

RECOMMENDATION ITU-R M.1642

**Methodology for assessing the maximum aggregate equivalent power
flux-density at an aeronautical radionavigation service station
from all radionavigation-satellite service systems
operating in the 1 164-1 215 MHz band**

(2003)

Summary

This Recommendation gives a methodology and the reference antenna characteristics for assessing the maximum aggregate equivalent power flux-density (epfd) level produced at the input of a station of the aeronautical radionavigation service (ARNS) by all radionavigation-satellite service (RNSS) systems operating in any portion of the 1 164-1 215 MHz band.

The ITU Radiocommunication Assembly,

considering

- a) that in accordance with the Radio Regulations (RR), the band 960-1 215 MHz is allocated on a primary basis to the aeronautical radionavigation service (ARNS) in all the ITU Regions;
- b) that WRC-2000 introduced a co-primary allocation for the radionavigation-satellite service (RNSS) in the frequency band 1 164-1 215 MHz (subject to the conditions specified under RR No. 5.328A), with a provisional limit on the aggregate pfd produced by all the space stations within all radionavigation-satellite systems at the Earth's surface of -115 dB(W/m²) in any 1 MHz band for all angles of arrival;
- c) that WRC-2000 invited ITU-R to conduct, as a matter of urgency and in time for WRC-03, the appropriate technical, operational and regulatory studies on the overall compatibility between the RNSS and the ARNS in the band 960-1 215 MHz, including an assessment of the need for an aggregate pfd limit, and revision, if necessary, of the provisional pfd limit given in RR No. 5.328A concerning the operation of RNSS systems in the frequency band 1 164-1 215 MHz;
- d) that analyses show that RNSS signals in the 1 164-1 215 MHz band can be designed not to cause interference to the DME/TACAN ARNS receivers operating in this band;
- e) that the ARNS is a safety service in accordance with RR No. 1.59 and special measures need to be taken by administrations to protect these services in accordance with provision RR No. 4.10;
- f) that a protection criterion for the ARNS has been developed and is expressed in terms of equivalent power flux-density (epfd), which is set out in Recommendation ITU-R M.1639,

recommends

1 that the methodology in Annex 1 and the reference ARNS characteristics in Annex 2 should be used to calculate the maximum aggregate epfd produced by emissions from all RNSS systems at any aeronautical radionavigation station¹.

Annex 1

Methodology for assessing the maximum aggregate epfd at an ARNS station from all RNSS systems operating in the 1 164-1 215 MHz band

Summary of the method

With the method described in this Annex it is possible to calculate the maximum aggregate epfd level of all RNSS systems in the band 1 164-1 215 MHz.

This method allows different systems to be combined easily, so that the effect of changes such as including or excluding one or various systems or the effect of changing the characteristics of specific systems can be examined during a consultation meeting.

The method accommodates both non-GSO systems, with constellations of satellites in circular orbits of any inclination, and GSO systems.

The method is based on a two-step process:

Step 1: Calculation of the epfd of each individual RNSS system. This step may be performed by each operator independently prior to the consultation meeting, provided that results are submitted in a compatible format (see § 1.3, for non-GSO systems, and § 1.4, for GSO systems).

Step 2: Combination of the maximum epfd of the individual systems, by superposition of the maps, if necessary at different frequencies, to obtain the maximum aggregate epfd (see § 2) in the band 1 164-1 215 MHz.

Description of the method

1 Method for calculating the maximum epfd from satellites of one RNSS system

1.1 Definition of epfd

The definition of equivalent power flux-density (epfd) is based upon RR No. 22.5C.1 as adopted at WRC-2000.

¹ The applicability of the method in Annex 1 to elliptical and highly-elliptical orbits has yet to be determined.

When an antenna receives power, within its reference bandwidth, simultaneously from transmitters at various distances, in various directions and at various levels of incident pfd, the epfd is that pfd which, if received from a single transmitter in the far field of the antenna in the direction of maximum gain, would produce the same power at the input of the receiver as is actually received from the aggregate of the various transmitters.

