

RECOMMENDATION ITU-R S.1325-1

SIMULATION METHODOLOGIES FOR DETERMINING STATISTICS OF SHORT-TERM INTERFERENCE BETWEEN CO-FREQUENCY, CODIRECTIONAL NON-GEOSTATIONARY-SATELLITE ORBIT (NON-GSO) FIXED-SATELLITE SERVICE (FSS) NETWORKS AND OTHER NON-GSO FSS OR GSO FSS NETWORKS

(Questions ITU-R 206/4 and ITU-R 231/4)

(1997-2000)

The ITU Radiocommunication Assembly,

considering

- a) that emissions from the earth stations as well as from the space station of a satellite network (GSO FSS; non-GSO FSS; non-GSO mobile-satellite service (MSS) feeder links) in the FSS may result in interference to another such network when both networks operate in the same bands;
- b) that it is desirable to have a common methodology of simulation for assessing interference between systems that have co-frequency, codirectional feeder links when one of the systems is non-GSO;
- c) that it is possible to make some simplifying assumptions for these systems;
- d) that the simplifications in *considering* c) should not adversely affect the output results;
- e) that it would be desirable to have a common set of input parameters for each of the two communication systems;
- f) that it is necessary for the methodology to consider the type of fade compensation to counteract signal fading such as adaptive power control;
- g) that the methodology should have the ability to accurately calculate the time dependence of a single interference event in order to more accurately assess the impact on the interfered system;
- h) that the vast majority of the non-GSO FSS networks are in circular orbits;
- j) at the stages of notification and recording of satellite networks at the ITU the information on their earth stations number and precise location is usually unavailable,

recommends

- 1** that the methodology given in Annex 1 may be used to obtain cumulative probability statistics for assessing short-term interference between systems that have co-frequency, codirectional links with one system employing a non-GSO MSS feeder link or non-GSO FSS network;
- 2** that the output should be evaluated against an agreed set of common output statistics;
- 3** that the methodology given in Annex 2 may be used to compute the aggregate total interference produced by a non-GSO satellite network into a GSO satellite network and may be used to calculate the cumulative density function of the equivalent power flux-density (epfd) for a given antenna diameter of the GSO earth station or the epfd of the non-GSO network in the uplink direction;
- 4** that the following Notes should be considered part of this Recommendation.

NOTE 1 – Short-term interference refers to cumulative probability distribution of those bit error ratios (or C/N values) that are calculated for 1% of the time or less.

NOTE 2 – The methodology of Annex 1 also can be used to evaluate the time dependent nature of the interference during a single near in-line event.

NOTE 3 – Annex 2 provides a methodology for computing the epfd_{\uparrow} and epfd_{\downarrow} of a non-GSO network. Annex 3 provides approaches to relate the methodology of Annex 1 to compute epfd_{\uparrow} and epfd_{\downarrow} of a non-GSO network.

NOTE 4 – It should be assumed that the noise is thermal in nature and is referenced to the total system noise power including the antenna thermal noise at the input to the demodulator.

NOTE 5 – There is need to develop a methodology for characterizing and calculating the long-term interference between non-GSO FSS and GSO FSS networks.

NOTE 6 – Annex 3 is the description and example of computational methodology.

NOTE 7 – Annex 4 provides a list of subjects for continuing work on this Recommendation.

ANNEX 1

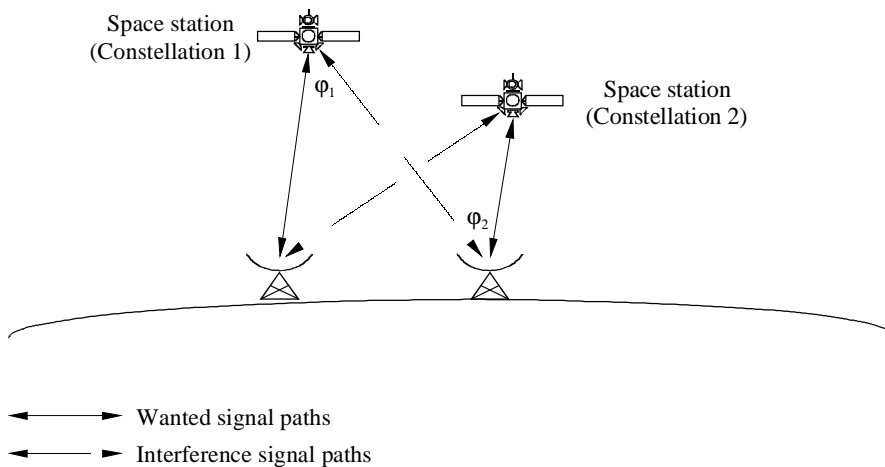
Methodology for determining statistics of short-term interference between co-frequency, codirectional non-GSO FSS networks and other non-GSO FSS or GSO FSS networks

1 Method and simulation approach description

The framework for this methodology is to model the satellite systems in their orbits and allow each space station and earth station to track their respective aimpoints while taking into account the Earth's rotation. A simulation of this framework is sampled over a period of time at a relatively fine rate. At each sample the range gain product is computed. The raw data is a time history of the interference level versus time. It can be shown that if power control is not used on either system then the range gain product (defined in equation (2)) can be directly related to the interference level. The raw data can be evaluated to compute the per cent of time that the range gain product for all interference paths is above a certain level. The interference geometry is shown in Fig. 1, and the interference paths considered are those below:

	Space station (Constellation 1)	Earth station (Constellation 1)
Space station (Constellation 2)	None	Uplink ₁ → Uplink ₂ Downlink ₂ → Downlink ₁
Earth station (Constellation 2)	Downlink ₁ → Downlink ₂ Uplink ₂ → Uplink ₁	None

FIGURE 1
Interference geometry



To compute the interference to noise ratio, I_0/N_0 , the following equation can be used:

$$\begin{aligned} \frac{I_0}{N_0} &= \frac{P_t}{BW_{tx}} G_t(\varphi_1) G_r(\varphi_2) \left(\frac{\lambda}{4\pi R} \right)^2 \frac{1}{k T} \frac{1}{L_p} \\ &= \frac{P_t}{BW_{tx}} \frac{\lambda^2}{4\pi} \frac{1}{k T} \frac{1}{L_p} \frac{G_t(\varphi_1) G_r(\varphi_2)}{4\pi R^2} \end{aligned} \quad (1)$$

where:

- P_t : available transmit power (W)
- BW_{tx} : transmit bandwidth (Hz)
- $G_t(\varphi_1)$: transmit gain (relative intensity)
- $G_r(\varphi_2)$: receiver gain (relative intensity)
- φ_1 : off bore-sight angle of the transmitter in the direction of the receiver
- φ_2 : off bore-sight angle of the receiver in the direction of the transmitter
- λ : wavelength of transmitter (m)
- R : range (m)
- k : Boltzmann's constant (1.38×10^{-23} J/K)
- T : noise temperature (K)
- L_p : polarization isolation factor.

If there is no range compensating power control on the links between the space station and the earth station, the only elements of equation (1) that are dependent variables for the time varying simulation are the receiver gain angle, the transmitter gain angle and the range between transmitter and receiver. To compute I_0/N_0 the range gain product can be multiplied by the constant:

$$\frac{P_t}{BW_{tx}} \frac{\lambda^2}{4\pi} \frac{1}{k T} \frac{1}{L_p}$$

For example the range gain product for space station 1 downlink into earth station 2 downlink is computed as (Fig. 1):

$$\frac{G_t(\varphi_1) G_r(\varphi_2)}{4\pi R^2} \quad (2)$$

For interference assessment from satellite networks with multiple ground terminals, the interference from all of the ground terminals must be combined to determine the total interference. The interference data can be combined at each simulation time step during the simulation, or by combining the data from a set of individual simulations. In either case the GSO satellite antenna discrimination in the direction of each earth terminal must be considered when calculating the total uplink interference, $epfd_{\uparrow}$.

For the purpose of the interference calculation, it is necessary to account for the GSO satellite receiving antenna discrimination to more accurately represent the interference as seen by the satellite receiver. The $epfd_{\uparrow}$ definition will be:

$$epfd_{\uparrow} = 10 \log \left(\sum_i 10^{P_i/10} \frac{G_t(\varphi_{1i}) G_r(\varphi_{2i})}{4\pi R_i} \frac{1}{G_{r_{max}}} \right) \quad (2a)$$

where:

- $G_t(\varphi_{1i})$: gain of the earth station transmitting antenna in the direction of the interfered satellite
- $G_r(\varphi_{2i})$: gain of the satellite receiving antenna in the direction of the interference source
- $G_{r_{max}}$: maximum gain of the satellite receiving antenna. φ_{2i}

In terms of I_0/N_0 , $epfd_{\uparrow}$ can be expressed as:

$$10^{epfd_{\uparrow}/10} = \sum_i P_i \frac{G_t(\Phi_{1i})}{4\pi R_i^2} \frac{G_r(\Phi_{2i})}{G_{r_{max}}} \quad epfd_{\uparrow}(\text{dB(W/(m}^2 \cdot \text{MHz)})), \quad P_i \text{ (W/MHz)} \quad (2b)$$

$$10^{epfd_{\uparrow}/10} = \sum_i \frac{P_{t_i}}{BW_{tx}} \frac{G_t(\Phi_{1i})}{4\pi R_i^2} \frac{G_r(\Phi_{2i})}{G_{r_{max}}} \quad epfd_{\uparrow}(\text{dB(W/(m}^2 \cdot \text{Hz)})), \quad P_{t_i} \text{ (W)} \quad (2c)$$

$$= \sum_i \frac{P_{t_i}}{BW_{tx}} \frac{G_t(\Phi_{1i})}{4\pi R_i^2} \left(\frac{\lambda^2}{4\pi} \frac{1}{kT} \frac{1}{L_p} \right) \frac{G_r(\Phi_{2i})}{G_{r_{max}}} \left/ \left(\frac{\lambda^2}{4\pi} \frac{1}{kT} \frac{1}{L_p} \right) \right. \quad (2d)$$

where $epfd_{\uparrow}$ is in dB(W/(m² · Hz)), P_{t_i} is in W, and BW_{tx} is the transmit bandwidth in Hz.

Substituting I_0/N_0 (equation (1)):

$$10^{epfd_{\uparrow}/10} = \sum_i \frac{I_{0i}}{N_0} \left/ \left(G_{r_{max}} \frac{\lambda^2}{4\pi} \frac{1}{kT} \frac{1}{L_p} \right) \right. \quad (2e)$$

so:

$$epfd_{\uparrow} = 10 \log \left[\sum_i \frac{I_{0i}}{N_0} \left/ \left(G_{r_{max}} \frac{\lambda^2}{4\pi} \frac{1}{kT} \frac{1}{L_p} \right) \right. \right] \quad (2f)$$

$$epfd_{\uparrow} = 10 \log \left(\sum_i \frac{I_{0i}}{N_0} \right) - \frac{G_{r_{max}}}{T} - 10 \log \left(\frac{\lambda^2}{4\pi} \right) - 228.6 + 10 \log(L_p) \quad \text{dB(W/(m}^2 \cdot \text{Hz))} \quad (2g)$$

2 Simulation assumptions

2.1 Orbit model

The orbit model to simulate the space stations in their orbits is for circular orbits only accounting for precession of the line of nodes in the equatorial plane due to asphericity of the Earth.

2.1.1 Discussion

The orbit model represents satellite motion in a geocentric inertial coordinate frame shown in Fig. 2. The origin of this inertial frame is at the centre of the Earth. The x-axis points to the first point in the constellation Aries (i.e., vernal equinox), the z-axis is the mean rotation axis of the Earth, and the y-axis is determined as the cross product of the unit vectors in the z and x direction, i.e. $\vec{y} = \vec{z} \times \vec{x}$.

