RECOMMENDATION ITU-R S.1592

Methodology to assess compliance of non-geostationary fixed-satellite service satellite systems in circular orbits with the additional operational limits on downlink equivalent power flux-density in Article 22 of the Radio Regulations

(2002)

The ITU Radiocommunication Assembly,

considering

a) that the World Radiocommunication Conference (Istanbul, 2000) (WRC-2000) adopted, in Article 22 of the Radio Regulations (RR), limits to the downlink equivalent power flux-density (epfd↓) radiated by non-geostationary (GSO) fixed-satellite service (FSS) systems in certain frequency bands, to protect GSO FSS and broadcasting-satellite service (BSS) networks operating in the same frequency bands;

b) that RR Article 22 includes single-entry validation limits to the epfd↓ in RR Tables 22-1A to 22-1D, single-entry operational limits to the epfd↓ in RR Tables 22-4A, 22-4B and 22-4C, and single-entry additional operational limits to the epfd↓ into antennas of certain sizes in RR Table 22-4A1, which apply to non-GSO FSS systems for the protection of GSO FSS networks;

c) that compliance of a proposed non-GSO FSS system with the single-entry validation limits will be evaluated by the Radiocommunication Bureau (BR), under RR Nos. 9.35 and 11.31, based on masks of pfd provided by the non-GSO FSS operator, using software defined in Recommendation ITU-R S.1503;

d) that compliance of a proposed non-GSO FSS system with the single-entry operational limits to the epfd↓ and, for certain antenna sizes, single-entry additional operational limits to the epfd↓ is subject to verification by administrations;

e) that RR Appendix 4, as modified by WRC-2000, requires an administration responsible for a non-GSO FSS system to ensure that the single-entry additional operational limits to the epfd↓ are met,

recognizing

a) that administrations with assignments to GSO FSS networks in frequency bands where additional operational limits to the epfd↓ have been established require a reliable and independent means to determine whether a particular non-GSO FSS system is in compliance with the single-entry additional operational limits to the epfd↓, for their GSO FSS networks, *recommends*

1 that the methodology defined in Annex 1 to this Recommendation, based on a full simulation of downlinks in a non-GSO FSS satellite system interfering into an operating GSO FSS earth station with a 3 m or 10 m antenna, be used to assess the levels of interference generated by the non-GSO FSS system, in order to verify compliance by the non-GSO FSS system with the additional operational limits to epfd↓ in RR Article 22;

2 that the methodology in Annex 1 to this Recommendation, based on full simulation of downlinks in a non-GSO FSS satellite system interfering into a GSO FSS network, be used by GSO operators as guidance to assess the levels of interference generated by non-GSO systems into any diameter antenna of planned or operational GSO FSS networks.

NOTE 1 – Annex 2 discusses an approach that could be used to demonstrate that additional operational limits are met by an operational non-GSO system interfering into an operational GSO FSS earth station. In contrast with Annex 1, which is based on a full simulation approach, Annex 2 is based on the pfd mask approach adopted in Recommendation ITU-R S.1503.

ANNEX 1

Methodology to assess compliance with additional operational limits of the interference generated by non-GSO FSS systems* sharing frequency bands with GSO FSS networks

1 Introduction

This methodology is based on modelling the satellite systems in their orbits and allows each space station and earth station to track their respective targets, while taking into account the Earth's rotation. A simulation of this model is sampled over a period of time at a suitably fine sampling rate, and at each sample the range gain product is computed. This range gain product can be related directly to the level of interference, and the sampled data can be evaluated to determine the percentage of time that the range gain product for all interference paths exceeds a given level.

* The methodology defined in Annex 1 currently applies to only non-GSO systems using circular orbits. Further study is needed for non-circular orbits.

TABLE 1

Symbols and definitions used in this Annex

a	Angular velocity of satellite in Earth-fixed coordinates	degrees/s
B_t	Transmit bandwidth	Hz
$C_{traffic}$	Traffic coefficient depending on local time	–
D	Antenna diameter	m
E	Argument of latitude	degrees
epfd↓	Downlink equivalent power flux-density into earth station	dB(W/m^2) in reference bandwidth
g	Acceleration due to Earth's gravity	M/s^2
G	Universal (Newtonian) gravitational constant	Nm^2/kg^2
G_t	Relative gain of transmit antenna	–
G_r	Relative gain of receive antenna	–
G_{rmax}	Maximum gain of GSO FSS earth station receiving antenna	–
G_{rw}	Maximum gain of wanted receive antenna	–
I	Inclination of satellite orbit	degrees
I_0	Interference power	W
J_2	Second harmonic Earth potential constant	–
k	Boltzmann's constant	J/K
L_p	Polarization isolation factor	–
m_s	Mass of satellite	kg
M_e	Mass of the Earth	kg
N_0	Noise power	W
N_a	Number of transmitting non-GSO satellites visible from GSO FSS receiving earth station	–
N_{coarse}	Integer ratio of coarse time step size to fine step size to define dual time step simulations	–
N_{hits}	Number of mainbeam-to-mainbeam coupling events between non-GSO satellite antenna and GSO FSS earth station antenna	–
P_t	RF power at input to transmitting antenna	W
r	Orbital radius of satellite	km
r_c	Radius of non-GSO service area cell	km
r_g	Radius of GSO	km
r_n	Orbital radius of non-GSO satellite	km
R	Range between non-GSO satellite and GSO FSS earth station	m
R_e	Radius of perfectly spherical Earth	km
T	Receiver noise temperature	K

TABLE 1 (*end*)

T_o	Orbit period	s
T_w	Wanted receiver noise temperature	K
Δt	Simulation time increment	s
ε	Earth station elevation angle	degrees
φ	Topocentric angle defining exclusion zone for non-GSO satellite switching strategy	degrees
φ_{coarse}	Topocentric angle defining coarse step size in dual time-step simulation	degrees
$\varphi_{FSR\text{-}1}$	Topocentric angle defining fine step region (FSR)	degrees
$\varphi_{FSR\text{-}2}$	Topocentric angle defining boundary of exclusion zone	degrees
φ	Antenna off-boresight angle	degrees
φ_3	Antenna 3 dB beamwidth	degrees
λ	Wavelength	m
μ	Earth attraction constant	km^3/s^2
v	Constant velocity of satellite	degrees/s
v_e	Orbital velocity of the Earth	degrees/m
v_r	Orbital velocity of non-GSO satellite relative to the Earth's surface	degrees/s
v_n	Orbital velocity of non-GSO satellite	degrees/s
ω	Angular velocity of satellite	degrees/s
Ω	Right ascension of the ascending node (RAAN)	degrees
Ω_0	RAAN at time t_0	degrees
Ω_e	Rotational angular velocity of the Earth	degrees/s
Ω_r	Orbital precession rate of satellite	degrees/s
ψ	GSO arc avoidance switching angle	degrees
ψ_d	GSO arc avoidance switching angle desired at the edge of non-GSO service area cell	degrees
ψ_m	GSO arc avoidance angle to be modelled to achieve desired switching angle at edge of cell	degrees

2 Input parameters required

In order for this methodology to be applied, the following input parameters will need to be provided by the non-GSO operator. Note that, in the absence of complete information on all these parameters, this Recommendation gives some guidance on, for example, possible distributions of non-GSO FSS earth stations to be modelled in the simulations.

2.1 Orbit parameters

Number of space stations

Number of planes

For each orbital plane:

- orbit altitude
- inclination of plane
- longitude of the ascending node
- argument of latitude for each space station in the orbital plane.

Precession.

2.2 Antenna parameters

Non-GSO space stations:

- antenna radiation pattern
- maximum transmit gain (dBi)
- maximum number of co-frequency and co-polarization antenna beams and their spatial orientation.

Non-GSO earth stations:

- antenna radiation pattern
- maximum receive gain (dBi)
- location (latitude, longitude).

2.3 Operational and computational parameters

- Frequency/polarization reuse plan, if used
- Minimum elevation angle for communication
- Simulation time period
- Simulation time step
- Implementation of downlink power control on range, if used by non-GSO system
- Implementation of GSO arc avoidance technique, if used by non-GSO system
- Traffic model, if appropriate (for example, see Fig. 9).

