International Telecommunication Union



Recommendation ITU-R S.1857 (01/2010)

Methodologies to estimate the off-axis e.i.r.p. density levels and to assess the interference towards adjacent satellites resulting from pointing errors of vehicle-mounted earth stations in the 14 GHz frequency band

> S Series Fixed-satellite service



International Telecommunication

Foreword

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Series	Title			
BO	Satellite delivery			
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RA	Radio astronomy			
RS	Remote sensing systems			
S	Fixed-satellite service			
SA	Space applications and meteorology			
SF	Frequency sharing and coordination between fixed-satellite and fixed service systems			
SM	Spectrum management			
SNG	Satellite news gathering			
TF	Time signals and frequency standards emissions			
V	Vocabulary and related subjects			

Note: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.

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RECOMMENDATION ITU-R S.1857

Methodologies to estimate the off-axis e.i.r.p. density levels and to assess the interference towards adjacent satellites resulting from pointing errors of vehicle-mounted earth stations in the 14 GHz frequency band

(Question ITU-R 208/4)

(2010)

Scope

This Recommendation presents the general antenna pointing error characteristics of vehicle-mounted earth stations with active antenna tracking systems and provides a method to estimate the statistics of off-axis e.i.r.p. variations due to pointing errors. Furthermore, it provides a methodology to assess the potential interference towards adjacent satellites operating in the GSO, FSS systems.

The ITU Radiocommunication Assembly,

considering

a) that FSS GSO satellites are well suited to provide Internet and data services through a wide range of network configurations;

b) that there is an increasing need to support user mobility and broadband services to end-users;

c) that vehicle-mounted earth station (VMES) terminals can provide a wide range of communication services over FSS satellites in the 14 GHz frequency band;

d) that it is necessary to protect networks of the FSS from any potential interference from these VMES terminals;

e) that efficient use of the radio-frequency spectrum and the GSO by VMES terminals can be accomplished through use of a model for the off-axis e.i.r.p. density and interference from such terminals;

f) that VMES require statistical approaches to determine their off-axis e.i.r.p. density levels and interference to adjacent satellites;

g) that satellite networks using VMES can be designed to comply with the interference limits required by adjacent satellite system operators;

h) that it would be useful to have methodologies for assessing the interference levels and impact on link availability of victim satellite networks resulting from variations in off-axis e.i.r.p. density levels of VMES antennas that are too small in diameter to be meaningfully assessed using currently available methods,

noting

a) that maximum permissible levels of off-axis e.i.r.p. density from very small aperture terminals (VSATs) are provided in Recommendation ITU-R S.728;

b) that maximum permissible levels of inter-network interference caused by the earth and space station emissions of all other satellite networks operating in the same frequency band are provided in Recommendation ITU-R S.1323,

recommends

1 that the methodology and associated model given in Annex 1 can be used to estimate the off-axis e.i.r.p. density levels caused by antenna pointing errors of VMES;

2 that the methodology given in Annex 2 can be used to assess the interference levels resulting from variations in off-axis e.i.r.p. density levels of VMES;

3 that the methodology given in Annex 2 can be used to assess the impact to the link unavailability of the interfered system in situations where time-varying antenna pointing errors from VMES antennas of the type described in Note 2 are significant;

4 that the Notes 1 to 5 should be regarded as part of this Recommendation:

NOTE 1 – The methodology given in Annex 2 may be used to assess potential interference impacts of VMES.

NOTE 2 – The methodologies presented in this Recommendation were developed for VMES with directional reflector antennas having equivalent diameters ranging from 0.3 m to 1.0 m; mechanical or electronic tracking systems, and support vehicle speeds up to 100 km/h. However, the methodologies can be applied to other antenna sizes and vehicle speeds.

NOTE 3 – The parameters and the examples provided in the annexes represent some systems that operate in the 14 GHz frequency band.

NOTE 4 – The methodology described in this Recommendation applies when the VMES tracking system is locked to its target satellite.

NOTE 5 – To use this Recommendation it is necessary to know the representative values of α and *c*, as used in § 2 of Annex 1.

Annex 1

A model to estimate off-axis e.i.r.p. density levels caused by antenna pointing errors of VMES

1 Introduction

Recent demand for on-the-move communication applications has generated interest in a new type of satellite terminal. These terminals, which are mounted on vehicles, generally consist of small, high-performance antennas, tracking systems with servo controllers and positioners, and include the respective intermediate-frequency (IF) and RF equipment. The antenna size and other transmission parameters are selected to provide two-way communications under various terrains and operational conditions. The terminals considered in this annex will operate over FSS in the 14 GHz frequency band. Currently these terminals are being tested for use in terrestrial vehicles and trains.

The terminals mounted on vehicles, as detailed in this contribution, may cause additional interference to adjacent satellites due to motion-induced antenna pointing errors. From a satellite operator's perspective, this interference should be maintained at a minimum level. On the other hand, service providers will seek to design their systems such that the terminals provide enough transmit power to support end-user applications at reasonable data rates. This annex addresses these conflicting demands, i.e. the need to transmit sufficient power to support reasonable data rates while maintaining an interference level that is acceptable to the satellite operators.

In on-the-move communication applications, because of the motion of the antenna platform, errors in the antenna pointing and tracking system can lead to antenna pointing errors. Typically, these motion-induced antenna pointing errors are small and random, and produce random variations of the off-axis e.i.r.p. density. In order to assess the impact of interference to other satellites it is necessary to model and quantify the e.i.r.p. density from these terminals.

This annex presents a statistical model to estimate the e.i.r.p. density levels due to antenna pointing errors and presents an approach to developing an illustrative statistical mask for the e.i.r.p. density in the off-axis directions. This illustrative statistical mask considers typical operational characteristics of terminals mounted on vehicles and can be used to limit the off-axis emissions from these terminals. For a satellite earth terminal the e.i.r.p. density in its off-axis directions is directly proportional to the e.i.r.p. density in the boresight¹ direction. This annex provides a methodology to determine the appropriate levels for the boresight e.i.r.p. density so as to satisfy the above illustrative statistical mask.

2 Motion-induced antenna pointing errors

Under certain motion conditions of the antenna platform the boresight of the antenna will be displaced. The antenna pointing error can be represented by a random variable, ϕ , which is the angular distance between the actual and the intended directions of the antenna boresight. In many practical realizations, the antenna pointing error is measured in terms of its components: elevation error, ϕ_{ε} , and azimuth error, ϕ_a . These error components may be represented by mutually independent random variables whose statistical distributions are estimated by measurements carried out over representative drive paths. The probability density function (PDF) of ϕ_x is denoted by f_{ϕ_x} ,

where $x = \varepsilon_{,a}$. For illustrative purposes it is useful to represent these PDFs by well-known statistical distributions. Laboratory measurements of motion-induced antenna pointing errors have indicated that these pointing errors have long-tailed characteristics, that is, the PDF will not decay fast for large values of the antenna pointing error. The symmetric α -stable ($S\alpha S$) distribution [Shao and Nikias, 1993; Samorodnitsky and Taqqu, 1994], is an example for a distribution with long-tailed characteristics and it is employed to represent, illustratively, the PDFs of the elevation and azimuth antenna pointing errors. The $S\alpha S$ distribution has many parameters that can be used to generate different PDFs and the Gaussian distribution is a special case. The characteristic function of the S αS distribution with zero location parameter is given as:

$$\Psi(x) = e^{-|cx|^{\alpha}} \tag{1}$$

where c > 0 is the scale parameter or the dispersion and α , $0 < \alpha \le 2$, is the characteristic exponent. The tail of the distribution is determined by α , with smaller values giving rise to longer tails, and c is proportional to the width of the PDF. Note that when $\alpha = 2$ the above gives the special case of the Gaussian distribution with mean zero and variance $2c^2$. Figure 1 shows the cumulative distribution function (CDF) of the S α S distribution for c = 0.14 and 0.35° and for different values of α . It is seen that by varying the values of these two parameters it is possible to represent many types of antenna pointing errors encountered in practice.

An intuitive justification for choosing the $S\alpha S$ distribution to model the motion-induced antenna pointing errors can be given as follows. The observed antenna pointing errors depend on many parameters, for example, antenna characteristics; terrain conditions; antenna platform speed; elevation and azimuth angles; antenna tracking loop; location and position estimators and signal

¹ The boresight direction is defined as the direction in which the antenna gain is largest, which is the axis of the antenna.

strength measurements. The errors contributed by all these different parameters may be assumed independent. In this case, the generalized central limit theorem [Samorodnitsky and Taqqu, 1994] can be applied to model the cumulative effect of these error sources by an $S\alpha S$ distribution. Note that a similar central limit theorem argument has been used in long-range optical links to model the pointing and tracking errors with a Gaussian distribution [Chen and Gardner, 1989; Correl, 1996]. However, unlike the optical application, the operational environment considered in this annex includes rugged terrains; therefore, error components with longer-tailed distributions have to be considered.



FIGURE 1

3 Statistical characterization of the off-axis e.i.r.p. density

In the preceding section the antenna pointing errors were considered to be random variables. These random pointing errors will cause the resulting e.i.r.p. density level to vary in a random manner. In this section the off-axis e.i.r.p. density level is considered to be a random variable and its CDF is determined.

In order to determine the off-axis e.i.r.p. density level, for illustrative purposes, consider the following normalized gain pattern for a parabolic dish antenna with circular aperture [Maral and Bousquet, 2000]:

$$G(\varphi) = \left(\frac{2^{n+1}(n+1)!J_{n+1}(\pi d/\lambda \times \sin\varphi)}{(\pi d/\lambda \times \sin\varphi)^{n+1}}\right)^2$$
(2)

where:

 φ : off-axis angle

 J_{n+1} : Bessel function of the first kind and order (n+1)

- *d*: diameter of the circular aperture
- λ : wavelength.