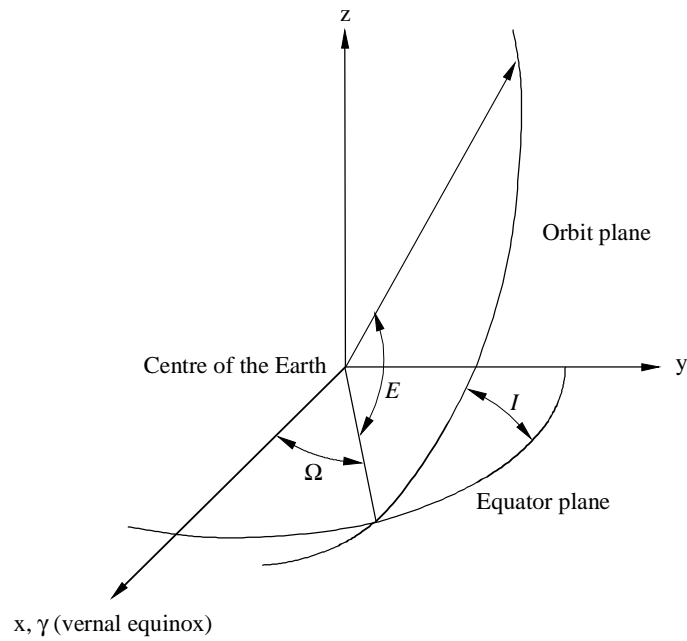
The orbital model is based on Newton's equation of motion for a satellite orbiting a perfectly spherical Earth in a circle. The characteristics of this motion that make it easy to model is that the satellite orbital radius and velocity are constant. These parameters are connected by Newton's second law. The equation of motion is:

$$\frac{m_{sv} v^2}{r} = \frac{G M_E m_{sv}}{r^2} \quad (3)$$

where:

- m_{sv} : mass of the space station
- v : constant velocity of the space station
- G : Newtonian gravitational constant ($6.673 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$)
- r : radius of orbit
- M_E : mass of the Earth ($5.974 \times 10^{24} \text{ kg}$).

FIGURE 2
Representation of Keplerian orbital elements



1325-02

Equation (3) can be written in the form:

$$v^2 = \frac{G M_E}{r} = \frac{G M_E}{R_E^2} \frac{R_E^2}{r} \quad (4)$$

where R_E is the radius of a perfectly spherical Earth (6 378 km). Since at the surface of the Earth:

$$m g = \frac{G M_E m}{R_E^2} \quad (5)$$

where g is the acceleration due to gravity at the surface of the Earth is:

$$g = \frac{G M_E}{R_E^2} = 9.806 \text{ m/s}^2 \quad (6)$$

we find that (4) can be written as:

$$v^2 = g \frac{R_E^2}{r} \quad (7)$$

or:

$$v = R_E \sqrt{\frac{g}{r}} \quad (8)$$

The period of the orbit, T , is given by the expression:

$$T = \frac{2\pi r}{v} = \frac{2\pi}{R_E} \sqrt{\frac{r^3}{g}} \quad (9)$$

These equations completely describe the dynamics of circular orbit motion about a perfectly spherical Earth.

The description of this motion in the geocentric coordinate system shown in Fig. 2 is based on specifying the satellite position using the Keplerian orbital parameters. These variables are defined as:

- Ω : the right ascension of the ascending node (RAAN) of the orbit. The angle as measured from the x-axis in the equatorial plane (x-y plane).
- I : the inclination of the orbit. The angle as measured from the equatorial plane to the orbital plane of the space station.
- E : the argument of latitude (true anomaly). The angle as measured from the line of nodes to the radius vector at the position of the space vehicle.

It should be noted that the true anomaly is a function of the angular position of the space station at time t_0 and the angular velocity of the space station. It can be expressed as:

$$E = E_0 + \omega t \quad (10)$$

where:

- E_0 : angular position of the space station at time t_0 (rad)
- ω : angular velocity of the space station (rad/s)
= v/r .

To account for orbital precession the RAAN of the orbit is also a function of the RAAN at time t_0 and the orbital precession rate. It can be expressed as:

$$\Omega = \Omega_0 + \Omega_r t \quad (11)$$

where:

- Ω_0 : RAAN of the space station at time t_0 (rad)
- Ω_r : orbital precession rate of the space station (rad/s).

$$\Omega_r = -\frac{3}{2} J_2 \cos(I) R_E^2 \frac{\sqrt{r\mu}}{r^4} \quad (12)$$

where:

- μ : Earth attraction constant ($3.986 \times 10^5 \text{ km}^3/\text{s}^2$)
- J_2 : second harmonic Earth potential constant (1.0826×10^{-6}).

The representation of the space station position in terms of the geocentric inertial coordinate system is:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = r \begin{bmatrix} \cos \Omega \cos E - \sin \Omega \cos I \sin E \\ \sin \Omega \cos E + \cos \Omega \cos I \sin E \\ \sin I \sin E \end{bmatrix} \quad (13)$$

The representation of the space station velocity in terms of the geocentric inertial coordinate system, ignoring the relatively long-term variation in Ω , is:

$$\begin{bmatrix} dx/dt \\ dy/dt \\ dz/dt \end{bmatrix} = r\omega \begin{bmatrix} \cos \Omega \sin E - \sin \Omega \cos I \cos E \\ \sin \Omega \sin E + \cos \Omega \cos I \cos E \\ \sin I \cos E \end{bmatrix} \quad (14)$$

2.2 Consideration of polarization isolation

The polarization isolation factor, L_p , is the amount of polarization isolation that can be assumed between the transmitter and receiver (see Annex 4).

2.3 Operational assumptions

2.3.1 Non-GSO earth stations location

The simulation requires taking into account the number of non-GSO earth stations, their geographical location on the Earth's surface and the number of earth stations which could co-frequency operate with an earth station of the non-GSO network. In some cases information on the number and exact location of non-GSO earth stations may be unavailable. Therefore the simulation could be effected on the following terms:

- a) number and coordinates of non-GSO earth stations are unknown (typical stations),
- b) number and coordinates of non-GSO earth stations are known.

In case a) interference statistics could be estimated with the assumption that in the long term mean traffic (load) of all earth stations in a non-GSO network is similar. For each simulation step the non-GSO earth stations' position could be specified with regard to a predicted number of the earth stations located on a unit Earth area in a specific geographical region, to a maximum resource of one on-board antenna beam and to a resource of a space station as a whole. Deriving the valid estimates requires the assumption that at each simulation step any non-GSO space station establishes a channel with a maximum possible number of earth stations, and that one of the on-board antenna beams operates at maximum traffic with the worst emission direction in terms of producing interference.

In case b) the simulation should be conducted with regard to an algorithm of establishing a radio channel between a space station and an earth station in the non-GSO network.

2.3.2 Non-GSO space station selection

There are several different satellite selection strategies which non-GSO system operators may employ. Studies have shown that the choice of the selection strategies affects the medium to long-term interference levels. Non-GSO system operators may use different selection strategies to reduce the interference into other systems. Some of the selection strategies are listed below in the following subsections.

2.3.2.1 Space station selection based upon longest dwell time

The space station selection process discussed in this section is based on establishing a link to the satellite in view of the non-GSO earth station for the longest period of time. This process will minimize the number of hand-offs of the data flow. If a satellite system is designed to have multiple satellites in view of the earth station for an extended period of time, then an additional constraint may be imposed to optimize on interference avoidance or diversity.

It is assumed that the earth station, associated with a constellation, tracks the corresponding space station once it has a communication link established. When this space station is beyond the minimum elevation angle it is assumed that the next space station can be acquired before the next simulation time step. If more than one space station can be acquired at the next time step, the algorithm to select the next space station is based on the vector from the earth station to the potential space station, \vec{r} , and the unit vector in the direction of the space stations velocity, \vec{v} . The selection criterion is to minimize the dot product of \vec{r} and \vec{v} :

$$\min_{\substack{\text{All satellites above} \\ \text{minimum elevation}}} \vec{r} \cdot \vec{v} \quad (15)$$

This selection procedure is shown in Fig. 3. The top view representation shows the space station velocity vector, denoted by \vec{v}_1 directed towards the earth station. The dot product is negative, so space station number 1 is selected over the other space station (see Annex 4).

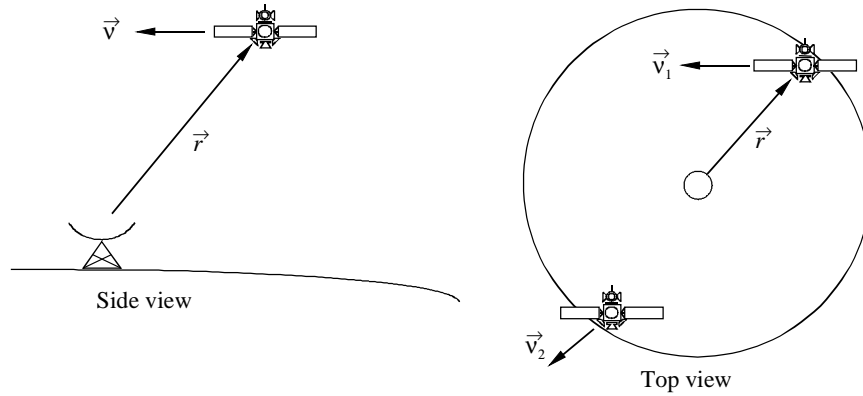
2.3.2.2 Space station selection based upon highest elevation angle

This selection strategy will require a higher number of hand-offs than longest dwell time but may be used to improve link performance for the non-GSO system. Active satellites are selected if it has the highest elevation angle from a non-GSO earth station and an available transponder. There are two possible hand-over techniques for highest elevation angle:

- the satellite with the highest elevation angle is always selected as the active satellite;
- the highest elevation satellite is selected once the active satellite drops below a minimum elevation angle.

FIGURE 3

Selection criteria for the next space station from the earth station to establish a communication link



1325-03

2.3.2.3 Space station selection based upon largest separation angle from the GSO arc

Non-GSO systems may choose satellites based upon the farthest separation angle from the look angle to the GSO arc. This reduces the level of interference generated by the non-GSO satellites into a GSO earth station but has some drawbacks. It may result in a less than optimum link performance and also require a large amount of hand-offs.

2.3.3 Power control on range

Power control on a non-GSO space station is to account for differences in the range (between the earth station and the space station). This section describes an algorithm to perform power control on range. The concept of power control on range is for the transmitting station to reduce or increase its transmit power as the receiver moves towards or away from the transmitter, i.e. the received power is kept constant. The required input parameter for the simulation is the desired receiver power density at the input to the wanted antenna, P_r (dB(W/Hz)). This receive power can be expressed as:

$$P_r = \frac{P_t(R)}{BW_{tx}} G_t(0) \left(\frac{\lambda}{4\pi R_w} \right)^2 \quad (16)$$

where R_w is the length of the wanted signal path (i.e. distance between earth station and space station of constellation 1) and $P_t(R)$ is the transmit power required to close the link. P_r can be related to the carrier to noise level at the wanted receiver by:

$$C_0/N_0 = \frac{P_r(R) G_{rw}(0)}{k T_w} = \frac{P_t(R)}{BW_{tx}} \frac{G_t(0) G_{rw}(0)}{k T_w} \left(\frac{\lambda}{4\pi R_w} \right)^2 \quad (17)$$

where:

$G_{rw}(0)$: maximum wanted receive gain of the satellite

T_w : wanted receiver noise temperature.

When power control on range is considered, the equation to compute the interference level can be expressed as:

$$\begin{aligned} I_0/N_0 &= \frac{P_t(R)}{BW_{tx}} G_t(\varphi_1) G_r(\varphi_2) \left(\frac{\lambda}{4\pi R} \right)^2 \frac{1}{k T} \frac{1}{L_p} \\ &= P_r \frac{G_t(\varphi_1) G_r(\varphi_2)}{G_t(0)} \left(\frac{R_w}{R} \right)^2 \frac{1}{k T} \frac{1}{L_p} \end{aligned} \quad (18)$$

2.4 Antenna parameters

2.4.1 Earth station and non-GSO space station antenna parameters

The antenna pattern for the earth station is an input parameter to the simulation. Suggested patterns include but are not limited to the following ones:

- measured antenna patterns;
- RR Appendix S8;
- Recommendation ITU-R S.465;
- Recommendation ITU-R S.672;
- Recommendation ITU-R S.1428.

