

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:

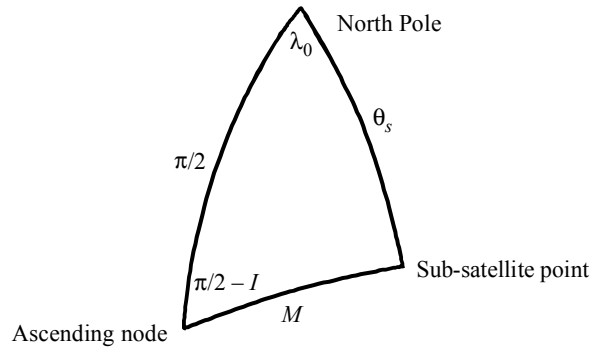
- R_s : orbital radius, the distance from the centre of the Earth to the satellite
- I : inclination angle (rad), the angle between the orbital plane and the Earth's equatorial plane. It is measured from 0 to π and is less than $\pi/2$ if the satellite is headed eastward as it crosses the equatorial 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 $(0, \pi)$:

$$\theta_s = \arccos (\sin M \sin I) \quad (1)$$

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 λ_0 for the entire range $(\theta, 2\pi)$.

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

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:

$$\lambda_s = \lambda_0 + \Omega_s - \Delta E t \quad (3)$$

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

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

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

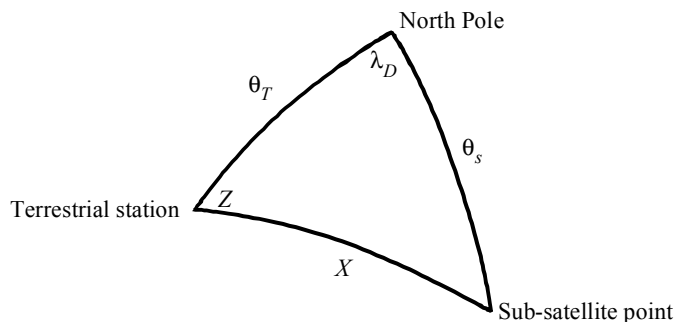
The difference in longitude from the terrestrial station to the sub-satellite point, λ_D , is just

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

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:

$$X = \arccos (\cos \theta_T \cos \theta_s + \sin \theta_T \sin \theta_s \cos \lambda_D) \quad (9)$$

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



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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:

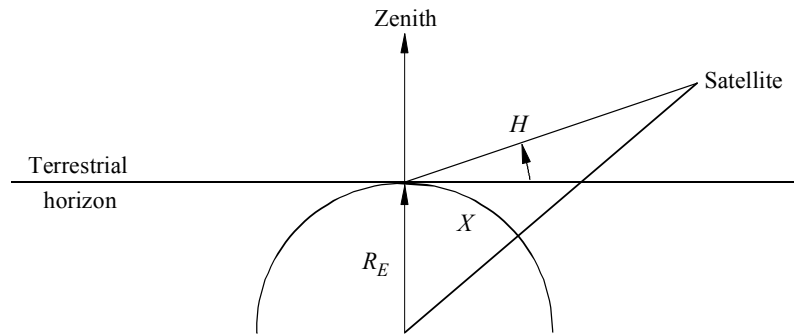
$$Z = \begin{cases} \arccos \left[\frac{\cos \theta_s - \cos \theta_T \cos X}{\sin \theta_T \sin X} \right] & \text{for } \sin \lambda_D \geq 0 \\ 2\pi - \arccos \left[\frac{\cos \theta_s - \cos \theta_T \cos X}{\sin \theta_T \sin X} \right] & \text{for } \sin \lambda_D < 0 \end{cases} \quad (10)$$

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° , may be obtained by referring to Fig. 3.

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

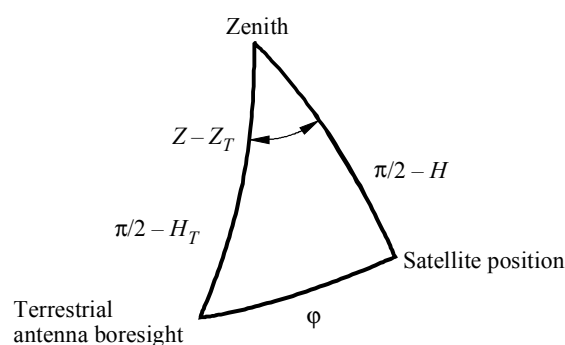
FIGURE 3
Plane containing Earth centre, terrestrial station, and satellite



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:

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

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 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:

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

2.2 Output

The output of the program is a single data file named Leo.dat. Information is provided for each simulated 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 $1/2^\circ$ 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.