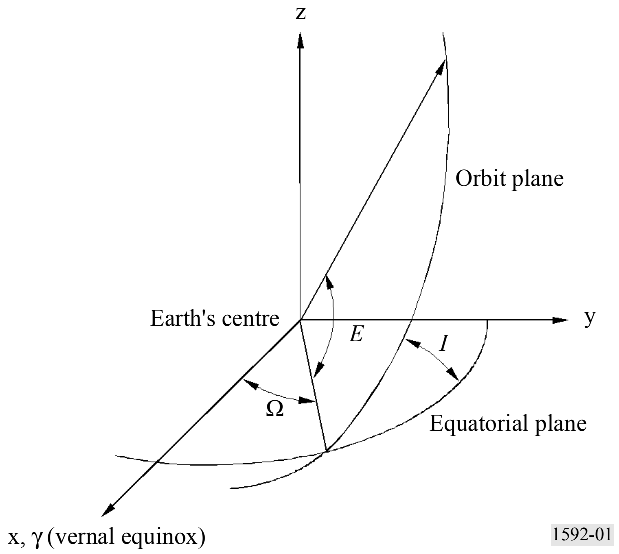
3 The orbital model

The orbital model characterizes satellite motions in a geocentric inertial coordinate frame, shown in Fig. 1, the origin of which is at the centre of the Earth. The x axis is on the equatorial plane and points towards the vernal equinox (the first point in the constellation Aries), the z axis is the mean rotation axis of the Earth and points towards the North Pole, and the y axis is determined as the cross product of the unit vectors in the z and x direction, i.e. $\vec{y} = \vec{z} \times \vec{x}$.

Extension of the equatorial plane to infinity, intersecting a hypothetical sphere of infinite radius (the celestial sphere), defines the celestial plane.

FIGURE 1

Representation of Keplerian orbital elements



The orbital model is based on Newton's Laws of Motion for a satellite orbiting in a circle around a perfectly spherical Earth. This model is simple to implement since the motion is characterized by a constant satellite orbital radius, r, and a constant velocity, v, which are related through Newton's Second Law of Motion:

$$\frac{m_s v^2}{r} = \frac{G M_e m_s}{r^2} \tag{1}$$

where:

m_s: mass of the satellite

v: constant velocity of the satellite

G: universal gravitational constant (Nm^2/kg^2)

r: orbit radius

M_e: mass of the Earth (kg).

Equation (1) can be written in the form:

$$v^2 = \frac{G M_e}{r} = \frac{G M_e}{R_e^2} \cdot \frac{R_e^2}{r} \tag{2}$$

where R_e is the radius of a perfectly spherical Earth (km).

At the surface of the Earth,

$$mg = \frac{G M_e m}{R_e^2} \tag{3}$$

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

$$g = \frac{G M_e}{R_e^2} \qquad \text{m/s}^2 \tag{4}$$

and equation (2) can be rewritten in the form:

$$v = R_e \sqrt{\frac{g}{r}} \tag{5}$$

The orbital period, T_o, is then given by the expression (Kepler's Third Law):

$$T_o = \frac{2\pi r}{v} = \frac{2\pi}{R_e} \sqrt{\frac{r^3}{g}} \tag{6}$$

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

The motion is characterized, in the geocentric coordinate system shown in Fig. 1, by specifying the position of the satellite using the Keplerian orbital parameters:

Ω: right ascension of the ascending node, i.e. where the satellite moves from south to north, of the orbit RAAN, measured from the x axis in the equatorial plane (x-y plane);

I: inclination of the orbit, i.e. the angle from the equatorial plane to the orbital plane of the satellite; and

E: argument of latitude, i.e., the angle from the line of nodes (the line determined by the intersection of the orbital plane and the celestial equator) to the radius vector at the position of the satellite.

The true anomaly, i.e. the angle on the plane of the satellite's orbit between the perigee and the position of the satellite, as seen from the centre of the Earth, is a function of the angular position of the satellite at time t_0 and its angular velocity and can be expressed as:

$$E = E_0 + \omega t \tag{7}$$

where:

E_0: angular position of the satellite at time t_0 (degrees)

$\omega = v/r$: angular velocity of the satellite (degrees/s).

Similarly, the RAAN of an orbit can also be expressed as a function of time to account for orbital precession:

$$\Omega = \Omega_0 + \Omega_r t \tag{8}$$

where:

Ω_0: RAAN of the satellite at time t_0 (degrees)

Ω_r: orbital precession rate of the satellite (degrees/s):

$$\Omega_r = -\frac{3}{2} \mathrm{J}_2 \cos(I) R_e^2 \frac{\sqrt{r\mu}}{r^4} \tag{9}$$

where:

μ: Earth attraction constant (km^3/s^2)

J_2: second harmonic Earth potential constant.

The position of the satellite can then be represented in terms of the geocentric inertial coordinate system as:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = r \begin{bmatrix} \cos\Omega\cos E - \sin\Omega\cos I\sin E \\ \sin\Omega\cos E + \cos\Omega\cos I\sin E \\ \sin I\sin E \end{bmatrix} \tag{10}$$

and the velocity of the satellite is similarly represented in terms of the geocentric inertial coordinate system, ignoring the relatively long-term variation in Ω, as

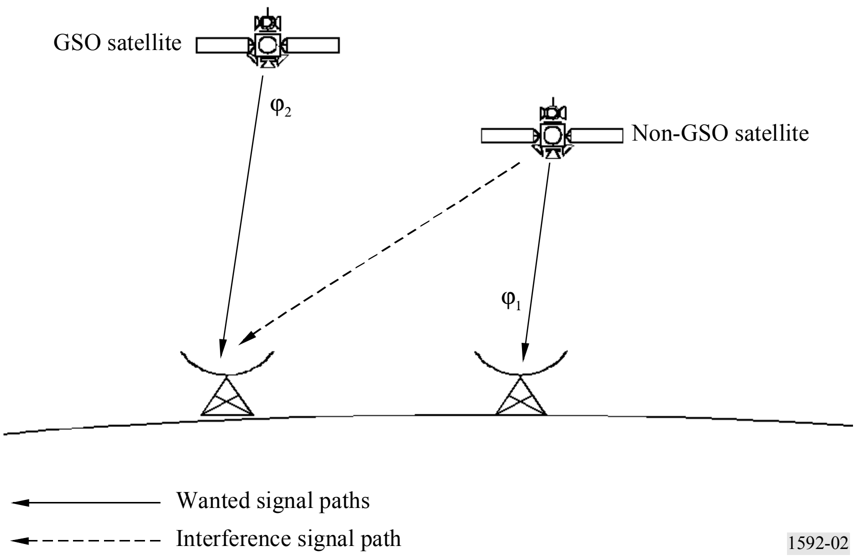
$$\begin{bmatrix} dx/dt \\ dy/dt \\ dz/dt \end{bmatrix} = \omega r \begin{bmatrix} -\cos\Omega\sin E - \sin\Omega\cos I\cos E \\ -\sin\Omega\sin E + \cos\Omega\cos I\cos E \\ \sin I\cos E \end{bmatrix} \tag{11}$$

4 Calculation of interference

In this methodology, the interference being considered is from the downlink of a non-GSO FSS satellite system into receiving earth stations operating to GSO FSS satellites. Figure 2 illustrates the geometry of the wanted and interference paths.

FIGURE 2

Interference geometry



If power control is not used, the interference-to-noise ratio, I_0/N_0, can be determined from the following equation:

$$\begin{aligned} \frac{I_0}{N_0} &= \frac{P_t}{k\,T\,B_t}\,G_t\,(\varphi_1)\,G_r\,(\varphi_2)\left(\frac{\lambda}{4\pi R}\right)^2\frac{1}{L_p} \\ &= \frac{P_t}{k\,T\,B_t}\,\frac{\lambda^2}{4\pi}\,\frac{1}{L_p}\,\frac{G_t\,(\varphi_1)\,G_r\,(\varphi_2)}{4\pi R^2} \end{aligned} \tag{12}$$

where:

P_t: available transmit power (W)

T: noise temperature of the receiver (K)

B_t: transmit bandwidth (Hz)

$G_t(\varphi_1)$: relative gain as a numerical ratio of the non-GSO satellite transmit antenna

$G_r(\varphi_2)$: relative gain as a numerical ratio of the GSO FSS earth station receive antenna

λ: wavelength of the transmitter (m)

R: interference path length (m)

L_p: polarization isolation factor

k: Boltzmann's constant (1.38×10^{-23} J/K).