2.4.2 GSO space station antenna patterns

The required parameters are the GSO space station receive/transmit gain in the direction of the non-GSO earth station. This is because the location of the non-GSO earth station is constant relative to the GSO space station, therefore the receive/transmit gain of the GSO space station is constant in the direction of the non-GSO earth station.

With unknown location of non-GSO earth stations the GSO space station pattern should be shown in the form of the gain as a function of off-axis antenna angle.

2.5 Input data

The required input parameters for each of the two communication systems are:

2.5.1 Orbit parameters

- Number of space stations
- Number of planes
- For each orbital plane:
 - Orbit altitude
 - Inclination of plane
 - RAAN
 - Argument of latitude for each space station in the orbital plane.

2.5.2 Antenna parameters

- Space station
 - If non-GSO system:
 - Antenna pattern
 - Maximum transmit gain (dBi)
 - Maximum receive gain (dBi)
 - Maximum number of co-frequency antenna beams and their spatial orientation.
 - If GSO system:
 - Transmit gain (dBi) in direction of non-GSO earth station
 - Receive gain (dBi) in direction of non-GSO earth station
 - Antenna pattern.
- Earth station
 - Antenna pattern
 - Maximum transmit gain (dBi)
 - Maximum receive gain (dBi)
 - Location (latitude, longitude).

2.5.3 Operational and computational parameters

- Minimum elevation angle for communication
- Simulation time start
- Simulation time end (see § 2.7)
- Simulation time increment (see § 2.7)
- Precession (see § 2.7)
- If non-GSO system and power control on range is used: the desired receiver power density at the input to the wanted antenna (dB(W/Hz))
- Predicted density of non-GSO earth stations located in different geographical regions of the non-GSO network service zone
- Maximum number of non-GSO earth stations that can operate with a non-GSO space station at the same frequency.

2.5.4 Frequency to be used for the assessment of interference

The interference into the desired network should be assessed at the lowest frequency which is shared by the interfering and the desired networks, in circumstances where the antenna patterns are defined by an envelope.

2.6 Output data

The raw output data of the simulation is a time history of the interference to noise level, I_0/N_0 , versus time. This data can be analysed to obtain the following information:

- A plot of the interference to noise level, I_0/N_0 (dB), as a function of the per cent time (on a logarithmic scale) that this level is exceeded.
- A time history of a peak interference event (I_0/N_0 versus time).
- The number of events (and duration of those events) for which the interference-to-noise ratio is above a pre-defined level. For example let the pre-defined level be -1 dB, then in this case an event starts when the interference level is above -1 dB and ends when it falls below -1 dB, the time that this event is above the -1 dB level is the duration of the event. This method will give an indication of how long the interference level will be above a particular value.

2.7 Calculation of the total simulation time, simulation time increment and precession

2.7.1 Introduction

The calculation method described in this section may be used for simulation when the interference is from non-GSO satellite to GSO FSS earth station or from non-GSO earth station to GSO FSS satellite. Calculation methods for other interference cases and for elliptical orbits need further study (see Annex 4).

2.7.2 Simulation time increment

For accurate results the simulation time increment should be as short as possible, but on the other hand the total simulation time should be reasonable. For comparable accuracy in different simulations the time steps can be related to the antenna beamwidth of the interfered systems.

Satellite speed in Earth-fixed coordinates depends on the sub-satellite point latitude but the variation can be neglected for this purpose and the highest speed at equator can be used in the calculation. The angular speed of the satellite, as seen from a point on Earth, is highest when the satellite is moving directly towards or away from that point. The angular speed can be calculated by the following equations:

$$a = \sqrt{(\omega \cos I - \Omega_e)^2 + (\omega \sin I)^2}$$

$$\theta_\varepsilon = \arccos \left(\frac{R}{R+h} \cos \varepsilon \right) - \varepsilon$$

$$\Delta t = \frac{\Phi_{3 \text{ dB}}}{N_{\text{hits}}} \frac{\sin \theta_\varepsilon}{a \cos \varepsilon}$$

where:

- a : satellite angular velocity in Earth-fixed coordinates (geocentric geosynchronous reference coordinate system)
- Ω_e : Earth rotation angular velocity at the equator, $\cong 7.29 \times 10^{-5}$ rad/s
- ω : satellite angular velocity in space fixed coordinates (geocentric heliosynchronous reference coordinate system)
- I : satellite orbit inclination
- θ_e : geocentric angle between the interfered earth station and the satellite sub-point when it is at the main beam axis of the earth station
- R_e : Earth radius (6 378 km)
- h : satellite altitude
- ε : earth station antenna elevation
- $\varphi_{3\text{ dB}}$: earth station 3 dB beamwidth
- N_{hits} : number of hits in interfered station 3 dB beamwidth ($N_{hits} = 5$)
- Δt : simulation time increment.

2.7.3 Precession and total simulation time

A satellite of a non-GSO constellation on a circular orbit traces out a path on the Earth's surface. After a time, which is specific to the system, the satellite or another satellite of the constellation returns to the same or practically to the same point. The time between these two cases is the repeat period of the constellation. The repeat periods of different constellations are from a few days to several months.

With similar orbits in the non-GSO network the period of the orbital constellation recurrence could be derived using the following methodology:

Step 1: Define an angular spacing between subsatellite points at $t = t_0$ and $t = t_0 + T$ ignoring bias along ascending node longitude, where T is the satellite orbit period.

$$\Delta\lambda_0 = 2\pi - 2\pi \frac{T}{T_E}$$

where T_E is the Earth rotation period.

Step 2: Define an angular spacing between subsatellite points at $t = t_0$ and $t = t_0 + T_j$, where j is the number of orbits around the Earth.

$$\Delta\lambda_j = j\Delta\lambda_0 + jT\Omega_r$$

Step 3: Define the least integer j , for which is met the following condition:

$$(\Delta\lambda_j) \bmod (2\pi) \leq \Delta\lambda_{T_p}$$

where $\Delta\lambda_{T_p}$ is the required accuracy of the orbital constellation recurrence period (rad).

Step 4: Define the period of the orbital constellation recurrence:

$$T_{NOB} = J_{min} T$$

where J_{min} is the least integer j , for which Step 3 condition is met.

Total simulation time and the precession should be such that the distribution of the satellite paths along a latitude line is uniform and there are enough traces passing through the interfered station beamwidth. For a compromise between accuracy and simulation programme run time the number of passes through the area should be the same as the number of hits during one pass (see simulation time increment).

If the repeat period is so short that there will not be the required number of passes through the area, the programme is run for several values of the initial right ascension of the node. The angle between the initial ascensions of the node should correspond to the required spacing between the passes through the area and the number of program runs should be such that the initial right ascensions of one plane reaches the corresponding initial point of the next plane.

If the repeat period is so long that the number of passes through the area is unnecessarily high an artificial precession which gives shorter repeat period can be used. In this case the satellite e.i.r.p. should not be time dependent.

The effect of the fractional relation between a cycle of time dependent variation of satellite e.i.r.p. and satellite passes through the area needs further study.

2.7.4 Dual time step sizes

It may be desirable to use two time step sizes to increase the speed of the simulation run time. Section 2.7.2 addresses the computation of simulation time increment. The time increment can vary orders of magnitude between large and small receiving earth station antennas, becoming very small for narrow beamwidths due to the requirement for the number of hits in the main beam ($N_{hits} = 5$). This requirement is necessary but it increases the run time significantly. To alleviate this problem, a dual time step can be used to reduce the variance and overall length of simulation run time for all sizes of earth station antennas, especially for those earth stations with narrow beamwidths.

For this dual step algorithm, the time step size addressed in § 2.7.2 should be used for all simulations and is referred to here as the fine step size. This step size is dependent on the antenna beamwidth and should be used only during portions of the simulation where the non-GSO satellite is close to the regions of maximum epfd, near the main beam or edge of the exclusion zone. The percentage of time that satellites are in the regions far off-axis from the main beam, past the first side lobe, is much larger than the percentage of time satellites will be within the main beam. Because of this and the fact that past the first side lobe the epfd values do not change as rapidly with the spacecraft position, for regions away from the main beam a constant coarse step size can be used. This coarse step size is defined as a topocentric angle:

$$\varphi_{coarse} = 1.5^\circ$$

This coarse step size can be used for all antenna sizes.

There are two possible fine step regions because of the two possible worst-case locations of a non-GSO:

- When a non-GSO satellite is near the main beam, the fine step region (FSR) is defined as a fixed topocentric angle from the axis of the GSO earth station beam:

- If $D/\lambda > 100$, set the edge of the first side-lobe region to φ_r of the GSO earth station pattern:

$$\varphi_1 = \varphi_r = 15.85(D/\lambda)^{-0.6}$$

- If $D/\lambda < 100$, set the edge of the first side-lobe region to that defined in the GSO earth station pattern:

$$\varphi_1 = 95 \lambda/D$$

The off-bore angle for the fine step region is defined as the greater of 3.5° or φ_1 :

$$\varphi_{FSR_1} = \max(3.5^\circ, \varphi_1)$$

- When a non-GSO satellite is near the exclusion zone, the fine step region measured from the boundary of the exclusion zone is defined as:

$$\varphi_{\text{FSR}_2} = \varphi_{\text{coarse}}$$

The size of the coarse step needs to be an integer multiple of fine steps for statistical purposes. Since the coarse step size is constant, the ratio of coarse steps to fine steps is dependent only upon the beamwidth of the GSO earth station ($\varphi_{3 \text{ dB}}$). This ratio is defined as:

$$N_{\text{coarse}} = \text{floor} ((N_{\text{hits}} \times \varphi_{\text{coarse}}) / \varphi_{3 \text{ dB}})$$

where "floor" is a function that truncates the decimal part of the ratio and outputs the integer part of the ratio. This produces a conservative ratio of fine steps to coarse steps to ensure that a coarse step is never larger than the target topocentric size of 1.5° . Since this ratio is only dependent on the beamwidth of the GSO earth station antenna, $\varphi_{3 \text{ dB}}$, the time savings increases as the beamwidth decreases. This is desired since simulations with narrow beamwidths require much more time to run.

If a non-GSO satellite is with φ_{FSR_1} of the main beam or φ_{FSR_2} of the exclusion zone, the fine step size should be used for the simulation. For all other regions in space when a non-GSO is not near the aforementioned regions, the coarse time step is then computed by multiplying N_{coarse} by the fine step size.

ANNEX 2

Methodology for determining statistics of codirectional, co-frequency interference levels between non-GSO FSS networks and GSO FSS networks in frequency bands below 30 GHz

1 Introduction

This Annex provides the algorithms to compute the aggregate total interference produced by a non-GSO network into a GSO network.

This algorithms can be used to calculate the cumulative density function (cdf) of the epfd for a given antenna diameter of the GSO earth station or the epfd \uparrow of the non-GSO network. The following cases of interference are studied:

- uplink interference from the transmit earth stations of a non-GSO network into a GSO network space station;
- downlink interference from the transmit space stations of a non-GSO network into a receive earth station of GSO network.

This methodology also permits computation of the probability density function (pdf) and cdf of the C/I , as a function of the characteristics of both networks.

In order to determine the worst interference case, a two-step approach is proposed. The first step leads to the location of the worst case. The second step is the implementation of the epfd \downarrow and epfd \uparrow calculation at the identified worst-case location.