In the above, n is the aperture illumination parameter that corresponds to the following aperture illuminations:

n = 0, ideal uniform

n = 1, parabolic

n = 2, parabolic squared.

The main-lobe of many practical aperture systems falls between the normalized gain patterns corresponding to n = 1 and n = 2. Note that the side lobes of practical antennas may not be accurately represented by equation (2); however, this is not a shortcoming in the analysis since the focus of this work is on ultra small aperture terminals whose performance is limited by the main-lobe rather than the side-lobes.

FIGURE 2

Geometry representing an antenna pointing error, ϕ . The notation used is as follows: earth terminal is at the origin, O, S is the intended satellite, OB is the antenna boresight direction, ϕ is the off-axis angle at a point S_{ϕ} , and $\theta_{BS_{\phi}}$ is the angular distance between boresight direction and S_{ϕ} direction



Consider the off-axis e.i.r.p. density level in the presence of an antenna pointing error, ϕ . As defined in § 2, ϕ is the error in the boresight direction of the antenna. Figure 2 shows the geometry of the antenna boresight, OB, in the presence of an antenna pointing error. Here the earth terminal is at O, and S represents the location of the intended satellite so the axis of the antenna in the absence of pointing errors is OS. The off-axis angle is ϕ and this direction is shown as OS_{ϕ}. In the presence of antenna pointing errors, the angular distance between the antenna boresight and OS_{ϕ} is denoted by $\theta_{BS\phi}$. Observe that in the absence of antenna pointing errors $\theta_{BS\phi} = \phi$. Now the off-axis e.i.r.p. density level in the direction of OS_{ϕ} can be expressed as:

$$E_{\phi}(\phi) = E_B \left(\frac{2^{n+1}(n+1)! J_{n+1}(\pi d/\lambda \times \sin \theta_{BS_{\phi}})}{(\pi d/\lambda \times \sin \theta_{BS_{\phi}})^{n+1}} \right)^2$$
(3)

where E_B is the e.i.r.p. density in the boresight direction. In order to determine the CDF of $E_{\phi}(\phi)$ it is necessary to express this in terms of the underlying random variables, ϕ_{ε} and ϕ_a . Observe that $\theta_{BS\phi}$ is a function of ϕ_{ε} and ϕ_a , and using the geometry in Fig. 2 this can be expressed in terms of the elevation and azimuth angles in the directions OB and OS_{ϕ}, as:

$$\cos \theta_{BS_{\varphi}} = \cos \varepsilon_{BS_{\varphi}}^{-} - (\cos \varepsilon_{BS_{\varphi}}^{+} + \cos \varepsilon_{BS_{\varphi}}^{-}) \times \sin^{2} \frac{a_{BS_{\varphi}}}{2}$$
(4)

where $\varepsilon_{BS_{\phi}}^- = (\varepsilon_B - \varepsilon_{S_{\phi}})$ and $\varepsilon_{BS_{\phi}}^+ = (\varepsilon_B + \varepsilon_{S_{\phi}})$ are the difference and sum between the elevation angles in directions OB and OS_{ϕ}, and $a_{BS_{\phi}}^- = (a_B - a_{S_{\phi}})$ is the difference between the azimuth angles in directions OB and OS_{ϕ}, respectively. For given values of the locations of the earth terminal and points S and S_{ϕ}, the following functions of the elevation and azimuth angles can be computed: $\varepsilon_{SS_{\phi}}^- = (\varepsilon_S - \varepsilon_{S_{\phi}})$, $\varepsilon_{SS_{\phi}}^+ = (\varepsilon_S + \varepsilon_{S_{\phi}})$, and $a_{SS_{\phi}}^- = (a_S - a_{S_{\phi}})$. Next, since in the absence of pointing errors the antenna boresight direction is along OS, $\varepsilon_B = (\varepsilon_S - \phi_{\varepsilon})$ and $a_B = (a_S - \phi_a)$. Combining these expressions:

$$\begin{aligned}
\bar{\varepsilon}_{BS_{\varphi}}^{-} &= (\bar{\varepsilon}_{SS_{\varphi}}^{-} - \phi_{\varepsilon}) \\
\bar{\varepsilon}_{BS_{\varphi}}^{+} &= (\bar{\varepsilon}_{SS_{\varphi}}^{+} - \phi_{\varepsilon}) \\
\bar{a}_{BS_{\varphi}}^{-} &= (\bar{a}_{SS_{\varphi}}^{-} - \phi_{a})
\end{aligned}$$
(5)

For a given geometry of the earth terminal and the satellite points S and S_{φ} , the quantities $\varepsilon_{SS_{\varphi}}^{-}, \varepsilon_{SS_{\varphi}}^{+}, \varepsilon_{SS_{\varphi}}^{+}$, and $a_{SS_{\varphi}}^{-}$ can be determined. Then, substituting equation (5) in equation (4) $\theta_{BS_{\varphi}}$ is expressed as a function of the errors in the elevation and azimuth angles and the predetermined elevation and azimuth angles to points S and S_{φ} .

Using the above procedure and equation (3) the e.i.r.p. density level in the off-axis direction φ , $E_{\varphi}(\varphi)$, can be expressed in terms of the antenna pointing error random variables, φ_{ε} and φ_{a} . Denote by $f_{E_{\varphi}}$ the PDF of $E_{\varphi}(\varphi)$. Since, for illustrative purposes, the PDFs of φ_{ε} and φ_{a} are represented by SaS distributions $f_{E_{\varphi}}$ can be determined using equations (3), (4) and (5). The desired PDF may be

determined using either analytical techniques or Monte-Carlo simulations. The CDF of the e.i.r.p. density is $\Pr\{E_{\varphi}(\phi) < y\} = F_{E_{\phi}}(y) = \int_{0}^{y} f_{E_{\phi}}(x) dx$. Note that this CDF is a function of the boresight e.i.r.p. density E_{B} .

4 Computing the probability of exceeding a reference e.i.r.p. density level

In the previous section a procedure to determine the CDF of the off-axis e.i.r.p. density level was presented. Using this procedure the probability that the off-axis e.i.r.p. density level exceeds a certain reference threshold level can be determined. Denote this reference level by $E_{Ref}(\varphi)$, which in general can be a function of φ . The probability that the e.i.r.p. density level is greater than this reference level in the off-axis direction φ , $\Pr\{E_{\varphi}(\varphi) > E_{Ref}(\varphi)\}$, is expressed as:

$$\Pr\left\{E_{\phi}\left(\phi\right) > E_{Ref}\left(\phi\right)\right\} = \int_{E_{Ref}\left(\phi\right)}^{\infty} f_{E_{\phi}}\left(x\right) dx = 1 - F_{E_{\phi}}\left(E_{Ref}\left(\phi\right)\right)$$
(6)

This is the complementary CDF (CCDF) of the off-axis e.i.r.p. density level computed at $E_{Ref}(\varphi)$ and is a function of the off-axis angle, φ ; boresight e.i.r.p. density, E_B ; and the locations of the earth terminal and the satellite represented by the sum and difference of elevation and azimuth angles $\varepsilon_{SS_{\varphi}}^+$, $\varepsilon_{SS_{\varphi}}^-$ and $a_{SS_{\varphi}}^-$. Intuitively, it is clear that by reducing E_B the above probability can be reduced, and it is instructive to express this probability so that E_B is an explicit parameter. To accomplish this equation (3) may be written as $E_{\varphi}(\varphi) = E_B G(\varphi_{BS\varphi})$, where $G(\varphi_{BS\varphi})$ is the normalized antenna gain pattern such that G(0) = 1. The probability in equation (6) can be written as:

$$\Pr\left\{G\left(\theta_{BS\phi}\right) > E_{Ref}\left(\phi\right) / E_{B}\right\} = 1 - F_{G_{\left(\theta_{BS\phi}\right)}}\left(E_{Ref}\left(\phi\right) / E_{B}\right)$$
(7)

where $F_{G(\theta_{BS_{\varphi}})}$ is the CDF of $G(\theta_{BS_{\varphi}})$ and is not a function of E_B . The probability that the e.i.r.p. density level exceeds the reference level $E_{Ref}(\varphi)$ is as given above; however, this does not address the level of excess e.i.r.p. density above $E_{Ref}(\varphi)$. This aspect can be addressed by examining the probability that the off-axis e.i.r.p. density level exceeds (EIRP_{excess} × $E_{Ref}(\varphi)$), where EIRP_{excess} ≥ 1 is a scale factor. Using this in equation (7) the required probability is:

$$\Pr\left\{E_{\phi}(\phi) > (E_{Ref}(\phi) \times \text{EIRP}_{excess})\right\} = \Pr\left\{G(\theta_{BS\phi}) > E_{Ref}(\phi) \times \text{EIRP}_{excess} / E_{B})\right\}$$
(8)
= $1 - F_{G_{(\theta_{RS\phi})}}(E_{Ref}(\phi) \times \text{EIRP}_{excess} / E_{B})$

The above probability is the CCDF of $G(\theta_{BS\phi})$ computed at $(E_{Ref}(\phi) \times \text{EIRP}_{excess} / E_B)$.

The procedure for computing the probability in equation (8) is as follows:

Step 1: The underlying random variables here are the antenna pointing error components, ϕ_{ε} and ϕ_a , whose PDFs, for illustrative purposes, are assumed to be known as in § 2.