The instantaneous epfd is calculated using the following formula:

$$epfd = 10 \log_{10} \left[\sum_{i=1}^{N_a} 10^{10} \cdot \frac{P_i}{4\pi d_i^2} \cdot \frac{G_t(\theta_i)}{G_{r,max}} \right]$$

where:

- N_a : number of space stations that are visible from the receiver
- i : index of the space station considered
- P_i : RF power (in the reference bandwidth) at the input of the antenna (or RF radiated power in the case of an active antenna) of the transmitting space station (dB(W/MHz))
- θ_i : off-axis angle (degrees) between the boresight of the transmitting space station and the direction of the receiver
- $G_t(\theta_i)$: transmit antenna gain (as a ratio) of the space station in the direction of the receiver
- d_i : distance (m) between the transmitting station and the receiver
- φ_i : off-axis angle (degrees) between the pointing direction of the receiver and the direction of the transmitting space station
- $G_r(\varphi_i)$: receive antenna gain (as a ratio) of the receiver, in the direction of the transmitting space station (see Annex 2)
- $G_{r,max}$: maximum gain (as a ratio) of the receiver
- $epfd$: instantaneous equivalent power flux-density (dB(W/(m² · MHz))) at the receiver.

NOTE 1 – It is assumed that each transmitter is located in the far field of the receiver (that is, at a distance greater than $2D^2/\lambda$, where D is the effective diameter of the receiver antenna and λ is the observing wavelength in the same unit). In the case under consideration this will always be satisfied.

1.2 General consideration

In the first step of the method, the maximum epfd for each constellation of RNSS satellites is calculated at each latitude and longitude over the whole surface of the Earth for each 1 MHz of spectrum occupied by the system.

As the victim ARNS receiver may be mounted on an aircraft flying at an altitude up to 40 000 ft (12 192 m) (see § 2 of Annex 2), the calculation should include all satellites with elevation angles from 90° down to -3.54° .

Calculation of the epfd distribution of each system is only necessary at a single reference frequency, preferably the frequency at which signal power is maximum. The RNSS signal spectral shape should be supplied to a consultation meeting, so that results of the calculation can then be multiplied by the appropriate spectral shaping factors to obtain the results at any other frequency.

1.3 Method for calculating the maximum epfd for a non-GSO RNSS system

The simulation methodology given in Appendix 1 to Annex 1, which is based entirely on Recommendation ITU-R S.1325, may be used to accomplish this.

The methodology, given in Appendix 2 to Annex 1, is based entirely on an analytical technique. The method could be used for obtaining prompt estimates but it does not yield an exact upper bound result.

1.4 Method for calculating the maximum epfd for a GSO RNSS system

The maximum epfd for each GSO satellite is required to be calculated at each latitude and longitude over the whole surface of the Earth for each 1 MHz of spectrum occupied by the system.

In this case the epfd will not be dependent on time, so a single table of results can be calculated directly.

2 Method for calculating the maximum aggregate epfd from all RNSS systems

2.1 Data required for each system

Each non-GSO RNSS system will, having followed the methodology of § 1.3, provide a consultation meeting with a list of maximum epfd versus latitude (applicable at all longitudes) and a signal spectral shape.

Each GSO RNSS system will, having followed the methodology of § 1.4, provide a consultation meeting with a table of maximum epfd versus latitude and longitude and a signal spectral shape.

2.2 Combination of epfds of systems with similar signal characteristics

The determination of aggregate epfd of RNSS systems with the same frequency of signal spectral maximum may be achieved using three steps:

Step 1: point-by-point summation of maximum epfd's in the 1 MHz of the band where the signal has maximum power at each latitude of all the non-GSO lists to obtain the list of non-GSO aggregate epfd versus latitude;

Step 2: point-by-point summation of maximum epfd's in the 1 MHz of the band where the signal has maximum power at each point of latitude and longitude of all the GSO tables to obtain the table of GSO aggregate epfd versus latitude and longitude;

Step 3: point-by-point summation of the list of non-GSO aggregate epfd versus latitude to each longitude column of the table of GSO aggregate epfd versus latitude and longitude to obtain the overall the table of aggregate epfd versus latitude and longitude.

