International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Recommendation ITU-R M.1477

(05/2000)

Technical and performance characteristics of current and planned radionavigation-satellite service (space-to-Earth) and aeronautical radionavigation service receivers to be considered in interference studies in the band 1 559-1 610 MHz

M Series

Mobile, radiodetermination, amateur and related satellite services

International Telecommunication Union

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Note*: This ITU-R Recommendation was approved in English under the procedure detailed in Resolution ITU-R 1.*

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RECOMMENDATION ITU-R M.1477*

Technical and performance characteristics of current and planned radionavigation-satellite service (space-to-Earth) and aeronautical radionavigation service receivers to be considered in interference studies in the band 1 559-1 610 MHz

(Questions ITU-R 91/8 and ITU-R 217/8)

(2000)

The ITU Radiocommunication Assembly,

considering

a) that the band 1 559-1 610 MHz is allocated on a primary basis to RNSS (space-to-Earth) and ARNS;

b) that Recommendations ITU-R M.1088 and ITU-R M.1317 provide characteristics and descriptions of several types of receivers that are used with the radionavigation-satellite systems, known as the GPS and the GLONASS;

c) that there is an essential need to protect systems operating in the ARNS and RNSS in the band 1 559-1 610 MHz;

d) that GPS and GLONASS navigation safety services exist for a variety of applications including aeronautical, land and marine applications, and that the use of these services will expand in the future;

e) that any properly equipped earth station may receive navigation information from the GPS, GLONASS and other RNSS systems on a worldwide basis;

f) that the International Civil Aviation Organization (ICAO) is developing standards for the GNSS, whose elements include GPS and GLONASS;

g) that the International Maritime Organization (IMO) requires ships to equip with RNSS for navigation in narrow waterways and for docking;

h) that RR No. 4.10 states that the safety-of-life aspects of radionavigation and other safety services require special measures to ensure their freedom from harmful interference (see also RR No. 1.169),

recognizing

a) that there are a number of receivers of GPS and its augmentations used in safety-of-life applications that process the GPS signals in different ways as described in Annex 1, within the RNSS/ARNS band;

b) that there are a number of receivers of GLONASS used in safety-of-life applications that process the GLONASS signals in different ways, as described in Annex 2, within the RNSS/ARNS band;

c) that at the current time, the Standards and Recommended Practices (SARPs) of ICAO do not recognize, for use in aircraft, the use of the wideband signals of GPS or GLONASS, nor their use of carrier frequencies above 1 604.25 MHz, on a worldwide basis, after 2005;

* Radiocommunication Study Group 8 made editorial amendments to this Recommendation in 2004 in accordance with Resolution ITU-R 44.

d) that there are a number of different existing and planned augmentations of GPS and GLONASS which support safety-of-life services in aeronautical and other environments;

e) that there are a large number of non-aeronautical GNSS applications used in support of both safety-of-life and non-safety-of-life services;

f) that Recommendation ITU-R M.1343 defines the essential technical requirements of mobile earth stations (MESs) for global non-GSO MSS systems in the bands 1-3 GHz,

recommends

1 that the characteristics of the receivers described in Annexes 1 to 4 be used in performing interference analyses that include ARNS and RNSS in the band 1 559-1 610 MHz (see Note 1);

2 that a safety margin, as discussed in Annex 5, be applied for the protection of the safety-of-life aspects and applications of RNSS and ARNS, when performing interference analyses.

NOTE 1 – This Recommendation is not intended to be used to form the basis for future modifications to maximum unwanted emission levels for the band 1 559-1 610 MHz that are stated in the Annexes to Recommendation ITU-R M.1343. The maximum unwanted emission levels for the band 1 559-1 610 MHz stated in Recommendation ITU-R M.1343 have been developed pursuant to a specific interference scenario, and are not intended to be applied to any service other than MSS MESs operating in the 1-3 GHz range without further study.

Annex 1

GPS receiver and signal characteristics

1 GPS receiver characteristics

Several GPS receiver types are described in this Annex. There are three aeronautical receivers for which the requirements are relatively well developed. Each has its counterpart for land and/or marine applications, and it is intended that the characteristics stated in this Annex would apply to GPS receivers that are used in such applications. At this time it is not known whether the non-aviation applications are more susceptible to interference or less, nor is it known how susceptible future applications will be, considering both the current GPS with its augmentations and evolutions of GPS.

The first aeronautical receiver is a civil navigation receiver designed to provide category I precision approach guidance. It must meet the requirements of a satellite-based augmentation system (SBAS) specification. It must track both GPS satellites and SBAS satellites, which have GPS-like codes and transmit at the same centre frequency of 1 575.42 MHz. The SBAS signal is modulated with data using a symbol rate of 500 bit/s, which is then decoded with a convolutional decoding scheme to output information at a rate of 250 bit/s.

