RECOMMENDATION ITU-R M.1831

# A coordination methodology for RNSS inter-system interference estimation*

(Questions ITU-R 217/8 and ITU-R 239/8)

(2007)

**Scope**

This Recommendation gives a methodology for radionavigation-satellite service (RNSS) intersystem interference estimation to be used in coordination between systems and networks in the RNSS. As Resolution 610 (WRC-03) applies to all systems and networks in the RNSS and contains measures that are designed to facilitate the make of RNSS inter-system compatibility determination, this Recommendation is applicable to the RNSS in the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz.

The ITU Radiocommunication Assembly,

*considering*

a)      that systems and networks in the radionavigation-satellite service (RNSS) provide worldwide accurate information for many positioning and timing applications including critical ones related to safety of life;

b)      that WRC-03 adopted new and expanded allocations for the radionavigation-satellite service;

c)      that any properly equipped earth station may receive navigation information from systems and networks in the RNSS on a worldwide basis;

d)      that there are several operating and planned systems and networks in the RNSS and an increasing number of RNSS filings at the Radiocommunication Bureau proposing to use the new allocations;

e)      that methods need to be developed for use in coordination discussions which provide a common basis for the estimation of interference between such systems and networks in the RNSS;

f)      that technical and operational characteristics of, and protection criteria for, system and network receivers in the RNSS (space-to-Earth and space-to-space) in the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz can be found in M-Series ITU-R Recommendations or are currently under study in the ITU-R;

g)      that technical and operational characteristics of system and network transmitters in the RNSS (Earth-to-space, space-to-Earth and space-to-space) in the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz can be found in M-Series ITU-R Recommendations or are currently under study in the ITU-R;

h)      that Recommendation ITU-R M.1318 provides a model for evaluating interference from environmental sources into RNSS systems in the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz,

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*      This Recommendation does not address application-specific criteria, which may also be addressed during bilateral coordination, as relevant.

*recognizing*

a)      that the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz are allocated on a primary basis to RNSS (space-to-Earth, space-to-space) in all three Regions;

b)      that the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz are also allocated on a primary basis to other services in all three Regions;

c)      that No. 4.10 of the Radio Regulations (RR) states that the safety aspects of RNSS "require special measures to ensure their freedom from harmful interference";

d)      that under RR No. 5.328B systems and networks in the RNSS intending to use the bands 1 164-1 215 MHz, 1 215-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz for which complete coordination or notification information, as appropriate, is received by the Radiocommunication Bureau after 1 January 2005 are subject to the application of the provisions of RR Nos. 9.12, 9.12A and 9.13, and studies to determine additional methodologies and criteria to facilitate such coordination are being planned;

e)      that under RR No. 9.7, stations in radionavigation-satellite service networks using the geostationary-satellite orbit are subject to coordination with other such stations, and studies to determine additional methodologies and criteria to facilitate such coordination are being planned;

*noting*

a)      that Resolution 610 (WRC-03) applies to all systems and networks in the RNSS in the bands mentioned in *recognizing* a), and contains measures that are designed to facilitate the making of RNSS inter-system compatibility determinations,

*recommends*

**1**      that the methodology in Annex 1 should be used in carrying out coordination between RNSS systems operating or proposed to operate in one or more of the same frequency bands identified in *recognizing* a) (see Note 1);

**2**      that the guidance in Annexes 2 and 3 should be taken into account by RNSS system operators before and during RNSS coordination.

NOTE 1 – The methodology in Annex 1 may be difficult to apply to multi-satellite FDMA RNSS systems. In this case, Annex 2 may be implemented.

# Annex 1

# A method for estimating inter-system interference
# between systems and networks in the RNSS

## 1 Introduction

This methodology is intended to provide a technique of estimating the interference between systems and networks in RNSS. As such, it is useful for inter-system RNSS coordination. (For the purpose of brevity, the word "system" will be used instead of "system or network" in the remainder of this document.) The methodology applies to RNSS systems that use CDMA and FDMA to allow sharing of RNSS bands, and recognizes that a simple summation of transmission power density is inadequate to determine what effect an RNSS system will have on others. Unlike RNSS CDMA systems, which typically have only one carrier per occupied band, FDMA systems have several carriers in a single occupied band. It may not be practical to apply the methodology below to each carrier frequency used in a multi-satellite FDMA system.

## 2 Interference analysis methodology

Typically, effective carrier-to-noise density ratio $C / N_0'$, is used to measure the impact of the interference from various sources on the operational performance of the intended receivers. $C / N_0'$ is dependent on the receiver, antenna and external noise. However, it is used in assessing inter-system interference of RNSS systems.

$C / N_0'$ For the case of continuous interference[1], $C / N_0'$ is given by:

$$\frac{C}{N_0'} = \frac{C}{\nu N_0 + I_{ref} + I_{int} + I_{ext}}$$

(1)

where:

> $C$:    post-correlator received desired-signal power (W) from the satellite in the reference constellation including any relevant processing losses[2]

> $N_0$:    receiver pre-correlator thermal noise power spectral density (W/Hz)

> $C / N_0'$:    post-correlator effective receiver thermal noise power spectral density (W/Hz)

> $I_{ref}$:    post-correlator equivalent white-noise power spectral-density (W/Hz) due to the aggregate interference from all the signals, except the desired signal; transmitted by each satellite in the reference constellation including any relevant processing losses

> $I_{int}$:    post-correlator equivalent white-noise power spectral-density (W/Hz) due to the aggregate interference from all the signals transmitted in the frequency band of interest by all RNSS satellites other than those in the reference constellation including any relevant processing losses

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[1]   When significant pulsed interference is present, equation (1) must be modified. Pulsed interference reduces signal-to-noise ratio by suppressing the desired signal and increasing the effective noise floor.

[2]   *Relevant processing losses* include transmitter and receiver antenna gains; receiver implementation loss, such as filtering and quantization losses; and mismatch losses between the received signal and the reference code.

$I_{ext}$: post-correlator equivalent white-noise power spectral-density (W/Hz) due to the aggregate interference from all radio signals other than those of the RNSS including any relevant processing losses

ν: dimensionless effective thermal noise factor given by:

$$\nu = \int_{-\infty}^{\infty} \left| \overline{H}(f) \right|^2 S(f)\,\mathrm{d}f$$

$\overline{H}(f)$: normalized equivalent transfer function, at frequency $f$ (Hz) given by:

$$\overline{H}(f) = \frac{H(f)}{\max_{\gamma} \left| H(\gamma) \right|}$$

$H(f)$: equivalent receiver filter transfer function (dimensionless), at frequency $f$ (Hz), representing all of the pre-correlator receiver front-end filtering

$S$: ideal equivalent power spectral density, at frequency $f$ (Hz) of the unfiltered pre-correlator desired signal, normalized to one over an infinite bandwidth, and is computed assuming random spreading codes

γ: dummy variable.