The range gain product for the non-GSO satellite downlink into the earth station downlink from the GSO satellite is given by:

$$\frac{G_t(\varphi_1)\, G_r(\varphi_2)}{4\pi R^2} \tag{13}$$

If there is no path length compensating power control on the links between the satellite and the earth station, this expression includes all the elements in equation (12) which may vary with time. The interference ratio, I_0/N_0, is then determined by multiplying the range gain product by the constant factor:

$$\frac{P_t}{k\,T\,B_t}\,\frac{\lambda^2}{4\pi}\,\frac{1}{L_p} \tag{14}$$

If power control is used on a non-GSO satellite to account for differences in range between the satellite and the earth station, then this must be taken into account in the simulation. The transmitting satellite reduces or increases its transmit power as it moves towards or away from the receiving earth station in order to maintain constant power received at the non-GSO FSS earth station. The input parameter for the simulation is the desired receiver power density at the input to the wanted antenna, P_r (dB(W/Hz)), which can be expressed as:

$$P_r = \frac{P_t(R)}{B_t}\,G_t(0)\left(\frac{\lambda}{4\pi R_w}\right)^2 \tag{15}$$

where:

R_w: wanted signal path length, i.e. the distance between the satellite and the earth station (m)

$P_t(R)$: transmit power required to set up the link

P_r can be related to the carrier-to-noise ratio at the wanted receiver:

$$\frac{C_0}{N_0} = \frac{P_r(R)\,G_{rw}(0)}{k\,T_w} = \frac{P_t(R)}{B_t}\,\frac{G_t(0)\,G_{rw}(0)}{k\,T_w}\left(\frac{\lambda}{4\pi R_w}\right)^2 \tag{16}$$

where:

$G_{rw}(0)$: maximum gain of the interfered with earth station receive antenna

T_w: interfered with earth station receiver noise temperature (K).

When power control on range is considered, the level of interference is determined from the following equation:

$$\begin{aligned}\frac{I_0}{N_0} &= \frac{P_t(R)}{k\,T\,B_t}\,G_t\,(\varphi_1)\,G_r\,(\varphi_2)\left(\frac{\lambda}{4\pi R}\right)^2\frac{1}{L_p}\\ &= P_r\,\frac{G_t(\varphi_1)\,G_r\,(\varphi_2)}{G_t(0)}\left(\frac{R_w}{R}\right)^2\frac{1}{k\,T}\,\frac{1}{L_p}\end{aligned} \tag{17}$$

To assess the interference from non-GSO networks with multiple satellites and earth stations, the interference from all of the non-GSO satellite downlinks must be combined to determine the total interference into a GSO satellite receiving earth station. The interference can be combined at each time step in the simulation or by combining the data from a set of individual simulations.

The epfd of interference from a non-GSO satellite into a GSO FSS receiving earth station, epfd↓, is defined as the sum of the interference pfds produced at a receiving station of the victim system, by all the transmitting stations within the interfering non-GSO system, taking into account the off-axis discrimination of the receiving antenna pointing in its nominal direction:

$$epfd_{\downarrow} = 10\log\left(\sum_{i=1}^{N_a} 10^{P_t/10}\,\frac{G_t(\varphi_{1i})}{4\pi R_i^2}\,\frac{G_r(\varphi_{2i})}{G_{r_{max}}}\right) \tag{18}$$

where:

$epfd_{\downarrow}$: equivalent power flux-density (dB(W/m^2) in reference bandwidth)

N_a: number of transmitting stations in the interfering non-GSO satellite system which are visible from the receiving earth station of the victim GSO system

i: index of the transmitting station considered in the interfering non-GSO satellite system

P_t: RF power at the input of the antenna of the transmitting space station in the non-GSO satellite system (dBW in reference bandwidth)

$G_t(\varphi_{1i})$: relative transmit antenna gain of the *i*-th transmitting space station in the non-GSO satellite system

$G_r(\varphi_{2i})$: relative receive antenna gain of GSO FSS earth station in the direction of the *i*-th transmitting station in the non-GSO satellite system

$G_{r_{max}}$: maximum gain of the GSO FSS receiving earth station antenna

φ_{1i}: antenna off-boresight angle of the i-th transmitting station in the non-GSO satellite system in the direction of the GSO FSS receiving earth station

φ_{2i}: antenna off-boresight angle of the GSO FSS receiving earth station in the direction of the i-th transmitting station in the non-GSO satellite system

R_i: distance between i-th transmitting station in the non-GSO satellite system and the GSO FSS receiving earth station.

In linear terms, this can be written

$$10^{epfd_{\downarrow}/10} = \sum_i P_t \frac{G_t(\varphi_{1i})}{4\pi R_i^2} \frac{G_r(\varphi_{2i})}{G_{r_{max}}} \tag{19}$$

and expressing the transmit power of the i-th transmitting station P_{ti} (W), this becomes

$$10^{epfd_{\downarrow}/10} = \sum_i \frac{P_{ti}}{B_t} \frac{G_t(\varphi_{1i})}{4\pi R_i^2} \frac{G_r(\varphi_{2i})}{G_{r_{max}}} \tag{20}$$

where:

B_t: transmit reference bandwidth (Hz).

Substituting equation (12) into this expression results in the following:

$$epfd_{\downarrow} = 10 \log \sum_i \frac{I_0/N_0}{\left(G_{r_{max}} \frac{\lambda^2}{4\pi} \frac{1}{k\,T} \frac{1}{L_p} \right)} \tag{21}$$

which can be rewritten logarithmically as:

$$epfd_{\downarrow} = 10 \log \left(\sum_i \frac{I_0}{N_0} \right) - \frac{G_{r_{max}}}{T} - 10 \log \left(\frac{\lambda^2}{4\pi} \right) + 10 \log L_p + 10 \log k \qquad \text{dB(W/m}^2 \cdot \text{Hz)} \tag{22}$$

5 Elements in the simulation

5.1 Non-GSO FSS earth station location

The identification of beams used at any given location and time from a non-GSO satellite depends on both the switching strategy and the location of non-GSO FSS earth stations. This section considers methods to determine the locations of non-GSO FSS earth stations, while switching strategies are described in § 5.2.

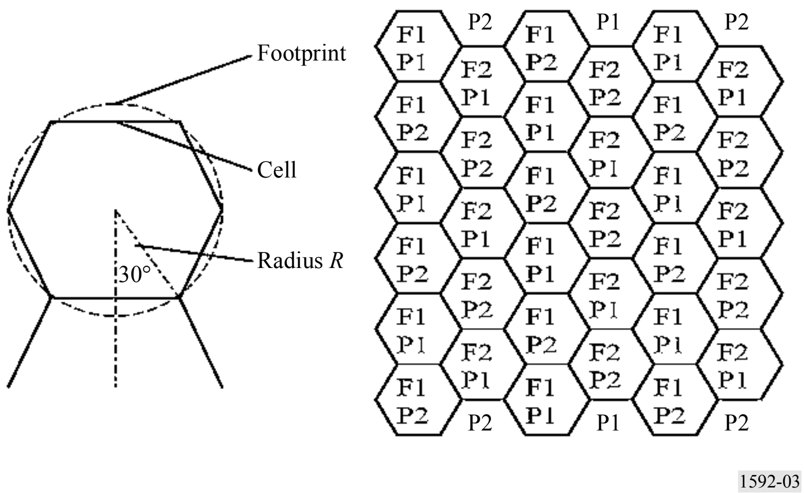
The simulation requires the number and geographic location of non-GSO FSS earth stations on the Earth's surface which could operate co-frequency and co-polarized. If the exact locations of all the non-GSO FSS earth stations are known, then the simulation should use these locations, since these constitute the most accurate configuration of the non-GSO system. However, in many cases, this information may not be available, so it will be necessary to make some appropriate assumptions.

If every non-GSO FSS earth station whose downlink would interfere with the downlink of a given victim GSO FSS earth station is modelled, the simulation running time may become excessive, and in many cases it will be possible to limit the number of non-GSO FSS earth stations included in the model, thus substantially reducing, the simulation runtime without significant loss of accuracy in the computed epfd↓ statistics. In most cases, the downlinks to non-GSO FSS earth stations nearest to the victim GSO FSS earth station will make the largest contributions to epfd↓, while the contributions from downlinks to other non-GSO FSS earth stations will become progressively smaller as their distance from the victim GSO FSS earth station increases. One method to minimize the required time for a definitive simulation is to perform an initial short run with a limited number of non-GSO FSS earth stations located symmetrically around the victim earth station, and then add a concentric ring of non-GSO FSS earth stations and perform a further short run. This process is repeated until the epfd↓ statistics produced by successive short runs do not increase significantly. The resulting model can then be used for the definitive simulation.

If no information is available on the exact locations of the non-GSO FSS earth stations, then a uniform distribution should be used in the first instance, based on a knowledge of the service area cell size or footprint and the distance between the centres of adjacent cells in the non-GSO FSS system. As an example, a system with a 4-cell frequency/polarization reuse pattern would have hexagonal cells as shown schematically in Fig. 3, where F1, F2 and P1, P2 refer to two different frequencies and polarizations. In such a scheme, no adjacent cells would have the same frequency and polarization.