The second aeronautical receiver is an air navigation receiver designed to provide Category II/III precision approach guidance. It must meet the requirements of a ground-based augmentation system (GBAS). It must track GPS satellites and pseudolites. Pseudolites are ground-based transmitters which emit a signal having the characteristics of GPS, but utilizing different spreading codes. There are wideband and narrow-band pseudolites currently under consideration. Wideband pseudolites emit a code similar to the Y code (see Note 1), thus the signal has the spectral characteristics of the Y code. The pseudolites are pulsed with a duty cycle of less than 4%. The narrow-band pseudolites emit a signal having C/A code characteristics, offset from the L1 (L1 band is at 1 559-1 610 MHz) centre frequency by ±10.23 MHz. They are pulsed, with a duty cycle of about 9%.

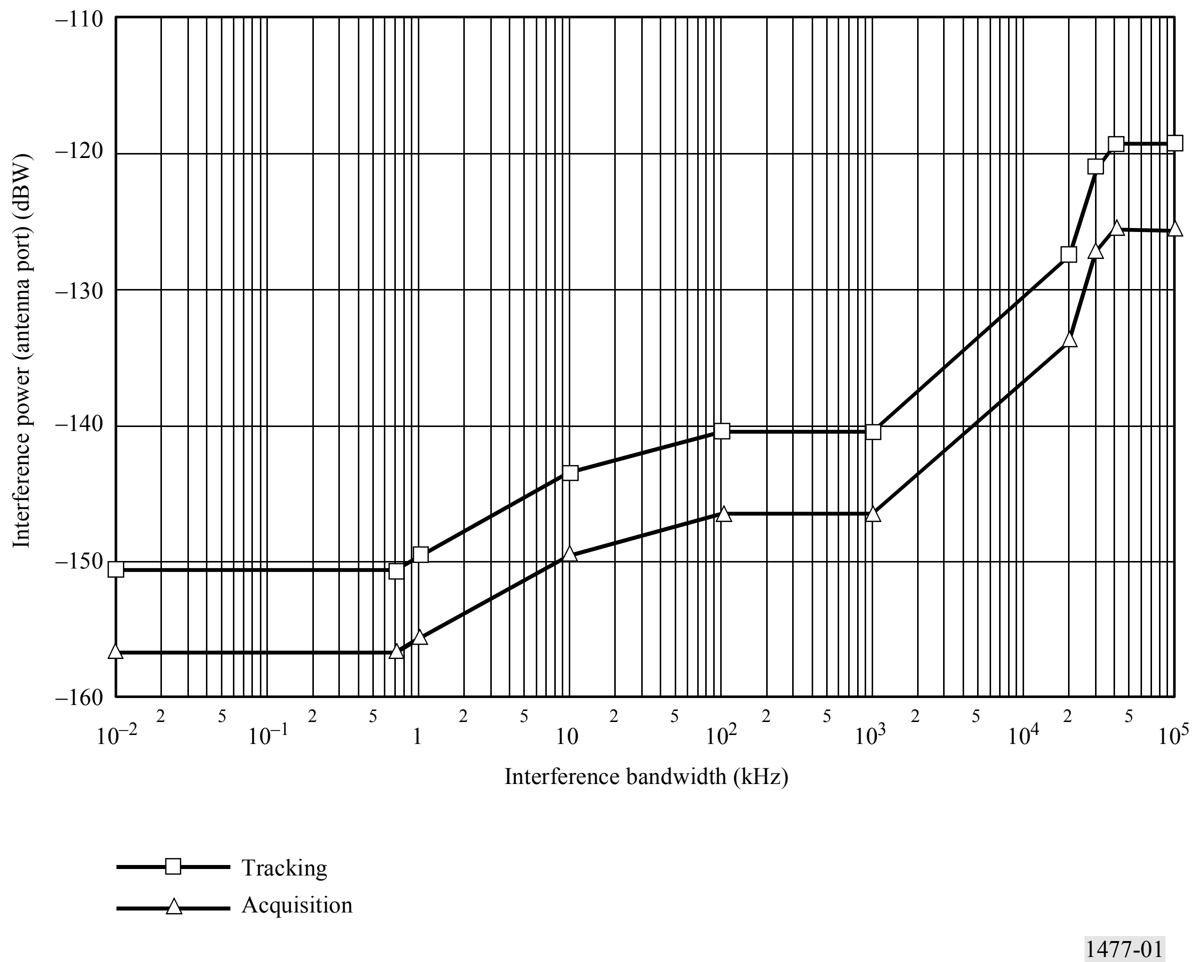
NOTE 1 – Y code is a modified P code, having the same chipping rate and spectral characteristics as that of the P code.