The receiver's effective post-correlator thermal noise level, in the absence of external noise, reduces to $N_0' = \nu N_0$. In addition, if $H$ represents an ideal bandpass filter (rather than the detailed magnitude transfer function of the receiver's front-end filter), then ν simplifies to:

$$\nu = \int_{-B_R/2}^{B_R/2} S(f)\,\mathrm{d}f \leq \int_{-\infty}^{\infty} S(f)\,\mathrm{d}f = 1$$

Note that the value of $C/N_0'$ is minimized by assuming $\nu = 1$.

It should be noted that $I_{int}$ (W/Hz) can be further broken down to consider the interference due to a specific RNSS system:

$$I_{int} = I_{alt} + I_{rem}$$

where:

$I_{alt}$: post-correlator equivalent noise power spectral-density (W/Hz) due to the aggregate interference from all the signals transmitted in the frequency band of interest by all the satellites of a specific "alternate" constellation

$I_{rem}$: post-correlator equivalent noise power spectral-density (W/Hz) due to the aggregate interference from all the signals transmitted in the frequency band of interest by all "remaining" RNSS satellites; i.e. those that are not in either the reference constellation or the alternate constellation.

To calculate the equivalent noise power spectral densities we define the spectral separation coefficient, β (in units of 1/Hz), of an interfering signal from the $n$-th signal of the $m$-th constellation to a desired signal, $x$, as:

$$\beta_{m,n}^x = \int_{-\infty}^{\infty} \left| \overline{H}(f) \right|^2 \overline{S_x}(\nu)\,\overline{S}_{m,n}(\nu)\,\mathrm{d}\nu \tag{2}$$

where:

$\overline{S}_x(f):$ normalized (unit power over the transmitted bandwidth) two-sided power spectral density, at frequency $f$ (Hz) of the desired signal:

$$\overline{S}_x(f) = \begin{cases} \dfrac{S_x(f)}{\displaystyle\int_{-B_T/2}^{B_T/2} S_x(\gamma)\,d\nu} & |f| \le B_T/2 \\ 0 & \text{elsewhere} \end{cases}$$

$B_T$: bandwidth (Hz) over which the interfering signal's power is defined

$S_x(f)$: two-sided power spectral density, at frequency $f$ (Hz) of the unfiltered desired signal (1/Hz), normalized to unity over an infinite bandwidth

$\overline{S}_{m,n}(f):$ normalized (to unity over the transmission bandwidth) two-sided power spectral density (1/Hz) of the unfiltered $n$-th interfering signal from the $m$-th constellation:

$$\overline{S}_{m,n}(f) = \begin{cases} \dfrac{S_{m,n}(f)}{\displaystyle\int_{-B_T/2}^{B_T/2} S_{m,n}(\gamma)\,d\nu} & |f| \le B_T/2 \\ 0 & \text{elsewhere} \end{cases} \quad ;\text{ and}$$

$S_{m,n}(f):$ two-sided power spectral density (W/Hz) of the interfering signal, at frequency $f$ (Hz).

Equation (2) implicitly assumes that the code, represented by $S$, can be approximated as a continuous spectrum in the aggregate interference spectrum. This may not be true of short codes for which the cross-correlation between spectral lines in the fine structure of the code's spectrum can be significant. In this case, rather than the analytical model described here, a simulation model based on dynamic link budgets for a given receiver, considering the exact spectral property of the signals (including spectrum lines), is to be considered. Further explanations are provided in § 6.

Let:

$M_{ref}$: number of visible satellites in the reference satellite constellation

$N_{ref}$: number of interfering signals (not including the desired signal from the desired satellite) that is transmitted by a satellite in the reference satellite constellation

$M_{alt}$: number of visible RNSS satellites in the alternate constellation

$N_{alt}$: number of signals transmitted by an alternate satellite (which can be assumed the same for all satellites in the alternate constellation if an absent signal's power is set to zero)

$M_{rem}$: number of visible RNSS satellites that are not in the reference or the alternate constellation

$N_{rem}$: number of signals transmitted by a satellite that is not in the reference or alternate constellation

$P_{m,n}^{ref}:$ maximum interfering power (W) of the $n$-th interfering signal on the $m$-th satellite in the reference constellation

$N_{m,n}^{ref}:$ (dimensionless) processing loss of the $n$-th interfering signal on the $m$-th satellite in the reference constellation

$P_{m,n}^{alt}$ :     maximum interfering power (W) of the $n$-th signal on the $m$-th satellite in the alternate constellation

$L_{m,n}^{alt}$ :     (dimensionless) processing loss of the $n$-th signal on the $m$-th satellite in the alternate constellation

$P_{m,n}^{rem}$ :     maximum interfering power (W) of the $n$-th signal on the $m$-th satellite in the remaining RNSS constellations

$L_{m,n}^{rem}$ :     be the (dimensionless) processing loss of the $n$-th signal on the $m$-th satellite in the remaining RNSS constellations.

With these definitions we can write equations to calculate the effective interference power spectral density to reception from the reference constellation, the alternate constellation, and the remaining constellations as follows:

$$I_{ref} = \sum_{m=1}^{M_{ref}} \sum_{n=1}^{N_{ref,n}} \frac{\beta_{m,n}^{x} P_{m,n}^{ref}}{L_{m,n}^{ref}} \tag{3}$$

$$I_{alt} = \sum_{m=1}^{M_{alt}} \sum_{n=1}^{N_{alt,m}} \frac{\beta_{m,n}^{x} P_{m,n}^{alt}}{L_{m,n}^{alt}} \tag{4}$$

$$I_{rem} = \sum_{m=1}^{M_{rem}} \sum_{n=1}^{N_{rem,m}} \frac{\beta_{m,n}^{x} P_{m,n}^{rem}}{L_{m,n}^{rem}} \tag{5}$$

Using equations (1) to (5) the effective carrier-to-noise density ratio $C/N_0'$ can be calculated. This number can then be compared with a $C/N_0'$ threshold based upon the receiver mode, code acquisition, code tracking, carrier tracking and data demodulation, to measure the effect of interference.

Other methodologies based on the effective carrier-to-noise ratio $C/N_0'$, including its degradation due to a specific alternate constellation only, may be used. The degree of interoperability among signals, or specific inter-system code cross-correlation properties, may also be taken into account. Examples of the application of these measures are shown in § 5.2.

# 3      Data used in the calculations

The data used in the calculations will often be measured, determined by simulations, or adjusted to produce results consistent with experience. In addition, calculation of these values for each satellite and each signal is typically simulated over a period of time over an area of interest, and the statistics of inter-system interference values can then be obtained for consideration.

The subsections below provide further comment on how input for the calculations may be obtained.

## 3.1      Constellation and satellite transmitter models

Dynamic constellation simulation models with the respective orbital parameters are used to determine the received power levels for the desired and the interfering signals. A simplified satellite transmitter model is shown in Fig. 1.

FIGURE 1

**Simplified satellite transmitter model**



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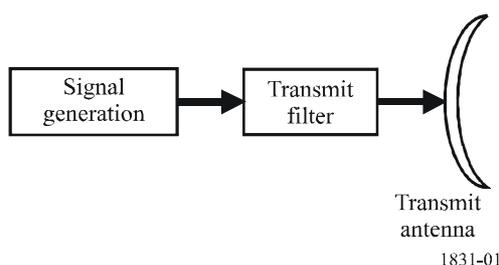
### 3.1.1 Worst-case received signal levels

For the worst-case interference calculation the desired signal is taken at the minimum power and the interfering signal is taken at the maximum power. This includes all RNSS signals in the reference constellation except the desired signal.

