 + \Omega_0 - (\Delta L + \Delta E)\, t \tag{4}$$

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:

$$M = M_0 + \Delta M\, t \tag{5}$$

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), θ_T and λ_T, may be obtained with the following two relations.

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

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

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

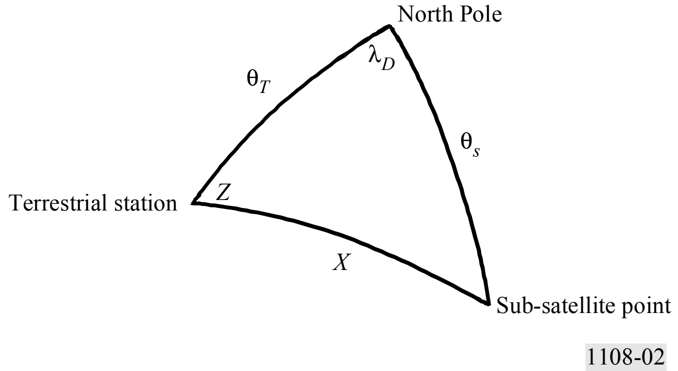
$$\lambda_D = \lambda_S - \lambda_T \tag{8}$$

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:

$$X = \arccos\,(\cos\theta_T \cos\theta_s + \sin\theta_T \sin\theta_s \cos\lambda_D) \tag{9}$$

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 θ_s in Fig. 2:

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

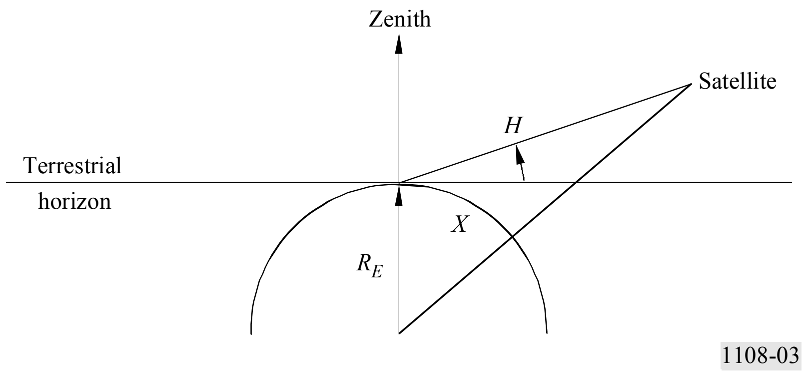
5 Satellite elevation and angular distance from main beam

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

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

FIGURE 3

Plane containing Earth centre, terrestrial station, and satellite

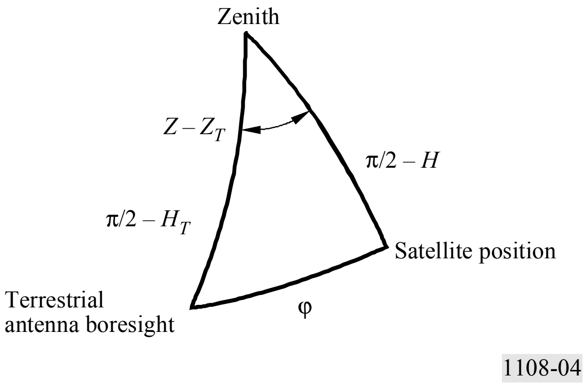


Assume that the receiving antenna of the terrestrial antenna is aimed along the azimuth Z_T with an elevation angle of H_T rad above the local horizontal. The angular distance φ from the main beam of this terrestrial station antenna to the satellite may be obtained by considering the spherical coordinate 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 φ gives:

$$\varphi = \arccos\left(\sin H_T \sin H + \cos H_T \cos H \cos (Z - Z_T)\right) \quad (12)$$

FIGURE 4

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



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:

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

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 fixed wireless 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 fixed wireless 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 fixed wireless receiver in a concentration randomly distributed fixed wireless routes. The program accumulates interference density data for each fixed wireless 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 fixed wireless route trendlines,
– fixed wireless 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 fixed wireless 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:

$$pfd_{low} \quad \text{for} \quad 0 \leq \theta \leq 5°$$

$$pfd = pfd_{low} + 0.05\,(pfd_{hi} - pfd_{low})\,(\theta - 5) \quad \text{for} \quad 5° < \theta \leq 25°$$

$$pfd_{hi} \quad \text{for} \quad 25° < \theta \leq 90°$$

2.2 Output

The output of the program is a single data file named Leo.dat. Information is provided for each simulated fixed wireless 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 fixed wireless 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 fixed wireless 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 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^2) (4 kHz bandwidth) for all angles of arrival), as might be expected, that orbit altitude, i.e. 800 km and 10 330 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 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 5

FS interference versus frequency
(800 km, 50 hop routes, 33 dB antenna gain, 40° latitude, pfd = –154/–144 dB(W/(m² · 4 kHz)))

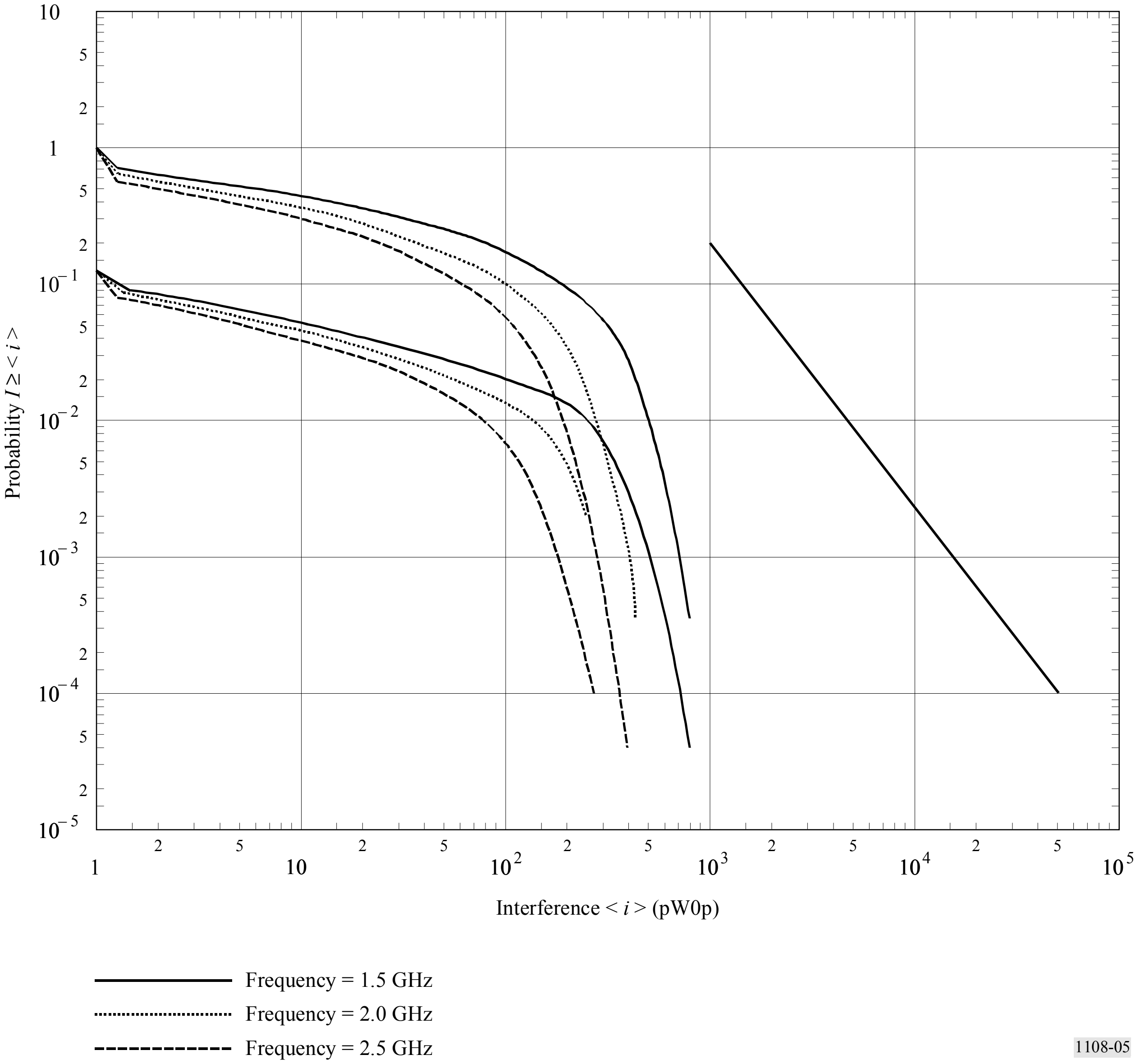
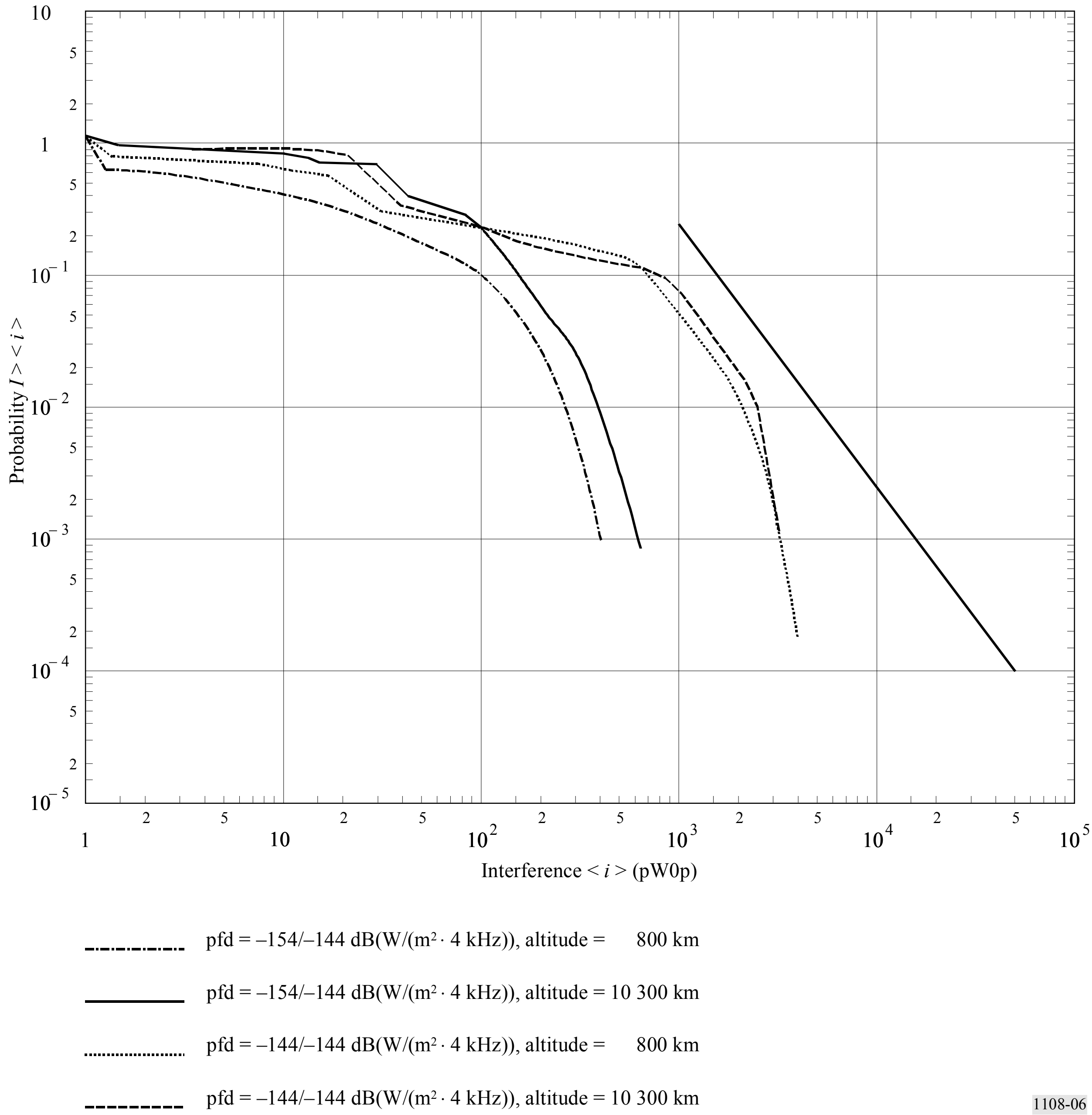