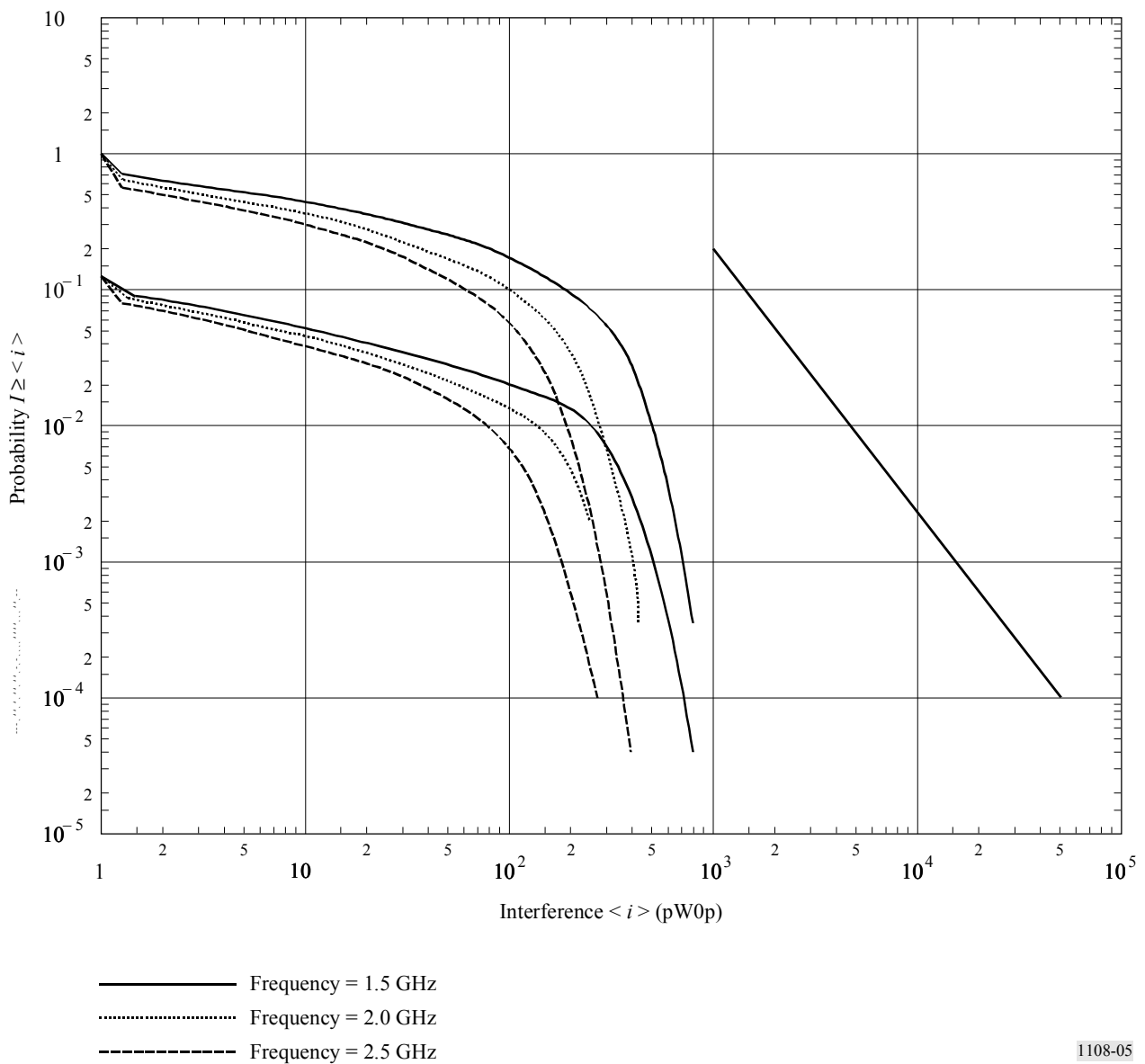
Figure 6 demonstrates the effects of changes in orbit altitude and low angle of arrival pfd on the interference received by the FS from one LEO in continuous view. For this LEO scenario the pair of dashed curves shows ($\text{pfd} = -144 \text{ dB(W/m}^2\text{)}$) (4 kHz bandwidth) for all angles of 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