Step 2: For known locations of the earth terminal, satellite and the off-axis direction, the sum and difference of elevation and azimuth angles, $\varepsilon_{SS\phi}^+$, $\varepsilon_{SS\phi}^-$ and $a_{SS\phi}^-$, are computed as described in § 3. These angles are then be used in equation (5) and the result substituted in equation (4) to express $\theta_{BS\phi}$ in terms of the random variables, ϕ_{ε} and ϕ_{a} . The PDF of $\theta_{BS\phi}$ can then be determined using the PDFs of ϕ_{ε} and ϕ_{a} . Making use of the relationship in equation (2), the PDF of $\theta_{BS\phi}$ so determined is then used to compute the CCDF of the random variable $G(\theta_{BS\phi})$.

Step 3: Finally, the desired probability in equation (8) is determined from the CCDF of $G(\theta_{BS\phi})$ with E_B and e.i.r.p._{excess} as parameters.

5 An illustrative statistical e.i.r.p. density mask to limit off-axis emissions

In order to limit off-axis emissions, in the presence of motion-induced antenna pointing errors, an upper bound on the probability that the e.i.r.p. density level exceeds a reference level may be used. However, it is clear that the probability computed in equation (8) depends on the locations of the earth terminal and the satellite, and the off-axis angle. Since the earth terminal may be located anywhere on the Earth's surface it is highly desirable to limit the off-axis emissions using a function that is independent of the earth terminal and satellite locations. Ideally, it is instructive to derive an upper bound for the probability $Pr{E_{\phi}(\phi) > (E_{Ref}(\phi) \times EIRP_{excess})}$ by a single function, P_{max} (EIRP_{excess}), which is applicable anywhere on the Earth's surface and for all off-axis angles. This desired probability function, P_{max} (EIRP_{excess}), limits the off-axis e.i.r.p. density emissions and constitutes a statistical mask on the e.i.r.p. density level.

To obtain a statistical e.i.r.p. density level mask as discussed above consider the special case when the points *S* and S_{φ} are on the GSO and the earth terminal is placed on the equator and directly below *S*. For this configuration, $\varepsilon_S = 90^\circ$, $\varepsilon_{S\varphi} = (90^\circ - \varphi)^\circ$, $a_S = 90^\circ$ and $a_{s_{\varphi}} = 90^\circ$ or 270° , and it follows that $\varepsilon_{SS\varphi}^+ = (180 - \varphi)^\circ$, $\varepsilon_{SS\varphi}^- = \varphi$ and $a_{SS\varphi}^- = 0^\circ$ or 180° . Using these expressions in equation (5) and substituting the result in equation (4), $\theta_{BS\varphi}$ can be written as:

$$\cos \theta_{BS_{\varphi}} = \cos(\varphi - \phi_{\varepsilon}) - (\cos(\varphi - \phi_{\varepsilon}) - \cos(\varphi - \phi_{\varepsilon})) \times \sin^2 \frac{\phi_a}{2}$$
(9)

The CDF of $G(\theta_{BS\varphi})$ obtained using the above $\theta_{BS\varphi}$ will not be a function of the specific elevation and azimuth angles from the earth terminal to the satellite; however, this CDF will be a function of the off-axis angle, φ . To derive a function that is applicable to all off-axis angles consider the maximum of the probability in equation (8) over all off-axis angles. From equation (8) this desired maximum probability is expressed as:

$$P_{E_B} = (\text{EIRP}_{excess}) = \max_{\varphi} \Pr\left\{ G\left(\theta_{BS_{\varphi}}\right) > (E_{Ref}\left(\varphi\right) \times \text{EIRP}_{excess} / E_B) \right\}$$
(10)

The above function for the excess probability is not dependent on the specific locations of the earth terminal or the satellite, or the particular off-axis angle; therefore, this function is a suitable candidate for the illustrative off-axis e.i.r.p. density mask, P_{max} (EIRP_{excess}).

To apply the above approach to limit the off-axis e.i.r.p. density emissions of a practical antenna system, the following should be specified as operational constraints: a reference off-axis e.i.r.p. density level, $E_{Ref}(\varphi)$ and the maximum probability that the e.i.r.p. density level may exceed the level ($E_{Ref}(\varphi) \times \text{EIRP}_{excess}$) over all off-axis angles, P_{max} (EIRP_{excess}), which is an illustrative statistical mask for the off-axis e.i.r.p. density level. For a particular antenna system the following values should be known: normalized antenna gain pattern, pointing error statistics and the locations of the earth terminal and the desired satellite. The objective is to set the boresight e.i.r.p. density level are satisfied. This is accomplished by computing the CCDF of $G(\theta_{BS\varphi})$ as a function of E_B as in equation (8), and then determining the appropriate value of E_B so that this CCDF is upper bounded by the constraint P_{max} (EIRP_{excess}) for all values of φ and e.i.r.p.excess. An illustrative step-by-step method to utilize the probability function in equation (10) to limit the off-axis e.i.r.p. density level in a practical antenna system is given in § 7.

To derive a specific illustrative statistical mask for the e.i.r.p. density level consider the following reference level for the e.i.r.p. density:

$$E_{Ref}(\varphi)(dBW/40 \text{ kHz}) = \begin{cases} 25 - 25 \log(\varphi) & 2 \leq \varphi < 7\\ 4 & 7 \leq \varphi < 9.2\\ 28 - 25 \log(\varphi) & 9.2 \leq \varphi < 48\\ -14 & 48 \leq \varphi \leq 180 \end{cases}$$
(11)

This is the off-axis e.i.r.p. density mask as specified in Recommendation ITU-R S.728 combined with Note 1 in this Recommendation. Figure 3 shows the right-hand side of equation (10) (without maximization), $\Pr\{G(\theta_{BS\phi}) > (E_{Ref}(\phi) \times EIRP_{excess}/E_B)\}$ as a function of ϕ for fixed values of e.i.r.p. excess and E_B . Observe that when e.i.r.p. excess is varied the maximum of this probability will occur at different values of φ . Figure 4 shows this maximum value, P_{E_B} (EIRP_{excess}), for parameters α and c of the PDFs of the motion-induced antenna pointing error components, ϕ_{ε} and ϕ_a , and the boresight e.i.r.p. density, E_B . Here it is assumed that the above two random variables are identically distributed and mutually independent. For the antenna pattern given in equation (2) the following representative values were chosen for 14 GHz frequency band applications: d = 0.51 m, n = 1 and frequency = 14.2 GHz. Observe that, for larger values of α the PDF of the antenna pointing error will have a shorter tail and, therefore, P_{E_R} (EIRP_{excess}) will decay faster. Also, for smaller values of c the PDF of the antenna pointing errors will be narrower and this will result in a smaller probability for P_{E_B} (EIRP_{excess}). Clearly, the curves shown in Fig. 4 depend on E_B : smaller values of E_B will result in correspondingly smaller values for P_{E_B} (EIRP_{excess}). For the curves shown in this figure E_B is set at its maximum value so that the resulting P_{E_B} (EIRP_{excess}) is just below its value corresponding to the parameters: $\alpha = 1.5$, $c = 0.35^{\circ}$ and $E_B = 21.53$ (dBW/40 kHz). In the next section, the details of determining the specific values for E_B shown in this figure are discussed.



FIGURE 3



Any of the curves shown in Fig. 4 are suitable candidates for the illustrative statistical mask for the off-axis e.i.r.p. density. In this annex the upper curve in this figure, which corresponds to the parameters $\alpha = 1.5$, $c = 0.35^{\circ}$ and $E_B = 21.53$ (dBW/40 kHz), is selected as an illustrative statistical mask for the e.i.r.p. density, P_{max} (EIRP_{excess}). This curve is selected because some measurement results indicate that these parameter values (α and c) are representative of typical operating terrain conditions and vehicle speeds. The process of determining the value of E_B is discussed in § 6. The above illustrative statistical off-axis e.i.r.p. density mask can be approximated by the following expression:

$$P_{max}(x) = \exp\left(0.016x^2 - 0.561x - 1.297\right) \quad 0 \le x \le 10 \tag{12}$$

where $x = \text{e.i.r.p.}_{excess}$ (dB). In order for an antenna system to comply with this example mask, the probability for this antenna system as computed according to equation (10), P_{EB} (e.i.r.p. $_{excess}$), should be less than P_{max} (EIRP $_{excess}$), that is:

$$\max_{E_B} P_{E_B} (\text{EIRP}_{excess}) \le P_{max} (10 \times \log_{10} (\text{EIRP}_{excess})) \quad 1 \le \text{EIRP}_{excess} \le 10$$
(13)

where the maximum is over E_B . As seen from the curves in Fig. 4, the example mask, P_{max} (EIRP_{excess} (dB)), can be satisfied by antenna systems with various values for the parameters α and *c* with reasonable levels of E_B .

6 Computing the boresight e.i.r.p. density

As seen from the derivations in the preceding section, the boresight e.i.r.p. density, E_B , plays a key role in determining the performance of terminals mounted on vehicles. Observe that the probability function given in equation (10) imposes a limit on the boresight e.i.r.p. density. Also, increasing the boresight e.i.r.p. density increases interference to adjacent satellites, and Annex 2 presents a

detailed analysis of interference from these terminals. The desired boresight e.i.r.p. density level must satisfy two competing demands: the need to transmit sufficient power to support reasonable data rates, and ensure that the resulting interference is acceptable to operators of adjacent satellites. The value of E_B necessary to transmit at reasonable data rates in vehicle-mounted earth stations may be determined by comparing it with the corresponding value for static earth terminals. Figure 5 shows the e.i.r.p. density mask for static earth terminals as established in Recommendation ITU-R S.728 and expressed in equation (11). This figure also shows the maximum values of the off-axis e.i.r.p. density corresponding to an antenna of aperture diameter, d = 0.51 m. This off-axis e.i.r.p. density level for the antenna is obtained by gradually increasing E_B until the resulting off-axis e.i.r.p. density pattern is just below the ITU-R S.728 mask. Clearly, the value of E_B that satisfies the mask increases with the antenna aperture diameter and for d = 0.51 m, $E_B = 23$ dB(W/40 kHz).