FIGURE 6

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

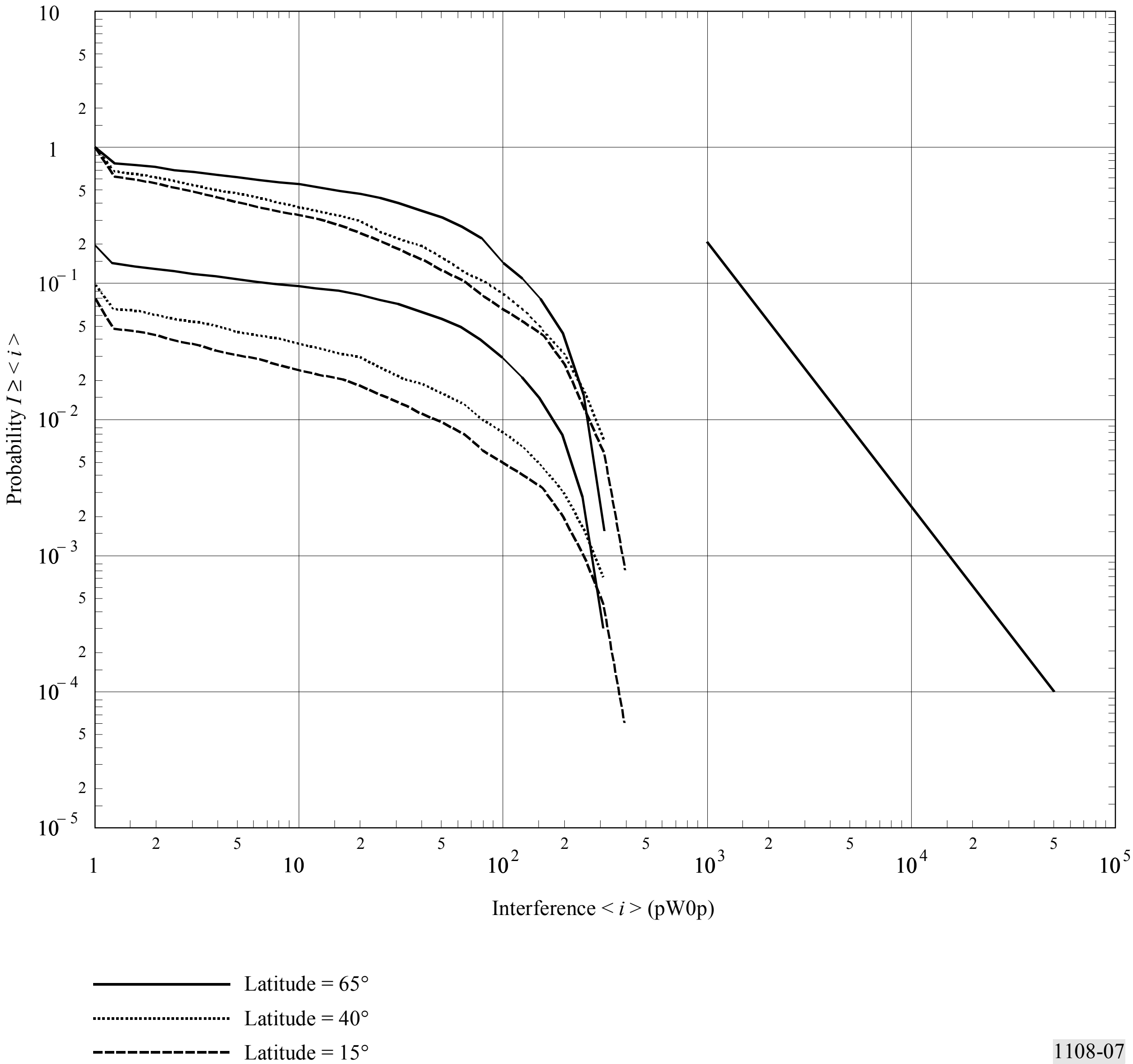


The lower group of three curves in Fig. 7 represent the distributions of received interference distributions at different latitudes from single orbiting satellites that have high orbit angles (80°). It is interesting to note here that if the curve plots were extrapolated back to the y axis for $X = 0$ 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 fixed wireless routes does appear to intercept the y axis at a much higher point.

FIGURE 7

Interference (*i*) pW in 4 kHz bandwidth

FS interference versus latitude
(50 hops, 33 dB antenna gain, pfd = –154/–144 dB(W/(m² · 4 kHz)), 2 GHz)



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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 bevisible 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°) 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° with inclinations of 56° and 4 satellites per plane.

FIGURE 8

Interference (*i*) pW in 4 kHz bandwidth

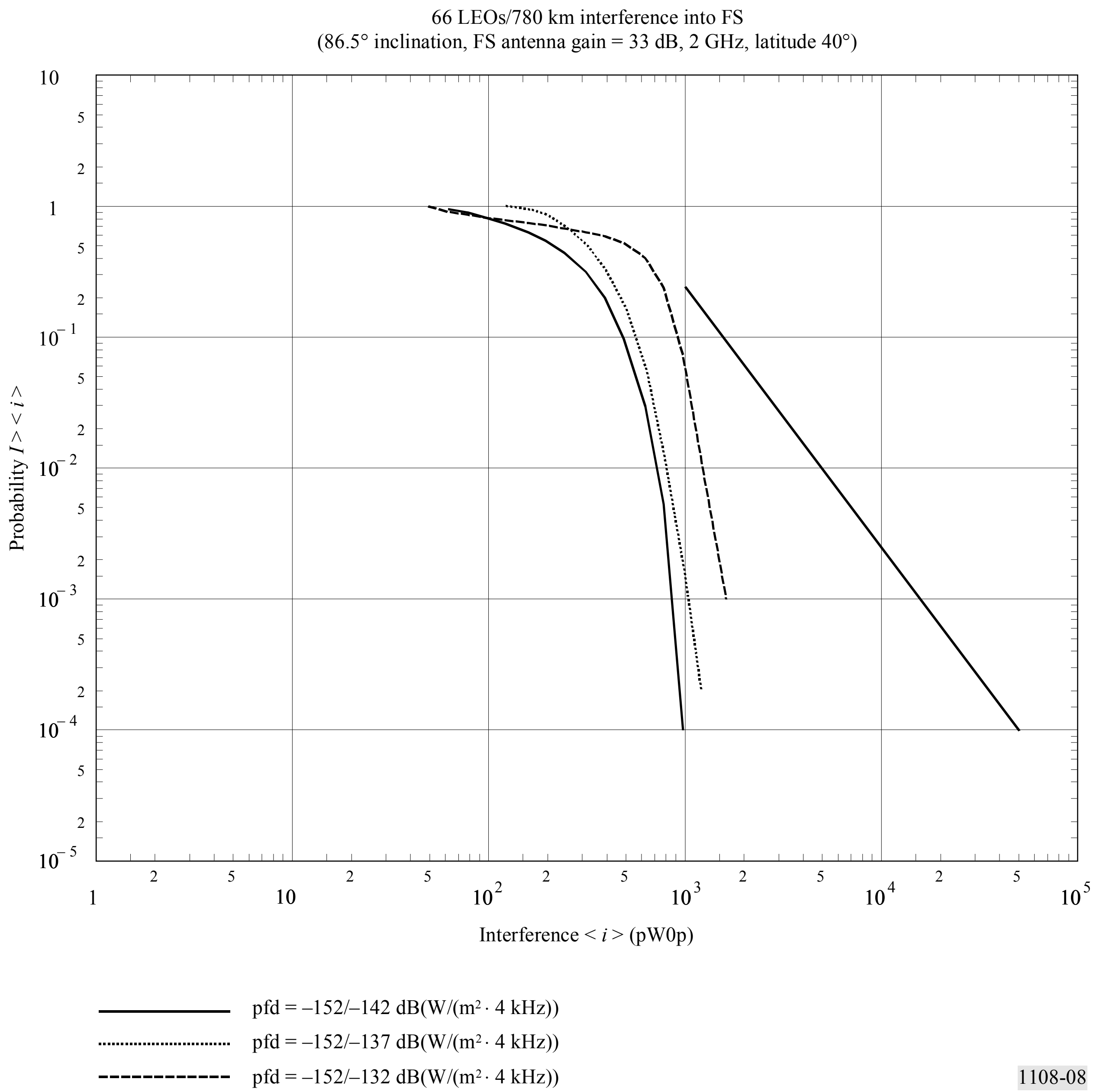
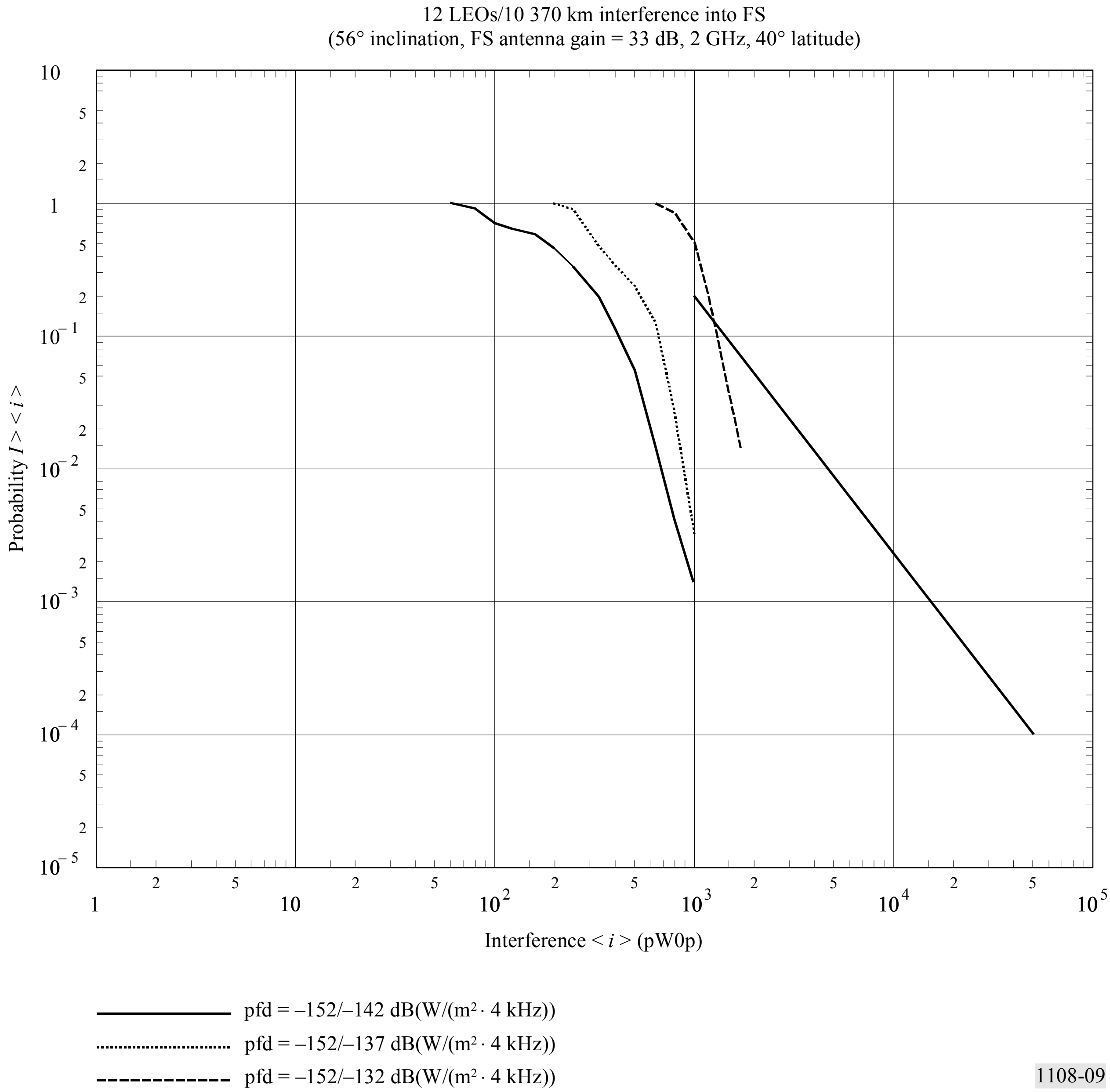