FIGURE 3

Hexagonal cell configuration for 4-cell frequency/polarization reuse scheme



If the radius of the footprint is R, then the distance between stations located at the centre of each footprint, which may be used in the simulation to define the locations of the footprint, is $2R \cos 30°$.

In order to ensure the most accurate determination of epfd↓ for comparison with the additional operational limits, the frequency/polarization scheme should be modelled, using the appropriate polarization isolation factor, L_p. In cases where the non-GSO FSS system employs circular polarization, with alternate right-hand circular (RHC) and left-hand circular (LHC), and the GSO FSS system employs linear polarization, either horizontal or vertical, the simulation can be simplified without loss of accuracy by modelling only one circular polarization, either RHC or LHC, since the polarization isolation to linear polarization will be identical for both RHC and LHC.

5.2 Tracking strategies

5.2.1 GSO arc avoidance

Some non-GSO systems have been designed to reuse the frequency bands already heavily used by GSO systems, and this frequency reuse is made feasible through the exploitation of several techniques, some of which are described in this section.

5.2.1.1 GSO arc avoidance based on latitude

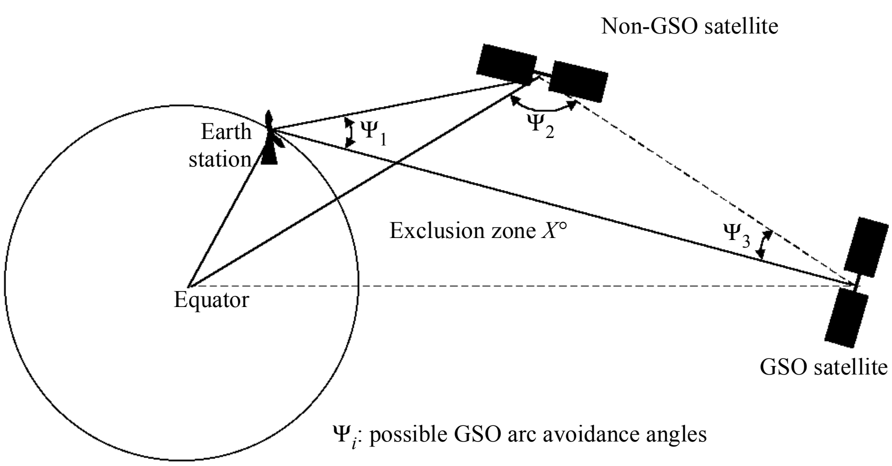
In order to minimize the levels of interference, some systems use a technique which avoids coupling between the main beam of the satellite antennas and the main beam of the GSO FSS earth station antenna. An exclusion zone is defined by an angle $\pm X°$ around the equator, and when a non-GSO satellite enters the exclusion zone, the traffic of the beam where there is main-beam coupling is handed over to another satellite not in the zone.

In addition, systems have been designed in such a way that there is a minimum angle, either at the earth station or in space, of at least $\psi°$ between the GSO satellite and a non-GSO satellite within which traffic is diverted to other non-GSO satellites.

These techniques are illustrated in Fig. 4.

FIGURE 4

Schematic of tracking strategies using exclusion zones and avoidance angles



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5.2.1.2 GSO arc avoidance based on angle between non-GSO satellite and GSO arc

The GSO arc protection implemented by some systems consists of switching off the beams when the angular separation between the GSO arc and a non-GSO satellite of less than $\psi°$, as seen from any Earth point within a service area. The value of ψ is system dependent, but, for an Earth-based arc avoidance angle, it is typically assumed to be 10°.

It is important to note that when a non-GSO footprint is defined by a tracking beam from the non-GSO satellite to an earth station at its centre, the switching angle ψ will occur first for a GSO FSS earth station at the trailing edge of the beam in the plane of the satellite's motion relative to the Earth. The actual GSO arc avoidance angle to be used in the simulation should then be modified to take this into account, to ensure that all points within the beam service area defined by the footprint are protected. The geometry is illustrated in Figs. 5 and 6, where the switching angle required at the edge of the beam service area is denoted ψ_d and the switching angle at the beam centre to achieve this value is ψ_m. In these Figures, the worst case is assumed, i.e. where the non-GSO satellite's earth track passes exactly through the centre of the footprint of the beam concerned.

The orbital velocity of a non-GSO satellite, v_n, is defined in terms of its orbit period, T_n (min), as $v_n = 360 / T_n$ degrees/min, where T_n is given by equation (6) with an orbital radius of r_n. If the orbital inclination is I, then the velocity relative to the Earth's surface of given by:

$$v_r = \sqrt{\left(v_n^2 + v_e^2 - 2 v_n v_e \cos I\right)} \tag{23}$$

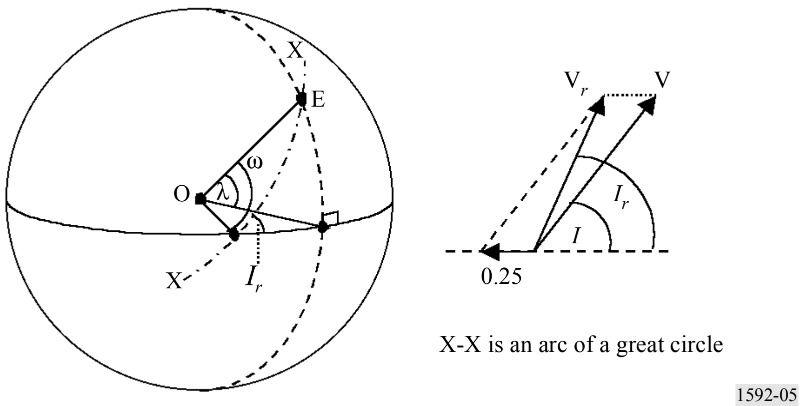
where v_e is the orbital velocity of the Earth (degrees/min). The angle I_r in Fig. 5 is:

$$I_r = I + \arcsin\left(\frac{v_e}{v_r} \sin I\right) \tag{24}$$

Now, since $\dfrac{\sin I_r}{\sin \lambda} = \dfrac{\sin 90}{\sin \omega}$, then $\omega = \arcsin\left(\dfrac{\sin \lambda}{\sin I_r}\right)$, where λ is the latitude.

FIGURE 5

Velocity vectors of the non-GSO satellite



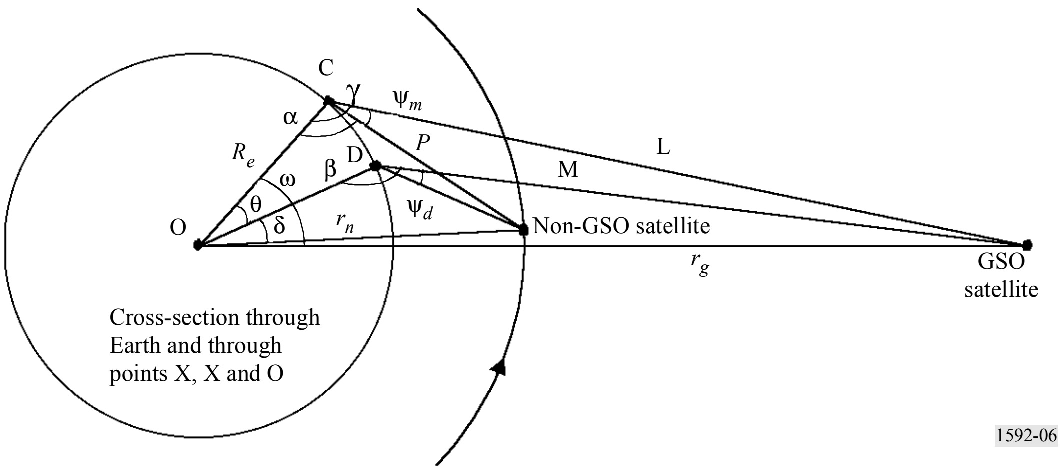
In Fig. 6, C is the beam centre and D is at the beam edge. The arc CD defines the beam service area radius of the cell, r_c, and the angle $\theta = r_c/R_e$ (rad). The distance L from the GSO satellite to the beam centre is given by:

$$L = \sqrt{\left(r_g^2 + R_e^2 - 2r_g\ R_e \cos\omega\right)} \tag{25}$$

where r_g is the radius of the GSO (42 162 km).