### 3.1.2 Spectral separation coefficients (β)

The β values are calculated with an assumption for both the transmission and receiver bandwidths. In addition, the values computed using equation (2) could be lower than those experienced. For example, this occurs for older pseudo-random codes with a shorter code period. This is due to a coarser spectral-line structure of shorter period codes that may not be accurately represented by a continuous power spectral-density function, which is normally used in equation (2).

## 3.2 User receiver model

The user receiver model is shown in Fig. 2. The receiver antenna, the output of which is input to the receiver front-end filter, receives both the desired and the interfering signals. The automatic gain control (AGC) loop keeps the voltage input to the analogue to digital converter (ADC) within the dynamic range of the ADC. Correlation is performed using the received signal and a locally generated signal matched to the transmitted signal prior to transmit filtering. All the losses namely, filtering, ADC and the correlator mismatch losses are grouped into a single loss factor. However, losses for the desired signal can be different than losses for interfering signals.

FIGURE 2

**Simplified user receiver model**



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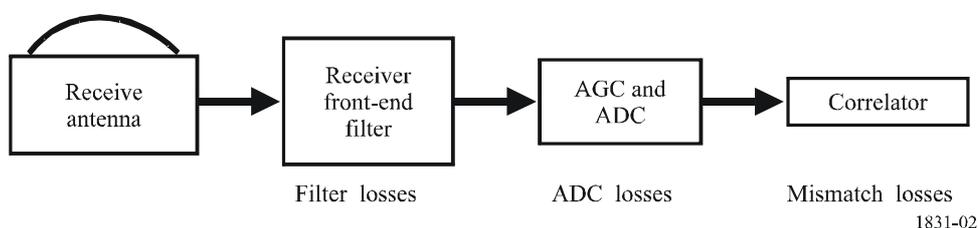
## 3.3 Interference and noise model

Navigation signal parameters are given in terms of data rate, spreading code chip rate and other code characteristics and modulation types. A continuous spectrum approximation is used to model the combined spectrum of the received interfering signals with the exception of short-period codes for which the spectral line nature of the code is taken into account.

User location can also be taken into account by measuring the interference power at every location on the earth over a 24-hour period. For a given type of interfering RNSS signal, that type's maximum aggregate interference level is calculated and compared to the maximum interfering power per satellite of a single such interfering signal to yield an aggregate gain factor ($G^{agg}$). In other words, $G^{agg}$ takes the maximum power of a single signal of an RNSS signal type, and is the increase needed to relate that power to the power of all interfering signals of that type. This factor thus accounts for all other signals of the same type as well as the variation in antenna gain towards all satellites transmitting that signal type.

For example, calculation of alternate constellation interference, $I_{alt}$, in equation (4) is simplified to:

$$I_{alt} = \sum_{m=1}^{Malt} \left[ G_m^{agg} \sum_{n=1}^{K_{alt}} \frac{\beta_{m,n}^{alt} P_{m,n}^{alt}}{L_{m,n}^{alt}} \right] \tag{6}$$

where the outer summation is taken over the number of RNSS constellations, $M'_{alt}$, and the inner summation is taken over the number of distinct signals in the alternate constellation, $K_{alt}$. In practice, a $G^{agg}$ value can be computed for a given constellation for a single signal, as shown in § 4, and then applied to all of that constellation's signals, or it may be the subject of coordination discussions. Similarly other interference values can also be simplified.

Interference from continuous external wideband sources is typically modelled as a noise source with a constant equivalent noise power spectral-density value, $I_{ext}$. This term is intended to account for all radio sources outside of the RNSS, and it may include in-band or out-of-band interference from other radio services.

Additional methods need to be defined for narrowband and pulsed interference.

## 4      A simulation-based approach for calculating $G^{agg}$

The post-correlator aggregate interference power spectral density to a desired signal, indexed by $k$, from all the satellites within a RNSS system to a receiver at a given location, indexed by $i$, can be written in terms of spectral separation coefficient, transmit power, transmit/receive antenna gain, path loss, and processing loss as follows:

$$I_{i,k}(t) = \sum_{m=0}^{M_i^S(t)} \left[ G_{i,m}^T(t) G_{i,m}^R(t) \alpha_{i,m} \sum_{n=1}^{N_m} \frac{\beta_{m,n}^k P_{m,n}}{L_{k,n}} \right] - G_{0,k}^T(t) G_{0,k}^R(t) \alpha_{k,0}(t) \cdot \frac{\beta_{0,k}^k P_{0,k}}{L_{k,k}} \tag{7}$$

where:

$i$:      receiver index

$k$:      index of the desired signal type

$t$:      time for which the aggregate interference power is being calculated

$M_i^S(t)$:    number of satellites in view at the $i$-th receiver's location at time $t$

$m$:      index of the summation over satellites in view and $m = 0$ for the desired signal's satellite index

$G_{i,m}^T$:      (dimensionless) transmit-antenna gain (relative to isotropic) between the $m$-th satellite to the $i$-th receiver location

$G_{i,m}^R$:      (dimensionless) receive-antenna gain (relative to isotropic) between the $i$-th receiver location and the $m$-th satellite

$\alpha_{i,m}$: (dimensionless) path loss from the $m$-th satellite to the $i$-th receiver location

$N_m$: total number of signal types on the $m$-th satellite

$\beta_{m,n}^k$: spectral separation coefficient (1/Hz) between the $k$-th signal type and $n$-th signal type of the $m$-th satellite

$P_{m,n}$: transmitted power (W) of the $n$-th signal on the $m$-th satellite

$L_{k,n}$: (dimensionless) processing loss for the $n$-th signal type (when the $k$-th signal type is desired).

In equation (7), the first term is the sum of all power spectral densities from all satellites in view and for all signals, including the desired signal from the desired satellite, while the second term is the power spectral density of the desired signal from the desired satellite.

As can be seen from equation (7) the equivalent power spectral density causes the thermal noise floor to go up. $I_{i,k}(t)$ is a function of time, user location and the spectral separation coefficient. A straightforward method to determine $I_{i,k}(t)$ is to use constellation simulation software in each and every interference scenario to determine the resulting amount of interference. It is too cumbersome and time consuming to perform this calculation using constellation simulation every time and place an interference analysis is needed. It is helpful to have a single factor that can be used repeatedly in interference analyses without resorting to the use of constellation simulation for every scenario. This factor can be derived using simulation models and thereby avoid the repeated computation of $I_{i,k}(t)$. This factor is called aggregate gain factor, $G^{agg}$, which can be obtained from taking an upper bound on equation (7) using the worst-case scenario. This overstates the interference in most situations, but it also provides confidence that the computed threshold interference level will not be exceeded.