FIGURE 9

Interference (*i*) pW in 4 kHz bandwidth



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 fixed wireless systems. Recommendation ITU-R SF.357 provides a criteria which might be used for establishing pfd limits for sharing with analogue fixed wireless 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 fixed wireless 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^2 · 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 φ is given by:

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

where λ 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:

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

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 critical 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:

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

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:

$$FML = 10 \log (1 + FDP) \tag{16}$$

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 1×10^{-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:

$$\frac{rC}{N_T} < k \tag{17}$$

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:

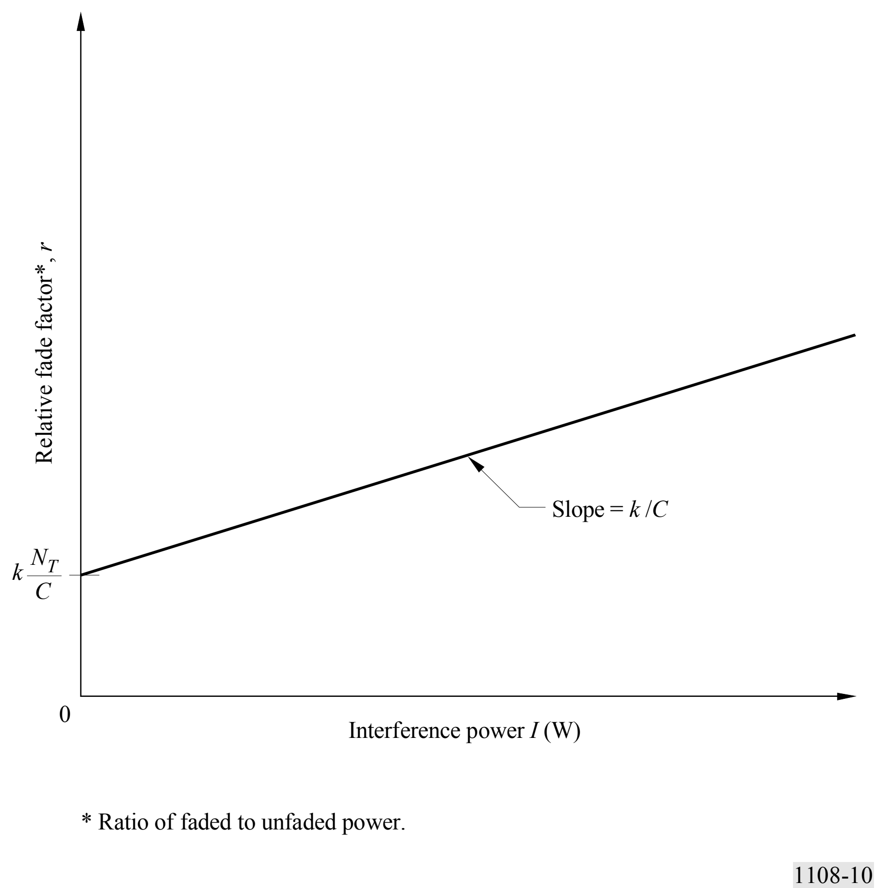
$$r \le k\left(\frac{N_T}{C} + \frac{I}{C}\right) \tag{19}$$

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:

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

FIGURE 10

Boundary of region where critical performance criterion is met



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.

$$p_r(r) = \beta \qquad r << 1 \tag{21}$$

where β 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).

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

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

$$I_{av} = \int_0^{\infty} I p_I\,(I)\,\mathrm{d}I \tag{23}$$

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

$$FDP = \frac{I_{av}}{N_T} \tag{24}$$

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^2 · 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^2 · 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 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