The results shown in Fig. 5 represent the case where there are no antenna pointing errors. Under antenna pointing errors, because of fluctuations of the off-axis e.i.r.p. density pattern, the boresight e.i.r.p. density has to be reduced. In the preceding section an illustrative statistical e.i.r.p. density mask for a particular antenna system was determined in equation (12). The desired value of E_B that satisfies this statistical mask is determined by increasing its value until P_{EB} (e.i.r.p.*excess*) just meets its maximum value as given on the right-hand side of equation (13).

Figure 6 shows the reduction of boresight e.i.r.p. density required to achieve the example mask defined in equation (12) so that antenna pointing errors can be accommodated. For fixed values of α , larger values of *c* correspond to larger pointing errors and this will result in a larger reduction of the boresight e.i.r.p. density. As seen from this figure, a small reduction in the boresight e.i.r.p. density to account for the antenna pointing errors, for example, when $\alpha = 1.5$ and $c = 0.2^{\circ}$ this reduction is 0.9 dB and this increases to about 1.45 dB for $\alpha = 1.5$ and $c = 0.35^{\circ}$.



7 An illustrative method to determine the boresight e.i.r.p. density to comply with the example statistical e.i.r.p. density mask

In this section a method is given to determine the compliance with the illustrative statistical off-axis e.i.r.p. density mask specified in equation (12) in § 5. Specifically, for a given set of elevation and azimuth angle errors, the method shows how to compute the maximum value of the boresight e.i.r.p. density of the antenna system. The illustrative method is as follows:

7.1 Input to the computation

a variable.

a) Representative sample values of the elevation and azimuth angle errors, $\phi_{\varepsilon}(m)$ and $\phi_{a}(m)$, m = 1, 2, ..., M, where M is the sample size. These should correspond to realtime measurements or data collected from sample paths that have characteristics similar to where the terminal is expected to operate. It is assumed that the sample size M is sufficiently large so that the statistical quantities computed using these samples are reasonably good estimates for the desired statistical values.

b) Elevation and azimuth angles to the wanted satellite, *S*, given, respectively, as ε_S and a_S . Elevation and azimuth angles in the direction of S_{φ} , given, respectively, as $\varepsilon_{S_{\varphi}}$ and $a_{S_{\varphi}}$. Figure 2 shows the relative geometry of S and S_{φ}. Here S_{φ} may be located at any point on the GSO and φ is

c) Normalized gain pattern of the antenna, $G(\varphi)$, where φ is the off-axis angle and, for illustrative purposes, it is assumed that the antenna pattern is symmetric about its boresight direction.

d) A statistical off-axis e.i.r.p. density mask as in equation (12).

7.2 Estimating the CDF of $G(\theta_{BS_{\alpha}})$

e) Using a) and b) above, compute the sum of the elevation angles toward the boresight and S_{φ} directions, $\varepsilon_{BS_{\varphi}}^{+}$; and the difference in the elevation and azimuth angles in these directions, $\varepsilon_{BS_{\varphi}}^{-}$ and $a_{BS_{\varphi}}^{-}$. Making use of equation (5), these are computed as:

$$\varepsilon_{BS\phi}^{-}(m) = (\varepsilon_{S} - \varepsilon_{S_{\phi}} - \phi_{\varepsilon}(m))$$

$$\varepsilon_{BS\phi}^{+}(m) = (\varepsilon_{S} + \varepsilon_{S_{\phi}} - \phi_{\varepsilon}(m))$$

$$a_{BS\phi}^{-}(m) = (a_{S} - a_{S_{\phi}} - \phi_{a}(m))$$

where the dependence on the sample index *m* is explicitly shown. Observe that $\varepsilon_{BS_{\varphi}}^{-}(m), \varepsilon_{BS_{\varphi}}^{+}(m)$ and $a_{BS_{\varphi}}^{-}(m)$ are functions of the off-axis angle φ .

f) Substitute the above values in equation (4) to compute the angle between the boresight and S_{φ} direction, $\theta_{BS_{\varphi}}(m)$. From equation (4):

$$\Theta_{BS\varphi}(m) = \cos^{-1} \left(\cos \varepsilon_{BS\varphi}(m) - \left(\cos \varepsilon_{BS\varphi}^+(m) + \cos \varepsilon_{BS\varphi}^-(m) \right) \times \sin^2 \frac{a_{BS\varphi}(m)}{2} \right)$$

g) By using the antenna gain pattern in c) and $\theta_{BS_{\varphi}}(m)$ computed above determine the antenna gain in the S_{φ} direction, $G(\theta_{BS_{\varphi}}(m))$. Note that $G(\theta_{BS_{\varphi}}(m))$ can be considered to be a random variable with *M* samples, and it is a function of the off-axis angle φ .

h) Estimate the CDF of $G(\theta_{BS_{\varphi}})$, $F_{G(\theta_{BS_{\varphi}})}$, using the *M* samples computed in g). Observe that since $F_{G(\theta_{BS_{\varphi}})}$ is a function of φ , the CDF has to be computed for each value of the variable φ .

7.3 Computing the maximum value for E_B that complies with the example statistical mask

i) Choose appropriate values for EIRP_{excess}, $1 \le \text{EIRP}_{excess} \le 10$, and $E_B, (E_{B,max} - \Delta E_B) \le E_B \le E_{B,max}$, and using the CDF estimated in h) determine the probability in equation (8) for each value of φ . Here $E_{B,max}$ is the maximum boresight e.i.r.p. density in the absence of antenna pointing errors and ΔE_B accounts for the reduction in the boresight e.i.r.p. density due to antenna pointing errors; for illustrative purposes set ΔE_B to $\Delta E_{B,max}/2$.

Note that equation (8) should be determined for all values of interest of EIRP_{excess} and E_B ; however, if it is known that the reduction in the boresight e.i.r.p. density is small, this computation may be simplified by limiting the range of values of E_B . Figure 6 shows the reduction in the value of E_B for the specific system parameters considered in § 6. For example, since this reduction is small a value $\Delta E_B = \Delta E_{B,max}/3$ is appropriate for the relevant system parameters.

j) For fixed values of EIRP_{excess} and E_B determine P_{EB} (e.i.r.p._{excess}) using the expression given in equation (10), which is the maximum value of the probability computed in i) with φ as the variable. The expression for P_{EB} (e.i.r.p._{excess}) is rewritten below:

$$P_{E_B} = (\text{EIRP}_{excess}) = \max_{\varphi} \Pr \left\{ G(\theta_{BS_{\varphi}}) > (E_{Ref}(\varphi) \times \text{EIRP}_{excess} / E_B) \right\}$$

Observe that $P_{EB}(e.i.r.p._{excess})$ is a non-decreasing function of E_B , when it is considered as a function of E_B for fixed values of EIRP_{excess}.

k) Finally, determine the maximum value of E_B so that $P_{EB}(e.i.r.p.excess)$ is less than the example mask in equation (12) for all values in the range of interest of EIRP_{excess}. The desired value of E_B satisfies equation (13) and is rewritten as:

 $\max_{E_B} P_{E_B} (\text{EIRP}_{excess}) \le P(10 \times \log_{10} (\text{EIRP}_{excess})) \quad 1 \le \text{EIRP}_{excess} \le 10$

Note that the above method is only for illustrative purposes and should not be construed to be the only method of computing the value of E_B .

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Annex 2

Methodology to assess interference levels resulting from variations in earth station off-axis e.i.r.p. due to pointing errors caused by movement of the vehicle-mounted platform

1 Introduction

The off-axis e.i.r.p. density level from terminals that are mounted on vehicle platforms is timevarying and hence will result in a time-varying interference signal at neighbouring geostationary satellites. This annex provides a methodology to analyse and quantify the time-varying interference resulting from vehicle-mounted earth stations. The interference effects from time-varying sources have been addressed in Recommendation ITU-R S.1323; this Recommendation also establishes the maximum permissible time allowance for short-term interference levels. This annex follows the guidelines established in Recommendation ITU-R S.1323 and develops a methodology to analyse the interference due to time-varying antenna pointing errors of terminals mounted on vehicles. The methodology provided will be useful in determining the appropriate level of the boresight e.i.r.p. density of these terminals such that they comply with the interference allowances to other satellite systems and satisfy the various performance objectives of those systems.

2 Interference assessment criteria

The performance of an FSS system critically depends on the interference it receives from other systems. Recommendation ITU-R S.1432 summarizes various considerations on interference that have been addressed in other ITU-R Recommendations. The interference criteria used in those relevant ITU-R Recommendations are based on the amount of interference that can be tolerated over long periods of time as well as during short time intervals. The former is known as the long-term criterion because the interference is averaged over a sufficiently long time. The latter criterion specifies the amount of interference over short time intervals; the interference over these intervals is typically time-varying and hence it is generally represented by a probability distribution.