The aggregate gain factor, for a particular signal type, can be derived as follows:

a)   At each position, indexed by $i$, in space (but usually on or near the Earth's surface) the received interference power (W) at the $i$-th receiver position can be written as:

$$P_i^R(t) = \sum_{m=0}^{M_i^S(t)} G_{i,m}^T(t) G_{i,m}^R(t) \alpha_{i,m}(t) P_m \tag{8}$$

Note that in equation (8), for the sake of simplicity, the index referring to the desired signal type, $k$, has been dropped and the processing losses, $L_m$, is are accounted for elsewhere (cf. equation (10)). If the desired and the interfering signals are of the same type, a minor adjustment in equation (8) is necessary in which one should subtract the desired signal power from equation (8).

b)   Now we can write, for each receiver position, the equation for $G^{agg}$ (dimensionless) as:

$$G^{agg} = \frac{\max_{all\ i} \left[ \max_{all\ i} \left( P_i^r(t) \right) \right]}{P_{max}^R} \tag{9}$$

Here $P_{max}^R$ is the maximum signal-power (W), at the antenna output and before the receiver's RF filter, from any single satellite, of the interference signal type under consideration, at a reference antenna's output and before the receiver's RF filter, taken over all indexed receiver locations using the gain, $G^R$, of their associated reference receiving antennas. Note that a reference receiving antenna (for a particular system) can be an appropriate anisotropic antenna. Such an antenna may not be matched to the received signal type in polarization, resulting in some additional attenuation. $G^{agg}$ is computed from equation (9) for all interfering signal types.

The resulting $G^{agg}$ is the worst-case value over all the receiver positions used in its calculation. This value is then used to represent the worst-case $G^{agg}$ for any receiver positions used in the interference analysis (for the desired signal type).

The power spectral density of interference from all RNSS signals from all RNSS satellites in view (W/Hz) can then be bounded above by:

$$I_0 = \sum_{n=1}^{N} \frac{G_n^{agg} \beta_n P_{max,n}^R}{L_n} \qquad (10)$$

where $\beta_n$ is the spectral separation coefficient between the desired signal and the $n$-th signal-type and $L_n$ is the processing loss between the desired signal and the $n$-th signal type. Note too that the path loss factors, $\alpha_{i,m}$, are absorbed into the $G^{agg}$ factors and the maximum received signal power, $P_{max,n}^R$, is used instead of the transmitted signal power.

As an example, a simulation run was done using the orbit-propagation model in Recommendation ITU-R M.1642. A 27-satellite constellation was used with the orbital parameters shown in Table 1. The received power level as a function of elevation angle is given in Fig. 3 and the receiver antenna pattern is given in Fig. 4. The maximum power over a period of 24 h at each location (in 5° steps in latitude and longitude) is given in Fig. 5. For a maximum received signal power of −153 dBW, the aggregate gain factor, taken over all receiver positions, is −141.6 − (−153) = 11.4 dB.

TABLE 1

**Example's orbital parameters**

| Satellite ID | Orbit radius (km) | Eccentricity | Inclination (degrees) | Right ascension (degrees) | Argument of perigee (degrees) | Mean anomaly (degrees) |
|---|---|---|---|---|---|---|
| 1 | 26559.8 | 0 | 55 | 58.21285 | 0 | 6.33 |
| 2 | 26559.8 | 0 | 55 | 58.21285 | 0 | 134.62 |
| 3 | 26559.8 | 0 | 55 | 58.21285 | 0 | 234.13 |
| 4 | 26559.8 | 0 | 55 | 58.21285 | 0 | 269.42 |
| 5 | 26559.8 | 0 | 55 | 118.21285 | 0 | 30.39 |
| 6 | 26559.8 | 0 | 55 | 118.21285 | 0 | 61.53 |
| 7 | 26559.8 | 0 | 55 | 118.21285 | 0 | 152.22 |
| 8 | 26559.8 | 0 | 55 | 118.21285 | 0 | 176.92 |
| 9 | 26559.8 | 0 | 55 | 118.21285 | 0 | 289.68 |
| 10 | 26559.8 | 0 | 55 | 178.21285 | 0 | 90.83 |
| 11 | 26559.8 | 0 | 55 | 178.21285 | 0 | 197.11 |
| 12 | 26559.8 | 0 | 55 | 178.21285 | 0 | 227.99 |
| 13 | 26559.8 | 0 | 55 | 178.21285 | 0 | 322.09 |
| 14 | 26559.8 | 0 | 55 | 238.21285 | 0 | 0.00 |
| 15 | 26559.8 | 0 | 55 | 238.21285 | 0 | 28.67 |
| 16 | 26559.8 | 0 | 55 | 238.21285 | 0 | 131.04 |
| 17 | 26559.8 | 0 | 55 | 238.21285 | 0 | 228.26 |

TABLE 1 (*end*)

| Satellite ID | Orbit radius (km) | Eccentricity | Inclination (degrees) | Right ascension (degrees) | Argument of perigee (degrees) | Mean anomaly (degrees) |
|---|---|---|---|---|---|---|
| 18 | 26559.8 | 0 | 55 | 238.21285 | 0 | 255.7 |
| 19 | 26559.8 | 0 | 55 | 298.21285 | 0 | 56.33 |
| 20 | 26559.8 | 0 | 55 | 298.21285 | 0 | 165.07 |
| 21 | 26559.8 | 0 | 55 | 298.21285 | 0 | 267.07 |
| 22 | 26559.8 | 0 | 55 | 298.21285 | 0 | 293.95 |
| 23 | 26559.8 | 0 | 55 | 358.21285 | 0 | 68.43 |
| 24 | 26559.8 | 0 | 55 | 358.21285 | 0 | 99.32 |
| 25 | 26559.8 | 0 | 55 | 358.21285 | 0 | 201.63 |
| 26 | 26559.8 | 0 | 55 | 358.21285 | 0 | 320.60 |
| 27 | 26559.8 | 0 | 55 | 358.21285 | 0 | 349.16 |