Examination of the highest epfd in this table will reveal whether the protection criterion in Recommendation ITU-R M.1639 in any 1 MHz of the band is respected.

2.3 Combination of epfd's of systems with different signal characteristics

It should be noted that the maximum aggregate epfd will be frequency dependent. If the spectra of all the RNSS systems under consideration have their maxima at the same frequency, a single analysis will suffice. However, if different systems have different maxima, either because they use different centre frequencies with overlapping spectra or because they use different modulation techniques, then analysis of the maximum aggregate epfd will require frequency to be taken into account.

The determination of maximum aggregate epfd of RNSS systems with different centre frequencies will require, as a minimum, the above three steps to be performed at each frequency for which any one system has its signal spectral maximum, and may also require analysis at intermediate frequencies.

For each frequency, each list or table will be factored by the appropriate spectral shaping factor before summation with other lists and tables.

Examination of the highest epfd in all of the resultant tables will reveal whether protection criterion in Recommendation ITU-R M.1639 in any 1 MHz of the band is respected.

2.4 Check of results

Following determination of the maximum aggregate epfd, a single simultaneous simulation of all RNSS systems at the ARNS station location where the absolute maximum aggregate epfd was determined may be considered to confirm results obtained using Appendix 1 or 2 to Annex 1.

Appendix 1 to Annex 1

A simulation methodology for determining the maximum epfd for a non-GSO RNSS system

1 Method and simulation approach description

The framework for this methodology based on Recommendation ITU-R S.1325 is to model all the satellites of one RNSS system at a specific reference frequency (typically the 1 MHz portion of the 1 164-1 215 MHz band with the maximum RNSS signal spectral density). A simulation of the constellation is sampled over a period of time at a relatively fine rate. At each sample the epfd is computed for all latitude and longitude points. The maximum sample should be recorded for each latitude and longitude point. Other samples may be discarded. The result is a table, which can be shown as a map, as illustrated in Fig. 3. Following this, the maximum epfd, for each latitude should be determined, which will eliminate approximations due to limited simulation time.

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.

The orbit model represents satellite motion in a geocentric inertial coordinate frame shown in Fig. 1. 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.

2.1.1 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 rotation angular velocity = $2\pi/T_e \cong 7.29 \times 10^{-5}$ rad/s

t : elapsed time (s).

2.1.2 Non-GSO satellite system space station related constants

For the non-GSO satellite system space stations (see Fig. 1), the constants are as follows:

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

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

h_{sat} : satellite altitude above the Earth (km)

r : radius of the satellite orbit (km) = $h_{sat} + R_e$

I : inclination angle of the orbital plane above the Equator (rad)

RAAN: right ascension of the ascending node

$\Omega_{i,0}$: RAAN of each of the non-GSO satellites at the initial time (rad)

$E_{i,0}$: argument of latitude of each of the non-GSO satellites at the initial time (rad)

T : satellite orbit period (s) = $2\pi (r^3/\mu)^{1/2}$

ω : mean motion of the satellite (rad/s) = $2\pi/T$

$E_{i,t}$: argument of latitude of the satellite at the time of computation (rad) = $E_{i,0} + \omega t$

Ω_{ri} : nodal regression of the ascending node (rad/s)