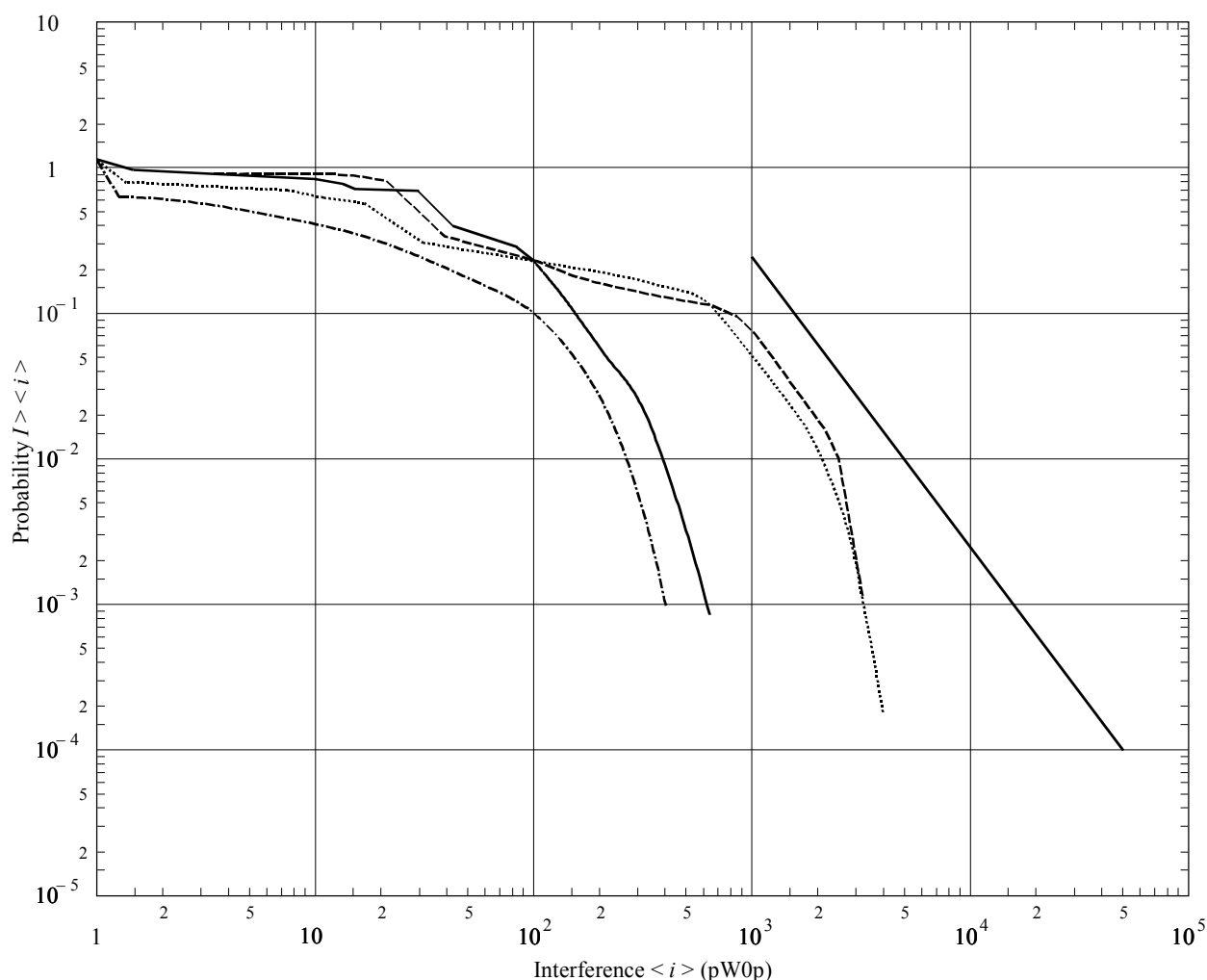
FS interference versus frequency
(800 km, 50 hop routes, 33 dB antenna gain, 40° latitude, pfd = -154/-144 dB(W/(m² · 4 kHz)))