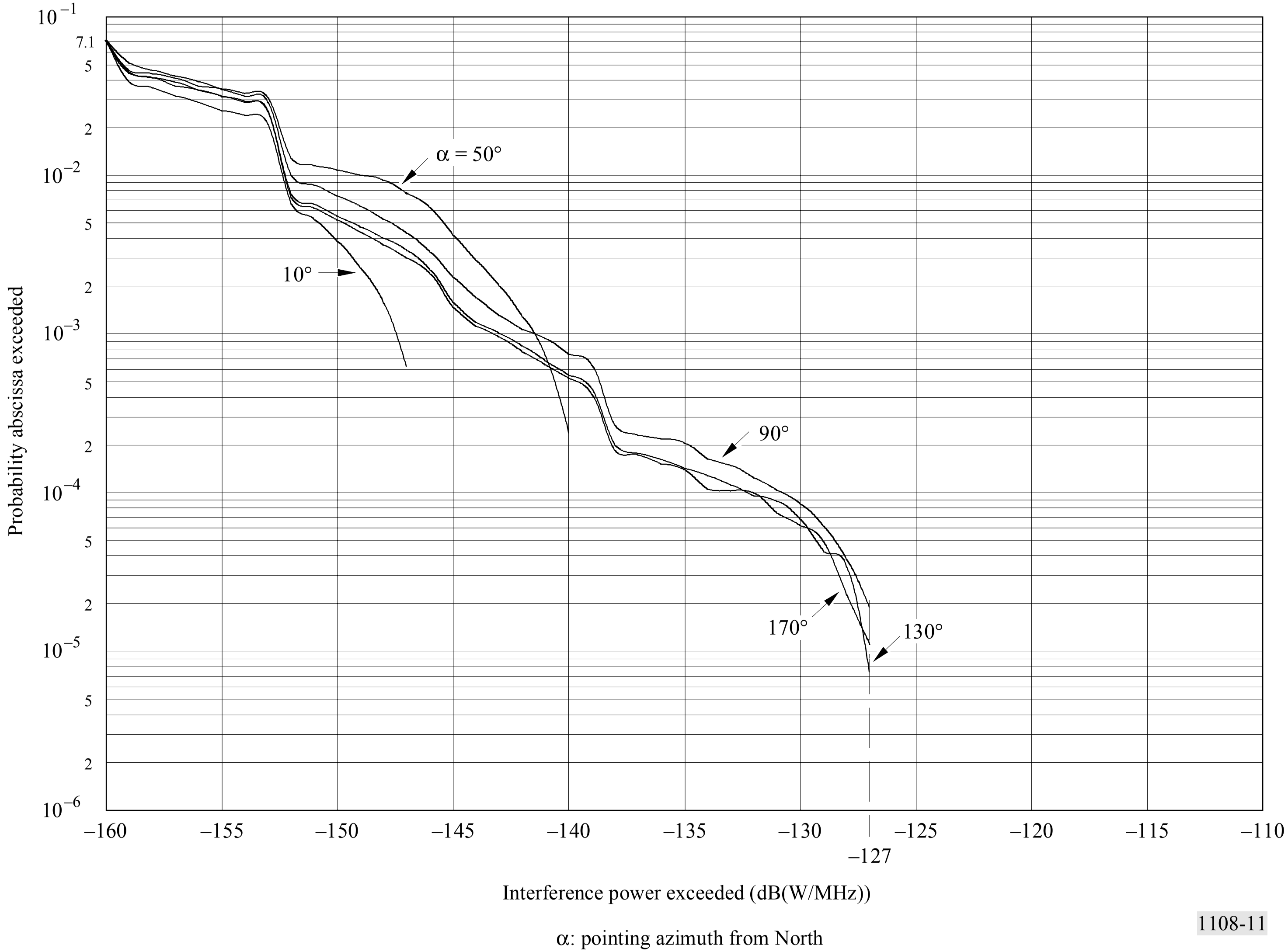


FIGURE 12

Percentage performance degradation for the case in Fig. 11

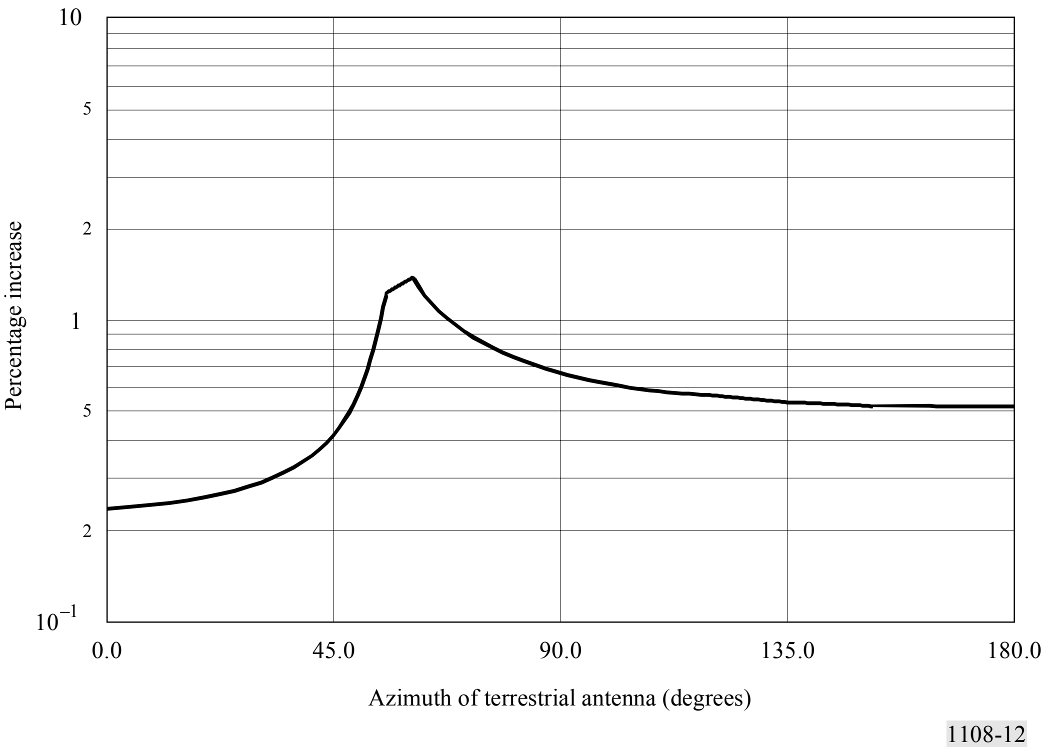


Figure 13 shows the cumulative distribution of received interference power for the same situation except for the orbital inclination which is 89.5°. Clearly the effect of azimuth is much less pronounced in this case.

FIGURE 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

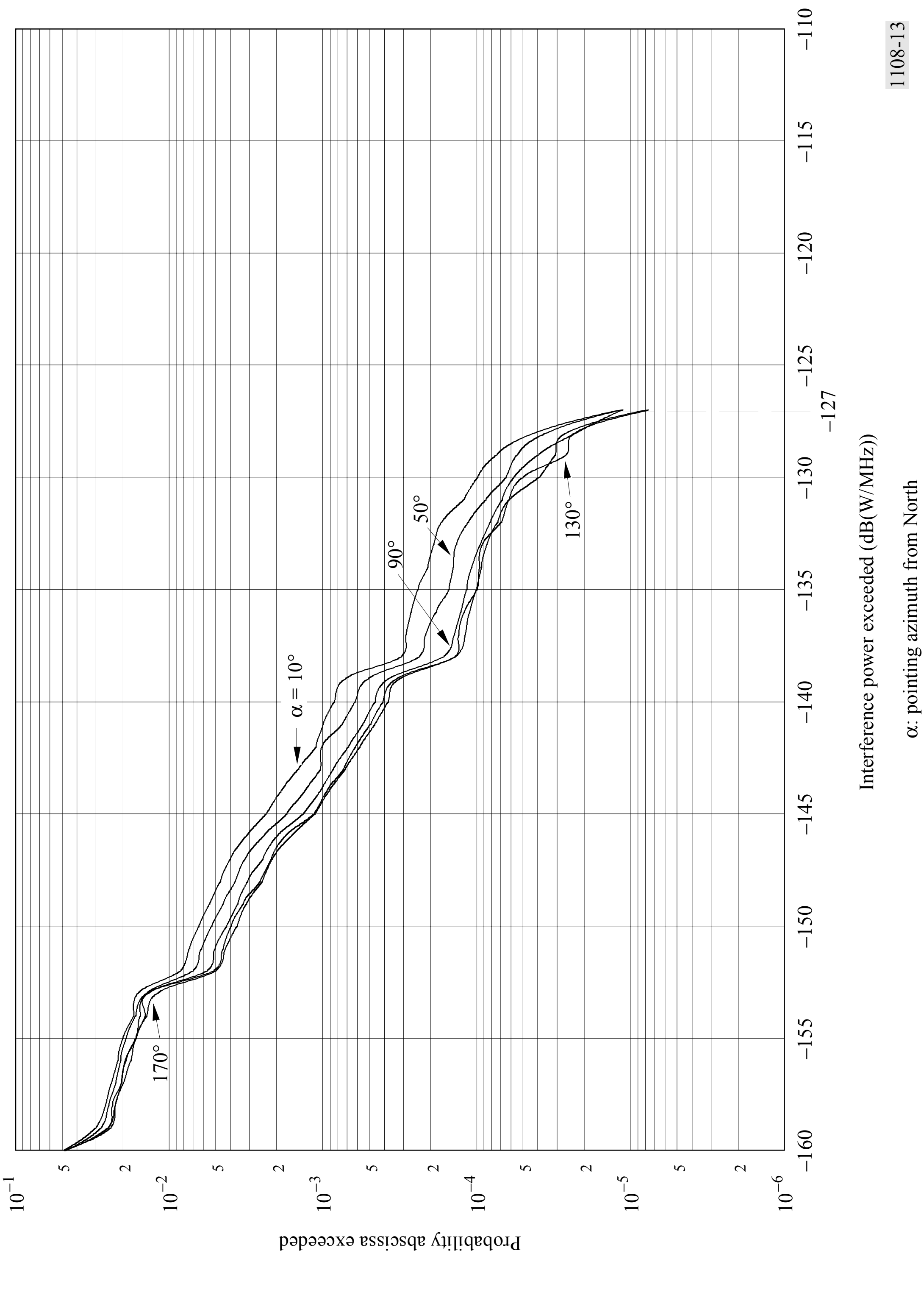
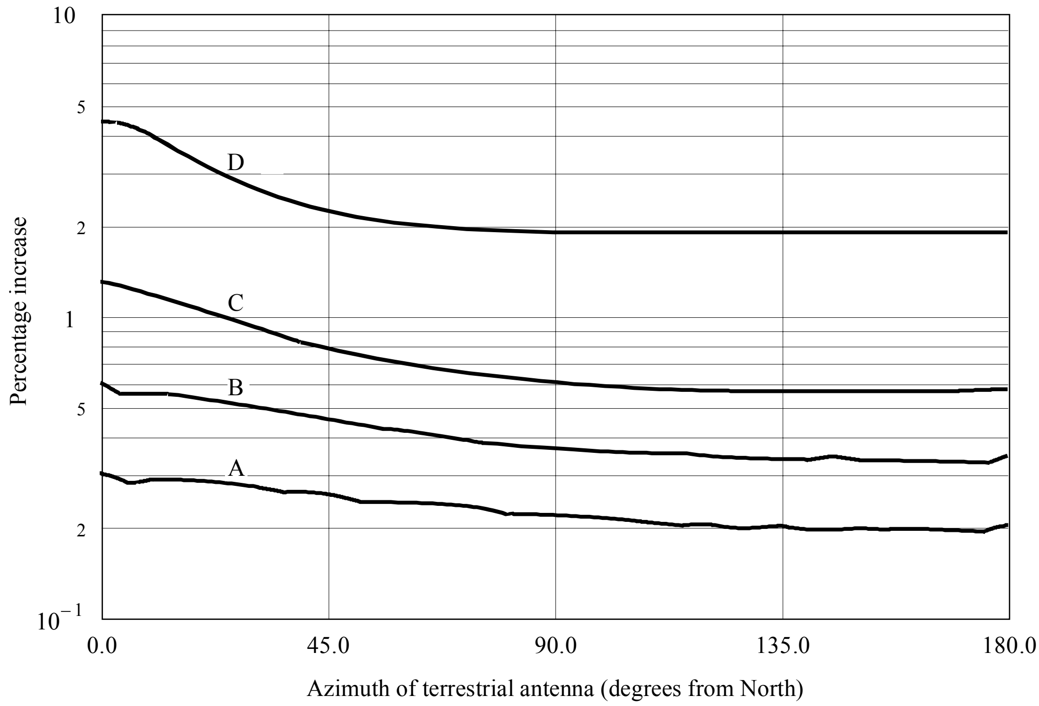


Figure 14 illustrates the effect of satellite altitude through a plot of percentage degradation in performance versus azimuth angle. The performance degradation caused by a satellite increases linearly with orbital altitude up to nearly 10 000 km as does the area of the Earth visible to the satellite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



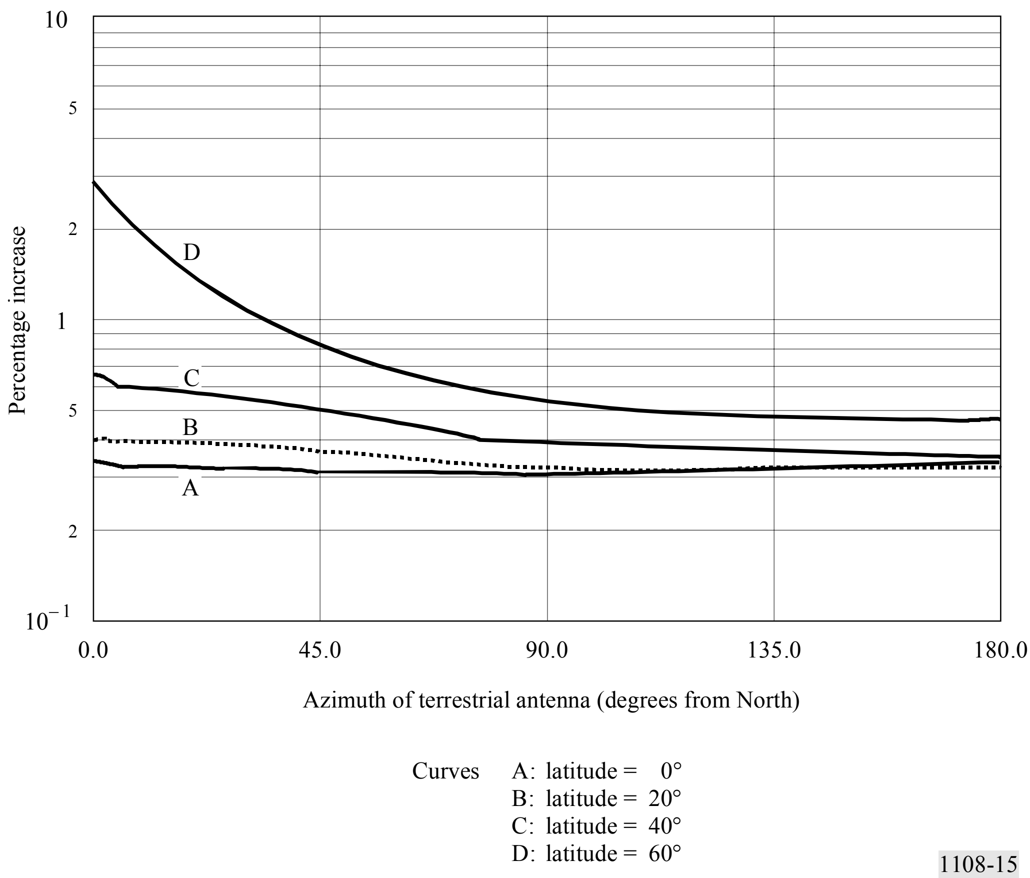
Curves A: altitude = 400 km
B: altitude = 800 km
C: altitude = 1 600 km
D: altitude = 10 000 km