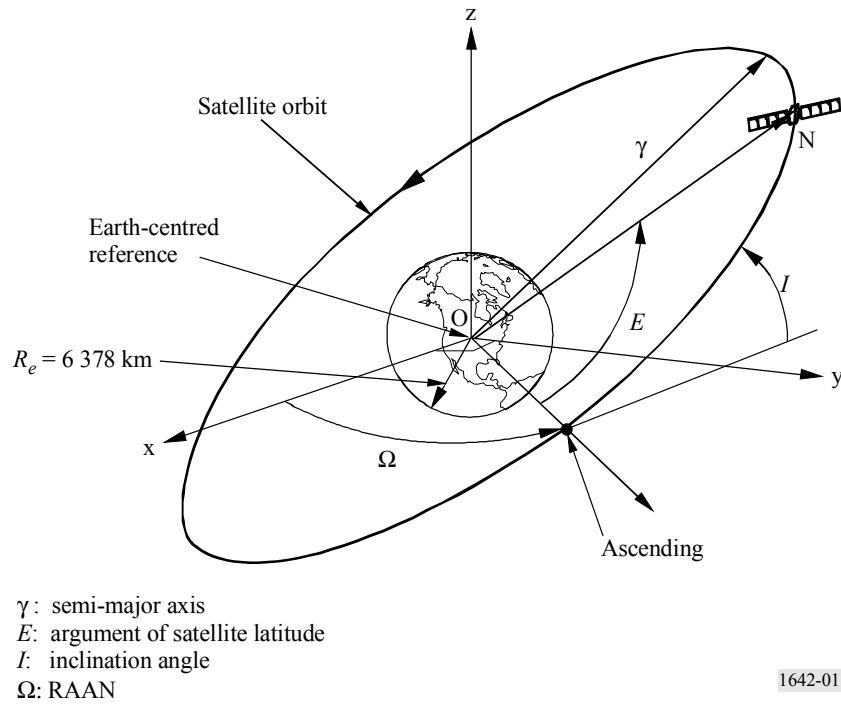
$$= -\frac{3}{2} J_2 \cos(I) R_e^2 \frac{\sqrt{r\mu}}{r^4}$$

$\Omega_{i,t}$: RAAN of the satellite at the time of computation (rad) = $\Omega_{i,0} + \Omega_{ri}t$

\vec{ON}_i : coordinate vector (inertial coordinate system) of a non-GSO satellite in the Earth-centred fixed coordinate frame:

$$\vec{ON}_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = r \begin{bmatrix} \cos(E_{i,t}) \cdot \cos(\Omega_{i,t}) - \cos(I) \cdot \sin(E_{i,t}) \cdot \sin(\Omega_{i,t}) \\ \cos(E_{i,t}) \cdot \sin(\Omega_{i,t}) + \cos(I) \cdot \sin(E_{i,t}) \cdot \cos(\Omega_{i,t}) \\ \sin(E_{i,t}) \cdot \sin(I) \end{bmatrix}$$

FIGURE 1
Orbit geometry



1642-01

The non-GSO perturbation can be considered in calculating the non-GSO constellation related constants, as the position of the satellites may vary when taking perturbation into account.

2.1.3 ARNS station related constants

Lat: latitude of ARNS station (rad)

Lon: longitude of ARNS station (rad)

h_{ARNS} : altitude of ARNS station (km)

\vec{OM} : ARNS station coordinates in the Earth-centred, inertial coordinate system

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

2.2 Antenna parameters

2.2.1 ARNS station antenna parameters

The antenna pattern for the ARNS station is an input parameter to the simulation (see Annex 2).

2.2.2 Non-GSO space station antenna parameters

In order to perform interference analysis, non-GSO satellite antennas should be modelled using either of the following patterns, subject to availability:

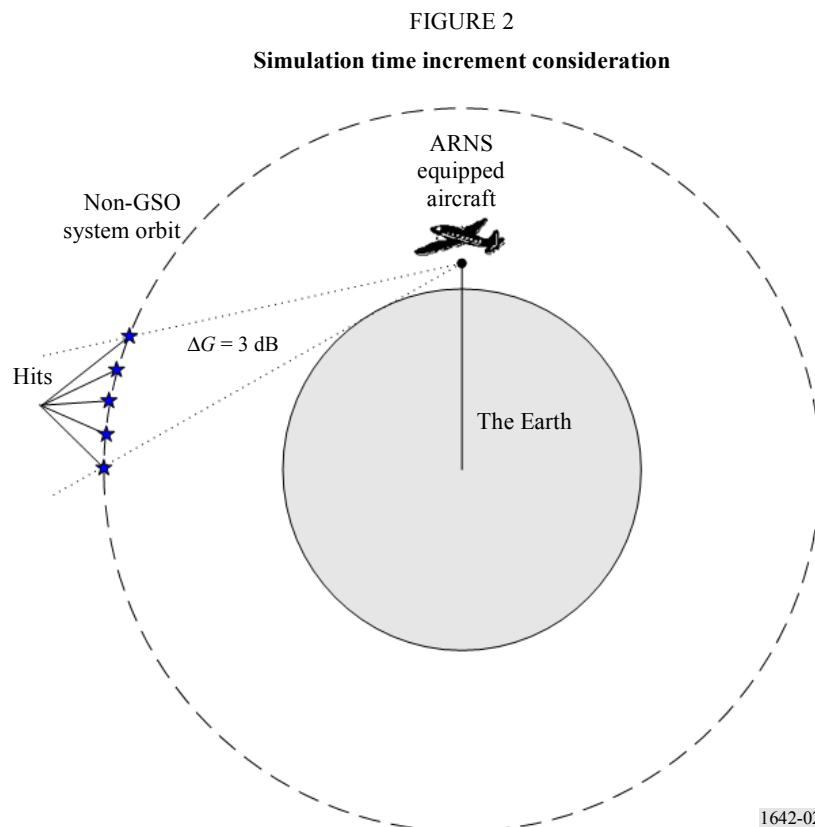
- measured antenna patterns;
- proposed reference antenna patterns;
- an analytical function which models the radiation pattern of the non-GSO satellite antenna.

2.3 Calculation of the simulation time

2.3.1 Simulation time increment

For obtaining accurate results the simulation time increment, t_{inc} , should be as short as possible, but on the other hand the total simulation time should be reasonable. To attain the accuracy required it is necessary to ensure a sufficient number of epfd measurements (N_{hits}) when non-GSO RNSS spacecraft falls into the ARNS antenna pattern of maximum gain visible to a space station. $N_{hits} = 5$ is thought to be sufficient.

The maximum gain visible to a space station occurs at -3.54° to $+3^\circ$ elevation angle (Annex 2) for an aircraft at 40 000 ft (12 192 m). It is important to have 5 N_{hits} within this range, implying that simulation increments of 1° of constellation movement is sufficient.