The third receiver is a ground-based receiver which is used in SBAS operations to determine ionospheric delays. It is also used in non-SBAS ground applications. This receiver uses a semi-codeless technique that exploits a unique feature of the GPS architecture whereby the L1 and L2 (L2 band is at 1 215-1 260 MHz) Y code signals are cross-correlated to provide a measurement of signal delay at L2, thus making it possible to determine the signal delay due to the ionosphere. The cross-correlation scheme is made possible by the fact that the GPS L1 and L2 signals have identical codes. This receiver must acquire and track both GPS and SBAS satellites at L1. Semi-codeless receivers are more sensitive to interference because they operate without benefit of knowing the Y code.

In the following descriptions power levels at the antenna input refer to the power that would be received by an isotropic, circularly polarized antenna of the proper polarity, while power levels at the antenna output refer to the power levels that account for the antenna gain in the direction of the specific signal or interference source. The specification of interference levels and bandwidths is shown in Fig. 1.

FIGURE 1

Aggregate interference threshold for SBAS and GBAS air navigation receivers



The maximum interference levels in Tables 1 to 10 do not refer to the allowable level of interference but rather to the interference level that manufacturers must design equipment to withstand, while still meeting performance requirements. The total allowable level of interference from known sources must be significantly below this value, namely by the safety margin (see Annex 5). This is to allow for variations in GNSS receiver performance and unknown sources of interference.

1.1 Land vehicle and marine navigation receiver

Land vehicle and marine navigation receivers are designed to provide metre-level guidance, using differential corrections obtained from any of a number of GPS augmentation systems, including SBASs, radiobeacon networks, or other local area broadcasts that use one of several frequencies from HF to UHF. Their characteristics are similar to those of the first aeronautical receiver described above.

1.2 Semi-codeless receivers

Semi-codeless GPS receivers use a technique unique to GPS whereby the L1 and L2 Y code signals are cross-correlated to provide an estimate of the ionospheric delay or an independent set of carrier phase measurements that support rapid removal of wavelength ambiguities, even when the receiver is in motion. This process provides improved position accuracy. The cross-correlation scheme is made possible by the fact that L1 and L2 have identical, synchronized Y codes. This receiver will have characteristics similar to the third aeronautical receiver described above, but may differ in its susceptibility to interference.

TABLE 1

SBAS air navigation receiver, Category I precision approach operations

L1 carrier centre frequency	1 575.42 MHz
C/A code chip rate	1.023 Mbit/s
Navigation data rate, GPS	50 bit/s
Navigation data rate, SBAS, with FEC, rate 1/2	500 symbols/s
Word error rate (1 word = 250 information bits)	10^{-3} per s
Minimum received power level at antenna input, SBAS	–161 dBW
Minimum antenna gain towards satellite at 5° elevation	–4.5 dBic
Maximum antenna gain in upper hemisphere	+7 dBic
Assumed antenna gain in lower hemisphere	–10 dBic
Maximum pre-correlation filter 3 dB bandwidth(1)	±16.5 MHz
Receiver noise figure	4.4 dB
RF pulse overload recovery time	25×10^{-6} s
Receiver aggregate wideband interference threshold in track mode(2), (3)	–140.5 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–146.5 dB(W/MHz)
Receiver aggregate narrow-band interference threshold in track mode(2), (3)	–150.5 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–156.5 dBW

(1) A more stringent pre-correlator filter may be needed to protect receiver operations from adjacent band RF emissions.

(2) The interference threshold already takes into account the effects of GPS intra-system interference-based on random code analysis. See § 2. The threshold must account for all other aggregate interference. The applicability of a safety margin is discussed in Annex 5.

(3) Wideband interference has a bandwidth in the range 100 kHz to 1 MHz; narrow-band interference has a bandwidth less than or equal to 700 Hz. For other bandwidths, refer to Fig. 1.

1.3 Commercial ground network receiver

Some commercial ground network receivers operate at a single frequency, in which case their characteristics will be similar to the first aeronautical receiver described. Two frequency receivers may also be used in commercial networks. If so, their characteristics are similar to the third aeronautical receiver, except that instead of performing relative carrier phase computations, the cross-correlated L1 and L2 signals are processed to determine the ionospheric delay in the signals. This information is used by the network to improve accuracy over a large region.