FIGURE 3

**Example terrestrial received power as a function of elevation**
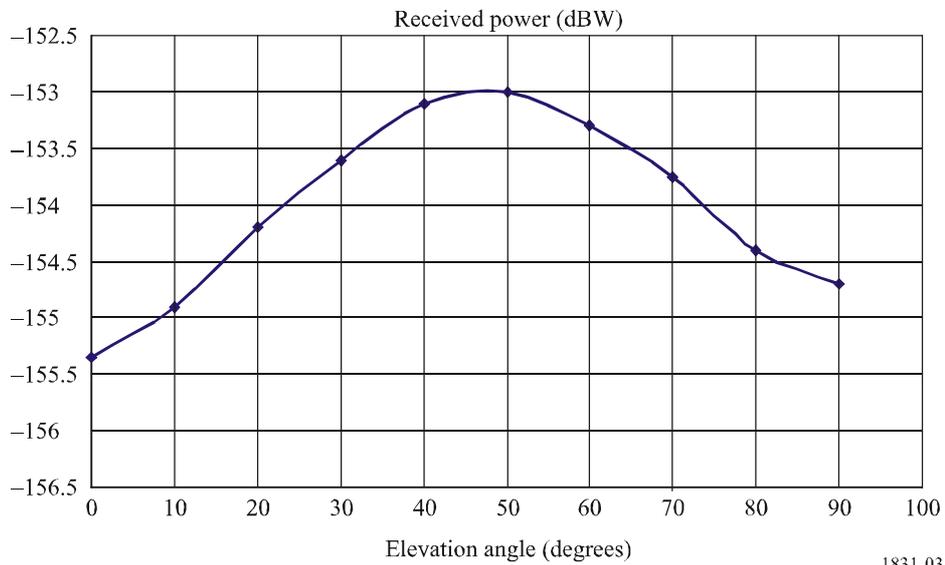


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FIGURE 4

**Example receive antenna gain as a function of elevation angle**
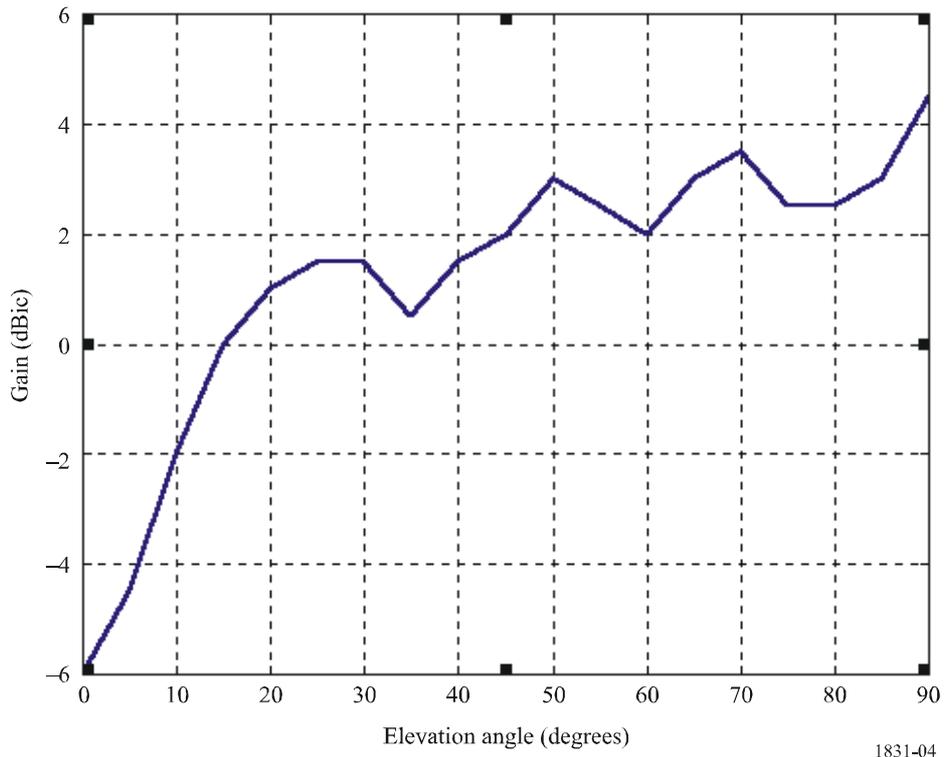


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FIGURE 5

**Example maximum power over 24 h**
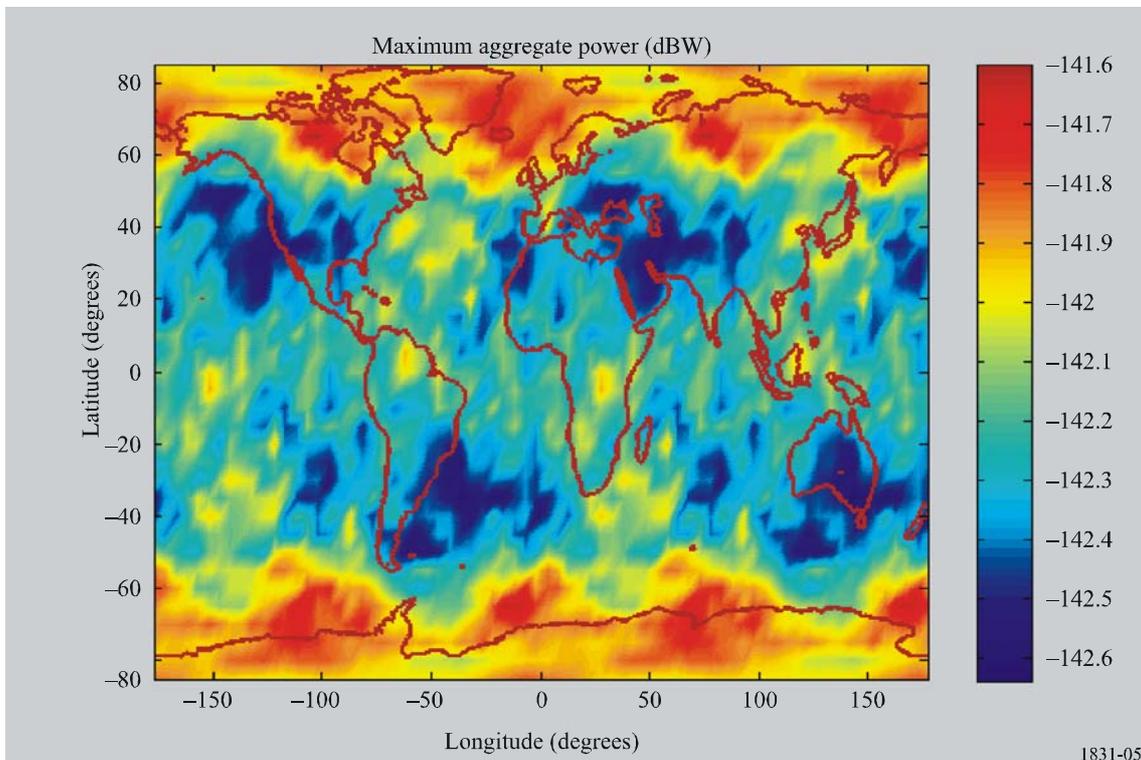


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## 5    A hypothetical example of the methodology's application

### 5.1    An assessment of interference levels

To illustrate how the methodology would apply in an analysis of interference due to another RNSS system, a hypothetical example is presented in Table 2. Note that the values used are only for illustration, and are subject to coordination discussions.