2.3.2 Total simulation time

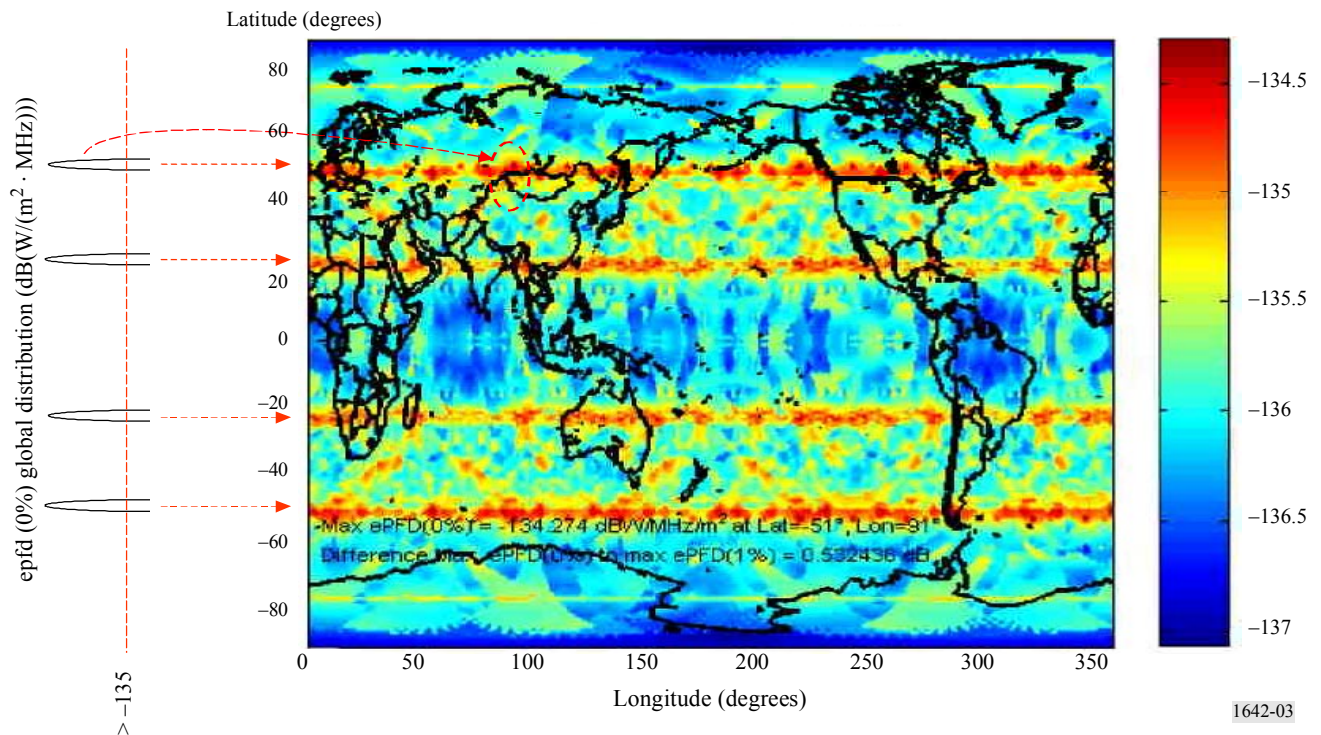
A satellite of a non-GSO constellation on a circular orbit traces out a path on the Earth’s surface. After a time, which is specific to the system, the satellite or another satellite of the constellation returns to the same or practically to the same point. The time between these two cases is the repeat period of the constellation. The repeat periods of different constellations are from a few days to several months. Typical results of the epfd calculation of a RNSS system over one constellation repeat period is illustrated in Fig. 3.

The exact longitude precession rate of the satellites in a non-GSO constellation will be affected by drifts due to longitudinal station keeping errors. This effect can be modelled and integrated in the simulations. The effect of this will result in the maximum epfd at any longitude becoming, in fact, the maximum epfd at all longitudes. (In other words, if the simulation were to be extended to cover all possible states of the constellation, the “high spots” of maximum epfd on the map in Fig. 3 would spread horizontally to become uniform horizontal stripes.) It is therefore considered more correct to take, for each latitude, the maximum epfd at any longitude and use it for all longitudes. This converts the table of maximum epfd versus latitude and longitude into a simple list of maximum epfd versus latitude.

If this is done, then the simulation time could be reduced to a single orbit. The “map” produced by such a limited simulation would show only a few “high spots” but, at each latitude, the value of the “high spots”, representing the maximum epfd at any longitude, would be the same.

As a by-product, the amount of information which must be presented to the consultation meeting would be considerably reduced.

FIGURE 3
Example of maximum epfd global distribution



Appendix 2 to Annex 1

Analytical methodology for assessing the maximum epfd of a single RNSS system operating in the band 1 164-1 215 MHz

1 Introduction

The intent of this methodology is to show how the maximum epfd of a single RNSS system can be evaluated.

The definition of epfd is given in § 1.1 of Annex 1.