2 Analysis methodology

An analysis methodology is presented that shows that for worst-case conditions, full availability of GPS service, in the presence of additional external interference, may not be met due to the effects of C/A-code co-channel self-interference. A model for predicting these location and time specific events is developed in this Annex. Preliminary experimental validation of the results (not shown) has been conducted; additional tests are in progress.

TABLE 2

GBAS air navigation receiver, Category II/III precision approach operations

L1 carrier, wideband pseudolite frequency	1 575.42 MHz
Narrow-band pseudolite carrier frequency	L1 ± 10.23 MHz
C/A code, narrow-band pseudolite chip rate	1.023 Mbit/s
Wideband pseudolite code chip rate	10.23 Mbit/s
Navigation data rate, GPS	50 bit/s
Minimum received C/A code power level at antenna input	–161 dBW
Minimum average wideband pseudolite power level at antenna input	–140 dBW
Minimum average narrow-band pseudolite power level at antenna input	–140 dBW
Minimum antenna gain towards pseudolite	–21 dBic
Minimum antenna gain towards GPS satellite at 5° elevation	– 4.5 dBic
Maximum antenna gain in upper hemisphere	+7 dBic
Maximum pre-correlation filter, 3 dB bandwidth(1)	±16.5 MHz
Receiver noise figure	4.4 dB
RF pulse overload recovery time	25×10^{-6} s
Receiver aggregate wideband interference threshold in track mode(2), (3)	–140.5 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–146.5 dB(W/MHz)
Receiver aggregate narrow-band interference threshold in track mode(2), (3)	–150.5 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–156.5 dBW

(1) A more stringent pre-correlator filter may be needed to protect receiver operations from adjacent band RF emissions.

(2) The interference threshold already takes into account the effects of GPS intra-system interference-based on random code analysis. The threshold must account for all other aggregate interference. The applicability of a safety margin is discussed in Annex 5.

(3) Wideband interference has a bandwidth in the range 100 kHz to 1 MHz; narrow-band interference has a bandwidth less than or equal to 700 Hz. For other bandwidths, refer to Fig. 1.

2.1 Same service interference

In an analysis to determine the effect of external interference to GPS, the effects of thermal noise as well as the interference caused by the GPS signals must first be accurately analysed. In this way, a baseline is established for GPS, which produces same-service or intra-system interference, to which the signals from other systems seeking allocation can be added. It is recognized that different criteria apply to same-service interference than to external interference from other services. GPS as well as planned augmentations, due to the constant monitoring and control, will avoid harmful levels of self-interference. Such assurances cannot be made for other services.

2.2 Random noise versus short code

In analysing same-service interference, this Annex presents results that recognize the distinct co-channel self-interference that GPS signals experience. GPS is a single-frequency CDMA system that uses a family of short pseudo-random-noise codes known as Gold codes. The result is a system with a limited CDMA capacity, due in part to the short (1 ms) length of the Gold code. While earlier studies assumed Gaussian noise models for co-channel self-interference from GPS, the mutual interference of the codes is much greater than that from random noise. Therefore, when analysing the performance of GPS in the presence of external sources of interference, an accurate model of co-channel self-interference from the GPS must be used as well. In order to analyse the co-channel self-interference, the non-linear behaviour of the GPS receiver needs to be taken into account.

TABLE 3

SBAS ground network receiver, semi-codeless*

L1 carrier frequency	1 575.42 MHz
L2 carrier frequency	1 227.6 MHz
C/A code chip rate	1.023 Mbit/s
Y-code chip rate	10.23 Mbit/s
Navigation data rate, GPS	50 bit/s
Navigation data rate, SBAS, with FEC, rate 1/2	250 bit/s
Word error rate (1 word = 250 information bits)	10^{-3} per s
Minimum carrier power at antenna input (L1/CA)	–160 dBW
Minimum carrier power at antenna input (L1/Y)	–163 dBW
Minimum carrier power at antenna input (L2/Y)	–166 dBW
Minimum antenna gain towards satellite at 5° elevation	–4.5 dBic
Maximum antenna gain	+7 dBic
Maximum pre-correlation filter 3 dB bandwidth(1)	±16.5 MHz
Receiver noise figure	4.4 dB
RF pulse overload recovery time	25×10^{-6} s
Receiver aggregate wideband interference threshold in the Y-code track mode(2), (3)	–146.5 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–146.5 dB(W/MHz)
Receiver aggregate narrow-band interference threshold in the Y-code track mode(2), (3)	–154.5 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–156.5 dBW

* These receivers serve critical roles at SBAS ground stations at known fixed locations. Hence appropriate physical buffer zones should exist around such receivers. This Table also represents the characteristics of non-SBAS GPS semi-codeless receivers.