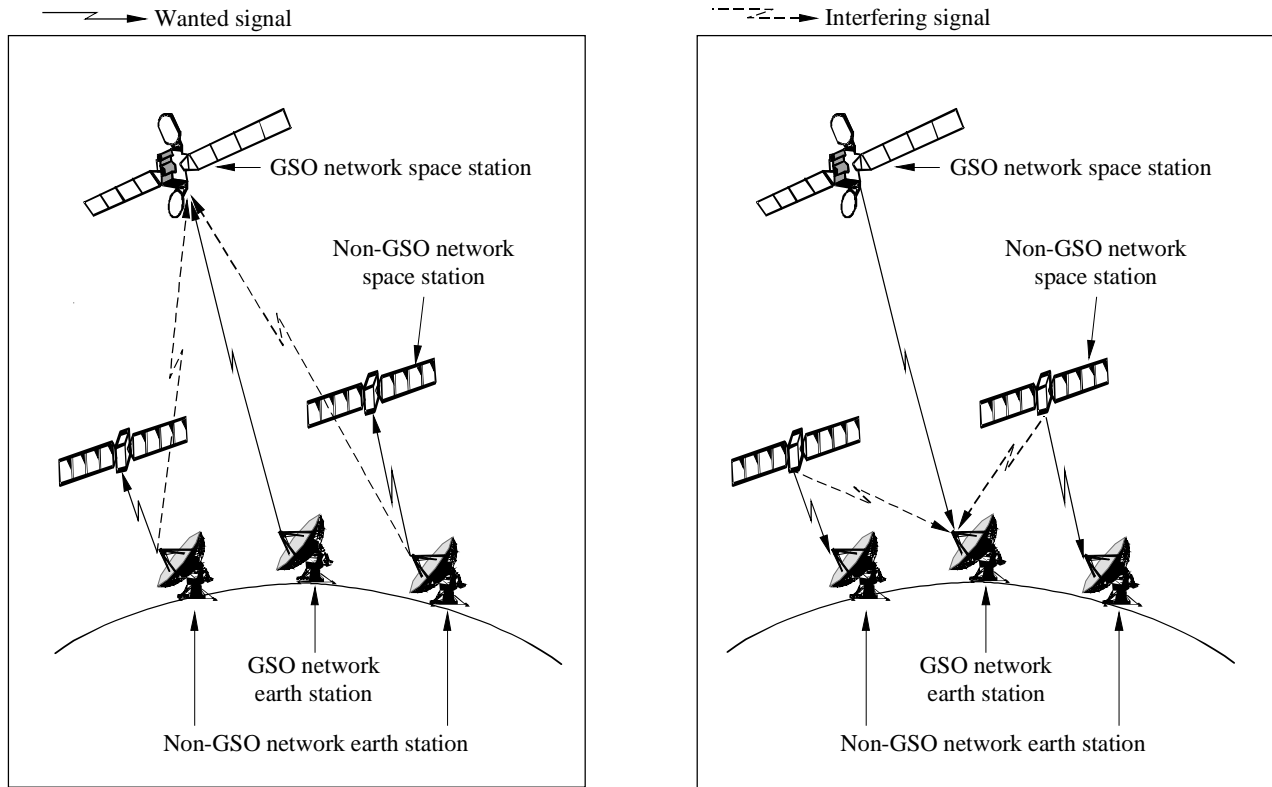
2 Interference scenario

The non-GSO network is the interfering network. Figure 4 describes this interference scenario:

FIGURE 4

Interference scenario

Interference from a non-OSG satellite network into a GSO satellite network



a) Uplink interference

b) Downlink interference

1325-04

3 Terminology

3.1 Earth related constants

For the Earth, the general constants are:

R_e : Earth radius (6 378 km)

O : Earth centre

μ : Earth attraction constant ($3.986 \times 10^5 \text{ km}^3/\text{s}^2$)

J_2 : second harmonic Earth potential constant ($1\,082.6 \times 10^{-6}$)

T_e : Earth rotation period (23 h 56' 04" = 86 164 s)

Ω_e : Earth angular velocity

$$= 2\pi/T_e \cong 7.29 \times 10^{-5} \text{ rad/s}$$

t : elapsed time (s).

3.2 Non-GSO satellite network space station related constants

For the non-GSO satellite network space stations (see Fig. 5), the constants are as follows:

N : number of space stations of the non-GSO network

i : index for each of the non-GSO satellites ($0 \leq i < N$)

3.3 GSO satellite network space station related constants

For the geostationary satellites, the parameters are as follows:

h : satellite altitude above the Earth (35 786 km)

r : semi-major axis of the satellite orbit

$$= h + R_e = 42\,164 \text{ km}$$

I : inclination angle of the orbital plane above the Equator (generally 0° , but may vary between $+5^\circ$ and -5°)

Ω_0 : RAAN of each of the non-GSO satellites at the initial time, rad. It can also be considered as its longitude if this is the case at the initial time

T : satellite orbit period

$$= 2\pi (r^3/\mu)^{1/2} \cong 86\,164 \text{ s}$$

ω : mean motion of the satellite

$$= 2\pi/T \cong 7.29 \times 10^{-5} \text{ rad/s}$$

E_0 : argument of latitude at the initial time (rad)

E_t : argument of latitude of the satellite at the time of computation (rad)

$$= E_0 + \omega t$$

Ω_r : nodal regression of the RAAN

$$= -\frac{3}{2} J_2 \cos(I) R_E^2 \frac{\sqrt{r\mu}}{r^4} = -2.71 \times 10^{-9} \text{ rad/s } (I = 0)$$

Ω_t : RAAN of the satellite at the time of computation (rad)

$$= \Omega_0 + \Omega_r t$$

\rightarrow

\vec{OG} : coordinate vector of the GSO satellite in the Earth-centred fixed reference centre

$$= \begin{cases} x = a (\cos E_t \cos \Omega_t - \cos I \sin E_t \sin \Omega_t) \\ y = a (\cos E_t \sin \Omega_t + \cos I \sin E_t \sin \Omega_t) \\ z = a \sin E_t \sin I \end{cases}$$

3.4 Earth station related constants

a) With known location of earth stations in the non-GSO network: An earth station is defined by:

lat: latitude of earth station (rad)

lon: longitude of earth station (rad)

\rightarrow

\vec{OM} : earth station coordinates in the Earth-centred fixed reference centre:

$$= \begin{cases} X = R_e \cos \text{Lat} \cos (\text{Lon} + \Omega_e t) \\ Y = R_e \cos \text{Lat} \sin (\text{Lon} + \Omega_e t) \\ Z = R_e \sin \text{Lat} \end{cases}$$

b) With unknown location of earth stations in the non-GSO network:

δ_i : predicted density of non-GSO earth stations location in the i -th geographical region of the non-GSO service zone.

4 Interference computation

4.1 Step 1: Worst-case identification

There is a need to identify the worst-case situation. In the proposed methodology, the worst-case search is based on a geometrical analysis. The Radiocommunication Working Group 4A studies have shown that when considering the interference situations between non-GSO and GSO networks, the worst-case situation is found whenever an in-line or

quasi in-line event occurs. The occurrence and time statistics of the in-line events only depend on the geometrical configuration of both the non-GSO and the GSO system.

In order to assess the worst geometrical configuration, leading to the worst interference case, the non-GSO/GSO interactions will be calculated for GSO earth stations within a representative GSO coverage. It is proposed to use earth stations located every degree between 0° and 70° in latitude. The GSO satellites are distributed along an 180° arc in longitude every degrees. Figure 5 describes the geometrical configuration.

For each couple (GSO earth station, GSO satellite), the non-GSO constellation has to be run over a constellation period. The angular statistics are calculated for the in-line or quasi in-line events: the aggregate time when a non-GSO satellite enters a cone of 2° width in the direction of the GSO satellite is calculated for each couple.

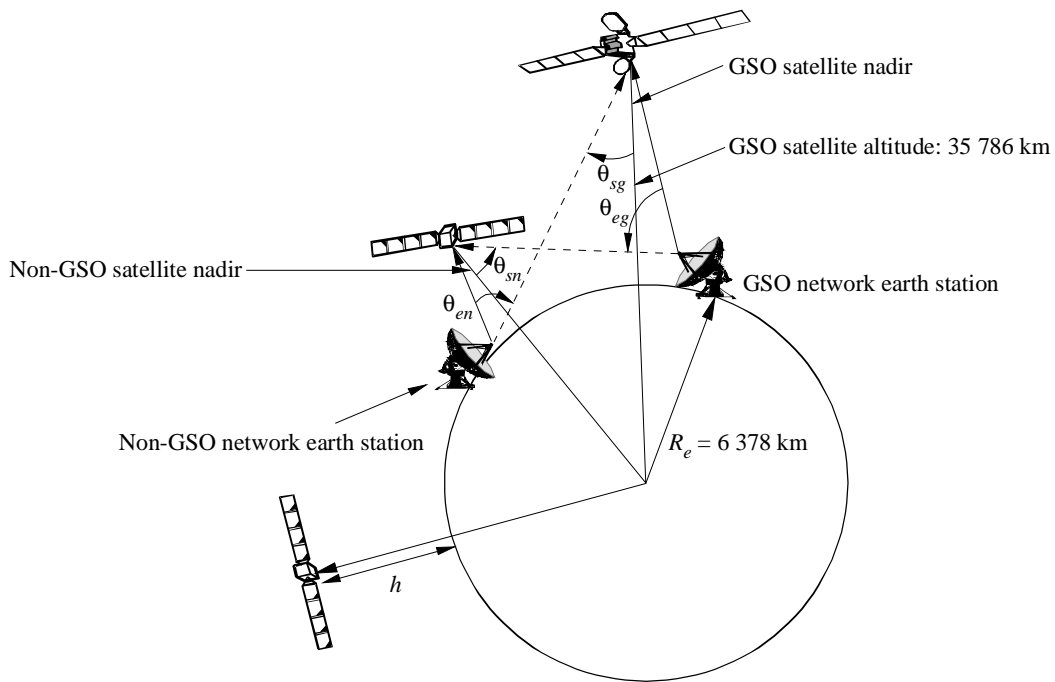
The angular statistics for the in-line or quasi in-line events may be calculated using Recommendation ITU-R S.1257.

The worst couple (the one with the most important aggregated statistic) is selected as worst test point in order to run Step 2 of the simulation programme.

4.2 Step 2: Interference calculations at worst case

Figure 6 describes the above-mentioned scenarios in a configuration of reference:

FIGURE 6
Configuration of reference



h : non-GSO satellite altitude

1325-06

4.2.1 Uplink interference computation

The following notation is used for computing the interference link budgets on the GSO network uplink wanted carrier:

- θ_{en} : angle measured from the non-GSO network earth station, and between the GSO network space station and the non-GSO satellite network space station towards which the non-GSO network earth station is pointing (rad)
- θ_{sg} : angle measured from the GSO network space station, and between the GSO network space station receive antenna boresight and the interfering non-GSO network earth station (rad)

$d_{en,sg}$:	distance between the interfering non-GSO network earth station and the GSO network space station (km)
$G_{rx,sg}(\theta_{sg})$:	receive antenna gain of the GSO satellite in the direction of the interfering non-GSO network earth station (dBi)
$G_{tx,en}(\theta_{en})$:	transmit antenna gain of the interfering non-GSO network earth station in the direction of the GSO network space station (dBi)
$P_{tx,en}$:	power density at the transmit antenna of the non-GSO network earth station (dB(W/Hz))
Δf :	reference bandwidth (Hz)
f :	frequency of the carrier at which the computation is performed (GHz)
c :	speed of the light (0.3 m/ns)
λ :	the wavelength of the carrier (m)
=	c/f

The interfering pfd (dB(W/(m² · Hz))) in the reference bandwidth produced on the uplink by a single non-GSO network earth station into the wanted carrier of a GSO network received by the geostationary space station is:

$$pfd_{i,\uparrow} = P_{tx,en} + 10 \log(\Delta f) + G_{tx,en}(\theta_{en}) - 10 \log(4\pi d_{en,sg}^2) - 60 \quad (\text{see Note 1})$$

The total interfering power flux-density, designated as the $epfd_{\uparrow}$ is the aggregate of the power flux-densities of all the non-GSO earth stations visible in the GSO space station coverage weighted by the discrimination of the receive antenna of the GSO satellite. The resulting equation is:

$$epfd_{\uparrow} = 10 \log_{10} \left(\sum 10^{pfd_{i,\uparrow}/10} G_{rx,sg}(\theta_{sg}) / G_{max} \right)$$

where:

$G_{rx,sg}(\theta_{sg})/G_{max}$ is the normalized linear gain of the GSO receiving antenna.