2 Description of the methodology

If one assumes that the non-GSO RNSS-system constellations consist of a number of orbital planes, then it is most likely that, in any one particular plane, a maximum of one satellite per plane will be within the -3.54° to $+3^\circ$ elevation angle of the ARNS antenna pattern (Annex 2). In addition, for non-GSO systems, it is likely that, when a satellite is within the ARNS antenna pattern of maximum gain visible to a space station, other satellites in the plane will have a relatively insignificant epfd contribution. Using these assumptions, one can formulate the non-GSO RNSS constellation maximum epfd ($epfd_{max}$) as:

$$epfd_{max} = 10 \log N_p + epfd_{i,max} \quad \text{dB(W/(m}^2 \cdot \text{MHz))}$$

where:

N_p : number of orbital planes in the constellation

$epfd_{i,max}$: maximum single-satellite epfd contribution (dB(W/(m² · MHz))).

3 Non-GSO examples

For a single-satellite maximum epfd contribution of -136.9 dB(W/(m² · MHz)) within a non-GSO RNSS constellation of six planes using the equation in § 2 the $epfd_{max}$ is:

$$epfd_{max} = (-136.9) + 10 \log 6 = -129.12 \quad \text{dB(W/(m}^2 \cdot \text{MHz))}$$

A similar calculation, with a single-satellite maximum epfd contribution of -130.24 dB(W/(m² · MHz)), within a non-GSO RNSS constellation of three planes, using the equation in § 2 gives a maximum epfd of -125.47 dB(W/(m² · MHz)).

These values are in very good agreement with the simulation method in Appendix 1 to Annex 1, with only 1.2 dB difference.

Annex 2

**ARNS reference station characteristics
to be used in epfd calculation**

1 ARNS antenna characteristics

Table 1 provides the antenna gain for elevation values between -90° and 90° . For elevation values between two values of Table 1 a linear interpolation should be used. The G_r, max value is 3.4 dBi as specified in Recommendation ITU-R M.1639, including 2 dB of circular-to-linear polarization mismatch. It is assumed that the elevation and gain pattern is the same for all azimuth angles.

TABLE 1

Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)	Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)	Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)
-90	-17.22	22	-10.72	57	-15.28
-80	-14.04	23	-10.81	58	-15.49
-70	-10.51	24	-10.9	59	-15.67
-60	-8.84	25	-10.98	60	-15.82
-50	-5.4	26	-11.06	61	-16.29
-40	-3.13	27	-11.14	62	-16.74
-30	-0.57	28	-11.22	63	-17.19
-20	-1.08	29	-11.29	64	-17.63
-10	0	30	-11.36	65	-18.06
-5	-1.21	31	-11.45	66	-18.48
-3	-1.71	32	-11.53	67	-18.89
-2	-1.95	33	-11.6	68	-19.29
-1	-2.19	34	-11.66	69	-19.69
0	-2.43	35	-11.71	70	-20.08
1	-2.85	36	-11.75	71	-20.55
2	-3.26	37	-11.78	72	-20.99
3	-3.66	38	-11.79	73	-21.41
4	-4.18	39	-11.8	74	-21.8
5	-4.69	40	-11.79	75	-22.15
6	-5.2	41	-12.01	76	-22.48
7	-5.71	42	-12.21	77	-22.78
8	-6.21	43	-12.39	78	-23.06
9	-6.72	44	-12.55	79	-23.3
10	-7.22	45	-12.7	80	-23.53
11	-7.58	46	-12.83	81	-23.44
12	-7.94	47	-12.95	82	-23.35
13	-8.29	48	-13.05	83	-23.24

TABLE 1 (*end*)

Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)	Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)	Elevation angle (degrees)	Antenna gain including circular-to-linear polarization mismatch $G_r/G_{r,max}$ (dB)
14	-8.63	49	-13.14	84	-23.13
15	-8.97	50	-13.21	85	-23.01
16	-9.29	51	-13.56	86	-22.88
17	-9.61	52	-13.9	87	-22.73
18	-9.93	53	-14.22	88	-22.57
19	-10.23	54	-14.51	89	-22.4
20	-10.52	55	-14.79	90	-22.21
21	-10.62	56	-15.05		

2 ARNS station location

The ARNS station altitude should be taken at worst case (40 000 ft, i.e. 12 192 m), which gives maximum visibility of potentially interfering satellites from the ARNS receiving antenna.