1108-14

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



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

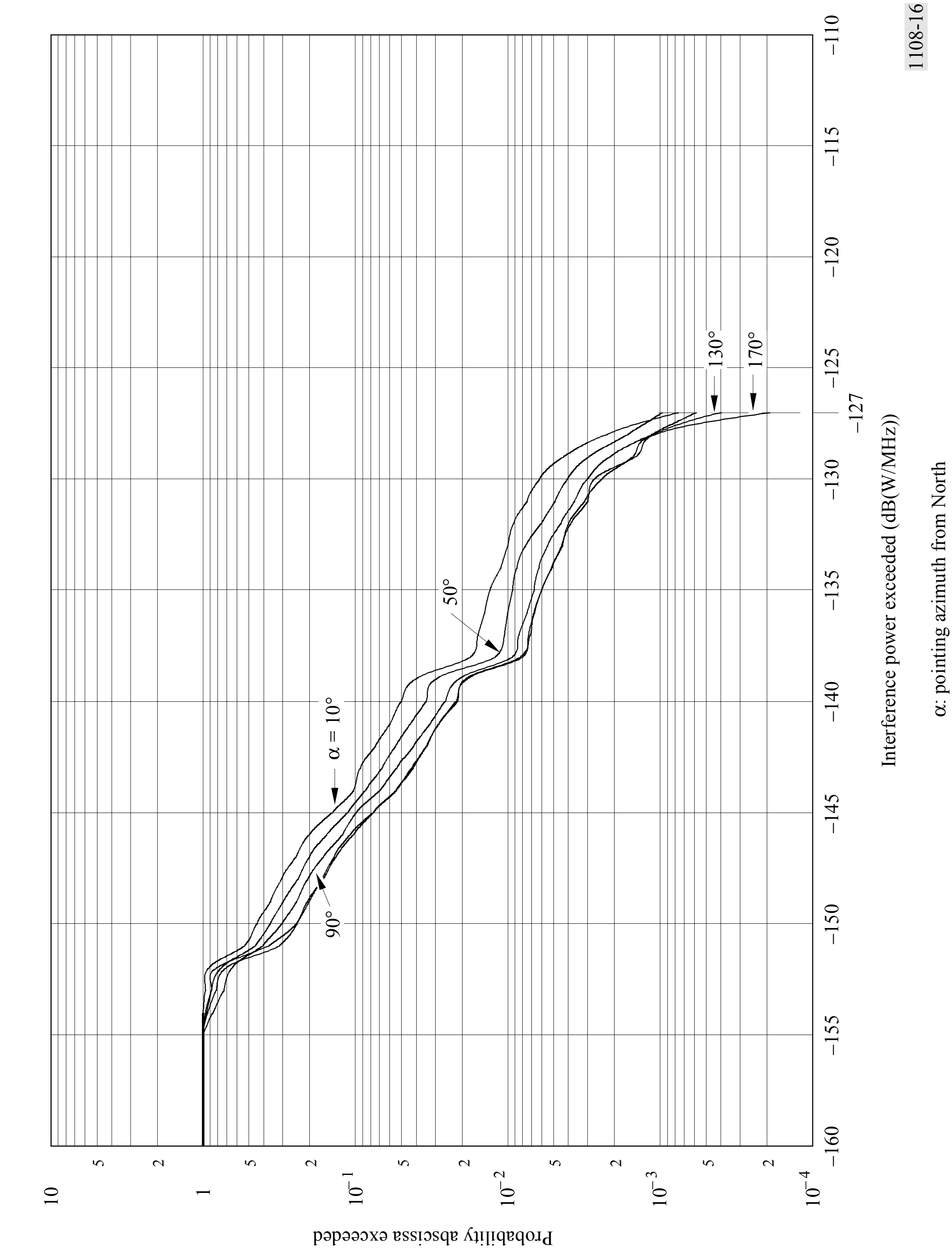
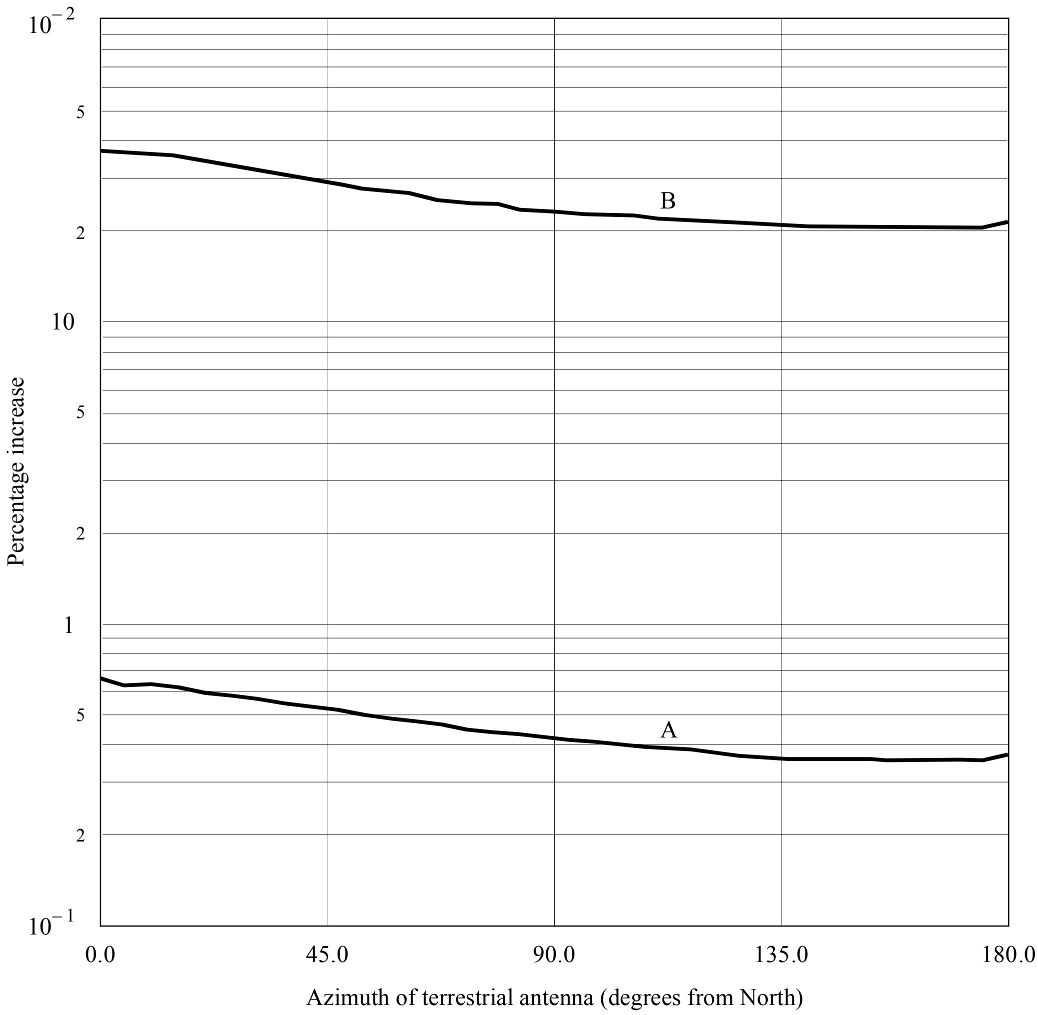


FIGURE 17

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

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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 HEO 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:

$$P_{0i} = \int_0^{\infty} \mathrm{d}I \, p_I(I) \int_0^{(k/C)(N_T + I_C)} \mathrm{d}r \, p_r(r) \qquad (25)$$

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:

$$p_r(r) = \gamma \, r \qquad r \ll 1 \qquad (26)$$

where the parameter γ 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:

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

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

$$DFDP = \int_0^\infty \left(\frac{2I_C}{N_T} + \frac{I_C^2}{N_T^2} \right) p_I(I) \, \mathrm{d}I \tag{28}$$

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:

$$DFDP = \int_0^\infty \left(\frac{2I}{N_T} + \frac{I^2}{N_T^2} \right) p_I(I) \, \mathrm{d}I \tag{29}$$

or:

$$DFDP = 2\frac{I_{av}}{N_T} + \frac{I_2}{N_T^2} \tag{30}$$

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

$$I_2 = \int_0^\infty I^2 p_I(I) \, \mathrm{d}I \tag{31}$$

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

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

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 φ radians, the interference power at the combiner output, I_C, would be given as:

$$I_C = 2I \cos^2 (\varphi/2) \tag{33}$$

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

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

or:

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

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

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

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:

$$DFML = 5 \log (1 + DFDP) \tag{37}$$

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

$$\sigma_I^2 = I_2 - I_{av}^2 \tag{38}$$

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

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

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 an 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:

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

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 2 180 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° azimuth from North with several values of parameter *qt*