TABLE 2

**A hypothetical example of the inter-system interference effect
from system B to the combined A and SBAS systems**

| Effective reference system noise power spectral density: $n_0$ + reference system self-interference, $I_{ref}$, due to thermal noise and other signals in the reference (System A) constellation | |
|---|---|
| Maximum signal 1 power (dBW) | −157.50 |
| Maximum signal 2 power (dBW) | −160.50 |
| Maximum signal 3 power (dBW) | −157.50 |
| Processing loss for the interfering signal (dB) | 1.00 |
| Aggregate gain factor, $G^{agg}$ (dB) | 12.00 |
| Spectral separation coefficient, β (dB/Hz) | |
| *Signal 1 to Signal 1* | −61.80 |
| *Signal 2 to Signal 1* | −70.00 |
| *Signal 3 to Signal 1* | −67.90 |
| Thermal noise density, $N_0$ (dB(W/Hz)) | −201.50[(1)] |
| $I_{ref}$ ( dB(W/Hz)) | −207.09 |
| $N_0 + I_{ref}$ (dB(W/Hz)) | −200.44 |
| **Effective inter-system noise power spectral density: $N_0 + I_{ref}$ + RNSS interference aside from Systems A and B, $I_{rem}$, due to thermal noise, other signals in the reference (System A) constellation, and interfering SBAS, but without System-B signal 0** | |
| Maximum SBAS power (dBW) | −160.50 |
| SBAS aggregate gain factor, $G^{agg}$ (dB) | 7.70 |
| Spectral separation coefficient, β (dB/Hz) | |
| *System A SBAS to Signal 1* | −61.80 |
| Processing loss for interfering signals (dB) | 1.00 |
| $I_{rem}$ (dB(W/Hz)) | −215.60 |
| $N_0 + I_{ref} + I_{rem}$ (dB(W/Hz)) | −200.31 |
| **Effective total system noise power spectral density: $N_0 + I_{ref} + I_{rem}$ + non-RNSS external interference, $I_{ext}$, due to thermal noise, other signals in the reference (System A) constellation, interfering SBAS, and non-RNSS external interference, but without System-B signal 0** | |
| $I_{ext}$ (dB(W/Hz)) | −206.50 |
| $N_0 + I_{ref} + I_{rem} + I_{ext}$ (dB(W/Hz)) | −199.37 |

TABLE 2 (*end*)

| Effective total inter-system noise power spectral density: $N_0 + I_{ref} + I_{rem} + I_{ext} +$ **System-B interference,** $I_{alt}$**,** due to thermal noise and all interfering RNSS signals and external interference | |
|---|---|
| Maximum Signal 0 power (dBW) | −154.00 |
| System B aggregate gain factor, $G^{agg}$ (dB) | 12.00 |
| Spectral separation coefficient, β (dB/Hz) | |
| *Signal 0 to Signal 1* | −67.80 |
| Processing loss for interfering signals (dB) | 1.00 |
| $I_{alt}$ (dB(W/Hz)) | −210.80 |
| $N_0 + I_{ref} + I_{rem} + I_{ext} + I_{alt}$ (dB(W/Hz)) | −199.07 |

[1]    This value is a typical value which may not be representative of low-noise receivers.

For this example, the System-A's Signal-1 signal is the desired signal and System A is the "reference system". All other System-A signals, other than the one desired Signal-1, are considered as interference sources, and this is normally the case as each type of signal should be independently examined. Thus the desired Signal 1 also has self-interference from other Signal-1 transmissions and System-A intra-system interference from other System-A signals. For this example, the other System-A signals are the Signal 2 and Signal 3. Each interfering System-A signal has its own spectral separation coefficient for this example.

The System-A aggregate gain factor, $G^{agg}$ (12.0 dB, or 7.7 dB for System-A SBAS interference), takes into account the System-A receiver antenna's gain pattern, the System-B transmitter gain pattern, and is relative to the received interference power that exceeds 99.99% of all cases relative to the maximum interference power from a single alternate-system satellite. (The actual percentage is subject to coordination discussions.) Note that combined noise power spectral density is −201.50 dB(W/Hz) prior to considering intra-system interference, but is −200.44 dB(W/Hz) after accounting for it.

The "remaining systems" in the calculation are represented by a single RNSS SBAS network. (In practice, several RNSS systems and networks would normally be included.) The external noise is assumed to be the aggregate from all interfering sources not operating in the RNSS and is assigned a power spectral density of −206.5 dB(W/Hz). The combination of the reference-system, remaining-system, and external interference is then shown to be −199.37 dB/Hz (hypothetically).

The System B is then included in the interference calculation as the "alternative system", and the System-B Signal 0 is then included in the interference calculation for the System-A Signal 1. The System-B aggregate gain factor is assumed to be the same as the one used for System A. (In practice, the aggregate gains would differ since the constellation will differ.) The final result, in Table 2, shows for this hypothetical example that System-B Signal 0 increases the overall receiver noise floor power spectral density of −199.07 dB(W/Hz).

## 5.2      An assessment of effective carrier-to-noise ratios and related degradation

To illustrate how the methodology would apply in an analysis of the change in effective $C/N_0$ due to another RNSS system, this section continues the hypothetical example of the previous section and is presented in Table 3. As in the previous section, the values used are only for illustration, and are subject to coordination discussions. Note that $C/N_0$ is 36.00 dB-Hz prior to considering intra-system interference, but is 33.87 dB-Hz after accounting for all interference except for Signal 0.

The System B is then included in the interference calculation as the "alternative system", and the System-B (Signal 0) is then included in the interference calculation for the System-A Signal 1. The final result, in Table 3, shows for this hypothetical example that System-B Signal 0 decreases the $C/N_0$ of System-A Signal 1 to 33.57 dB-Hz.

TABLE 3

**A hypothetical example of the $C/N_0$ decrease due to inter-system interference from system B on the combined A-and-SBAS system**

| **Effective signal (System A Signal 1) carrier-to-noise density ratio, $C/N_0$ (dB-Hz) due to thermal noise, $N_0$** | |
|---|---|
| Minimum signal-1 power (dBW) | −158.50 |
| Desired signal processing loss (dB) | 2.50 |
| Minimum receiver antenna gain (dBi) | −4.50 |
| Desired signal $_{power}$, $C$ (dBW) | −165.50 |
| Thermal noise density, $N_0$ (dB(W/Hz)) | −201.50[1] |
| $C/N_0$ (dB-Hz) | 36.00 |
| **Effective $C/N_0$ (dB-Hz): $N_0 + I_{ref}$ + SBAS interference, $I_{rem}$ + non-RNSS external interference, $I_{ext}$** | |
| $N_0 + I_{ref} + I_{rem} + I_{ext}$ (dB(W/Hz)) | −199.37 |
| $C/(N_0 + I_{ref} + I_{rem} + I_{ext})$ (dB-Hz) | 33.87 |
| **Effective inter-system $C/N_0$ (dB-Hz): $N_0 + I_{ref} + I_{rem}$, $+ I_{ext}$ + System-B signal 0 interference, $I_{alt}$** | |
| $N_0 + I_{ref} + I_{rem} + I_{ext} + I_{alt}$ (dB(W/Hz)) | −199.07 |
| $C/(N_0 + I_{ref} + I_{rem} + I_{ext} + I_{alt})$ (dB-Hz) | 33.57 |

[1]  This value is a typical value which may not be representative of low-noise receivers.