FIGURE 6

Geometry of GSO arc avoidance



The distance M from the GSO satellite to the edge of the beam service area is given by:

$$M = \sqrt{\left(r_g^2 + R_e^2 - 2r_g R_e \cos(\omega - \theta)\right)} \tag{26}$$

and the distance P from the non-GSO satellite to the beam centre is given by the following expression:

$$P = \sqrt{\left(r_n^2 + R_e^2 - 2r_n R_e \cos(\theta + \delta)\right)} \tag{27}$$

The angle δ is found from the sine rule:

$$\delta = 180 - (\beta - \psi_d) - \arcsin\left(\frac{R_e}{r_n}\sin(180 - \beta + \psi_d)\right) \tag{28}$$

where ψ_d is the GSO arc avoidance angle at the edge of the beam service area, and β is given by:

$$\beta = 180 - \arcsin\left(\frac{r_g}{M}\sin(\omega - \theta)\right) \tag{29}$$

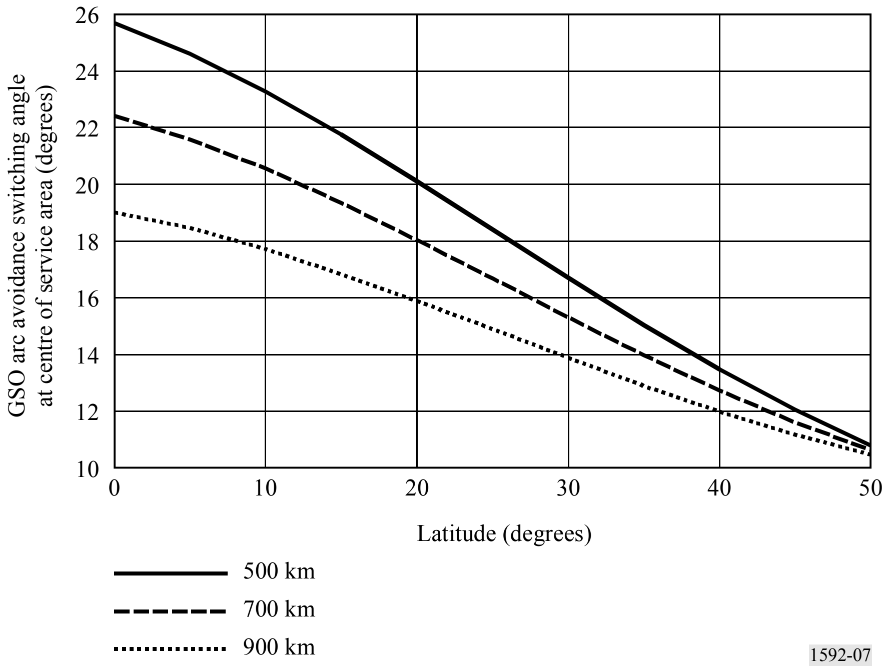
The switching angle at the centre of the beam service area, ψ_m, to achieve a switching angle of ψ_d at the edge of the beam service area can then be obtained from the following expression:

$$\begin{aligned}\psi_m &= \gamma - \alpha \\ &= \arcsin\left(\frac{r_n}{P}\sin(\theta+\delta)\right) - \arcsin\left(\frac{R_e}{L}\sin\omega\right)\end{aligned} \tag{30}$$

As an example, to achieve a GSO arc avoidance switching angle of 10° at the edge of a beam service area, Fig. 7 shows the switching angle to be included in the simulation, for the non-GSO links to the centre of the service area, as a function of latitude for different service area diameters.

FIGURE 7

GSO arc avoidance angle at centre of service area to achieve a switching angle of at least 10° at the edge



Note that further study is required to determine optimum arc avoidance angles in the case of non-GSO satellites which use non-tracking beams.

5.2.2 Non-GSO satellite selection

There are several different satellite selection strategies which non-GSO systems may employ, and the choice of selection strategy can affect the medium- to long-term interference levels. Non-GSO systems may use different selection strategies to reduce interference into other systems, and some of these strategies are summarized in the following sections. If available, the operational satellite selection could be used in order to provide an adequate simulation of the actual interference generated by the operational non-GSO system.

5.2.2.1 Satellite selection based on longest period of visibility (dwell time)

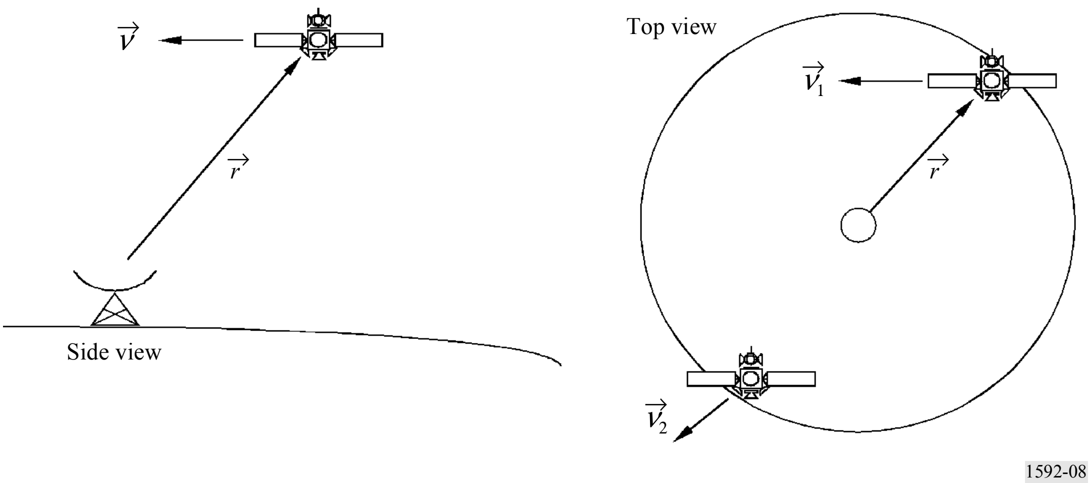
This strategy is based on establishing a link to the satellite which will be visible to the non-GSO FSS earth station above a given elevation angle for the longest period of visibility (dwell time), and minimizes the number of hand-offs in the data flow. If a satellite system is designed to have multiple satellites visible to earth stations for extended periods of time, then an additional constraint may be imposed to optimize on interference avoidance or diversity.

Once a communications link has been established, a non-GSO FSS earth station will track the corresponding satellite, and when this satellite moves beyond the minimum elevation angle, the next satellite must be acquired before the next simulation time step. If more than one satellite can be acquired at the next time step, the algorithm to select the next satellite is based on the vector from the earth station to the potential satellite, and the unit vector in the direction of the satellite velocity, $\vec{v}$. The selection criterion is that which minimizes the dot product of $\vec{r}$ and $\vec{v}$, i.e, minimum $\vec{r} \cdot \vec{v}$ for all satellites above the minimum elevation angle.

This selection strategy is illustrated in Figure 8, which shows a top-view representation of the satellite velocity vector, denoted by $\vec{v}_1$ directed towards the earth station. The dot product is negative, so satellite number 1 is selected over the other satellite.

FIGURE 8

Selection criterion for the next satellite based on longest dwell time



5.2.2.2 Satellite selection based on highest elevation angle

The strategy will require a higher number of hand-offs than that based on the longest dwell time, but may be employed to improve link performance for the non-GSO FSS system. Active satellites are selected to have the highest elevation angle viewed from a non-GSO FSS earth station together with an available transponder. There are two possible hand-over techniques for the 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 falls below a minimum elevation angle.

When satellite diversity is applied, the same selection should be made on the number of satellites required by the diversity scheme: the next satellite to be selected would be at the second highest elevation, the third satellite would be at the third highest elevation, and so on.

5.2.2.3 Satellite selection based on largest separation angle from GSO arc

Non-GSO FSS systems may select satellites based on the farthest separation angle from the look angle to the GSO arc. This reduces the level of interference generated by non-GSO satellites into GSO FSS earth stations, but may result in less than optimum non-GSO FSS link performance, as well as requiring a large number of hand-offs.