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FIGURE 6

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



- pfd = -154/-144 dB(W/(m² · 4 kHz)), altitude = 800 km
- pfd = -154/-144 dB(W/(m² · 4 kHz)), altitude = 10 300 km
- pfd = -144/-144 dB(W/(m² · 4 kHz)), altitude = 800 km
- pfd = -144/-144 dB(W/(m² · 4 kHz)), altitude = 10 300 km

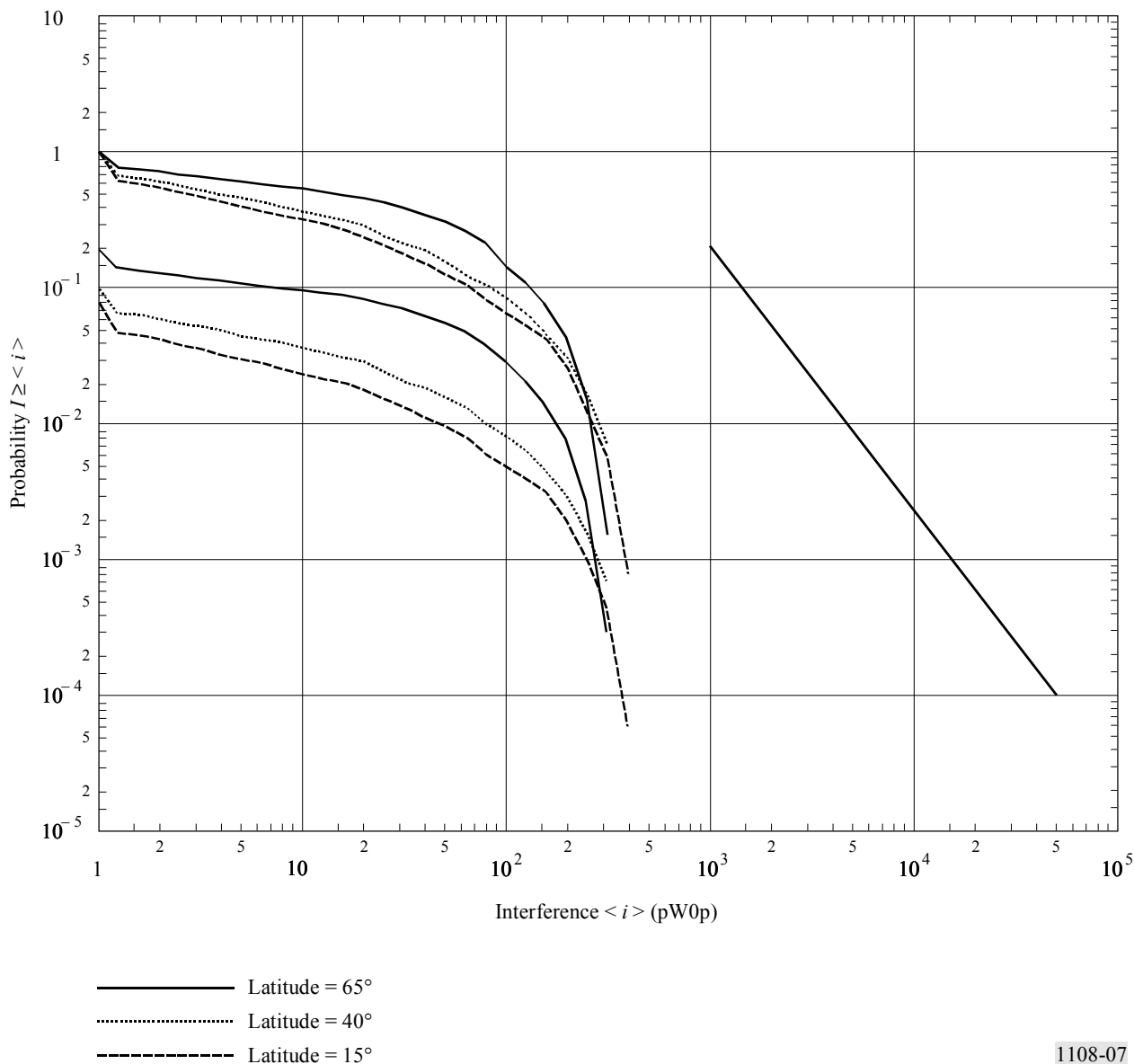
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The lower group of three curves in Fig. 7 represent the distributions of received interference distributions at different latitudes from single orbiting satellites that have high orbit angles (80°). It is interesting to note here that if the curve 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 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)