In addition to these calculations of effective carrier-to-noise ratios, other measures based on effective $C/N_0'$ may also be used. An example is to calculate the effect of the interference created specifically by System B Signal 0. This can be accomplished by setting the $I_{rem}$ and $I_{ext}$ parameters to zero, thereby considering only the intra-system interference, $I_{ref}$ of the reference system, for calculating the degradation given by equation (11), which is denoted by $\Delta C/N_0'$. This degradation value is compared with a $C/N_0'$ degradation threshold. An example calculation is given in Table 4.

$$\Delta\left(\frac{C}{N_0''}\right) = \frac{\left(\dfrac{C}{N_0 + I_{ref}}\right)}{\left(\dfrac{C}{N_0 + I_{ref} + I_{alt}}\right)} = 1 + \frac{I_{alt}}{N_0 + I_{ref}} \tag{11}$$

TABLE 4

**A hypothetical example of the inter-system interference effect
from system B to system A**

| Effective reference system noise power spectral density: | | |
|---|---|---|
| Maximum signal 1 power (dBW) | −157.50 | |
| Maximum signal 2 power (dBW) | −160.50 | |
| Maximum signal 3 power (dBW) | −157.50 | |
| Processing loss for the interfering signal (dB) | 1.00 | |
| Aggregate gain factor, $G^{agg}$ (dB) | 12.00 | |
| Spectral separation coefficient, β (dB/Hz): | | |
| *Signal 1 to Signal 1* | −61.80 | |
| *Signal 2 to Signal 1* | −70.00 | |
| *Signal 3 to Signal 1* | −67.90 | |
| Thermal noise density, $N_0$ (dBW/Hz) | −201.50[1] | −204.00[2] |
| $I_{ref}$ (dBW/Hz) | −207.09 | |
| **Effective total inter-system noise power spectral density:** | | |
| Maximum Signal 0 power (dBW) | −154.00 | |
| System B aggregate gain factor, $G^{agg}$ (dB) | 12.00 | |
| Spectral separation coefficient, β (dB/Hz): | | |
| *Signal 0 to Signal 1* | −67.80 | |
| Processing loss for interfering signals (dB) | 1.00 | |
| $I_{alt}$ (dBW/Hz) | −210.80 | |
| Thermal noise density, $N_0$ (dBW/Hz) | −201.50[1] | −204.00[2] |
| $C/N_0''$ Degradation determined by equation (11) (dB) | 0.38 | 0.57 |

[1]   This value is a typical value which may not be representative of low-noise receivers.

[2]   This value is a typical value of low-noise receivers.

The maximum acceptable $C/N_0''$ degradation may depend on whether the alternate system is interoperable with the reference system. In the case of interoperable systems, the $C/N_0''$ degradation threshold may be higher than for non-interoperable systems. The noise contribution of a non-interoperable alternate system, $I_{alt}$, can be modified to take into account specific inter-system code cross-correlation properties. In this case, $I_{alt}$ could be replaced by $I'_{alt} = \alpha \cdot I_{alt}$ where $\alpha \geq 1$.

Another example is to compute $C/N_0'$ degradation based on the expression given below in equation (12):

$$\Delta\left(\frac{C}{N_0'}\right) = \frac{\dfrac{C}{N_0 + I_{ref} + I_{rem} + I_{ext}}}{\dfrac{C}{N_0 + I_{ref} + I_{rem} + I_{ext} + I_{alt}}} = 1 + \frac{I_{alt}}{N_0 + I_{ref} + I_{rem} + I_{ext}} \tag{12}$$

Using equation (12) with the parameters of Table 3 the $C/N_0'$ degradation can be calculated to be 0.3 dB.

## 6 Line spectrum signal modelling

The analytical model described above approximates the spectrum of the received signals as an aggregate spectrum, where the fine structures of individual signal spectra are averaged together into a smooth spectrum. This "continuous spectrum" modelling is valid for signals corresponding to long spreading codes, and assumes that the Doppler shift between the different signals has negligible effect in the overall interference assessment.

However, this modelling is not appropriate for short-code signals, for which "real spectrum" modelling is required. This more realistic modelling takes into account the real properties of the signals, such as data rate and spreading code characteristics (code lengths and presence of "pilot" and/or "data" channels), through time/frequency transformation of the modulated signal.

Real spectra of signals with periodic spreading codes are characterized by an envelope and a fine structure. The fine structure is a sequence of spectral lines, which have different levels. When there is data, the fine structure spectral lines are smoothed. The spectral lines depend on the chip rate, the code length, the presence of a pilot code, and on the code structure, as illustrated in Fig. 6.

FIGURE 6

**Line spectrum signal representation**
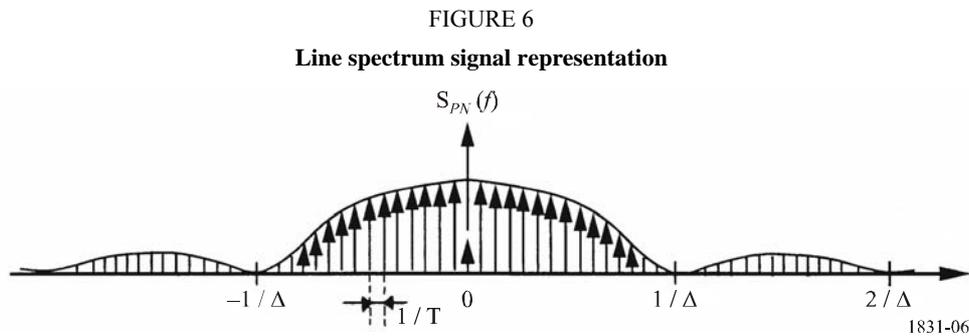


with:

$1/\Delta = R_c$ (code chip rate)

$T = N_c T_c$ (with $N_c$ code length and $T_c$ chip period)

The user receiver is assumed to be a terrestrial receiver at a fixed location, determined through a simulation as the worst case location for ($C/N_0'$) degradation. The Doppler shift between the desired signal and the interfering signals is to be accounted for in this model. Received powers, as well as Doppler shifts due to satellite motion, are computed dynamically through link budgets based on the orbital parameters of the different systems, satellite and user antenna gain patterns, as well as user receiver location.

## 7 Conclusion

The analysis methodology described above has shown itself to be useful in compatibility studies between RNSS systems, and therefore it would be useful for inter-system RNSS coordination activities. Although the principles are simple, a realistic model of all RNSS systems is necessary to obtain useful results. In addition, since the RNSS has non-geostationary systems, simulation is probably necessary to determine the statistics of interference between systems.

**Annex 2**

## Development of information and proposals for an assessment of RNSS external and intersystem interference

This Annex provides a methodology for determining how the RNSS interference budget may be shared amongst external (non-RNSS) sources and RNSS sources for the purpose of coordination amongst RNSS operators. Furthermore, some considerations for coordination between RNSS systems are provided.

## 1       RNSS Interference components

In the methodology of Annex 1, an aggregate value representing external interference (from non-RNSS sources), $I_{ext}$, is treated as additive white noise. How this value is determined is subject to coordination. Hence it can be simply a value that is accepted as representative by coordinating parties, or it can be calculated using the methodology in this Annex for determining an acceptable level of interference power to external interference and RNSS interference power. The approach that uses a single assumed value for external interference is referred to as the "aggregate approach". The approach discussed in this annex where the interference budget is shared amongst the interference sources is referred to as the "shared approach" and is discussed in detail in the subsection below.