NOTE 1 – Another way to proceed is to aggregate the interfering noise power density at the output of the GSO network space station receive antenna.

For a single interfering non-GSO network earth station, the interfering noise power density can be written as:

$$I_{0\uparrow} = pfd_{i,\uparrow} - 10 \log(4\pi/\lambda^2) + G_{rx,sg}(\theta_{sg})$$

The total interfering noise power density into the wanted GSO network carrier on the uplink can therefore be written as:

$$I_{0\uparrow,T} = 10 \log \left(\sum_k 10^{\frac{I_{0\uparrow,k}}{10}} \right)$$

where k is the index of each non-GSO network interfering earth station visible from the GSO network space station and which carrier is interfering into the wanted carrier.

The total interfering noise power can be computed by integrating the interfering noise power density over the receive bandwidth of the wanted carrier.

4.2.2 Downlink interference computation

The following notation is used for computing the interference link budgets on the GSO network downlink wanted carrier:

θ_{sn} :	angle measured from non-GSO network space station, and between the non-GSO network earth station towards which the non-GSO network space station is pointing and the considered GSO network earth station (rad)
θ_{eg} :	angle measured from the GSO network earth station, and between the GSO network space station towards which the GSO network earth station is pointing and the considered interfering non-GSO satellite network space station (rad)
$G_{rx,eg}(\theta_{eg})$:	receive antenna gain of the GSO network earth station in the direction of the interfering non-GSO network space station (dBi)

- $G_{tx,sn}(\theta_{sn})$: transmit antenna gain of the non-GSO network space station in the direction of the GSO network earth station (dBi)
- $P_{tx,sn}$: power density at the transmit antenna of the non-GSO network space station (dB(W/Hz))
- Δf : reference bandwidth (Hz)
- $d_{eg,sn}$: distance between the GSO network space station and the interfering non-GSO network earth (km).

The interfering pfd (dB(W/(m² · Hz))) in the reference bandwidth produced on the downlink by a single non-GSO network space station into the wanted carrier received by the GSO network earth station is:

$$dfp_{i,\downarrow} = P_{tx,sn} + 10 \log(\Delta f) + G_{tx,sn}(\theta_{sn}) - 10 \log(4\pi d_{eg,sn}^2) - 60$$

The epfd can be computed by summation of all the individual pfd. The resulting equation is:

$$epfd_{\downarrow} = 10 \log_{10} \left(\sum 10^{pfd_i/10} \cdot G_{rx,eg}(\theta_{eg_i}) / G_{max} \right) \quad (\text{see Note 2})$$

NOTE 2 – For a single interfering non-GSO network space station, the interfering noise power density can be written as:

$$I_{0\downarrow} = pfd_{i,\downarrow} - 10 \log(4\pi/\lambda^2) + G_{rx,eg}(\theta_{eg})$$

The total interfering noise power density into the wanted non-GSO network carrier on the downlink can therefore be written as:

$$I_{0\downarrow,T} = 10 \log \left(\sum_{\ell} 10^{\frac{I_{0\downarrow,\ell}}{10}} \right)$$

where ℓ is the index of each non-GSO network interfering space station visible from the GSO network earth station and which carrier is interfering into the wanted carrier.

5 Method to compute the aggregate interfering noise power

The non-GSO network presents inherently non-stationary geometrical and transmission parameters, therefore there is a need to identify the distribution of the interference power in the different possible configurations. Simulations are necessary in order to achieve this goal. This section describes the different steps to be applied at each time to compute the epfd or apfd and the interfering noise power in the worst case identified with Step 1.

5.1 Method to compute the interference on the uplink

For each of the considered time step, the following steps are applied:

Step 1: Computation of the position of the non-GSO network space stations.

Step 2: Computation of the position of the GSO network space station.

Step 3: *With known location of earth stations in the non-GSO network:* computation of the position of the non-GSO network earth stations visible from the GSO network space station and operating in the wanted carrier assigned frequency.

With unknown location of earth stations in the non-GSO network: selection of non-GSO space stations with service zones partially or completely overlapped with a visibility zone from the GSO space station.

Step 4: *With known location of earth stations in the non-GSO network:* identification of the beams and satellites used in the non-GSO network for each of the interfering non-GSO network earth stations.

With unknown location of earth stations in the non-GSO network: assigning positions of non-GSO earth stations based on their disposition probabilistic rule in the service zones of the non-GSO space stations selected at Step 3 above and selection of the non-GSO earth stations falling into a visibility zone of the GSO space station.

Step 5: Computation of the transmit power density of each non-GSO network earth station.

Step 6: Computation of the off-axis angle of each of the non-GSO network earth station between its assigned non-GSO network space station and the GSO network space station.

Step 7: Computation of the transmit gain of each of the non-GSO network earth stations in the direction of the GSO network space station.

Step 8: Computation of the distance between each of the non-GSO network earth stations and the GSO network space station.

Step 9: Computation of the receive antenna gain of the GSO network space station in the direction of each of the non-GSO network earth stations (see Note 1).

NOTE 1– In this method, the receive antenna gain of the GSO satellite is considered, in order for the methodology to be general. If applied to the epfd_{\uparrow} described in the RR and Resolution 130 (WRC-97), this gain should be set to 1 everywhere, since the actual definition does not take the satellite receiving gain into account.

Step 10: Computation of the received interfering pfd from each of the non-GSO network earth stations into the GSO network station.

Step 11: Computation of the apfd.

Step 12: Aggregation of the received interfering noise power if needed.

5.2 Method to compute the interference in the downlink

The method is similar to the method proposed in the § 5.1, and depends on the GSO antenna diameter chosen to study. The study should be repeated for each type of antenna size analysed:

For each of the considered time steps, the following steps are applied:

Step 1: Computation of the position of the non-GSO network space stations.

Step 2: Computation of the position of the GSO network earth station.

Step 3: Selection of the non-GSO network space stations visible from the GSO network earth station and operating in the wanted carrier assigned frequency.

Step 4: *With known location of earth stations in the non-GSO network:* identification of the beams and satellites used in the non-GSO network for each of the interfering non-GSO network earth stations.

With unknown location of earth stations in the non-GSO network: assigning positions of non-GSO earth stations based on their disposition probabilistic rule in the service zones of the non-GSO space stations selected at Step 3 above.

Step 5: Computation of the transmit power density of each non-GSO network space station.

Step 6: Computation of the off-axis angle of each of the non-GSO network space stations between its assigned non-GSO network earth station and the GSO network earth station.

Step 7: Computation of the transmit gain of each of the non-GSO network space stations in the direction of the GSO network earth station.

Step 8: Computation of the distance between each of the non-GSO network space stations and the GSO network earth station.

Step 9: Computation of the receive antenna gain of the GSO network earth station in the direction of each of the non-GSO network space stations for the chosen antenna.

Step 10: Computation of the interfering pfd received by the GSO network earth station from each of the non-GSO network space stations.

Step 11: Computation of the epfd for the chosen antenna diameter.

Step 12: Aggregation of the received interfering noise power if needed.

ANNEX 3

Description and example of computational methodology in Annex 1

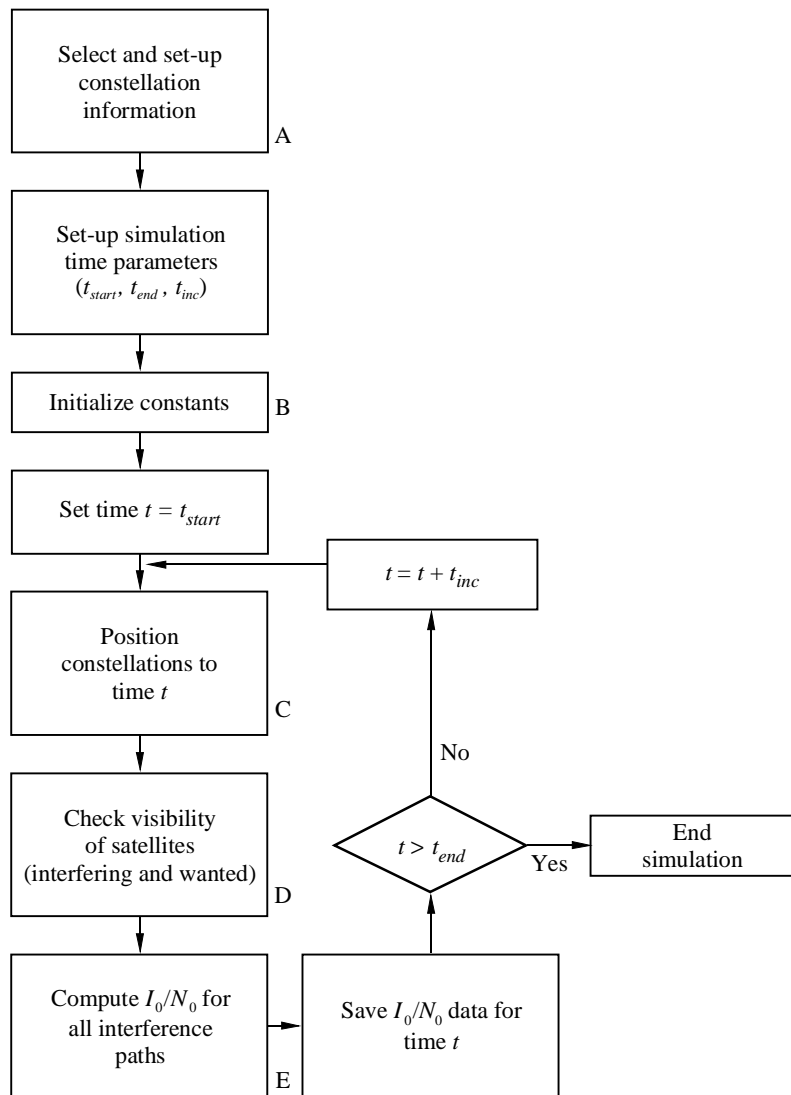
1 Introduction

The methodology described in Annex 1 is intended to be implemented via a computer program. This Annex outlines one such implementation along with a demonstration of an example of the results obtained using the geometric analysis defined in Annex 1 to interference analysis between a non-GSO system and a GSO satellite system.

2 Description of computation methodology

Shown in Fig. 7 is a top level description of an implementation, the blocks labelled A, B, C, D, E will be treated in more detail. To maximize efficiency this implementation computes interference from the four possible interference scenarios under consideration (Annex 1, § 1) at the same time. A data evaluation process evaluates the I_0/N_0 versus time data for each of the four scenarios, this evaluation process is not considered in this Annex.

FIGURE 7
Implementation of methodology



2.1 Block A – Constellation selection and set-up

Information about the constellations to be simulated are defined in this section of the program, see Fig. 7, block A. For this implementation the relevant data required by § 2.5 of Annex 1 is stored in a database and recalled for the simulation for each of the two constellations that are to be simulated. This portion of the program may also allow for variances from the standard set of parameters, such as different antenna patterns, modification of the location of the earth station associated with each constellation or the peak antenna gains associated with each antenna. For this discussion call the two constellations that are to be simulated Const_1 and Const_2.

This section of the program allocates and initializes the memory required to simulate the constellation. This memory is made of data structures that holds information about the position of the constellation, the velocity of the constellation, and pointing vectors of each satellite of the constellation (antenna boresight information). See Annex 1, § 2.1 for the relevant initial information that needs to be configured for a simple orbit model.