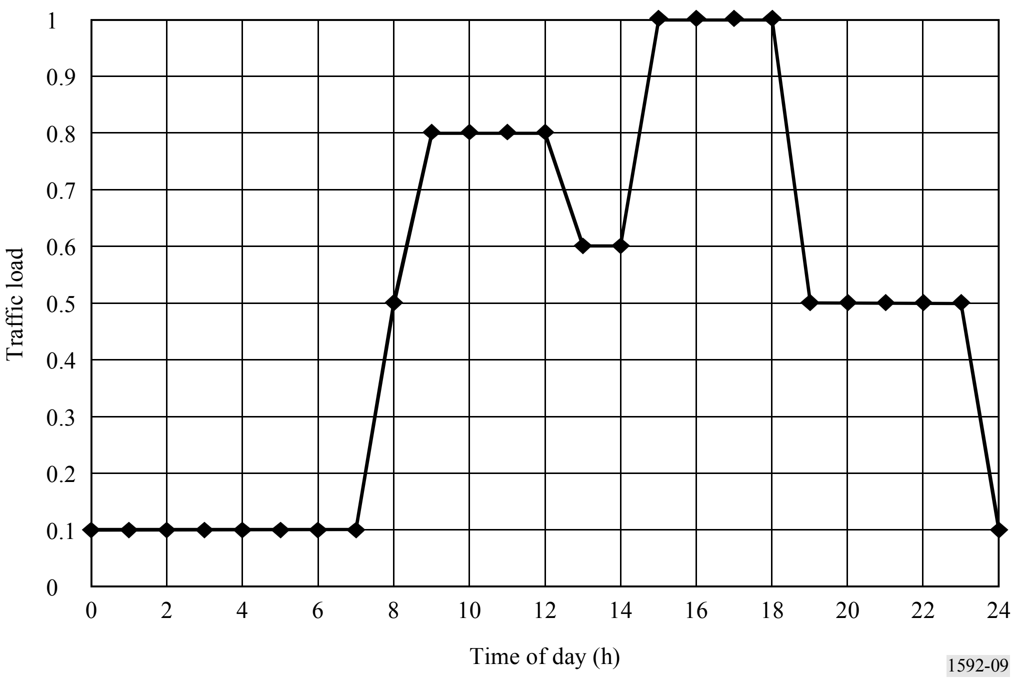
5.3 Traffic

The time-varying nature of the interference generated by a non-GSO system into a GSO network should be modelled, where necessary, in order to obtain an accurate assessment of the levels of epfd↓ for comparison with the additional operational limits. Traffic variation is a function of the local time of day at the non-GSO FSS earth station. For systems employing code division multiple access (CDMA) access schemes, the transmit power per carrier of the non-GSO FSS system will vary as a function of the traffic load on the specific carrier, and consequently the transmit power per carrier will vary at different times of the day, according to the traffic demand.

If the traffic model for the non-GSO FSS system being evaluated is known, then this should be used in the simulation. If the traffic model is not known, then the reference model illustrated in Fig. 9 could be used.

FIGURE 9

Traffic model for use in simulations



The traffic coefficient is taken into consideration in the maximum transmit power:

$$P_t = P_{max}\, C_{traffic} \tag{31}$$

where:

P_t: transmit power (W)

P_{max}: maximum transmit power (W)

$C_{traffic}$: traffic coefficient dependent on local time.

The traffic coefficient is only applicable to CDMA.

5.4 GSO station locations

This Recommendation is designed to evaluate the levels of epfd↓ generated by a non-GSO FSS system into 3 m and 10 m receiving antennas on earth stations in GSO FSS networks, to enable verification of compliance with the additional operational limits for the specific GSO FSS network under consideration. The locations of the GSO FSS satellite and its earth stations, and hence the earth station antenna pointing angles to the GSO satellite, should therefore be based on the actual parameters of that particular operational GSO network.

5.5 Antenna parameters

5.5.1 GSO FSS earth station antenna parameters

If available, the actual antenna radiation patterns of the 3 m and 10 m GSO FSS earth station antennas should be used in the simulation. The main lobe radiation pattern should be obtained either by measurement or from the manufacturer's data for a typical earth station antenna of the same type. The range over which the pattern is specified should extend at least down to the –20.75 dB gain level for a 3 m antenna, and the –19 dB gain level for a 10 m antenna. The data should be modelled by a polynomial approximation giving better than 0.1 dB accuracy at the 0, –5, –10, –15 and –20 dB points. Data for the actual operational frequency of the GSO FSS antenna should be used.

In the absence of actual antenna radiation patterns, the reference radiation pattern in Recommendation ITU-R S.1428, which has been developed specifically for such studies, should be used.

5.5.2 Non-GSO satellite antenna parameters

Non-GSO satellite multiple-beam antennas should be modelled using measured antenna radiation patterns, if available, proposed reference antenna radiation patterns in, for example the filing or in Recommendation ITU-R S.1328, if available, or an analytical function which models the side lobe of the non-GSO satellite antenna.

5.5.3 GSO satellite antenna parameters

There may be a requirement to model the GSO satellite antenna, in cases where a GSO FSS downlink is used to define the azimuth and elevation of the GSO FSS earth station antenna. In this case, the reference antenna radiation pattern in Recommendation ITU-R S.672 may be used.

5.6 Simulation time and simulation time increment

For accurate results, the simulation time increment should be as short as possible, while maintaining a reasonable total simulation running time.

For non-GSO FSS systems with repeating ground tracks, the simulation running time should cover at least one complete ground track period, and for all non-GSO FSS systems the running time should be sufficient to yield smooth cumulative statistics on the epfd↓ levels exceeded at time percentages less than the smallest specified for the additional operational limits pertaining to the antenna under test.

An estimate of the appropriate simulation time increment or step time can be obtained from a knowledge of the angular speed of the non-GSO satellite, and of the half-power width of the narrowest beam concerned together with an assumption about the number of main beam-to-main beam coupling events, or "hits" it is required to model.

The satellite angular velocity, a, expressed in Earth-fixed coordinates (i.e. the geocentric geosynchronous reference coordinate system), is a function of the Keplerian orbital parameters and the satellite angular velocity, ω, expressed in space-fixed coordinates (i.e. the geocentric heliosynchronous reference coordinate system):

$$a = \sqrt{(\omega \cos I - \Omega_e)^2 + (\omega \sin I)^2} \tag{32}$$

where:

Ω_e: rotational angular velocity of Earth at the equator ($\cong 7.29 \times 10^{-5}$ rad/s).

The geocentric angle between the victim earth station and the non-GSO satellite sub-point when it is at the main beam axis of the earth station, θ_ε, is given by:

$$\theta_\varepsilon = \arccos\left(\frac{R_e}{r_n} \cos \varepsilon\right) \tag{33}$$

where:

ε: earth station elevation angle.

The simulation time increment, Δt, to achieve a given number of hits can then be obtained from the following expression:

$$\Delta t = \frac{\varphi_3}{a N_{hits}} \frac{\sin \theta_\varepsilon}{\cos \varepsilon} \tag{34}$$

where:

φ_3: 3 dB beamwidth of earth station antenna

N_{hits}: number of hits in the victim earth station antenna 3 dB beamwidth ($N_{hits} = 5$).

It may be desirable to use two time-step sizes, in order to decrease the total simulation run time, since, for very small antenna beamwidths, the time increment may be very small to achieve the required number of hits in the main beam, thus requiring excessive run times. To alleviate this problem, a dual time step may be employed to reduce both the variance and overall duration of the simulation.

For the dual-step method, the time step determined from equation (34) should be used and is referred to as the fine step size. This step size depends on the antenna beamwidth, and should be used in the simulation when the non-GSO satellite is near the regions of maximum epfd↓, i.e. close to an earth station main beam or the edge of the exclusion zone. Since the non-GSO satellites spend longer percentages of time in regions far off-axis from the GSO FSS earth station main beam, beyond the first side lobe, than within the main beam of the GSO FSS earth station, and since the epfd↓ does not change as rapidly with satellite position when beyond the first side lobe, a coarse step size can be employed. This coarse step size is defined as a topocentric angle, $\varphi_{coarse} = 1.5^\circ$, and can be used for all antenna sizes.

There are two regions where the fine step size must be employed:

– When a non-GSO satellite is near the GSO FSS earth station main beam, the FSR is defined as a fixed topocentric angle from the axis of the GSO FSS earth station beam, and the edge of the first side-lobe region is set to the value of φ_r of the GSO FSS earth station antenna radiation pattern, for both 3 m and 10 m antennas:

$$\varphi_1 = \varphi_r = 15.85\left(\frac{D}{\lambda}\right)^{-0.6} \tag{35}$$

The off-boresight angle for the FSR is defined as the greater of 3.5° or φ_1:

$$\varphi_{FSR\text{-}1} = \max(3.5^\circ, \varphi_1) \tag{36}$$

– When a non-GSO satellite is near the exclusion zone, the FSR measured from the boundary of the exclusion zone is defined as:

$$\varphi_{FSR\text{-}2} = \varphi_{coarse} \tag{37}$$

The size of the coarse step must be an integer multiple of the fine step size, for statistical purposes. Since the coarse step size is constant, the ratio of coarse steps to fine steps depends only on the beamwidth of the GSO FSS earth station antenna, φ_3, and the number of hits to be modelled. This ratio is defined in terms of the quotient:

$$N_{coarse} = \text{quotient}\left(\frac{N_{hits}\ \varphi_{coarse}}{\varphi_3}\right) \tag{38}$$

This yields a conservative ratio of fine steps to coarse steps to ensure that a coarse step is never greater than the target topocentric size of 1.5°. As this ratio depends on the beamwidth of the earth station antenna, φ_3, the savings in time increases as the beamwidth decreases, which is advantageous since simulations with narrow antenna beams will require longer run times.