Recommendation ITU-R S.1323 addresses time-varying interference impacts and establishes the maximum allowable levels of interference from different sources. However, in that Recommendation, there is no specific apportionment of the link unavailability for FSS networks for time-varying interference produced by GSO VMES. The time allowance for link unavailability due to interference from GSO/VMES is simply an example value. The methodology has the flexibility to use any apportionment, as may be agreed between administrations or to be addressed in a future ITU-R Recommendation. The underlying assumption is that the satellite link is designed with sufficient link margin to account for propagation impairments such as signal fading due to rain, receiver noise variations, and long term interference effects from other satellite networks. To account for the impact of these degradations, the satellite link performance objectives are given in terms of outage values for the bit-error-rate or the carrier-to-noise power (C/N) ratio. For example, for a given set of (C/N) ratios and corresponding outage time allowance pairs, {(C/N)_{*i*}, p_i %}, i = 1, 2, ... I, the (C/N) ratio should be less than (C/N)_{*i*} only for p_i % of the time (in any month).

According to Recommendation ITU-R S.1323 the propagation effects should account for no more than 90% of the link unavailability. Hence, the above statement can be re-stated as follows: the (C/N) ratio, computed in the absence of the time-varying interference, should be less than $(C/N)_i$ for

at most $p_i \% \times 90\%$ of the time. The remaining 10% of the time allowance for link unavailability is allocated to the additional degradation due to the time-varying interference caused by the earth and space station emissions of all other satellite networks operating in the same frequency band. Hence, the overall (*C*/*N*) ratio, computed in the presence of propagation effects and the time-varying interference, should be less than (*C*/*N*)_{*i*} only for $p_i \%$ of the time, as required.

This document addresses the increase in interference to neighbouring satellite systems due to time-varying antenna pointing errors. This increase in interference is with respect to a terminal of the exact same characteristics but operating in a stationary environment and in the absence of antenna pointing errors. It is assumed that in this static case the terminal complies with the off-axis e.i.r.p. emission mask established in Recommendation ITU-R S.728 and satisfies the numerous interference requirements set forth in relevant recommendations. The increase in the long-term interference can be determined by averaging the interference due to the time-varying antenna pointing errors over a period T_{avg} and comparing this result with its corresponding value in the static case. The long-term interference parameter, T_{avg} , should represent a sufficiently long period so that it contains characteristic time variations of the interference signal. For this case, the interference level can be controlled by the boresight e.i.r.p. density of the terminal. Details of this methodology will be given in § 4.

To satisfy the short-term objectives the methodology given in Recommendation ITU-R S.1323 may be employed. However, it should be noted that this Recommendation has been established specifically for the case when the time-varying interference is due to non-GSO systems. This is emphasized by Note 1 of this Recommendation, which states that the 10% allocation for link outages due to interference sources, as discussed above, is not applicable to interference between GSO FSS systems. Therefore, since this document addresses interference originating from GSO FSS systems, the time allowance allocated for link outages for time-varying interference will be represented by the parameter T_{allow} %, rather than 10% as per Recommendation ITU-R S.1323. The objective of this document is to evaluate the effects of time-varying interference with respect to the static case, which includes the propagation effects and interference in the absence of time-varying antenna pointing errors.

Hence, the reference case for evaluating the effects of time-varying interference is considered to be the static case. Observe that the corresponding reference case in Recommendation ITU-R S.1323 is when the degradation is due to propagation effects only. Then, the performance objective is such that the link outages in the static case are allocated at most $(100 - T_{allow})\%$ of the time allowance. Using the earlier expression, the (C/N) ratio computed with propagation effects and interference in the static case, should be less than $(C/N)_i$ for at most $p_i\% \times (100 - T_{allow})\%$ of the time. Consequently, the overall (C/N) ratio, computed in the presence of time-varying antenna pointing errors and propagation effects, is less than $(C/N)_i$ for $p_i\%$ of the time, as required. As in the long-term interference case, the boresight e.i.r.p. density of the antenna can control the link outage; this aspect is discussed in detail in § 4.

3 Reference framework for the interference analysis

This section provides a reference framework used to assess the interference and it lists the parameters and notations used in the equations that follow.

Figure 7 illustrates the wanted and the interfering satellite networks. The wanted satellite is denoted as S_1 and its transmit and receive terminals are denoted by T_1 and R_1 , respectively. The interfering terminal is T_2 and its intended satellite is S_2 . The victim receiver, R_1 , receives the signal from both satellites, S_1 and S_2 , as shown in Fig. 7.

FIGURE 7

Wanted and interfering satellite networks. Terminals T_1 , R_1 and S_1 are in the wanted network; terminal T_2 and satellite S_2 are in the interfering network



The following is a list of parameters and the notation adopted in this Recommendation.

- φ : off-axis angle from T_2 to S_1 in the absence of antenna pointing errors
- θ : off-axis angle from R_1 to S_2
- $A\uparrow$: rain fading in the uplink from T_1 to S_1
- A_{\downarrow} : rain fading in the downlink from S_1 to R_1
- $A_{\uparrow,I}$: rain fading in the uplink from interference source T_2 to S_1 or S_2
 - B_s : e.i.r.p. density (W/Hz) in the boresight direction in the static case, which is the value in the absence of time-varying antenna pointing errors at T_2 . Here, boresight is the direction in which the antenna gain is at a maximum
 - B_t : e.i.r.p. density (W/Hz) in the boresight direction at T_2 in the presence of timevarying antenna pointing errors. Note that this parameter corresponds to E_B in equation (3)
- ΔB : reduction in boresight e.i.r.p. density, $\Delta B = B_s/B_t$
- $(C/N)_{cs}$: carrier-to-noise power ratio at R_1 under clear sky conditions. C is the wanted carrier power received at R_1 from T_1
- $(C/N)_s$: (C/N) ratio at R_1 in the static case, which is due to rain fading and interference from T_2 in the absence of time-varying antenna pointing errors
- $(C/N)_t$: (C/N) ratio at R_1 due to rain fading and interference from T_2 due to timevarying antenna pointing errors
- $G_1(\theta)$: normalized directive gain of R_1 antenna in the off-axis direction θ ($G_1(0) = 1$)
- $G_2(\varphi)$: normalized directive gain of T_2 antenna in the off-axis direction φ ($G_2(0) = 1$). Note that this parameter corresponds to $G(\varphi)$ in equation (2) of Annex 1
- $G_{2,t}(\varphi)$: normalized directive gain of T_2 antenna in the direction of φ in the presence of time-varying antenna pointing errors

*G*_{*S*1}: small signal gain at *S*₁. (e.i.r.p. at *S*₁ toward *R*₁) = (power flux-density from *T*₂)

$$\times \frac{\lambda^2}{4\pi} \times G_{S1}$$
, λ uplink wavelength

- G_{S2} : small signal gain at S_2 . (e.i.r.p. at S_2 toward R_1) = (power flux-density from T_2) $\times \frac{\lambda^2}{4\pi} \times G_{S2}$, λ uplink wavelength
- $(G/T)_1$: receive antenna gain-to-noise temperature at R_1
- $(G/T)_{S1}$: receive antenna gain-to-noise temperature at S_1 when receive direction is toward T_2
- $(G/T)_{S2}$: receive antenna gain-to-noise temperature at S_2 when receive direction is toward T_2
 - $I_{s,1}$: interference power from T_2 received at R_1 , via S_1 , in the absence of timevarying antenna pointing errors
 - $I_{s,2}$: interference power from T_2 received at R_1 , via S_2 , in the absence of timevarying antenna pointing errors
 - $I_{t,1}$: interference power from T_2 received at R_1 , via S_1 , in the presence of timevarying antenna pointing errors
 - $I_{t,2}$: interference power from T_2 received at R_1 , via S_2 , in the presence of timevarying antenna pointing errors
 - *k*: Boltzmann constant, 1.38×10^{-23} J/K

 $\log(X)$: $\log_{10}(X)$

- L_u : uplink loss (clear sky) from T_2 to S_1 or S_2
- L_d : downlink loss (clear sky) from S_1 or S_2 to R_1
- N_{\downarrow} : receiver noise power at R_1 , corresponding noise temperature T_{\downarrow}

 N_{\uparrow} : noise power from S_1 received at R_1

 $N_{\uparrow,2}$: noise power from S_2 received at R_1

- N_r : rain (sky) noise at receiver R_1 due to rain temperature T_r (downlink)
- $p_X(x)$: probability density function (pdf) of X

 $P_X(x) = \Pr\{X \le x\}$: cumulative distribution function (cdf) of X

- \overline{X} : variable expressed in dB, 10 log₁₀ X
- $\langle X \rangle$: average value of the random variable X
 - Z_s : $Z_s = \frac{(C/N)_{cs}}{(C/N)_s}$, degradation of (C/N) ratio due to effects of rain fading and

static interference from terminal T_2

 Z_t : $Z_t = \frac{(C/N)_{cs}}{(C/N)_t}$, degradation of (C/N) ratio due to effects of rain fading and time-varying interference from terminal T_2 .

4 Short-term interference effects: degradation of (C/N) ratio

This section computes the degradation of the (C/N) ratio at R_1 due to rain fading and interference from T_2 . The rain fading considered here will introduce statistical variations to the received (C/N)ratio². First, rain fading and interference from T_2 in the absence of time-varying antenna pointing errors are considered to compute the cdf of Z_s , which is the degradation of the (C/N) ratio at R_1 . This is discussed in § 4.1. Next, the time-varying antenna pointing errors are introduced at T_2 and the cdf of the resulting degradation of the (C/N) ratio at R_1 , which is denoted by Z_t , is determined. These cdfs are then used to compute the relative increase in the link unavailability due to the time-varying antenna pointing errors. This is discussed in § 4.2.

The analysis given in this section assumes that the victim receiver is subject to interference from only a single adjacent satellite; if the interference signals from other neighbouring satellites are not negligible they should be accounted for in a similar manner.