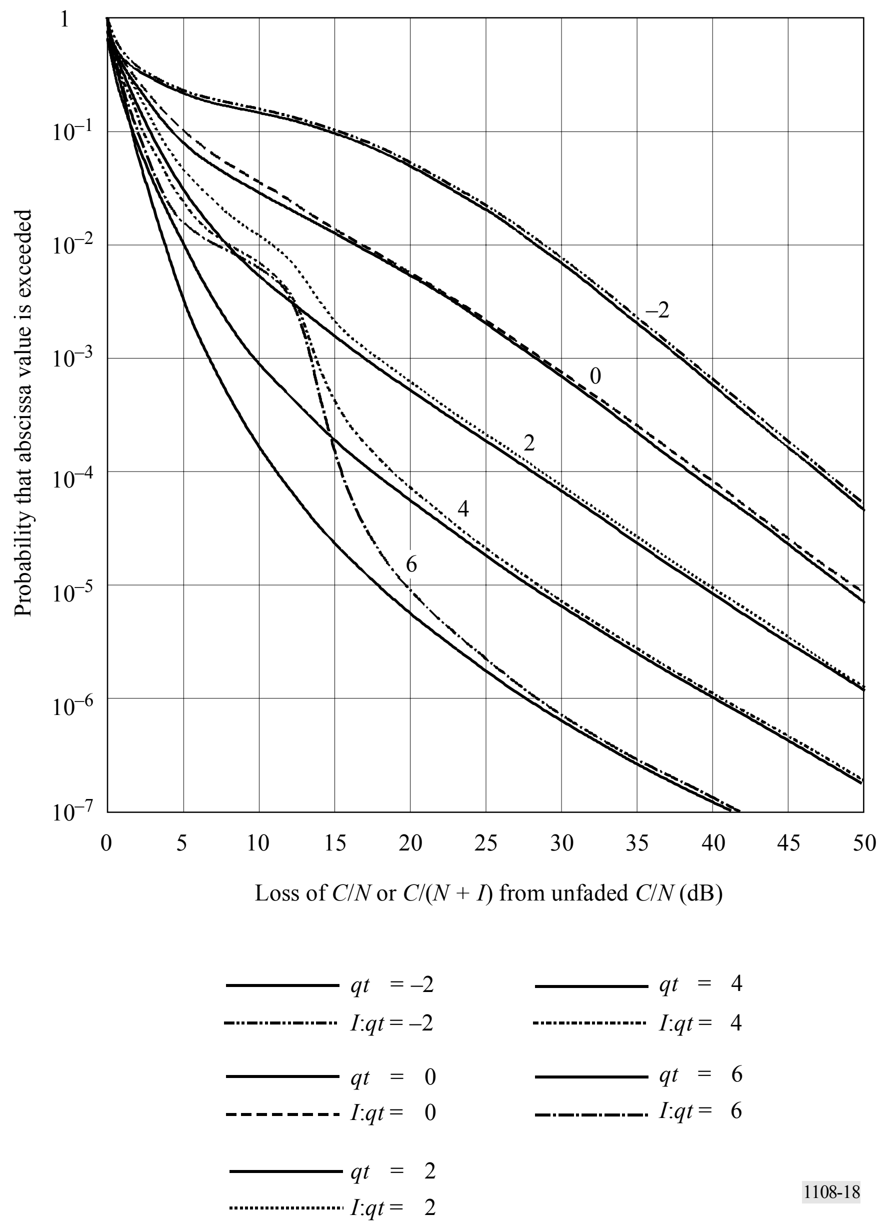
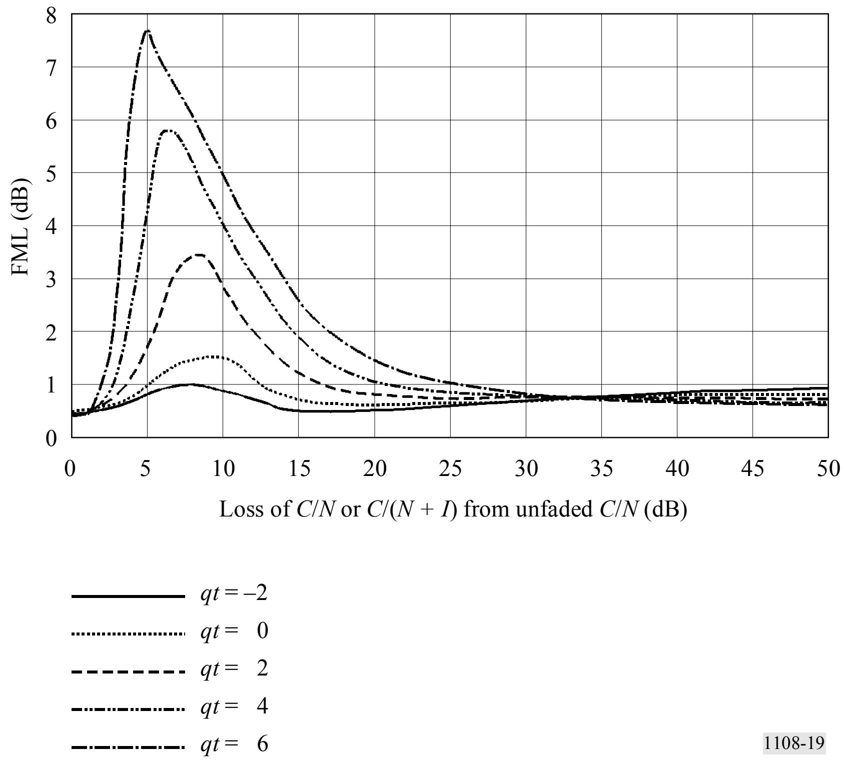


FIGURE 19

Non-diversity FML at a specified fade depth derived from simulation results used in Fig. 18

(Azimuth = 50°)



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.

Annex 7

Analytical method for evaluating the interference to a station in the FS from a non-GSO satellite constellation using circular or elliptical orbits including HEOs

1 Introduction

The following assumptions are made for a non-GSO satellite constellation:

– there are M_s orbital planes and N_s satellites in a plane;

– the separation angle between the adjacent orbital planes is uniform;

– the time interval between two adjacent satellites in a plane is uniform;

– orbital period is not rationally related to the Earth's revolution;

– all satellites are always transmitting at the same frequencies;

– the inclination angle, δ, is common to all satellites.

It is also assumed that, in the case of an elliptical orbit, the argument of perigee is common to all satellites.

The method in this Annex is applicable to the assessment of interference from a non-GSO satellite constellation employing medium or low Earth orbits and consisting of many satellites operating in a number of orbital planes, with a worldwide coverage. As for the applicable frequency range, there is no limit from the viewpoint of the principle of this method apart from any limitations that may be included in the relevant ITU-R Recommendations. Features of the analytical method in this Annex are summarized in § 6.

Some modifications to the method are necessary when carrying out assessment of interference from non-GSO satellite constellations employing HEOs.

Appendix 2 to this Annex presents the necessary modifications required in order to make the following analytical method applicable to non-GSO satellite constellations employing HEOs.

Although the analytical methods described in this Annex and in Appendix 2 to this Annex assume that an FS system is comprised of a single station, it is easy to extend the methods to the route basis evaluation of the aggregate interference into a multi-hop FS system in which the route basis FDP is defined by the formula as presented in Annex 2 to Recommendation ITU-R F.1107.

2 Case of circular orbits

In the case of circular orbits, the range of a satellite is constant. The probability density function (pdf), $p(u)$, of the argument of a satellite to be in a range $(u, u + \mathrm{d}u)$ is uniform as follows:

$$p(u) = 1/(2\pi) \tag{41}$$

Assuming that the period of a satellite is unity, without losing generality, the argument, u, at time, t $(0 \leq t < 1)$, is given by:

$$u = 2\pi t \tag{42}$$

Under the conditions given in § 1, we can assume that the pdf of the longitude of a satellite is uniform over 0-2π.

Therefore, when there are M_s orbital planes and N_s satellites in a plane, we can assume that the pdf of the argument of a reference satellite is uniform over 0-$2\pi/N_s$ and the pdf of the longitude of the reference satellite is uniform over 0-$2\pi/M_s$. Thus, when the argument and longitude of the reference satellite are u and φ, respectively, the argument, u_{ij}, and the longitude, φ_{ij}, of i-th satellite in j-th plane (for $i = 1, 2, \ldots, N_s$ and $j = 1, 2, \ldots, M_s$) are given by (see Note 1):

$$u_{ij} = u + (i - 1)\ 2\pi/N_s \tag{43a}$$

$$\varphi_{ij} = \varphi + (j - 1)\ 2\pi/M_s \tag{43b}$$

where $i = 1$ and $j = 1$ correspond to the reference satellite. Then, the interference can be determined generally according to the method described in § 4.

NOTE 1 – Equation (43a) assumes that there is no phase difference between satellites in different planes. If there is any phase difference, this equation should be modified as $u_{ij} = u + \beta_j + (i - 1)\ 2\pi/N_s$, where β_j is the phase difference of j-th plane ($\beta_1 = 0$).

3 Case of elliptical orbits

3.1 Range of a satellite

The range (from the centre of the Earth), $r(u)$, of a satellite in an elliptical orbit can be expressed as a function of the argument, u, as follows:

$$r(u) = \frac{r_0}{1 + e \cdot \cos(u - \omega)} \tag{44}$$

where e and ω are the eccentricity and the argument of perigee, respectively, and the ranges of the apogee and the perigee of the orbit from the centre of the Earth are given by $r_0/(1 - e)$ et $r_0/(1 + e)$, respectively. Conversely, r_0 and e can be expressed as follows:

$$r_0 = 2\ r_{max} \cdot r_{min} \ / \ (r_{max} + r_{min}) \tag{45a}$$

$$e = (r_{max} - r_{min}) \ / \ (r_{max} + r_{min}) \tag{45b}$$

where r_{max} and r_{min} are the ranges of apogee and perigee from the centre of the Earth, respectively.

3.2 pdf of the satellite argument

A well-known theorem of the elliptical orbit (Kepler's second law) is that "the swept area velocity is constant". This can be expressed as follows:

$$r^2(u) \cdot (\mathrm{d}u \ / \ \mathrm{d}t) = \text{constant} \tag{46a}$$

or

$$\mathrm{d}t \propto r^2(u) \cdot \mathrm{d}u \tag{46b}$$

Here, it should be noted that dt is proportional to the probability that the satellite argument lies in the range (u, u + du). Therefore, the pdf of a satellite, $p(u)$, as a function of the argument, u, is given by:

$$p(u) = \frac{\alpha}{[1 + e \cdot \cos(u - \omega)]^2} \tag{47}$$

If $p(u)$ is integrated with respect to u over 0-2π, the result should be equal to unity. From this, α is determined as follows:

$$\alpha = \frac{(1 - e^2)^{3/2}}{2\pi} \tag{48}$$

Here, it should be noted that the satellite latitude, θ, is determined as a function of the argument as follows:

$$\theta = \arcsin(\sin u \cdot \sin \delta) \tag{49}$$

where δ is the inclination angle of the orbit. This equation is applicable to circular orbits, too.

3.3 Determination of the argument as a function of time

For simplicity, we can assume that the period of the satellite is 1, without loss of generality. Very often it is necessary to determine the argument, $u(t)$, as a function of time, t, where $0 \leq t < 1$. This can be determined by solving the following equation:

$$t = \int_0^{u(t)} p(x) \cdot \mathrm{d}x \tag{50}$$

In order to simplify the calculation of $u(t)$ without loss of accuracy, the following approach may be appropriate. One period is divided by N, and t_k is defined as:

$$t_k = k/N \quad (k = 0, 1, \ldots, N) \tag{51}$$

The argument corresponding to t_k is designated as $u_k = u(t_k)$. Then, u_k is determined by:

$$\int_{u_{k-1}}^{u_k} p(x) \cdot \mathrm{d}x = \frac{1}{N} \tag{52}$$

An approximate value of u_k is given by (note that $u_0 = 0$):

$$u_k \cong u_{k-1} + \frac{1}{N \cdot p(u_{k-1})} \tag{53}$$

which is derived by assuming that $p(x)$ is constant in the range (u_{k-1}, u_k). This can be used as the initial approximate value and an accurate value of u_k can be determined, for example, by the Newton-Raphson's method (see Note 1). Thus, u_k can be determined for all values of t_k ($k = 0, 1, \ldots, N$). Note that $u_N = 2\pi$.