Required data for each earth station is also allocated memory and initialized for each station associated with the constellations. The data structure of the earth station keeps track of which satellite of the wanted constellation the earth station is currently communicating with, the locations of possible interfering satellites, and the minimum required elevation angle that the earth station can communicate (which is related to the maximum range to a satellite for communication to occur and also stored in the data structure). The initial satellite that the earth station is in communication with is also initialized in this portion of the program.

2.2 Block B – Initialize program constants

To promote efficient use of resources, constants of the simulation are factored out of the equation used to compute I_0/N_0 . For example consider equation (1), the variables of this equation that do not change with respect to time (assuming that power control on range is not employed, § 2.4.2 of Annex 1) are:

- P_t : available transmit power (W)
- BW_{tx} : transmit bandwidth (Hz)
- λ : wavelength of transmitter (m)
- k : Boltzmann's constant (1.38×10^{-23} J/K)
- T : noise temperature (K)
- L_p : polarization isolation factor.

Therefore, for each interference path the following four constants can be computed before the simulation starts to step on each time increment:

TABLE 1
Link constants of simulation

Interference path	Constant
Const_1 downlink → Const_2 downlink	$C_{12\downarrow} = \frac{P_{t1\downarrow}}{BW_{tx1\downarrow}} \frac{\lambda^2}{4\pi} \frac{1}{k T_{2\downarrow}} \frac{1}{L_{p12\downarrow}}$
Const_1 uplink → Const_2 uplink	$C_{12\uparrow} = \frac{P_{t1\uparrow}}{BW_{tx1\uparrow}} \frac{\lambda^2}{4\pi} \frac{1}{k T_{2\uparrow}} \frac{1}{L_{p12\uparrow}}$
Const_2 downlink → Const_1 downlink	$C_{21\downarrow} = \frac{P_{t2\downarrow}}{BW_{tx2\downarrow}} \frac{\lambda^2}{4\pi} \frac{1}{k T_{1\downarrow}} \frac{1}{L_{p21\downarrow}}$
Const_2 uplink → Const_1 uplink	$C_{21\uparrow} = \frac{P_{t2\uparrow}}{BW_{tx2\uparrow}} \frac{\lambda^2}{4\pi} \frac{1}{k T_{1\uparrow}} \frac{1}{L_{p21\uparrow}}$

In Table 1 the subscript 1_↓ corresponds to constellation 1 downlink, 2_↓ corresponds to constellation 2 downlink, 1_↑ corresponds to constellation 1 uplink and 2_↑ to constellation 2 uplink. The polarization isolation factor corresponds to the transmit/receive combination, i.e. 1_{2↓} indicates the polarization isolation between the downlink transmitter of constellation 1 to the downlink transmitter of constellation 2.

Once these constant factors are computed then for efficiency in the program the following equations are used to compute the I_0/N_0 level in each time step (block E).

TABLE 2

 I_0/N_0 computation using link constants

Interference path	Interference level
Const_1 downlink → Const_2 downlink	$I_0/N_0 = C_{12\downarrow} \frac{G_{t1\downarrow}(\varphi_1) G_{r2\downarrow}(\varphi_2)}{4\pi (R_{12\downarrow})^2}$
Const_1 uplink → Const_2 uplink	$I_0/N_0 = C_{12\uparrow} \frac{G_{t1\uparrow}(\varphi_1) G_{r2\uparrow}(\varphi_2)}{4\pi (R_{12\uparrow})^2}$
Const_2 downlink → Const_1 downlink	$I_0/N_0 = C_{21\downarrow} \frac{G_{t2\downarrow}(\varphi_1) G_{r1\downarrow}(\varphi_2)}{4\pi (R_{21\downarrow})^2}$
Const_2 uplink → Const_1 uplink	$I_0/N_0 = C_{21\uparrow} \frac{G_{t2\uparrow}(\varphi_1) G_{r1\uparrow}(\varphi_2)}{4\pi (R_{21\uparrow})^2}$

In Table 2 for example in the Const_1 downlink → Const_2 downlink path the variables are:

$G_{t1\downarrow}(\varphi_1)$: transmit gain of Const_1 downlink transmit antenna (relative intensity)

$G_{r2\downarrow}(\varphi_2)$: receiver gain of Const_2 downlink receive antenna (relative intensity)

$R_{12\downarrow}$: range between Const_1 transmitter (downlink) to Const_2 receiver (downlink) (m).

This section requires modification when power control on range is performed by one or both of the constellations under study.

2.3 Block C – Position constellation to time t

For each time step before any calculation of interference levels the position of the constellation is required to be computed. For this example the orbit model described in Annex 1, § 2.1 is employed. The velocity vector and position vector of each satellite are computed and stored in the data structure defined in block A of the simulation. The range between the earth station and the satellites of the constellation it is trying to communicate with is also computed in this step.

2.4 Block D – Check visibility of satellites (interfering and wanted)

This section determines which satellite is communicating to the earth station. First the satellite that the earth station was communicating with in the previous time step is checked to see if the earth station is able to continue communication (i.e. the range between the earth station and the satellite is compared to the maximum possible range a satellite can be to

continue communications, if larger than the communications need to be established with a new satellite). If communication with a new satellite needs to be established, then the algorithm shown in Annex 1, § 2.4.1 is used to select a new satellite for communication with the earth station.

Once each earth station has computed which satellite it is communicating with, the parameters associated with the interference between the satellite systems can be computed. This requires computing the range of the four interference paths and the off-axis angles associated with the interference paths (see Fig. 1).

2.5 Block E – Compute I_0/N_0 for all interference paths

The computation of the interference levels are now possible because all relative information has been computed in previous steps. The interference level for four interference paths between the two constellations are performed in this section (see Table 2). The interference levels are stored for later analysis.

2.6 Accounting for the aggregate impact of multiple Earth stations/satellites on the interference levels

This aggregate of interference from multiple Earth stations/satellites may be computed in either of two ways:

Case 1: By performing multiple simulations for each earth station.

Case 2: By performing one simulation that simulates all possible links.

The basic difference is when the aggregation of all Earth stations/satellites is performed, in Case 1 it is done after the simulation is complete and in Case 2 it is done during the simulation.

2.6.1 Aggregate based on multiple simulations

This method of computing the aggregate interference from multiple sources of interference has advantages in that the contribution from each source of interference can be assessed and evaluated to determine which source has the largest impact on interference. The disadvantage is that the simulation must be performed multiple times for each possible source of interference, which may be time consuming. The amount of data required to be stored is relatively large for simulations contain a large number of data points and operator error may arise in the aggregate results.

To compute the aggregate based on multiple simulations the non-GSO constellation(s) must be set up so as to have the same initial starting and ending point in time and the interference level I_0/N_0 is saved for later analysis. After all sources of interference are computed the interference levels can be added together in time to arrive at an aggregate interference level.

As an example of the aggregate based upon multiple simulations consider the example shown in Annex 3, § 3 and assume that it is desired to assess the aggregate impact of two GSO earth stations on the non-GSO up and downlinks. Both GSO earth stations are described by the parameters found in Tables 3 and 4, one of the GSO earth stations (GSO ET1) is located as found in Table 2 at 33:26:54 N, 112:04:24 W and the second GSO earth station (GSO ET2) located at 40:26:54 N, 112:04:24 W and is assumed to be served by a different satellite beam than that of GSO ET1. Both GSO earth stations are assumed to be co-frequency to the non-GSO station.

The next step is to run the simulation twice, once for each GSO earth station, and store the results for each time step. For example assume the following data sets are defined as:

$I_0/N_0 1(t)$: time series of uplink I_0/N_0 at the non-GSO receiver for the two co-located Earth stations (non-GSO and GSO ET1).

$I_0/N_0 2(t)$: time series of uplink I_0/N_0 at the non-GSO receiver for the two separated Earth stations (non-GSO and GSO ET2).

$I_0/N_0 A(t)$: time series of aggregate I_0/N_0 at the non-GSO receiver for all GSO Earth stations.

After the two data sets are created the aggregate can be computed by summing the results. The uplink aggregate interference to the non-GSO satellite, $I_0/N_0 A(t)$, is found by:

$$I_0/N_0 A(t_i) = I_0/N_0 1(t_i) + I_0/N_0 2(t_i)$$

where t_i is the time steps at which the interference is computed. Note a requirement for this approach is that the non-GSO constellation is initialized at the same time and has the same time step for both simulations, i.e. the starting location and all subsequent locations of the constellation in space is the same for both simulations, if this is not done the results will be incorrect.

2.6.2 Aggregate based on one simulation

This method of computing the aggregate interference from multiple sources of interference has advantages in that only one simulation is performed for all possible sources of interference and the resultant time savings in performing only one simulation. A disadvantage is that the data cannot have a detailed review to evaluate which source of interference may be the largest contributor to the aggregate results. This disadvantage can be removed by allowing the user to have an option to save each individual contribution as a function of time.

Again as an example of the aggregate based upon multiple simulations consider the example shown described in § 2.6.1 for computing the interference from two GSO earth stations. In this case the analysis program sets up both Earth stations and computes the aggregate interference for each time step.

2.7 Expressions of interference in terms of $epfd_{\uparrow}$ and $epfd_{\downarrow}$

In Resolution 130 (WRC-97) provisional $epfd_{\uparrow}$ and $epfd_{\downarrow}$ limits are indicated to protect GSO operations from co-channel non-GSO interference. This section describes how to relate the computed interference level of I_0/N_0 to $epfd_{\uparrow}$ values and downlink $epfd$ values.

2.7.1 Downlink $epfd$

The downlink $epfd$ ($W/(m^2 \cdot MHz)$) is computed by:

$$epfd_{\downarrow} = \sum_i 10^{pfd_i/10} \frac{G_r(\theta_i)}{G_{max}} \quad (19)$$

where:

- i : index of the source of interference
- pfd_i : pfd from the i -th source of interference ($dB(W/(m^2 \cdot MHz))$)
- $G_r(\theta_i)$: receive antenna gain of the victim receiver in the direction of the i -th source of interference (dBi)
- G_{max} : The maximum receive gain of the victim receiver (dBi).

The interference I_0/N_0 is computed by:

$$\begin{aligned} \frac{I_0}{N_0} &= \frac{P_t}{BW_{tx}} G_t(\varphi_1) G_r(\varphi_2) \left(\frac{\lambda}{4\pi R} \right)^2 \frac{1}{k T} \frac{1}{L_p} \\ &= \frac{P_t}{BW_{tx}} \frac{\lambda^2}{4\pi} \frac{G_t(\varphi_1)}{4\pi R^2} \frac{1}{L_p} \frac{1}{k T} G_r(\varphi_2) \end{aligned} \quad (20)$$

where:

- P_t : available transmit power (W)
- BW_{tx} : transmit bandwidth (Hz)
- $G_t(\varphi_1)$: transmit gain (relative intensity)
- $G_r(\varphi_2)$: receiver gain (relative intensity)
- φ_1 : off bore-sight angle of the transmitter in the direction of the receiver
- φ_2 : off bore-sight angle of the receiver in the direction of the transmitter
- λ : wavelength of transmitter (m)
- R : range (m)
- k : Boltzmann's constant (1.38×10^{-23} J/K)
- T : noise temperature (K)
- L_p : polarization isolation factor.

The epfd (W/(m² · Hz)) from *i*-th source taking into account the receive antenna discrimination and normalizing to the maximum receiver antenna gain can be expressed as:

$$epfd_i = \frac{P_{t_i}}{BW_{tx_i}} \frac{G_{t_i}(\varphi_1)}{4\pi R_i^2} \frac{1}{L_p} \frac{G_r(\varphi_2)}{G_{max}} \quad (21)$$

Therefore taking into account equations (20) and (21), epfd (W/(m² · MHz)) from the *i*-th source can be expressed in terms of I_{0_i}/N_0 from the *i*-th source as:

$$epfd_i = \frac{I_{0_i}}{N_0} \frac{4\pi \times 10^6}{\lambda^2} \frac{k T}{G_{max}} \quad (22)$$

Note that the factor $\frac{4\pi \times 10^6}{\lambda^2} \frac{k T}{G_{max}}$ is a constant for the simulation and can be applied to the results of the simulation. It should be noted that if the I_0/N_0 used is the aggregate from multiple sources, the conversion factor can still be applied to aggregate I_0/N_0 to arrive at the aggregate epfd results shown in equation (19).