## 2       The "shared approach" to RNSS interference

This approach is based on sharing the interference from one RNSS interfering system (or even one interfering satellite) to a receiver in another desired RNSS system. This approach is called the "shared approach".

The essence of this approach is to identify the share of one RNSS system (or satellite) in the total (aggregate) level of acceptable interference, and to compare this share with interference calculated for this RNSS system (or satellite). Let's consider a hypothetical RNSS system which can operate with the acceptable interference level $I_a$. Then dividing this into interference shares:

$$I_a = \sigma_{RNSS} \cdot I_a + \sigma_{ext1} \cdot I_a + \sigma_{ext2} \cdot I_a$$

where:

   $\sigma_{RNSS}$:   share of acceptable interference from all RNSS systems

   $\sigma_{ext1}$:   share of acceptable interference from all primary services other than the RNSS

   $\sigma_{ext2}$:   share of acceptable interference from all other external sources of interference and noise

   $I_a$ :   acceptable level of equivalent power spectral density of interference from all services, (W/Hz)

$$\sigma_{RNSS} + \sigma_{ext1} + \sigma_{ext2} = 1$$

Knowing the share of acceptable interference from all RNSS systems $\sigma_{RNSS}$, the share of acceptable interference from one RNSS satellite of a "reference" RNSS system, $\sigma_{ref}$, can be determined as

$$\sigma_{ref} = \sigma_{RNSS} / N$$

where:

   $\sigma_{ref}$:   share of acceptable interference from one RNSS satellite

$\sigma_{RNSS}$:  share of acceptable interference from all RNSS systems

$N$:  where, as a conservative estimate for non-GSO RNSS constellations that does not take into account transmitter and receiver antenna gain patterns, set $N = \max\{N_{max}^S, M_{ref}^S / 2\}$ wherein $N_{max}^S$ is the maximum number of satellites in view and $M_{ref}^S$ is the total number of satellites in the reference constellation.

Note too that the total acceptable non-RNSS interference is $I_{ext} = \sigma_{ext1} \cdot I_a + \sigma_{ext2} \cdot I_a$.

A similar approach may be applied to other services, for example, the fixed satellite service uses such a sharing plan.

The basic problem of this methodology is that initially it is necessary to determine the share of acceptable interference from different services and systems as compared to the threshold level of the aggregate interference. An acceptable share of interference from each service has to be studied and determined in advance.

The following interference shares could be considered as an example: $\sigma_{RNSS} = 0.89$ for the RNSS, $\sigma_{ext1} = 0.1$ for primary services other than the RNSS, and $\sigma_{ext2} = 0.01$ for interference sources other than the RNSS.

# Annex 3

# Guidance regarding coordination between RNSS systems

This Annex provides some guidance on the following general questions regarding coordination requirements and methodology, which are to be considered by any RNSS operator who needs to coordinate its planned system with other RNSS systems:

## 1 Which RNSS systems are to be taken into consideration in calculations?

According to ITU rules, RNSS systems with which coordination is to be sought by any new planned RNSS system are those for which the corresponding ITU filings have a frequency overlap, and for which the coordination requests (or notification information for non-geostationary systems filed prior to 1 January 2005) were received by the Radiocommunications Bureau earlier than that of this newly planned system. All these systems may have to be taken into consideration in calculations if they are actually developed.

The latest versions of ITU-R Recommendations contain information on some RNSS systems that have been notified to the ITU-R. Under Resolution 610 (WRC-03) entitled *"Coordination and bilateral resolution of technical compatibility issues for radio-navigation satellite service networks and systems in the bands 1 164-1 300 MHz, 1 559-1 610 MHz and 5 010-5 030 MHz"*, information on the status of development of planned RNSS systems can be exchanged between administrations during the process of coordination. This information may clarify whether a particular RNSS system, with which coordination is to be sought, is to be taken into consideration in calculations. More precisely, *resolves* 1 of the referenced Resolution states that an administration which has made filings for a RNSS system or network in the indicated bands shall, upon request by the responding

administration, inform the responding administration (with a copy to the Bureau) whether it has met the criteria listed in the Annex to Resolution 610 (WRC-03).

The criteria referred to include:

i)      submission of appropriate Advance Publication information;

ii)     clear evidence of a binding agreement for the manufacture or procurement of the system's satellites, or evidence of guaranteed funding of the system; and

iii)    clear evidence of a binding agreement to launch its satellites.


**2      Where notified networks are to be taken into consideration, in which order should this be done (e.g. based on coordination request date or another way)?**

*resolves* 1, 2, 3 and 4 of Resolution 610 (WRC-03) require that intersystem compatibility be first addressed for those systems meeting the criteria of the Annex to the Resolution. Administrations may coordinate amongst more than two systems in an order unrelated to the systems' filing dates as the situations dictate. Also administrations may choose to agree on their own coordination of interference criteria.

In cases where inter-system coordination matters under RR Article 9, Section II involve more than two RNSS systems, it may be useful to address them, during multilateral meetings involving all parties, in addition to during bilateral meetings between two of them.

Indeed, if for instance systems A, B and C should intend to operate within a given band within an RNSS allocation, with B having to complete coordination with A, and C having to complete coordination with both A and B, any agreements between B and C may individually need to take account of any agreement between A and B and between A and C.


**3      When coordination is to be undertaken, which characteristics are to be used?**

The characteristics to be used as a starting basis for a particular system are those associated with the ITU filings. However, calculations of inter-system interference should be based on real system characteristics to be exchanged between administrations during the coordination process. Characteristics required for calculations are usually more detailed than basic characteristics contained in the corresponding ITU filing, and have to be compatible with the envelope defined through this filing.


**4      How can the $I_{ext}$ parameter mentioned in Annexes 1 and 2 be assessed?**

The interference from other services, $I_{ext}$, has in some cases been taken into account in a performance recommendation. In other words, when designing a RNSS system, certain amounts of interference from other co-primary services in the same band have to be taken into account. The extent to which interference from these other services is to be taken into account varies from band to band. In some situations, regulatory limits are placed on other services in the same band based on studies. These may, for example, take the form of e.i.r.p. limits on terrestrial services. However, given that the user RNSS terminal is mobile, the approach should be to account for the aggregate increase in interference in the band from all sources.

Under the proposed approaches in Annexes 1 and 2, interference from services other than RNSS is modelled as a noise source with a constant equivalent noise power spectral-density value, $I_{ext}$. This term is intended to account for all radio sources outside of the RNSS, and it may include in-band or out-of-band interference from other radio services. As outlined in Annex 1, this method is appropriate to model continuous external wideband interference sources, but additional methods need to be defined for narrowband and pulsed interference.

In order to determine the value of $I_{ext}$, it is necessary to make a budget of all co-frequency and adjacent allocations under which a significantly contributing interference source may operate, and to obtain technical information on systems operated under these allocations in order to estimate the typical level of each of these sources. Guidance may for example be found in standards or in ITU-R Recommendations and Reports. The level of $I_{ext}$ may be dependent upon the location considered for the user of the reference system, since some systems may be operated only in specific countries or regions.

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