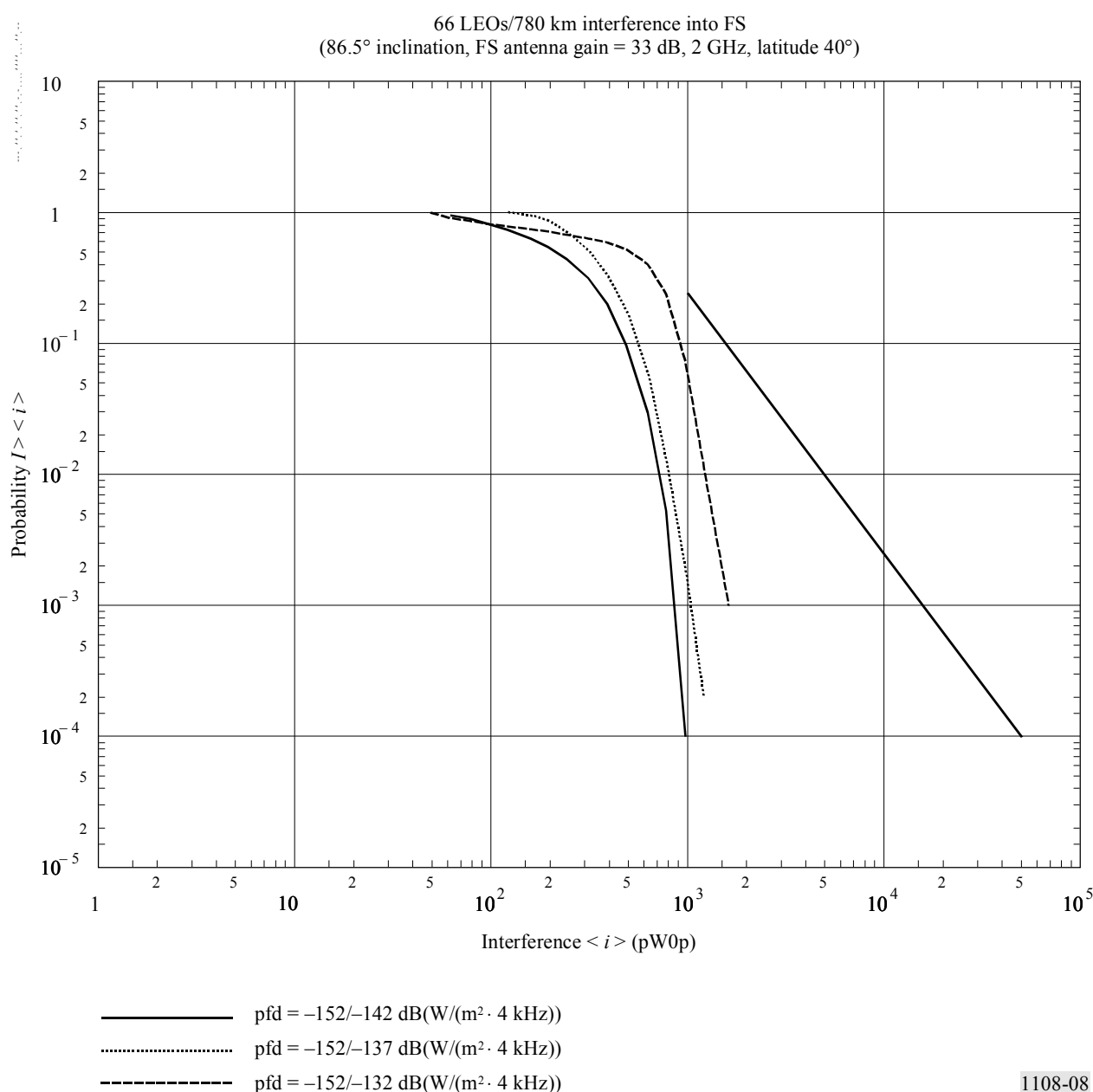


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This might be verified intuitively by considering that for every orbit of a highly inclined satellite system each satellite in the plane would be visible for a percentage of time to terrestrial sites at more northern or southern latitudes, whereas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