2.7.2 Uplink epfd

The uplink epfd (W/(m² · MHz)) is computed by:

$$epfd_{\uparrow} = \sum_i 10^{p_i/10} \frac{G_t(\varphi_i)}{4\pi R^2} \frac{G_r(\theta_i)}{G_{max}} \quad (23)$$

where:

$G_r(\theta_i)$: the receive antenna gain of the victim receiver in the direction of the *i*-th source of interference.

Rewriting equation (23) the uplink epfd (W/(m² · Hz)) from the *i*-th source can be expressed as:

$$epfd_{\uparrow_i} = \frac{P_{t_i}}{BW_{tx_i}} \frac{G_{t_i}(\varphi_1)}{4\pi R_i^2} \frac{1}{L_p} \frac{G_r(\varphi_2)}{G_{max}} \quad (24)$$

in which it is assumed that $p_i = 10 \log\left(\frac{P_t}{BW_{tx}}\right)$.

Therefore taking into account equations (20) and (24), $epfd_{\uparrow}$ (W/(m² · MHz)) from the *i*-th source can be expressed in terms of I_{0_i}/N_0 from the *i*-th source as:

$$epfd_{\uparrow_i} = \frac{I_{0_i}}{N_0} \frac{4\pi \times 10^6}{\lambda^2} \frac{k T}{G_{max}} \quad (25)$$

Note that the factor $\frac{4\pi \times 10^6}{\lambda^2} \frac{k T}{G_{max}}$ is a constant for the simulation and can be applied to the results of the simulation. It should be noted that if the I_0/N_0 used is the aggregate from multiple sources, the conversion factor can still be applied to aggregate I_0/N_0 to arrive at the uplink epfd results shown in equation (23).

3 Example of non-GSO and GSO interference methodology

This section demonstrates an example of the results obtained using the geometric analysis defined by this methodology to interference analysis between a non-GSO system and a GSO satellite system. The example presented in this Annex is for the LEO-A system and a GSO system. The input parameters for the constellations are in Table 3.

TABLE 3

Non-GSO and GSO simulation input parameters

Input parameter	Non-GSO	GSO
Number of space stations	66	1
Number of planes	6	1
Orbit altitude (km)	780.6	35 785.4
Inclination (degrees)	84.6	0
Right ascension of ascending node (degrees)	0.0, 31.6, 63.2, 94.8, 126.4, 158.0	261
Anomaly of first space station in each plane (degrees)	0.0, 16.35, 2.6, 18.95, 5.2, 21.55	0
Minimum elevation (degrees)	5	–
Space station antenna pattern	RR Appendix S8	–
Space station maximum transmit gain (dBi)	26.9	41.5 ⁽¹⁾
Space station maximum receive gain (dBi)	30.1	41.5 ⁽²⁾
Earth station north latitude (degrees:min:s)	33:26:54	
Earth station west longitude (degrees:min:s)	112:04:24	
Earth station antenna pattern	RR Appendix S8	
Earth station maximum transmit gain (dBi)	56.3	44.5
Earth station maximum receive gain (dBi)	53.2	43.0

(1) Space station transmit gain towards non-GSO earth station, 41.5 dBi is edge of coverage gain for narrow spot beam.

(2) Space station receive gain towards non-GSO earth station, 41.5 dBi is edge of coverage gain for narrow spot beam.

Table 4 shows the radio-frequency parameters for non-GSO and GSO links. The missing portions of the table is information that is not required for the simulation. In the GSO system no power control on range is employed, therefore the P_r row is not required, similarly for the non-GSO system employing power control on range P_t , BW_{tx} and P_t/BW_{tx} are not required.

TABLE 4

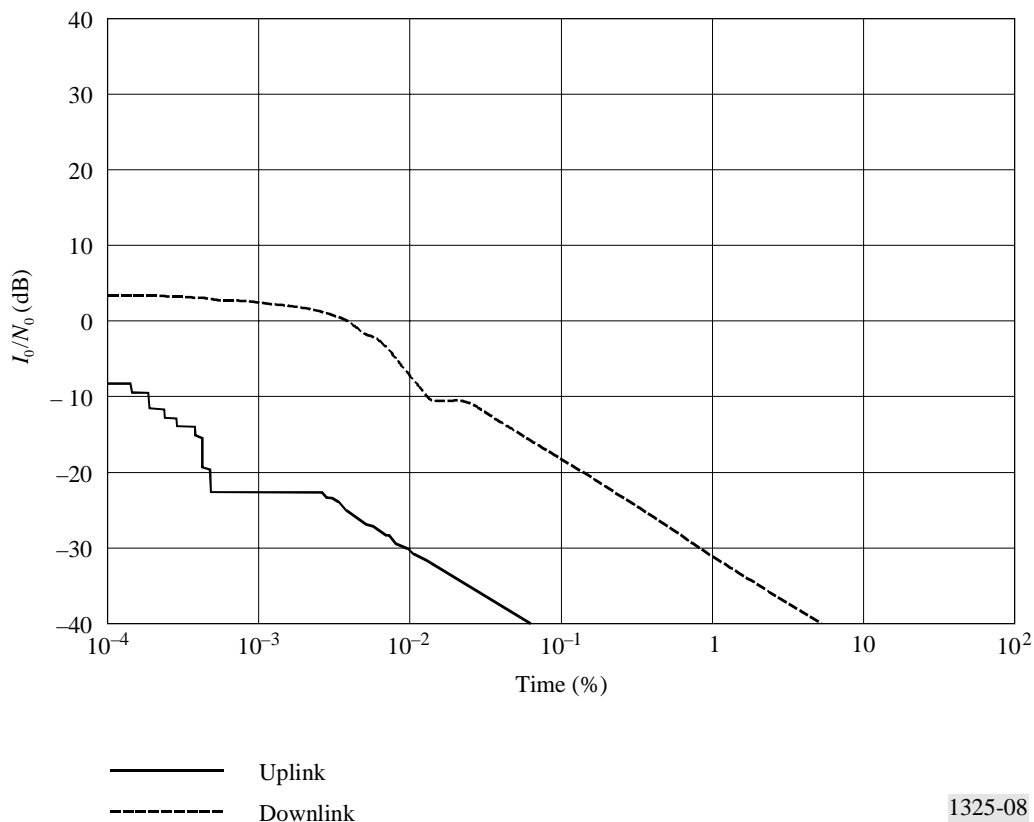
System radio-frequency parameters

Parameter	Non-GSO space station	Non-GSO earth station	GSO space station	GSO earth station
P_t (dBW)	–	–	12.5	–5.2
BW_{tx} (MHz)	–	–	125	0.5
P_t/BW_{tx} (dB(W/Hz))	–	–	–68.5	–62.2
P_r (dB(W/Hz))	–216.1	–243.6	–	–
L_p	1	1	1	1
Transmit λ (m)	0.0154	0.0103	0.0154	0.0103
T (K)	1 295.4	731.4	575	275

The results shown in Figs. 8 to 13 are for a simulation over 49 days sampled every 2 s. This results in over 2.1 million sample points.

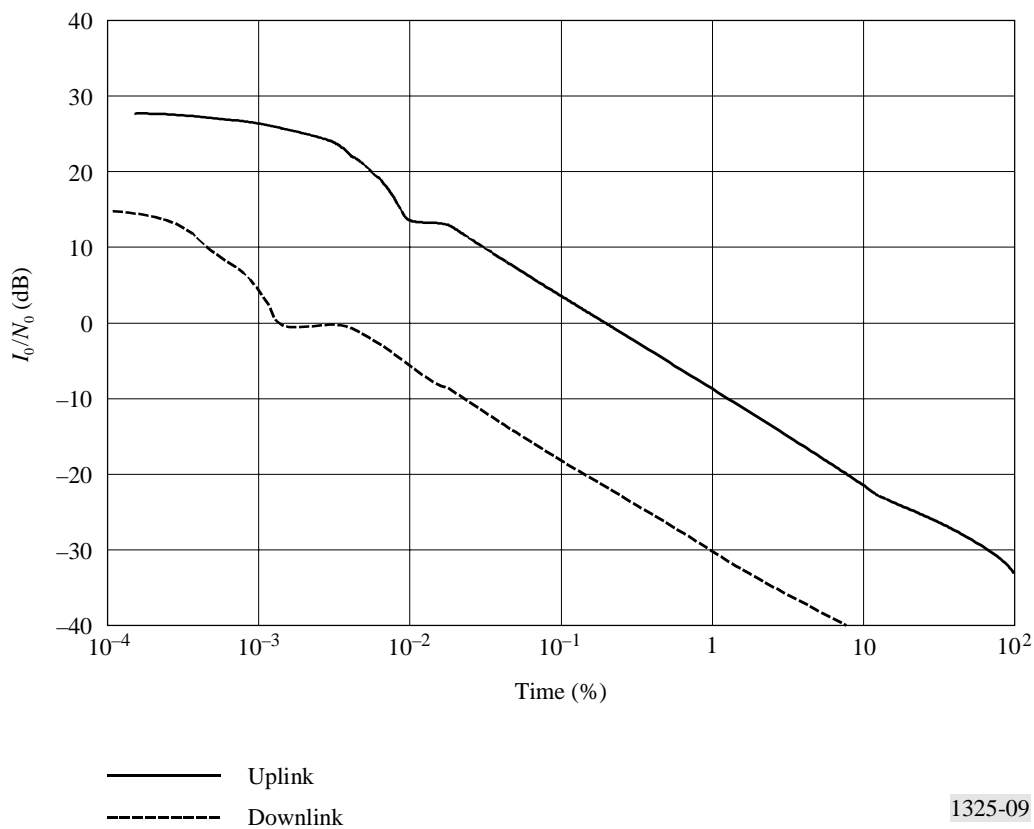
Shown in Figs. 8 and 9 is the I_0/N_0 versus the per cent time that level occurs. Figure 8 shows the interference ratio of the non-GSO network into the GSO network, Fig. 9 shows the interference ratio of the GSO network into the non-GSO network.

FIGURE 8
Interference from non-GSO network into GSO network



1325-08

FIGURE 9
Interference from GSO network into non-GSO network



1325-09

Shown in Figs. 10 and 11 is the number of events and duration of those events that the interference ratio is greater than a pre-specified level. Figure 10 is the effect of the non-GSO network into the GSO network when an event is defined as occurring when I_0/N_0 is above -16 dB, Fig. 11 is the effect of the GSO network into the non-GSO network when an event is defined as occurring when I_0/N_0 is above -1 dB.

Shown in Figs. 12 and 13 is the I_0/N_0 time history of the I_0/N_0 for interference from the GSO uplink into the non-GSO uplink. These graphs are shown during a period of time that the interference level reaches it peak. Figure 12 is over a time-scale of 1 h, the tics on the time axis are shown every 15 min. Figure 13 examines the peak interference event shown in Fig. 12.