4.1 Static case: Terminal T_2 transmitting in the absence of time-varying antenna pointing errors

The clear sky carrier-to-noise power ratio at the receiver, R_1 , for the satellite network shown in Fig. 1 is:

$$(C/N)_{CS} = \frac{C}{N_{\downarrow} + N_{\uparrow} + I_{S,1} + I_{S,2} + N_{\uparrow,2}}$$
(14)

Here the interference terms $I_{s,1}$ and $I_{s,2}$ are due to T_2 transmitting with boresight e.i.r.p. density B_s in the static case, which is in the absence of time-varying antenna pointing errors. When T_2 is a small aperture terminal it may be assumed that B_s complies with the off-axis e.i.r.p. mask given in Recommendation ITU-R S.728 and the relevant interference recommendations. Note that in equation (14) the term $N\uparrow + I_{s,1}$ is from S_1 and $I_{s,2} + N\uparrow_2$ is from S_2 . In the presence of uplink and downlink rain fading of the wanted signal, the (*C*/*N*) ratio is:

$$(C/N)_{S} = \frac{C/A_{\uparrow} A_{\downarrow}}{N_{\downarrow} + N_{\uparrow} / A_{\downarrow} + N_{r} (1 - 1/A_{\downarrow}) + (I_{S,1} + I_{S,2}) / (A_{\uparrow,I} A_{\downarrow}) N_{\uparrow,2} / A_{\downarrow}}$$
(15)

Here it is assumed that the satellites S_1 and S_2 are very closely spaced so that uplink rain fading components to these satellites from T_2 are approximately the same. Also, it is assumed that the downlink rain fading components from S_1 and S_2 to R_1 are similar. When S_1 and S_2 are not closely spaced these assumptions may not be valid; in such cases, the correlation between the respective fading components should be taken into account. Note that the term, $N_r (1 - 1 / A_{\downarrow}), (A_{\downarrow} \ge 1)$, in the enominator denotes the additional receiver noise due to the rain temperature, T_r .

From this the degradation of the (C/N) ratio in the presence of uplink and downlink rain fading can be expressed as:

$$Z_s = (A_{\uparrow} / A_{\uparrow I}) \times (A_{\downarrow} A_{\uparrow I} d_1 + A_{\uparrow I} d_2 + d_3)$$
(16)

² Satellite links are usually designed with fade margins in the link to account for such degradations.

where the link variables c_1 , c_2 , c_3 , c_4 , c_5 , d_1 , d_2 and d_3 are defined as:

$$c_{1} = \frac{I_{s,2}}{I_{s,1}}; c_{2} = \frac{I_{s,1}}{N_{\uparrow}}; c_{3} = \frac{N_{\uparrow}}{N_{\downarrow}}; c_{4} = \frac{N_{r}}{N_{\downarrow}}; c_{5} = \frac{N_{\uparrow,2}}{I_{s,2}}$$

$$d_{1} = \frac{1+c_{4}}{1+c_{1}c_{2}c_{3}(1+c_{5})+c_{2}c_{3}+c_{3}}$$

$$d_{2} = \frac{c_{1}c_{2}c_{3}c_{5}+c_{3}-c_{4}}{1+c_{1}c_{2}c_{3}(1+c_{5})+c_{2}c_{3}+c_{3}}$$

$$d_{3} = \frac{c_{1}c_{2}c_{3}+c_{2}c_{3}}{1+c_{1}c_{2}c_{3}(1+c_{5})+c_{2}c_{3}+c_{3}}.$$
(17)

These variables can be determined for a given set of link variables. Specifically:

$$c_{1} = \frac{G_{2}(0)}{G_{2}(\phi)} \frac{G_{S2}}{G_{S2}} \frac{G_{1}(\theta)}{G_{1}(0)}$$

$$c_{2} = \frac{B_{s} G_{2}(\phi) (G/T)_{S1}}{k L_{u}}$$

$$c_{3} = \frac{(G/T)_{1} G_{S1}}{(G/T)_{S1} L_{d}}$$

$$c_{4} = \frac{T_{r}}{T_{\downarrow}}$$

$$c_{5} = \frac{k L_{u}}{B_{s} G_{2}(0) (G/T)_{S2}}$$
(18)

where, in order to simplify the expressions, it is assumed that in the absence of rain fading the uplink propagation losses from T_2 to satellites S_1 and S_2 are the same. A similar assumption holds for the downlink propagation losses from satellites S_1 and S_2 to R_1 .

Taking the logarithm of Z_s in equation (16):

$$\overline{Z}_{s} = \overline{A}_{\uparrow} - \overline{A}_{\uparrow,I} + 10 \log \left(10^{(\overline{A}_{\downarrow} + \overline{A}_{\uparrow,I})^{/10}} d_{1} + 10^{(\overline{A}_{\uparrow,I})^{/10}} d_{2} + d_{3} \right)$$
(19)

It is easier to determine analytically the cdf of \overline{Z}_s in the special case when the uplink rain fade component $\overline{A}_{\uparrow,I}$ is ignored, that is $\overline{A}_{\uparrow,I} = 0$. Note that this particular case is considered only because of analytical simplicity; in the more general case the rain fading component should not be ignored. In this case the cdf of the degradation can be expressed as:

$$P_{s}(\overline{z}) = \Pr(\overline{Z}_{s} \le \overline{z}) = \iint_{R_{\overline{z}}} p_{\overline{A}_{\downarrow}}(u) p_{\overline{A}_{\uparrow}}(v) \, \mathrm{d}v \, \mathrm{d}u$$

where the region of integral is such that for $\overline{A}_{\downarrow}, \overline{A}_{\uparrow} \in R_{\overline{z}}$ the value of \overline{Z}_s satisfies $\overline{Z}_s \leq \overline{z}$. In the above it is assumed that the rain fading components, $\overline{A}_{\downarrow}$ and \overline{A}_{\uparrow} , are independent of each other.

Since \overline{Z}_s is a monotonically increasing function of $\overline{A}_{\downarrow} (\geq 0)$ and $\overline{A}_{\uparrow} (\geq 0)$ the region $R_{\overline{z}}$ can be expressed as the region bounded by $0 \leq \overline{A}_{\uparrow} \leq \overline{z} - 10 \log (10^{\overline{A}_{\downarrow}/10} d_1 + d_2 + d_3)$ and $0 \leq \overline{A}_{\downarrow} \leq 10 \log ((10^{\overline{z}/10} - d_2 - d_3)/d_1)$.

The above integral is then evaluated as:

$$p_{s}(\bar{z}) = \iint_{R_{\bar{z}}} p_{\bar{A}_{\downarrow}}(u) p_{\bar{A}_{\uparrow}}(v) dv du$$

= $\int_{u=0}^{u'} p_{\bar{A}_{\downarrow}}(u) \int_{v=0}^{u=\bar{z}-10 \log(10^{u/10} d_{1}+d_{2}+d_{3})} p_{\bar{A}_{\uparrow}}(v) dv du$ (20)
= $\int_{u=0}^{u'} p_{\bar{A}_{\downarrow}}(u) p_{\bar{A}_{\uparrow}}(\bar{z}-10 \log(10^{u/10} d_{1}+d_{2}+d_{3})) du$

where $u' = 10 \log ((10^{\overline{z}/10} - d_2 - d_3)/d_1).$

4.2 Terminal T₂ transmitting in the presence of time-varying antenna pointing errors

In this case time-varying antenna pointing errors are introduced at the transmit terminal T_2 . In order to limit additional interference in the presence of antenna pointing errors, the boresight e.i.r.p. density has to be reduced to B_t from B_s . The (*C*/*N*) ratio in the presence of rain fading and the time-varying antenna pointing errors follows from equation (2) as:

$$(C/N)_{t} = \frac{C/A_{\uparrow} A_{\downarrow}}{N_{\downarrow} + N_{\uparrow} / A_{\downarrow} + N_{r} (1 - 1/A_{\downarrow}) + (I_{t,1} + I_{t,2}) / (A_{\uparrow,I} A_{\downarrow}) + N_{\uparrow,2} / A_{\downarrow}}$$
(21)

where the time-varying interference terms $I_{t,1}$ and $I_{t,2}$ can be expressed as fractions of their corresponding values in the static case:

$$\frac{I_{t,1}}{I_{s,1}} = \frac{B_t \ G_{2,t}(\varphi)}{B_s \ G_2(\varphi)}$$

$$\frac{I_{t,2}}{I_{s,2}} = \frac{B_t \ G_{2,t}(0)}{B_s \ G_2(0)}$$
(22)

The above antenna gain factors, G_2 and $G_{2,t}$, can be obtained from the knowledge of the antenna gain pattern, for example, the normalized antenna gain pattern may be expressed as:

$$G(\varphi) = \left(\frac{2^{n+1}(n+1)! j_{n+1}(\pi d / \lambda \times \sin \varphi)}{(\pi d / \lambda \times \sin \varphi)^{n+1}}\right)$$
(23)

where φ is the off-axis angle, J_{n+1} is the Bessel function of the first kind and order (n + 1), d is the diameter of the circular aperture and λ is the wavelength. In the above n is the antenna aperture illumination parameter and this corresponds to the following aperture illuminations: n = 0, ideal uniform; n = 1, parabolic; and n = 2, parabolic squared. The main lobe of many practical aperture systems falls between the gain patterns corresponding to n = 0 and n = 2. Note that the side lobes of practical antennas may not be accurately represented by equation (23).