If a non-GSO satellite is in the FSR, i.e. within $\varphi_{FSR\text{-}1}$ of the GSO FSS earth station main beam or within $\varphi_{FSR\text{-}2}$ of the exclusion zone, the fine step size should be employed in the simulation. For all other regions in space where a non-GSO satellite is outside either of these two regions, the coarse step size is determined by multiplying the fine step size by N_{coarse}.

ANNEX 2

The operational mask approach

1 Introduction

At WRC-2000, a set of three single entry epfd limits was adopted and included in RR Article 22. It is composed of the validation limits, the operational limits and the additional operational limits. The validation limits are to be verified by BR with the help of a validation software whose specifications are included in Recommendation ITU-R S.1503. The operational limits are to be measured following guidelines which are included in Recommendation ITU-R S.1558. Concerning the additional operational limits (AOL), Resolution 137 (WRC-2000) invites the ITU-R to develop methodologies, to assess the interference levels (through simulation for AOL) that would be produced by a non-GSO FSS system in the frequency bands specified in RR Tables 22-4A, 22-4A1, 22-4B and 22-4C, which may be used to verify compliance with the AOL.

As a first answer to this request, Annex 1 of this Recommendation provides guidelines for the assessment of epfd statistics generated by a non-GSO FSS system into GSO FSS networks or other non-GSO FSS systems, and confirms compliance with the AOL, using representative hypothesis of a non-GSO FSS operational system.

In contrast with Annex 1, the approach discussed in this Annex makes use of the validation software currently revised by the BR and available to administrations. Because of the natural characteristics of this software, specified to assess the maximum possible worst-case situation, its adaptation to an operational system is far from being obvious.

Further work is needed to verify the applicability of the methodology described in this Annex. This methodology may not be practical for assessing the additional operational epfd levels into numerous points. It could be applied to an operational GSO FSS earth station of any antenna diameter suffering interference in excess of the additional operational epfd levels.

2 A possible starting basis: the validation software

2.1 The validation approach: a worst case far from operational parameters

Another possibility would be to apply the pfd mask approach in the checking of the validation software (i.e. Recommendation ITU-R S.1503) used by ITU. Knowing that this software was developed with the aim of checking epfd distributions against validation limits, it was first important to understand the fundamental differences between the validation approach and the AOLs.

The purpose of generating pfd masks is to define an envelope of the power radiated by the non-GSO space stations and the non-GSO FSS earth stations so that the results of calculations encompass what would be radiated regardless of what resource allocation and switching strategy are used at different periods of a non-GSO FSS system life. It was recognized that the software could not be based on parameters that could change over the life of the non-GSO FSS system, such as the number of beams illuminated and their pointing directions at any given time.

ITU-R wanted an open validation procedure and beam-switching algorithms contain highly sensitive commercial information regarding market demand. ITU-R developed a software specification that employs a number of worst-case and simplifying assumptions, including a worst-case beam configuration for the satellites of each system.

The software does not predict the actual epfd statistics that will be produced by a system in operation, but rather computes a conservative upper bound. The software will therefore overestimate the amount of interference generally experienced by GSO FSS networks, making it more difficult for a non-GSO system to demonstrate compliance with any given set of epfd limits.

ITU-R studies have shown that the worst-case interference from a non-GSO system into large GSO FSS earth stations is localized. The conservative upper bound computed by the BR software hides this important phenomenon.

pfd masks correspond to an envelope of the power radiated by each non-GSO space station so that the results of the calculations encompass what would be radiated whatever resource allocations used during the non-GSO FSS system life.

The consequence of such a methodology is an overestimation of:

– The long-term epfd level up to 15 dB for F-SAT MULTI1-B system, up to 10 dB for ROSTELESAT-N system.

– The short-term epfd level up to 5 dB for ROSTELESAT-N system, and up to about 1 dB for F-SAT MULTI1-B system.

Using the validation software without modifying the pfd input masks could be very far from the results obtained by an operating non-GSO FSS system into an operating GSO FSS earth station pointing towards an operating GSO satellite. There is therefore a need to adapt the methodology used to derive the worst-case pfd mask, generating this time an operating pfd mask for a given GSO FSS earth station.

2.2 Definition of the operational pfd mask

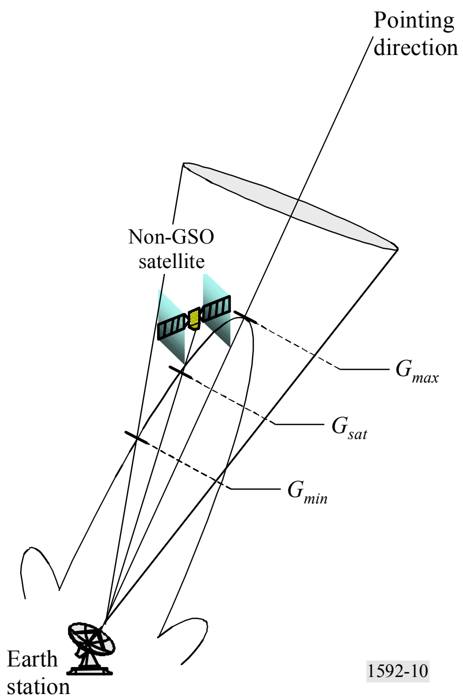
The aim of the operational pfd mask is to generate a mask, with the same format as the inputs to the validation software, but reflecting the real operations of the non-GSO constellation and the interference generated into a given GSO FSS earth station of 3 m or 10 m antenna.

The generation of a pfd mask to be used by the BR is a lengthy process. Two months on a six 800 MHz processor computer are necessary to obtain the final result. Although the operational pfd mask will be somewhat lighter, it will nevertheless be a time-consuming process. This will have to be kept in mind when implementing procedures to check these operational limits.

A complete new pfd mask cannot be generated. This would require too much time and complications in the assumptions to make if it is to be representative of the operational life of a non-GSO FSS system.

The method proposed is based on the assumption that most satellites of the non-GSO constellation will not generate significant interference at the GSO FSS earth station. The number of non-GSO satellites considered to calculate the epfd↓ can therefore be limited to the ones that contribute the most. To select the *N* non-GSO satellites, an operational cone (or "ring") is implemented in the simulations. This methodology is presented in Recommendation ITU-R S.1325.

FIGURE 10

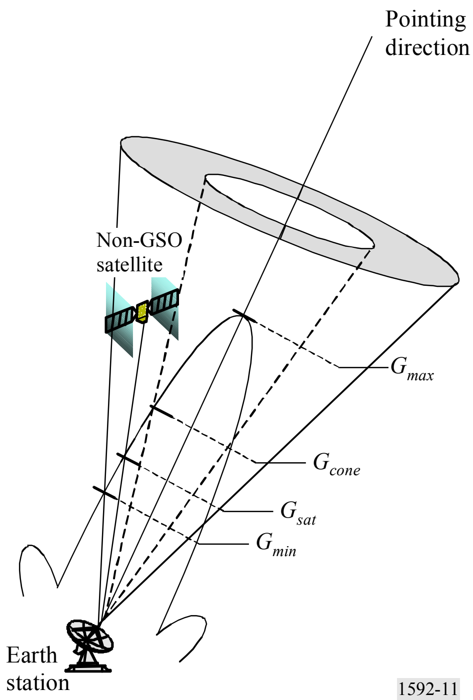


For cases where the highest level of epfd↓ generated by the interfering non-GSO FSS system 1 occurs when a non-GSO satellite is in line (or near in-line) with a satellite of the interfered system 2, and the earth station of this system, the cone is centred around the pointing direction of the earth station of the interfered system.

From a certain value of the angle which defines the cone, the epfd generated by a non-GSO satellite outside the cone at the earth station 2 would be lower than a given minimum level $epfd_{min}$.

For cases where the highest level of epfd↓ generated by the interfering non-GSO FSS system occurs when a non-GSO satellite is at the edge of the exclusion zone, a "ring" is defined around the exclusion area.

FIGURE 11



When non-GSO satellites of the interfering system 1 are visible inside the cone (or the "ring"), the contribution of each non-GSO satellite of system 1 visible from the earth station of system 2 is evaluated and summed to calculate the epfd generated at the earth station of system 2.