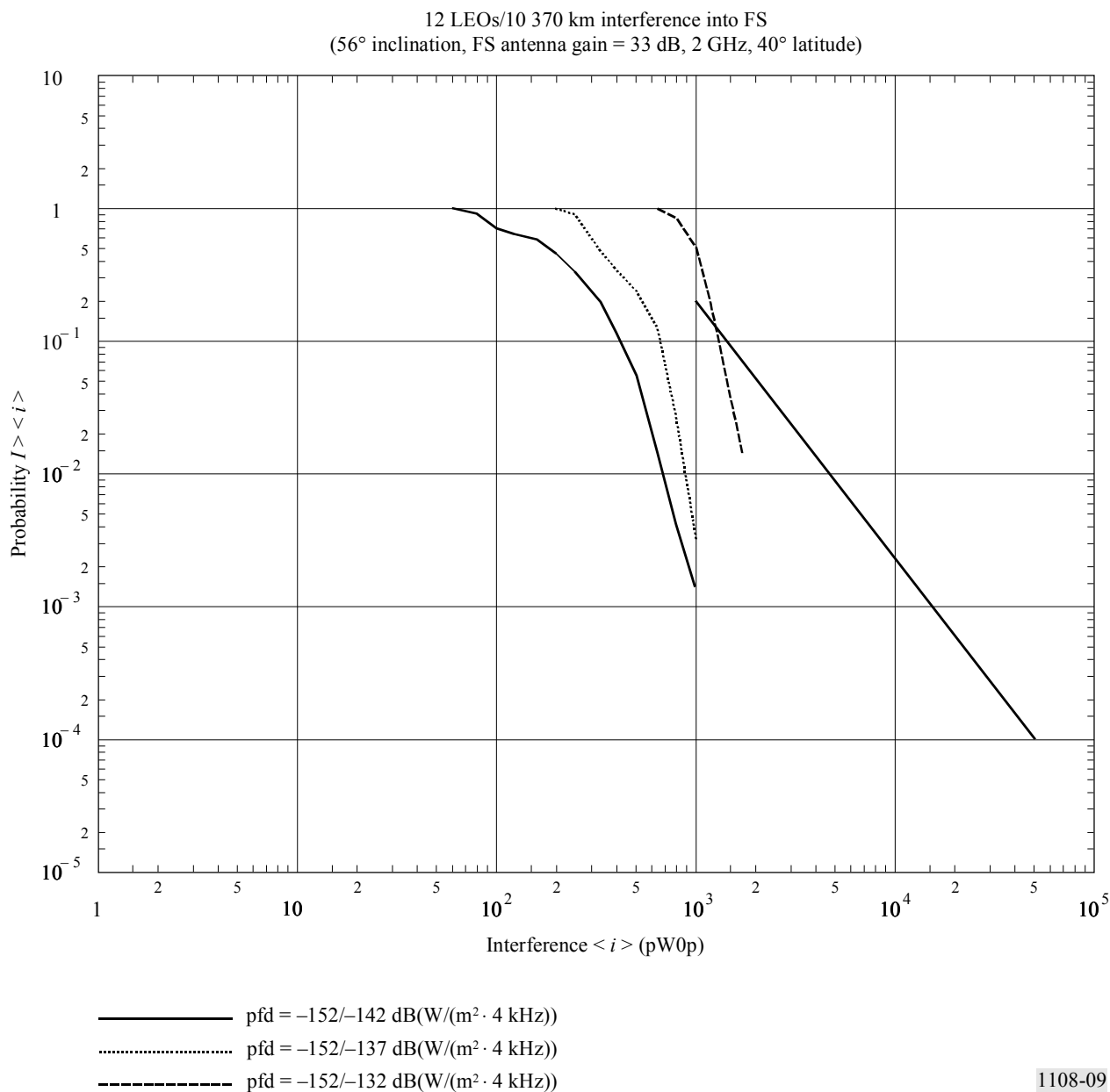
Finally, Figs. 8 and 9 illustrate the interference effects into the FS from constellations of satellites that might represent practical operating systems. Both systems are arranged such that 3 to 6 satellites are continually visible to the terrestrial site requiring service. Figure 8 investigates a satellite constellation consisting of 6 circular orbit planes with 11 satellites per plane. All planes have the same inclination (86.5°) 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 10370 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



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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.