FIGURE 10
Duration of interference events from non-GSO network into GSO network

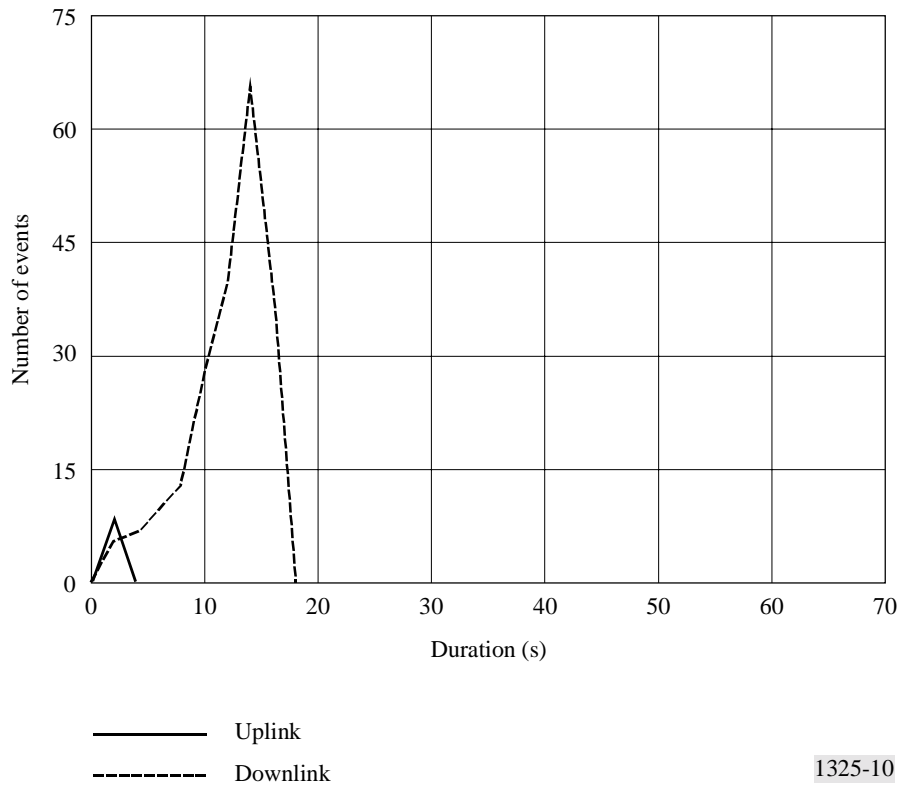


FIGURE 11
Duration of interference events from GSO network into non-GSO network

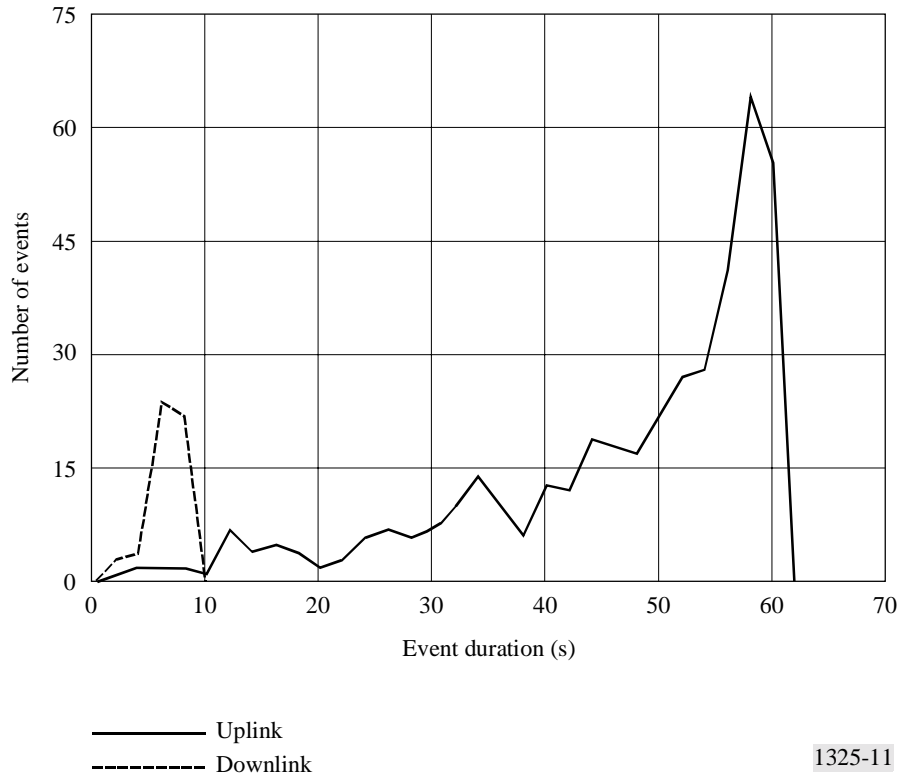


FIGURE 12
Time history of interference from GSO network into uplink of non-GSO network

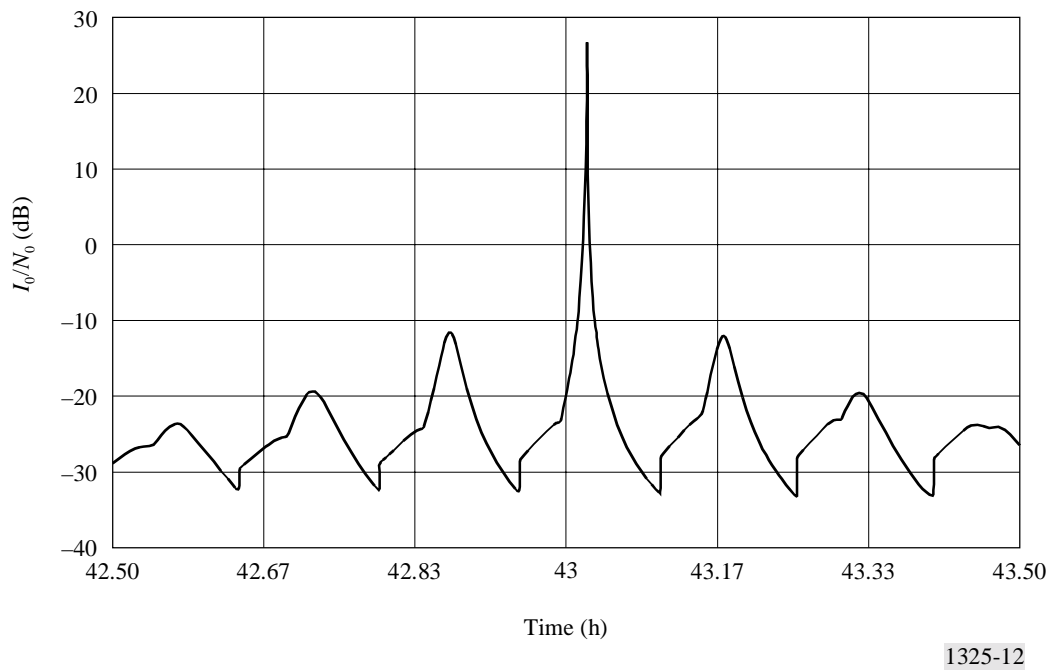
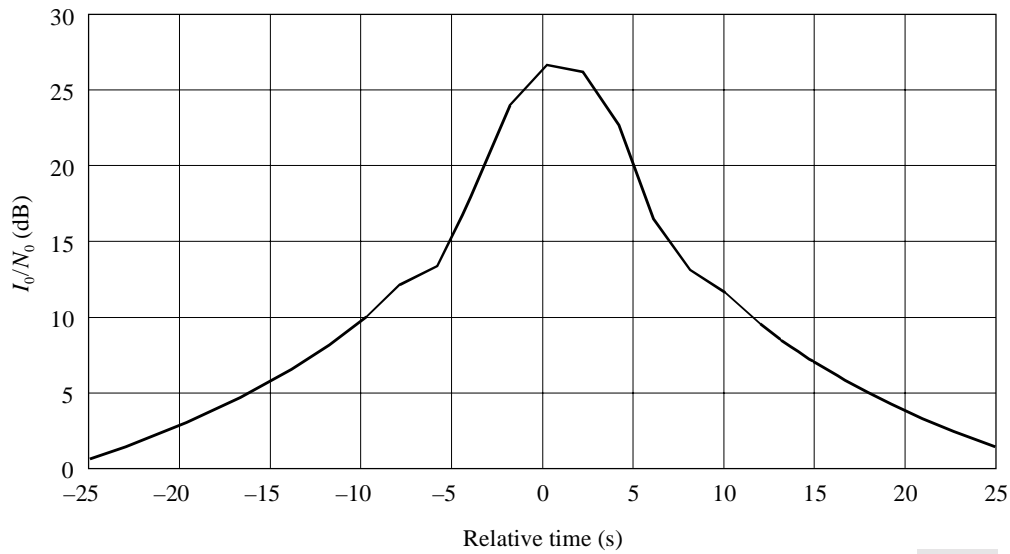


FIGURE 13
Detail of peak event from Fig. 12, centred at time $t = 43 \text{ h } 74 \text{ s}$



1325-13

3.1 Validation of interference results

To confirm that the interference levels computed in § 3 are within bounds of what is expected a comparison with a known check point is desired. A convenient check point is to compare the maximum interference levels shown in Figs. 8 and 9 with the interference level computed when the non-GSO satellite is directly in line with the path between the GSO earth station and the GSO satellite. Shown in Table 5 is the interference computation for the case of the non-GSO network interfering with the GSO network. The peak values of Fig. 8 and the interference value computed in Table 5 are the same.

TABLE 5

In-line computation of interference level from GSO network into non-GSO network

	Non-GSO uplink into GSO uplink	Non-GSO downlink into GSO downlink
P_r (dB(W/Hz))	-216.1	-243.6
Wanted path length (km)	998.7	998.7
Wanted path loss (dB)	-181.7	-178.4
Wanted transmit gain (dBi)	56.3	26.9
P_t/BW_{tx} (dB(W/Hz))	-90.7	-92.4
Wanted transmit gain (dBi)	56.3	26.9
Interference path length (km)	37 165.8	998.7
Interference path loss (dB)	-213.1	-178.4
L_p	1	1
Receive gain (dBi)	41.5	43.0
I_0 (dB(W/Hz))	-206.0	-200.6
Receiver noise, T (K)	575	275
N_0 (dB(W/Hz))	-201.0	-204.2
I_0/N_0 (dB)	-5.0	3.6

Shown in Table 6 is the interference computation for the GSO network interfering with the non-GSO network. The peak values of Fig. 9 and the interference value computed in Table 6 are the same.

TABLE 6

In-line computation of interference level from GSO network into non-GSO network

	GSO uplink into non-GSO uplink	GSO downlink into non-GSO downlink
P_t/BW_{tx} (dB(W/Hz))	-62.2	-68.5
Transmit gain (dBi)	44.5	41.5
Interference path length (km)	998.7	37 165.8
Interference path loss (dB)	-181.7	-209.6
L_p	1	1
Receive gain (dBi)	30.1	53.2
I_0 (dB(W/Hz))	-169.3	-183.4
Receiver noise, T (K)	1 295.4	731.4
N_0 (dB(W/Hz))	-197.5	-200.0
I_0/N_0 (dB)	28.2	16.6

ANNEX 4

Continuing work programme

The following is an outline for further work on this Recommendation.

- 1 Adjust the run time to be that of the first repetition of the non-GSO subsatellite ground track when the other network is a GSO, and/or provide a discussion of the initial conditions and suitable run time for various constellations to insure an unbiased statistical output.
- 2 Include a discussion in Annex 1, § 2.7 of the appropriate time step selection for various constellations, i.e. for constellations having elliptical orbits. This would be a function of the constellation altitude(s) and antenna size (beamwidth).
- 3 Further study is required to define the amount of isolation that can be assumed between the transmitter and receiver due to differing polarization. These studies should account for items such as atmospheric effects and systems that use phase comparative methods for tracking antennas.
- 4 Use of space station selection techniques when multiple satellites are in view of an earth station. Include a discussion of other techniques under consideration by other operators that may address interference avoidance or diversity techniques.
- 5 To take account in Annex 3, § 2.2 for systems employing power control based on the range between a non-GSO earth terminal and a non-GSO satellite.
- 6 To consider the appropriateness of including example of the methodologies in the Recommendation.
- 7 The desirability of including implementation details, such as optimizing constants as found in Annex 3, § 2.2, in the Recommendation. Consideration should also be given to the extent to which some parameters can be assumed to be constant, given factors such as adaptive peak gain antennas, power control and elliptical orbits.