The value of $u(t)$ corresponding to time t can be approximated as follows:

$$u(t) = N\,[(t_{k+1} - t) \cdot u_k + (t - t_k) \cdot u_{k+1}] \tag{54}$$

where $t_k \le t < t_{k+1}$ (if $t \ge 1$, this inequality should be replaced by $t_k \le t - 1 < t_{k+1}$). If N is sufficiently large (for example, $N = 10\,000$), equation (54) gives an accurate value of $u(t)$ as a function of time. A simplified calculation method which eliminates the need of integration in equation (52) is described in Appendix 1.

NOTE 1 – The Newton-Raphson's method is briefly described below.

Based on equation (53), the initial approximate value ν_0 of u_k is defined as:

$$\nu_0 = u_{k-1} + \frac{1}{N \cdot p(u_{k-1})} \tag{55}$$

When the approximate value ν_{i-1} is known, the next approximate value ν_i is given by:

$$\nu_i = \nu_{i-1} - \frac{f(\nu_{i-1})}{p(\nu_{i-1})} \qquad (i = 1, 2, 3,\ldots..) \tag{56}$$

where

$$f(\nu_{i-1}) = \int_{u_{k-1}}^{\nu_{i-1}} p(x) \cdot \mathrm{d}x - \frac{1}{N} \tag{57}$$

and both $p(\nu_{i-1})$ and $p(x)$ are given by equation (47) (note that $p(x)$ is the derivative of $f(x)$). By repeating the calculations according to equations (56) and (57), an accurate value of u_k is easily obtained. The convergence is very rapid. The value of $f(\nu_{i-1})$ can be calculated, for example, by the Simpson's method.

3.4 Determination of satellite locations

This section gives a method for determining locations of non-GSO satellites employing elliptical orbits. It is assumed that there are M_s orbital planes and N_s satellites in one orbital plane.

We can assume that the location (in time) of a reference satellite is uniformly distributed within $0 \le t < 1/N_s$ and its longitude, φ, is uniformly distributed within $0 \le \varphi < 2\pi/M_s$. The corresponding argument, $u(t)$, is given by equation (54). The arguments of other satellites in the same orbital plane can be determined as the arguments corresponding to $t + (k/N_s)$, where $k = 1$ to $N_s - 1$.

The latitudes of the satellites in this orbital plane containing the reference satellite can be determined by using equation (49). The arguments of satellites in other orbital planes may be considered to be the same as those of the reference orbital plane. It is easy to determine the longitudes of all satellites on the basis of the longitude and argument of the reference satellite.

For actual calculations, it is necessary to calculate the interference at sample points. For this purpose, the maximum time (= $1/N_s$) of the reference satellite is divided by N_t and the maximum longitude (= $2\pi/M_s$) of the reference satellite is divided by M_φ. Thus the probability of the reference satellite appearing at the following time and longitude is $1/(M_\varphi \cdot N_t)$:

$$t = \frac{1}{N_s} \cdot \frac{i_t - 0.5}{N_t} \qquad (i_t = 1, 2, \dots, N_t) \tag{58a}$$

$$\varphi = \frac{2\pi}{M_s} \cdot \frac{j_\varphi - 0.5}{M_\varphi} \qquad (j_\varphi = 1, 2, \dots, M_\varphi) \tag{58b}$$

Equations (49), (54), (58a) and (58b) can be used as a basis for determining the latitudes and longitudes of all satellites in the constellation.

From the viewpoint of computation time, the values of M_φ and N_t may not be sufficiently large. Therefore, in order to make detailed calculations in sensitive regions, the following approach should be adopted.

For each cell defined by equations (58a) and (58b), the antenna separation angles should be calculated for all visible satellites. If the minimum separation angle is smaller than a certain threshold angle, this cell should be regarded as a sensitive region, and it should be further divided into smaller cells (see Note 1).

When the time and longitude of the reference satellite are given by equations (58a) and (58b), respectively, the time, t_{ij}, and the longitude, φ_{ij}, of i-th satellite in j-th plane (for $i = 1, 2, \dots, N_s$ and $j = 1, 2, \dots, M_s$) are given by:

$$t_{ij} = t + (i - 1)/N_s \tag{59a}$$

$$\varphi_{ij} = \varphi + (j - 1)\, 2\pi/M_s \tag{59b}$$

where $i = 1$ and $j = 1$ correspond to the reference satellite. The argument, u_{ij}, of i-th satellite in j-th plane can be calculated by applying equations (54) and (59a) (see Note 2).

NOTE 1 – When the elevation angle of the interfered-with station (such as a station in the fixed service) is very low, there is a possibility that a sensitive cell may be overlooked due to the effect of the horizon. In order to avoid such situations, 9 cells including cells adjacent to the sensitive region should be regarded as sensitive cells and should be further divided into smaller cells. If the elevation angle of the FS antenna is not low, it may be unnecessary to further divide adjacent cells into smaller cells.

NOTE 2 – Equation (59a) assumes that there are satellites at the same argument in M_s different orbital planes. However, in certain cases the situation may be different. In such cases, the time, t_{ij}, of satellites in different planes should be determined as $t_{ij} = t + \tau_j + (i - 1)/N_s$, where τ_j is the time difference of j-th plane ($\tau_1 = 0$).

4 Elevation and azimuth angles to the satellites under free space propagation conditions

The longitude of i-th satellite in j-th plane is given by equation (43b) or (59b). The latitude, θ_{ij}, of i-th satellite in j-th plane can be calculated by using equation (49). The range, r_{ij}, of this satellite can be calculated by equation (44). These are expressed in polar coordinates as r_{ij}, θ_{ij}, φ_{ij}).

Assuming that the latitude (positive in the Northern hemisphere and negative in the Southern hemisphere) and longitude of the interfered-with FS station are θ_f and φ_f, respectively, the above coordinates are converted so that the FS station will be located at 0° latitude and 0° longitude. For this purpose, first the FS station longitude is converted to 0°. In this case, the new coordinates of the satellite relative to the 0° FS station longitude are given by (r_{ij}, θ_{ij}, $\varphi_{ij} - \varphi_f$) in polar coordinates. This location is expressed in rectangular coordinates as (x, y, z) which follow:

$$x = r_{ij} \cdot \cos\theta_{ij} \cdot \cos(\varphi_{ij} - \varphi_f) \tag{60a}$$

$$y = r_{ij} \cdot \cos\theta_{ij} \cdot \sin(\varphi_{ij} - \varphi_f) \tag{60b}$$

$$z = r_{ij} \cdot \sin\theta_{ij} \tag{60c}$$

Then the FS station latitude is converted to 0°. The new coordinates (x_1, y_1, z_1) of the satellite relative to the 0° FS station latitude are given by:

$$x_1 = x \cdot \cos\theta_f + z \cdot \sin\theta_f \tag{61a}$$

$$y_1 = y \tag{61b}$$

$$z_1 = -x \cdot \sin\theta_f + z \cdot \cos\theta_f \tag{61c}$$

The elevation angle, ε_{s0}, and azimuth angle, γ_s (measured clockwise from the North), of the satellite under free space propagation conditions as seen from the FS station are given by:

$$\varepsilon_{s0} = \arctan\left(\frac{x_1 - r_e}{\sqrt{y_1^2 + z_1^2}}\right) \tag{62a}$$

$$\gamma_s = \arctan\left(\frac{y_1}{z_1}\right) \qquad \text{for } z_1 > 0$$

$$\gamma_s = \arctan\left(\frac{y_1}{z_1}\right) + \pi \qquad \text{for } z_1 < 0 \tag{62b}$$

where r_e is an average value of the Earth's radius and is equal to 6 370 km.

It should be noted that the equations in this section are equivalent to corresponding equations in Annex 1 to this Recommendation.

5 Separation angles between the FS antenna direction and visible satellites

The satellite visibility can be determined by using Recommendation ITU-R F.1333 and, when the satellite is visible, the actual elevation angle, ε_s, taking into account atmospheric refraction, can also be determined by Recommendation ITU-R F.1333 which provides the methods for determining satellite visibility and for estimating actual elevation angles taking into account atmospheric refraction. These values can be used for determining the separation angle, *SA*, from the main beam direction of the FS antenna as follows:

$$SA = \arccos(\cos\varepsilon_s \cdot \cos\varepsilon_f \cdot \cos(\gamma_s - \gamma_f) + \sin\varepsilon_s \cdot \sin\varepsilon_f) \tag{63}$$

where ε_f and γ_f are the elevation and azimuth (measured clockwise from the North) angles, respectively, of the FS antenna main beam. Based on this separation angle, the FS antenna gain towards the satellite should be determined according to Recommendation ITU-R F.1245 in the case of a directional antenna. On the other hand, in the case of an omni-directional or sectoral antenna, the separation angle is given by $SA = |\varepsilon_s - \varepsilon_f|$, and the FS antenna gain towards the satellite should be determined according to Recommendation ITU-R F.1336.

NOTE 1 – Recommendation ITU-R SF.1395 or Recommendation ITU-R F.1404 may be used for calculating minimum atmospheric absorption loss which is important for evaluating interference to FS stations. For frequency bands not covered by these Recommendations, Recommendation ITU-R P.676 may be used for estimating minimum atmospheric absorption loss.

6 Summary of features of the analytical method

The analytical method in this Annex makes use of the fact that if the orbital period of a satellite is not rationally related to the Earth's revolution, the pdf of the satellite longitude is uniform over 0-2π. In the case of a circular orbit, the pdf of the argument, *u*, is also uniformly distributed over 0-2π. On the other hand, in the case of an elliptical orbit, the argument is not uniformly distributed, but if the argument is determined as a function of time, as shown in § 3.3, the probability of a satellite existing in a time interval $(t, t + dt)$ is proportional to d*t*. The satellite latitude can be calculated from the argument according to equation (49). Thus, the pdf of the satellite latitude can be regarded as independent of that of the satellite longitude. If this fact is taken into account, the location of a reference satellite can be determined analytically, as described in § 3.4.

If the assumptions in § 1 hold, it is sufficient to assume that the location (in time) of the reference satellite is uniformly distributed within $0 \le t < 1/N_s$ and its longitude, φ, is uniformly distributed within $0 \le \varphi < 2\pi/M_s$. The corresponding argument, $u(t)$, is given by equation (54). The locations of other satellites in the same satellite constellation can be easily calculated based on the location of the reference satellite.

If a certain cell is found sensitive (that is, the minimum separation angle from visible satellites is smaller than a certain threshold), the cell (and adjacent cells) should be further divided into smaller cells in order to evaluate interference in detail, but if not sensitive, a division into smaller cells is not necessary. This is an important factor that makes the analytical method very efficient in terms of the required computation time. Therefore, the analytical method is expected to be much faster than an ordinary simulation method under the condition that the calculation accuracy is the same. For example, if the number of sensitive cells, including adjacent cells, is 10% of all the cells under survey, the required computation time will be about 1/10.