The antenna gain factor in the absence of pointing errors, according to the notation used in equation (22), $G_2(\varphi) = G(\varphi)$. In the presence of antenna pointing errors, the errors in the boresight direction of the antenna can be characterized by elevation and azimuth errors denoted by ϕ_{ε} and ϕ_a , respectively. Then the required angular error, which is the angle between the boresight direction of the antenna and the direction from T_2 toward S_1 , can be expressed as $\Phi(\varphi, \phi_{\varepsilon}, \phi_a)$ where the function Φ can be determined for a specific geometry as shown in § 3 of Annex 1. The antenna gain factor in equation (22) is now expressed as:

$$I_{t,1} \le \frac{1}{\Delta B} \frac{1}{G_2(\phi)} I_{s,1}$$
 (24)

In the presence of antenna pointing errors, because of mispointing of the main beam of T_2 away from S_2 , it can be seen that $I_{t,2} < I_{s,2}$. That is, for interference received at R_1 via S_2 , the degradation due to antenna pointing errors is always less than its corresponding interference in the static case. For interference received via S_1 , from equation (22), the maximum value of the interference component occurs when $G_{2,t}$ (φ), that is, when the boresight of the antenna is aligned along the direction from T_2 to S_1 . This demonstrates that, for the two-satellite system considered here, the time-varying interference power can be upper bounded, irrespective of the magnitude of the pointing error.

From equations (14) and (21) the degradation of the (C/N) ratio in the presence of antenna pointing errors is:

$$Z_{t} = (A_{\uparrow} / A_{\uparrow,I}) \times (A_{\downarrow} / A_{\uparrow,I} e_{1} + A_{\uparrow,I} e_{2} + G_{2,t} (\varphi) / \Delta B e_{3} + G_{2,t} (0) / \Delta B e_{4})$$
(25)

where the link variables are defined as:

$$e_{1} = \frac{1 + c_{4}}{1 + c_{1}c_{2}c_{3}(1 + c_{5}) + c_{2}c_{3} + c_{3}}$$

$$e_{2} = \frac{c_{1}c_{2}c_{3}c_{5} + c_{3} - c_{4}}{1 + c_{1}c_{2}c_{3}(1 + c_{5}) + c_{2}c_{3} + c_{3}}$$

$$e_{3} = \frac{1}{G_{2}(\phi)} \frac{c_{2}c_{3}}{1 + c_{1}c_{2}c_{3}(1 + c_{5}) + c_{2}c_{3} + c_{3}}$$

$$e_{4} = \frac{1}{G_{2}(0)} \frac{c_{1}c_{2}c_{3}}{1 + c_{1}c_{2}c_{3}(1 + c_{5}) + c_{2}c_{3} + c_{3}}$$
(26)

Expressing equation (25) in logarithmic form:

$$\overline{Z}_{t} = \overline{A}_{\uparrow} - \overline{A}_{\uparrow,I} + 10 \log \left(10^{(\overline{A}_{\downarrow} + \overline{A}_{\uparrow,I})/10} e_{1} + 10^{\overline{A}_{\uparrow,I}/10} e_{2} + 10^{(\overline{G}_{2,t}(\phi) - \overline{\Delta}\overline{B})/10} e_{3} + 10^{(\overline{G}_{2,t}(0) - \overline{\Delta}\overline{B})/10} e_{4} \right) (27)$$

As in the static case, for analytical simplicity, consider the special case when $\overline{A}_{\uparrow,I} = 0$. In this case the cdf of \overline{Z}_{I} can be expressed as:

$$P_{t}(\overline{z}) = \Pr(\overline{Z}_{t} \le \overline{z})$$

=
$$\int_{R_{\overline{z}}} p_{\overline{G}_{2,t}(0)}(w) p_{\overline{G}_{2,t}(\phi)}(v) p_{\overline{A}_{\downarrow}}(u) p_{\overline{A}_{\uparrow}}(t) dt du dv dw$$

where the region of integral is such that for $\overline{G}_{2,t}(0), \overline{G}_{2,t}(\varphi), \overline{A}_{\downarrow}, \overline{A}_{\uparrow} \in R_{\overline{z}}; \overline{Z}_t \leq \overline{z}$. Here it is assumed that the respective random variables are statistically independent; note that, under general conditions, the random variables $\overline{G}_{2,t}(0)$ and $\overline{G}_{2,t}(\varphi)$ may not be statistically independent. In such cases the joint distribution of these two random variables should be considered in the above expression. Noting that \overline{Z}_t is a monotonically increasing function of the variables $\overline{G}_{2,t}(0), \overline{G}_{2,t}(\varphi), \overline{A}_{\downarrow}$ and \overline{A}_{\uparrow} , the above integral can be expressed as:

$$P_{t}(\bar{z}) = \int_{w=-\infty}^{w'} p_{\overline{G}_{2,t}}(0)(w) \int_{v=-\infty}^{v'} p_{\overline{G}_{2,t}}(\phi)(v) \int_{u=0}^{u'} p_{\overline{A}_{\downarrow}}(u)$$

$$p_{\overline{A}_{\uparrow}}(\bar{z} - 10 \log (10^{u/10} e_{1} + e_{2} + 10^{(v-\overline{\Delta}\overline{B})/10} e_{3} + 10^{(w-\overline{\Delta}\overline{B})/10} e_{4})) du dv dw$$
(28)

where the upper limits of the integrals are as follows:

$$u' = 10 \log\left(\frac{10^{\bar{z}/10} - e_2 - 10^{(v - \overline{\Delta}\overline{B})/10} e_3 - 10^{(w - \overline{\Delta}\overline{B})/10} e_4}{e_1}\right)$$

$$v' = 10 \log\left(\frac{10^{\bar{z}/10} - e_1 - e_2 - 10^{(w - \overline{\Delta}\overline{B})/10} e_4}{e_3}\right) + \overline{\Delta}\overline{B}$$

$$w' = 10 \log\left(\frac{10^{\bar{z}/10} - e_1 - e_2 - 10^{-\overline{\Delta}\overline{B}/10} e_3}{e_4}\right) + \overline{\Delta}\overline{B}$$
(29)

The relative increase in the link unavailability due to time-varying antenna pointing errors with respect to the total link unavailability, $R(\bar{z})$ (%), can be expressed as:

$$R(\bar{z})\% = 100\% \times \frac{(1 - P_t(\bar{z})) - (1 - P_s(\bar{z}))}{(1 - P_t(\bar{z}))}$$
 (30)

Note that it may be deduced from the discussion leading to equation (24) that for larger values of $\overline{\Delta B}$, $P_i(\overline{z})$ could be greater than $P_s(\overline{z})$. This implies that in some cases $R(\overline{z}) < 0$, that is, by reducing the boresight e.i.r.p. density it is possible to make the time-varying interference less than the corresponding interference in the absence of time-varying antenna pointing errors. To compute $R(\overline{z})$ as given in equation (30), assume the total link unavailability is p_i % and $(100 - T_{allow})$ % of this unavailability value is allocated to static interference. The fade margin required under static conditions for this link unavailability, \overline{z}^* , is computed from $(1 - P_s(\overline{z}^*)) = p_i \% \times (100 - T_{allow})\%$. The overall link unavailability for this fade margin in the presence of time-varying interference is $(1 - P_i(\overline{z}^*))$. From these the relative increase in the link unavailability for this fade margin, $R(\overline{z}^*)\%$, can be computed using the expression given in equation (30).

F arameters for the mix from I_2 to K_1			
Frequency uplink (GHz)	14.2		
Uplink, downlink losses (dB)	207, 205.3 (Ankara) 207.2, 205.3 (London)		
Boltzmann's constant (dBW/Hz/K)	-228.6		
Small signal gain at S_1 , G_{S1} (dB)	175.2		
$(G/T)_{S1}$ (dB/K)	2 (Ankara) 4 (London)		
Frequency downlink (GHz)	11.7		
$T_r(\mathbf{K})$	285		
Off-axis angle, from T_2 to S_1	2.22° (Ankara) 2.18° (London)		

Parameters for the link from T_2 to R_1

ΤA	BL	E	2

Parameters to compute rain attenuation

S_1 location (Eutelsat W1)	10° E
S_2 location	12° E
T_1 location (Canary Islands)	Latitude: 27.76° N Longitude: -15.63° E
T_1 altitude above mean sea level (m)	205
R_1 location (Matera, Italy)	Latitude: 40.39° N Longitude: 16.42° E
R_1 altitude above mean sea level (m)	527
T_2 location (Ankara, Turkey)	Latitude: 39.8° N Longitude: 32.8° E
T_2 location (London, England)	Latitude: 51.5° N Longitude: -0.12° E
T_2 altitude above mean sea level (m)	200 (Ankara) 200 (London)

5 Example calculation using the above methodology

This section provides an example calculation to illustrate the methodology given in § 4. Table 1 gives the link parameters used in this example. The rain attenuation components, A_{\uparrow} , A_{\downarrow} and $A_{\uparrow,I}$, are computed according to Recommendation ITU-R P.618 using the parameters given in Table 2. In this example a large aperture antenna is assumed for the receive terminal R_1 . Since the antenna gain is such that $G_1(\theta) \ll G_1(0)$, the interference received from S_2 at R_1 is neglected in this example.

Figure 8 shows the cdfs of the random variables $G_{2,t}(0)$ and $G_{2,t}(\varphi)$ in the presence of time-varying antenna pointing errors. The antenna pointing errors correspond to azimuth and elevation errors generated from an $S\alpha S$ distribution as discussed in § 2 of Annex 1, where the parameters of the distribution are: $\alpha = 1.5$ and $c = 0.35^{\circ}$. The specific antenna gain antenna pattern used is given in equation (23) with n = 1 and d = 0.51 m. In this example the off-axis angle from T_2 to S_1 , φ , is 2.22° and the corresponding normalized antenna gain, $G_2(\varphi) = -6.7$ dB. This figure shows the fluctuations of $G_{2,t}(\varphi)$ in the presence of antenna pointing errors. Note that in comparison to the static case, the interference to S_1 will be increased when $G_{2,t}(\varphi) > G_2(\varphi)$ and decreased when $G_{2,t}(\varphi) < G_2(\varphi)$.



