

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 ($\text{epfd}_{\downarrow}$) 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 $\text{epfd}_{\downarrow}$ in RR Tables 22-1A to 22-1D, single-entry operational limits to the $\text{epfd}_{\downarrow}$ in RR Tables 22-4A, 22-4B and 22-4C, and single-entry additional operational limits to the $\text{epfd}_{\downarrow}$ 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 $\text{epfd}_{\downarrow}$ and, for certain antenna sizes, single-entry additional operational limits to the $\text{epfd}_{\downarrow}$ 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 $\text{epfd}_{\downarrow}$ are met,

recognizing

- a) that administrations with assignments to GSO FSS networks in frequency bands where additional operational limits to the $\text{epfd}_{\downarrow}$ 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 $\text{epfd}_{\downarrow}$, 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 e_{pfd} 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
$epfd_{\downarrow}$	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
ϕ_{FSR-1}	Topocentric angle defining fine step region (FSR)	degrees
ϕ_{FSR-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

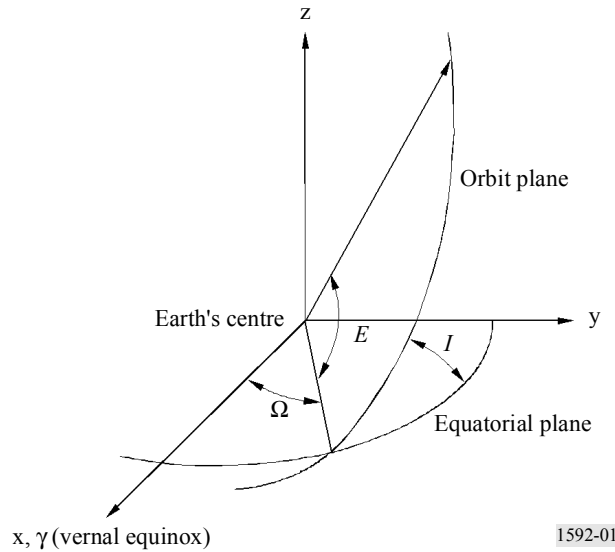
- Frequency/polarization reuse plan, if used
- Minimum elevation angle for communication
- Simulation time period
- Simulation time step
- Implementation of downlink power control on range, if used by non-GSO system
- Implementation of GSO arc avoidance technique, if used by non-GSO system
- Traffic 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



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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:

$$\frac{m_s v^2}{r} = \frac{GM_e m_s}{r^2} \quad (1)$$

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:

$$v^2 = \frac{GM_e}{r} = \frac{GM_e}{R_e^2} \cdot \frac{R_e^2}{r} \quad (2)$$

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

At the surface of the Earth,

$$mg = \frac{GM_e m}{R_e^2} \quad (3)$$

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

$$g = \frac{GM_e}{R_e^2} \quad \text{m/s}^2 \quad (4)$$

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

$$v = R_e \sqrt{\frac{g}{r}} \quad (5)$$

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

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

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:

$$E = E_0 + \omega t \quad (7)$$

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:

$$\Omega = \Omega_0 + \Omega_r t \quad (8)$$

where:

- Ω_0 : RAAN of the satellite at time t_0 (degrees)
- Ω_r : orbital precession rate of the satellite (degrees/s):

$$\Omega_r = -\frac{3}{2} J_2 \cos(I) R_e^2 \frac{\sqrt{r\mu}}{r^4} \quad (9)$$

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:

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

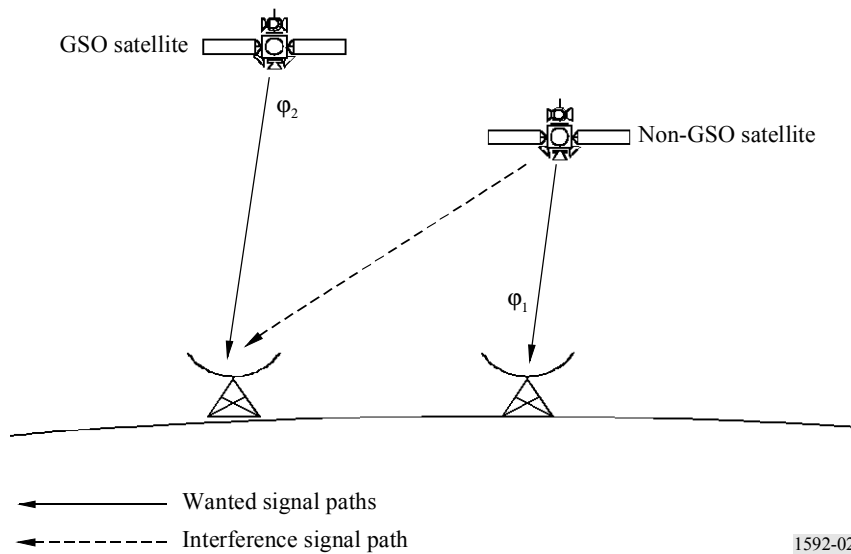
and the velocity of the satellite is similarly represented in terms of the geocentric inertial coordinate system, ignoring the relatively long-term variation in Ω , as

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

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



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

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

where:

- P_t : available transmit power (W)
- T : noise temperature of the receiver (K)
- B_t : transmit bandwidth (Hz)
- $G_t(\phi_1)$: relative gain as a numerical ratio of the non-GSO satellite transmit antenna
- $G_r(\phi_2)$: 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:

$$\frac{G_t(\phi_1) G_r(\phi_2)}{4\pi R^2} \quad (13)$$

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:

$$\frac{P_t}{k T B_t} \frac{\lambda^2}{4\pi} \frac{1}{L_p} \quad (14)$$

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:

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

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:

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