Appendix 1
to Annex 7

Simplified calculations for § 3.3 of Annex 7

The calculations for equation (50) in § 3.3 of Annex 7 can be simplified as follows by eliminating the need of integration in equation (52).

First, in equation (47), the variable u is converted to a new variable s as follows:

$$\frac{1}{1+e \cdot \cos(u-\omega)} = \frac{1-e \cdot \cos(s-s_0)}{1-e^2} \tag{64}$$

where $u = 0$ corresponds to $s = 0$ and, therefore, s_0 is defined as follows, assuming that $0 \le \omega < 2\pi$:

$$s_0 = \arccos\left(\frac{e+\cos\omega}{1+e\cdot\cos\omega}\right) \qquad \text{for } 0 \le \omega < \pi \tag{65a}$$

$$= 2\pi - \arccos\left(\frac{e+\cos\omega}{1+e\cdot\cos\omega}\right) \qquad \text{for } \pi \le \omega < 2\pi \tag{65b}$$

Here the value of the function arccos(x) is defined in the range (0, π). Equations (65a) and (65b) show that s_0 is an increasing function of ω. It is also assumed that u can be defined as an increasing function of s (that is, du/ds > 0). From equation (64), after some calculations, du/ds can be expressed as follows:

$$\frac{\mathrm{d}u}{\mathrm{d}s} = \frac{\sqrt{1-e^2}}{1-e\cdot\cos(s-s_0)} \tag{66}$$

By substituting equations (64) and (66) into equations (47) and (50) in Annex 7, the following equation can be derived:

$$\frac{1}{2\pi}\int_0^s \left(1-e\cdot\cos(s-s_0)\right)\mathrm{d}s = t \tag{67}$$

The left-hand side of equation (67) can be easily integrated and this equation is converted to the following:

$$s - e\cdot\sin(s-s_0) = 2\pi t + e\cdot\sin s_0 \tag{68}$$

This transcendental equation is a variation of the so-called Kepler's equation (note that $2\pi t$ is called mean anomaly and that a textbook on dynamics may define Kepler's equation only for $s_0 = 0$). For any t ($0 \le t < 1$), the value of s ($0 \le s < 2\pi$) satisfying equation (68) can be easily calculated by Newton-Raphson's method as follows (see Note 1).

The initial approximate value $s^{(0)}$ for s may be calculated by:

$$s^{(0)} = 2\pi t + e\cdot\sin s_0 \tag{69}$$

Then, ν-th approximate value $s^{(\nu)}$ is calculated by:

$$s^{(\nu)} = s^{(\nu-1)} - \frac{f(s^{(\nu-1)})}{f'(s^{(\nu-1)})} \qquad (\nu = 1, 2, 3, \ldots) \tag{70}$$

where:

$$\begin{aligned} f(s) &= s - e \cdot \sin(s - s_0) - 2\pi t - e \cdot \sin s_0 \\ f'(s) &= 1 - e \cdot \cos(s - s_0) \end{aligned} \tag{71}$$

Note that $f'(s)$ is the derivative of $f(s)$. The convergence of $s^{(\nu)}$ to an accurate value of s by the iterations according to equations (70) and (71) is very rapid.

The value of u corresponding to s is determined as follows, taking into account that u is an increasing function of s:

$$u = \omega - 2\pi + a \qquad \text{for } -2\pi < s - s_0 < -\pi \tag{72a}$$

$$= \omega - a \qquad \text{for } -\pi \le s - s_0 < 0 \tag{72b}$$

$$= \omega + a \qquad \text{for } 0 \le s - s_0 < \pi \tag{72c}$$

$$= \omega + 2\pi - a \qquad \text{for } \pi \le s - s_0 < 2\pi \tag{72d}$$

where:

$$a = \arccos\left(\frac{\cos(s - s_0) - e}{1 - e \cdot \cos(s - s_0)}\right) \tag{72e}$$

Thus, u_k corresponding to t_k defined by equation (51) in Annex 7 can be calculated for any value of k ($k = 0, 1, 2, ..., N$) ($u_0 = 0$).

The value of $u(t)$ corresponding to time t can be approximated as follows:

$$u(t) = N\,[(t_{k+1} - t) \cdot u_k + (t - t_k) \cdot u_{k+1}] \tag{73}$$

where $t_k \le t < t_{k+1}$ (if $t \ge 1$, this inequality should be replaced by $t_k \le t - 1 < t_{k+1}$). If N is sufficiently large (for example, $N = 10\,000$), equation (73) gives an accurate value of $u(t)$ as a function of time.

The equivalence of the calculation method in this Appendix and that in § 3.3 of Annex 7 was confirmed through computer calculations.

NOTE 1 – In the Newton-Raphson's method described here, the convergence to the desired results is stable and rapid for any values of t and s_0, provided that e is smaller than 0.81. For general applications, this condition will hold. However, if for some reason it is necessary to solve equation (68) for a larger value of e, it is safe to adopt a modified Newton-Raphson's method in order to guarantee a rapid convergence. One example method is given below (all calculations should be performed in double precision).

Step 1: Instead of the calculation according to equation (70), first choose $\lambda = 1$ and calculate $s^{(\nu)}$ in Step 2.

Step 2: Calculate:

$$s^{(\nu)} = s^{(\nu-1)} - \frac{\lambda \cdot f\left(s^{(\nu-1)}\right)}{f'\left(s^{(\nu-1)}\right)} \tag{74}$$

Step 3: If $|f(s^{(\nu)})<10^{-12}$, the entire calculation is finished (that is, $s^{(\nu)}$ has reached a sufficiently accurate value). If not and if $|f(s^{(\nu)})<|f(s^{(\nu-1)})|$, the calculation of $s^{(\nu)}$ is finished and go back to Step 1 in order to calculate for the next ν. If $|f(s^{(\nu)})| \geq |f(s^{(\nu-1)})|$, divide λ by 2 and go back to Step 2 and repeat the calculation.

The above modified method is effective for any e up to 0.999.

Appendix 2 to Annex 7

Modifications of the analytical method in Annex 7 for non-GSO satellite constellations employing HEOs

Non-GSO satellite networks employing HEOs can be characterized as follows. For the sake of simplicity, it is generally assumed that active HEO satellites exist in only one hemisphere, but it is easy to extend the calculation method to those in which active HEO satellites exist in the two hemispheres:

– there are M_s satellite constellations in one hemisphere;

– one satellite constellation consists of N_s satellites and only one satellite is active near its apogee at any time; when one satellite becomes inactive, another satellite becomes active, providing a continuous coverage and its ground track is identical with that of the previous active satellite;

– the orbital period, T_{orb} (h), of a satellite is rationally related to the Earth's revolution (typically being approximately 8, 12, 16 or 24 h);

– the inclination angle is common to all satellites;

– the argument of perigee (ω) is common to all satellites.

In the case of HEO satellite systems, it is possible that one constellation can provide services in more than one service area. For example, when the orbital period is about 8 h, one constellation can provide services in three different service areas on the surface of the Earth. However, for the purpose of statistical interference assessment, it is convenient to treat these service areas separately and, therefore, to assume that three service areas exist independently and that only one active satellite exists for each service area.

Generally, if active HEO satellites operate only in the northern hemisphere, $\omega = -\pi/2$ (or $\omega = 3\pi/2$) radians and if active HEO satellites operate only in the southern hemisphere, $\omega = \pi/2$ radians. If active HEO satellites operate in both hemispheres, these two values of ω should be used. The values of ω other than $\pm\pi/2$ are also possible for special applications.

The range of a HEO satellite from the Earth's centre is determined by the formulae in § 3.1 of Annex 7. The argument of an active HEO satellite is determined, as a function of time t, where $0 \leq t < 1$ (here, the orbital period is assumed to be 1, without loss of generality), by the formulae in § 3.3 of Annex 7 for which the formulae in § 3.2 of Annex 7 are used. Note that the calculations in § 3.2 and § 3.3 of Annex 7 implicitly assume that $u = 0$ at $t = 0$, but in the case of HEO satellite constellations it is more appropriate to assume that $u = \omega$ at $t = 0$. The satellite latitude is determined by equation (49) of Annex 7.

One active HEO satellite is chosen as a reference satellite. When T_{orb} does not exceed 24 h, the start active time, T_{start}, and the end active time, T_{end}, of this active satellite are given as follows, assuming that the orbital period for the left hand side of the equation is unity, without loss of generality, and that the satellite exists at the perigee at $t = 0$:

$$(T_{start} \geq 0) \qquad T_{start} = 0.5 - 12/(N_s \cdot T_{orb}) \tag{75a}$$

$$(T_{end} < 1) \qquad T_{end} = 0.5 + 12/(N_s \cdot T_{orb}) \tag{75b}$$

Equations (75a) and (75b) assume that the satellite is active when it is near the apogee and that the active arc is symmetrical with respect to the apogee. For example, if $N_s = 3$ and $T_{orb} = 12$ h, $T_{start} = 1/6$ and $T_{end} = 5/6$ (one active duration is 8 h) and if $N_s = 5$ and $T_{orb} = 8$ h, $T_{start} = 0.2$ and $T_{end} = 0.8$ (one active duration is 4.8 h). If the active arc is not symmetrical, the equations (75a) and (75b) should be modified accordingly.

The argument, $u(t)$, of the reference satellite at any time, t ($0 \leq t < 1$), in the range (T_{start}, T_{end}) can be determined by equation (54) of Annex 7. In this case, we should assume that $u_0 = \omega$ (therefore, $u_N = \omega + 2\pi$).

When there are a number of satellite constellations operating in one hemisphere and the satellite spacing is uniform, it is easy to determine the locations of all active satellites. For the purpose of sharing studies, it is generally sufficient to assume that the phases of all active satellites are the same. If phase differences between different satellite constellations are given, it is easy to incorporate them into calculations.

In addition, if the satellite spacing is not uniform and actual values of satellite spacing are defined, they can be incorporated into calculations appropriately.

After the locations of all active satellites are determined at any time instant, the aggregate interference to an FS station from all visible satellites can be evaluated according to the method described in § 4 and § 5 of Annex 7.

Finally, it should be noted that there is one important difference between the analytical method in Annex 7 and that in this Appendix. In Annex 7, the interference is evaluated analytically under an assumption that the latitude and longitude of a satellite are independent, but in the case of HEO satellites of this Appendix, the latitude of a satellite is not independent of its longitude. Therefore, it is necessary in this Appendix to determine the latitude and longitude of a satellite simultaneously at any time instant. However, it is sufficient to evaluate the interference only over one period, because satellites appear periodically and, therefore, the calculations are not time consuming.

On the other hand, the concept of sensitive regions, as described in § 3.4 of Annex 7, is not applicable to the analytical method in this Appendix.

Interference to FS systems is evaluated assuming an appropriate pfd mask as a function of the arrival angle produced by emissions from active HEO satellites.