When all the visible non-GSO satellites of system 1 are outside the cone (or the "ring"), the total epfd generated at the earth station of system 2 may be neglected, or may be set at $epfd_{min}$. $epfd_{min}$ is, system design dependent (type of constellation, number of satellites, position of orbits, antenna size…). The value of $epfd_{min}$ is adjusted progressively until variations of the short-term epfd statistics produced by successive runs are neglected.

The AOL are defined by a set of discrete points corresponding to given epfd levels. The lowest limit is set at −182 dB(W/(m^2 · 40 kHz)) for a 3 m antenna, and −185 dB(W/(m^2 · 40 kHz)) for a 10 m antenna. The objective of the simulation is to analyse the epfd generated by a non-GSO FSS system above this lowest epfd limit. In that case, the $epfd_{min}$ chosen can be set 1 dB below those lowest additional operational limits, giving a good accuracy in the results.

The assumptions taken to generate the operational pfd mask would be as given in the guidelines of Part C of Recommendation ITU-R S.1503, using the peak busy-hour traffic level associated to the non-GSO satellites considered in the cone (or ring). The important factor to be taken into account for the generation of an operational pfd mask is the real (i.e. operational) beam allocation of the non-GSO satellite.

The position of a non-GSO satellite inside the cone can be defined by its latitude (lat), the difference between its longitude and the GSO satellite longitude (Δlong) and the minimum angle between its position and any point on the GSO arc, as seen from the GSO FSS earth station (α). These three parameters define the 3-dimensional pfd mask.

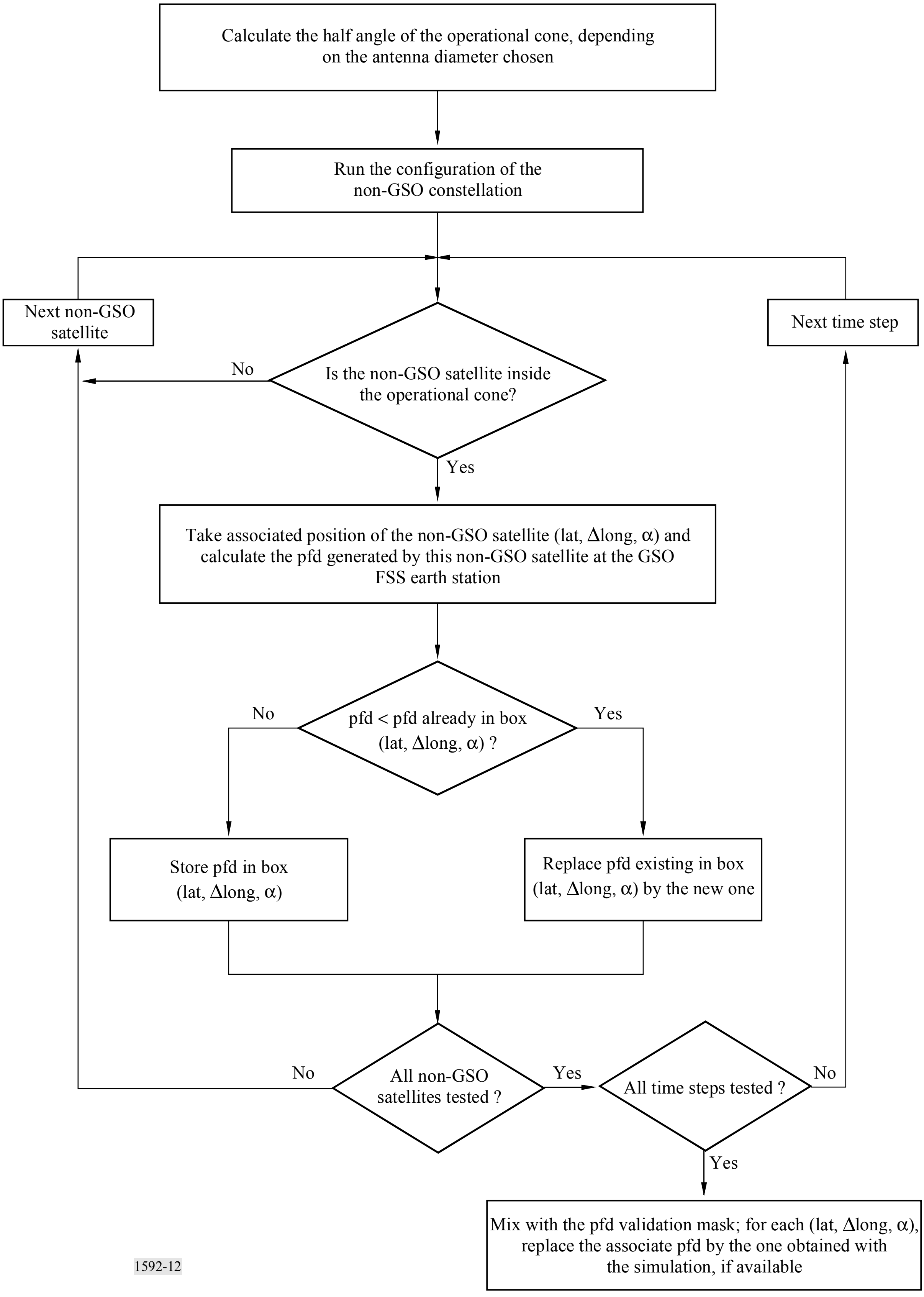
The simulation is then performed such that each time a non-GSO satellite is seen inside the cone (or the ring), the operational pfd generated at the GSO FSS earth station by this non-GSO satellite and its real beam allocation is calculated (excluding the contribution of the other non-GSO satellites visible from the GSO FSS earth station and outside the cone).

The 3-dimensional pfd mask is defined in latitude with a step of 1°, in Δlong with a step of 0.1°, and in α with a step of 0.5°. The cone (or ring) therefore needs to be divided in several boxes, each corresponding to a value of lat, a value of Δlong and a value of α. As several non-GSO satellites can be seen in the same box during the full simulation time, the non-GSO satellite over the full simulation time, that creates the maximum pfd would be retained, and this maximum pfd would be set and allocated to the box corresponding to a value of lat, Δlong and α.

This would give a pfd mask for a restricted number of triples (lat, Δlong, α). In order to obtain a complete pfd mask, this operational mask would be completed by a default value of −1 000 dB(W/(m^2 · 40 kHz)) for all other triples (lat, Δlong, α).

The simulation runtime to generate an operational pfd mask is thus considerably reduced, without significantly affecting the accuracy in the epfd statistics. It allows to have a more realistic and precise pfd mask, taking into account the real beam allocation of the non-GSO satellites that would contribute the most to the interference generated at the GSO FSS earth station.

2.3 Algorithm of the operational mask generation



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2.4 Traffic integration

As stated in § 2.1, the assumptions taken to generate the operational pfd mask are the same as those described in Part C of Recommendation ITU-R S.1503. They are therefore very conservative except the use of real beam allocation. To those assumptions, the use of the peak busy-hour traffic level associated to the non-GSO satellites can be added. This adds a very conservative hypothesis to the operational pfd mask and is not at all representative of an operational system, as it is known that the non-GSO satellite will not transmit continuously at the peak busy hour level, and that, in fact, the majority of passes through the GSO FSS antenna beam will occur outside of the busy hour.

The next step in evaluating the involvement of the non-GSO FSS system in the interference received at the GSO FSS earth station is to perform a convolution between the output cumulative distribution function (CDF) of the validation software obtained with the operational pfd mask, and a realistic traffic model that more adequately represents the daily variation in the emissions from the non-GSO satellites constellation.

The resultant epfd statistics CDF should be the last result to consider.

3 Conclusion

This Annex studies a process that could be applied in case of observation by a GSO FSS operator at an operational GSO FSS earth station of an excess in the interference level received. It studies the use of validated software and validated guidelines to perform simulations, that would be available to all administrations.

The validation software that would be used by BR to verify compliance of a non-GSO FSS system with the validation limits and given in Recommendation ITU-R S.1503 would be used, with modifications regarding the pfd mask, in order to use an operational pfd mask for the non-GSO satellites, that would more precisely represent the operational conditions of a non-GSO FSS system.

The methodology proposed hereby could enable to use the Recommendation ITU-R S.1503 software by generating an operational pfd mask. The process of pfd mask generation is long and tedious. This process cannot be used for assessing the respect of the additional operational limits for numerous points. It has to remain an operational process, applicable to an operational GSO earth station believed to be experiencing epfd in excess of AOL.