Figure 9 shows $R(\bar{z})\%$ for different values of the antenna boresight e.i.r.p. density. In this example a Monte-Carlo simulation of the degradation variables, \bar{Z}_s and \bar{Z}_t as given in equations (19) and (27), is carried out to determine the probabilities $P_s(\bar{z})$ and $P_t(\bar{z})$. In this example, for illustrative purposes, a 98% link availability condition is considered. As discussed in § 2, this is an input requirement to protect neighbouring satellites; hence for this example $p_i\% = 2\%$. Suppose 90% ($T_{allow}\% = 10\%$) of the link unavailability is assigned to rain fading and static interference, that is $(1 - P_s(\bar{z})) = (1 - 0.98) \times 90\%$. The corresponding fade margin, \bar{z}_{margin} , that satisfies the above is determined so that $(1 - P_s(\bar{z}_{margin})) = (1 - 0.98) \times 90\%$. Next, the overall link unavailability in the presence of antenna pointing errors and for this fade margin $1 - P_t(\bar{z}_{margin})$ is determined. The value of $R(\bar{z}_{margin})$ can be obtained from equation (30).

As seen from Fig. 19, in the presence of time-varying antenna pointing errors, the link unavailability can be substantially lowered by reducing the boresight e.i.r.p. density. Observe that, as stated above, for larger values of $\overline{\Delta B}$ the increase in the link unavailability could be such that $R(\overline{z}) < 0$. Also, for large values of the receive terminal (*G*/*T*) the receiver is more sensitive to interference received from the satellite; this increases the interference and thus increases the unavailability of the link.





6 Long-term interference effects

As stated earlier, the long-term interference power is computed by averaging the interference power over a satisfactorily long time period so that all representative variations of the time-varying interference signal are contained within this time period. Relevant ITU-R Recommendations that impose limits on the average interference power consider the interference power received to the total receiver system noise power ratio. In the absence of time-varying antenna pointing errors, considering the interference from T_2 that is received at R_1 via satellites S_1 and S_2 , this ratio for the interference power can be expressed as:

$$f_{s} = \frac{I_{s,1} + I_{s,2}}{N_{\downarrow} + N_{\uparrow} + I_{s,1} + I_{s,2} + N_{\uparrow,2}}$$

$$= \frac{c_{2}c_{3} + c_{1}c_{2}c_{3}}{1 + c_{1}c_{2}c_{3}(1 + c_{5}) + c_{2}c_{3} + c_{3}}$$
(31)

Next, time-varying antenna pointing errors are introduced to the above static case and the interference power is averaged over T_{avg} to obtain the time-averaged values of the interference terms $I_{t,1}$ and $I_{t,2}$, which are denoted by $\langle I_{t,1} \rangle$ and $\langle I_{t,2} \rangle$. The average interference power as a fraction of the total system noise power can then be expressed as:

$$f_{t} = \frac{\langle I_{t,1} \rangle + \langle I_{t,2} \rangle}{N_{\downarrow} + N_{\uparrow} + \langle I_{t,1} \rangle + \langle I_{t,2} \rangle + N_{\uparrow,2}} = \frac{c_{2} c_{3} \langle G_{2,t} (\varphi) \rangle / (\Delta B G_{2} (\varphi)) + c_{1} c_{2} c_{3} \langle G_{2,t} (0) \rangle / (\Delta B G_{2} (0))}{1 + c_{3} + c_{2} c_{3} \langle G_{2,t} (\varphi) \rangle / (\Delta B G_{2} (\varphi)) + c_{1} c_{2} c_{3} \langle G_{2,t} (0) \rangle / (\Delta B G_{2} (0)) + c_{1} c_{2} c_{3} c_{5}}$$
(32)

Thus, the increase in the long-term average interference with respect to the total interference is expressed as:

$$R_L(\%) = 100 \% \times \frac{f_t - f_s}{f_t}$$
(33)

7 An illustrative procedure to implement this methodology

This section presents a step-by-step procedure to implement the computations given in § 4. Specifically, the procedure, based on Monte-Carlo simulations, computes the increase in the link unavailability because of the time-varying antenna pointing errors. Note that this is an illustrative approach, as other approaches may be used.

7.1 Input to the computation

Link parameters: Longitudes and latitudes of T_1 , R_1 and T_2 ; longitudes of satellites S_1 and S_2 ; θ , $G_1(\theta)$, $(G/T)_1$, T_{\downarrow} ; ϕ , normalized antenna gain pattern of T_2 , $G_2(\phi)$; G_{S1} , G_{S2} , $(G/T)_{S1}$, $(G/T)_{S2}$; L_d , L_u , T_r .

Rain parameters: Rain rate (0.01% mm/h), altitude above mean sea level and rain height (for T_1 , R_1 and T_2). These parameters can also be computed using Recommendations ITU-R P.837 and ITU-R P.839.

Link unavailability: The required time percentages for link unavailability, p_i %. Time allowance allocated for link outages for time-varying interferences, T_{allow} %.

Monte-Carlo simulation parameter: Length of random vectors, N.

Antenna pointing error characteristics: Azimuth and elevation error vectors of length N, ϕ_{ε} and ϕ_{a} , generated as discussed in § 2 of Annex 1.

7.2 Degradation of (C/N) ratio in the absence of time-varying antenna pointing errors

Step 1: Determine B_s , the boresight e.i.r.p. density of T_2 , using $G_2(\varphi)$ and according to Recommendation ITU-R S.728. It is assumed that this B_s complies with various interference and coordination requirements as summarized in Recommendation ITU-R S.1432.

Step 2: Compute link variables.

- a) Using the link parameters compute the variables c_1 , c_2 , c_3 , c_4 , and c_5 , as given in equation (18).
- b) Compute d_1 and d_2 as shown in equation (17).

Step 3: Determine uplink and downlink rain fades.

- a) Using the rain parameters determine the cdfs of the uplink and downlink rain fades, \overline{A}_{\uparrow} , $\overline{A}_{\downarrow}$ and \overline{A}_{\uparrow} , according to Recommendation ITU-R P.618.
- b) From these cdfs determine 3 vectors of random variables, each of length N, for \overline{A}_{\uparrow} , $\overline{A}_{\downarrow}$ and $\overline{A}_{\uparrow,I}$.

Step 4: Using equation (19) generate the vector of random variables for \overline{Z}_s .

Step 5: Determine the cdf of \overline{Z}_s , $P_s(\overline{z})$, using this vector of random variables.

Step 6: Compute the fade margin, \overline{z}_i , required for link unavailability, $p_i\% \times (100 - T_{allow})\%$. The required \overline{z}_i satisfies the following: $(1 - P_s(\overline{z})) = p_i / 100 \times (100 - T_{allow}) / 100$.

7.3 Degradation of (C/N) ratio in the presence of time-varying antenna pointing errors

Step 7: Determine the link parameters e_1 , e_2 , e_3 and e_4 in equation (13).

Step 8: Generate two random vectors, each of length N, for $G_{2,t}(0)$ and $G_{2,t}(\phi)$.

- a) As discussed in § 2 of Annex 1 generate two random vectors, each of length *N*, for pointing error variables ϕ_{ϵ} and ϕ_{a} .
- b) Using the relative longitudes and latitudes and the pointing errors, compute the angle vectors from the boresight direction of T_2 to satellites S_1 and S_2 , Φ (φ , φ_{ϵ} , φ_a), Φ (φ , φ_{ϵ} , φ_a), and Φ (0, φ_{ϵ} , φ_a), as shown in § 3 of Annex 1. Note that according to the notation in Annex 1, Φ (φ , φ_{ϵ} , φ_a) corresponds to $\theta_{BS_{\infty}}$ expressed in equation (4).
- c) Determine the random vectors of length N for $G_{2,t}(0)$ and $G_{2,t}(\phi)$ as follows: $G_{2,t}(\phi) = G_2(\Phi(\phi, \phi_{\epsilon}, \phi_a)).$

Step 9: Set ΔB as a parameter.

Step 10: Generate \overline{Z}_t in equation (12), which is a random vector of length N.

Step 11: Determine the cdf of \overline{Z}_t , $P_t(\overline{z})$, using this vector of random variables.

Step 12: Determine the link availability for fade margin \overline{z}_i computed in Step 6, which is $P_t(\overline{z}_i)$.

Step 13: Determine the relative increase in link unavailability, $R(\overline{z_i})$, as in equation (30).

8 Summary

This annex has presented a methodology to assess the interference effects to neighbouring satellites due to time-varying antenna pointing errors of VMES.

The methodology specifically addresses the increase in interference with respect to a stationary terminal, which has exact same characteristics as the vehicle-mounted terminal but without the antenna pointing errors due to motion. The approach followed is similar to that established in Recommendation ITU-R S.1323 where propagation effects such as rain fading and receiver noise variations are responsible for at most 90% of the time allowance for link outages. In this Recommendation, the propagation effects and the interference due to a static terminal are assumed to be responsible for $(100 - T_{allow})$ % of the corresponding time allowance. A methodology to assess the increase in long-term interference with respect to the static case is also presented. In the long-term interference analysis, the signal is averaged over a period T_{avg} , which is assumed to be sufficiently large so that the statistical characteristics of the interference are reasonably well represented within this period.