(1) A more stringent pre-correlator filter may be needed to protect receiver operations from adjacent band RF emissions.

(2) The interference threshold already takes into account the effects of GPS intra-system interference-based on random code analysis. The threshold must account for all other aggregate interference. The applicability of a safety margin is discussed in Annex 5.

(3) Wideband interference has a bandwidth in the range 100 kHz to 1 MHz; narrow-band interference has a bandwidth less than or equal to 700 Hz. For other bandwidths, refer to Fig. 1.

2.3 Linear correlator and non-linear tracking-loop

A straightforward means of calculating the co-channel self-interference is to model the GPS receiver as a correlator that de-spreads the GPS signal. This linear model gives an estimate of the cross-correlation between pairs of GPS codes. In actuality, the GPS receiver, which must acquire and track the satellite signals, typically uses a closed tracking-loop. This is a non-linear process that results in multiple cross-correlation interference terms similar to intermodulation products. An example of a GPS receiver using an early/late tracking-loop is modelled in this Annex. The criterion for receiver performance is the post correlation C/N_0 resulting from this non-linear process.

2.4 Steady state signal versus satellite constellation model

Previous analyses have considered the average interference effect on the GPS receiver. Co-channel self-interference, however, depends on the relative phases and Doppler shifts of the coded signals at the GPS receiver that are time variant. Furthermore, the different GPS signals arrive at different elevation angles with respect to the receiver and experience different antenna gain levels. All the above-mentioned effects are a function of satellite and receiver geometry. A GPS constellation-driven model of the satellite orbits and an antenna specification are used herein to model all, including short duration, effects of interference. This is necessary since for the purposes of integrity effects with duration on the order of minutes can hamper safety uses of GPS.

2.5 Terrestrial versus spaceborne user

A fundamental difference between an interference analysis for terrestrial users of GPS, at least for high-integrity safety-of-life users, and communication satellite systems, is the need for a high number of contacts with multiple satellites. In spaceborne applications, the user only needs to close the link to the minimum satellites necessary for updating the model of the space vehicle trajectory. Terrestrial users, however, require that a simultaneous link be established with a larger number of satellites. Typically, users that need high integrity may need to maintain contact with between six and eight satellites at a time. Furthermore, these necessary satellite links must constantly include low-elevation satellites to reduce the dilution-of-precision (DOP) and consequently the positioning or timing error. The problem of maintaining a link with a large number of satellites is exacerbated by the fact that the terrestrial user antennas, in order to minimize illumination of the ground and therefore multipath, favour the higher elevation angle satellites with more gain. Thus, the interference for the terrestrial user to a low elevation satellite, burdened by lower user antenna gain, is more easily interfered with by the signal from a high elevation satellite. The co-channel self-interference model, which predicts degradation to C/N_0 to at most one satellite at a time, would impact the terrestrial (high availability) user, but not the spaceborne user.

Another factor in the co-channel self-interference model is the length of time that the relative Doppler differences between pairs of satellites remains small. For terrestrial users, this time has been found to be long (tens of seconds to minutes). Spaceborne users, on the other hand, will most probably experience only very short duration instances of low relative Doppler differences between satellites because of orbital velocities. For the above-mentioned reasons, while the co-channel self-interference model should be applied to terrestrial users, it is probably inappropriate for analysing the interference environment of spaceborne users.

3 C/A-code characteristics

The specific characteristics of the GPS C/A code as they may impact interference studies are described in this Annex. The use of the Gold code by GPS results in cross-correlation levels that yield greater co-channel interference than pseudo-random (PN) codes of the same length. It can be shown that the interference level is inversely related to the length of the code.

When the PN code period is very large, a continuous approximation for the power spectral density (psd) is possible. The resulting co-channel self-interference psd at the output of a linear correlator can be calculated by convolving the psd of the received interfering code signal with the psd of the reference code signal in the receiver. This can been shown to be 2/3 (f_c) times the interference power (P_I), where f_c is the chipping rate of the spread spectrum code. This interference level, corresponding to a random (non-periodic) code, can be expressed as –61.8 + 10 log(P_I) dB(W/Hz) with respect to the carrier.

However, for the Gold code and especially the ones having short periods, a random code analysis does not predict the wide variations of co-channel self-interference over time and location of the receiver. Such a variation is very important in safety-of-life applications wherein even events lasting only a relatively short period of time can be critical. In such cases, a more precise co-channel self-interference analysis is mandatory. Subsequently, interference analyses performed in support of frequency coordination must include the short-term effects of co-channel self-interference as described in this Recommendation.

Therefore, the method for calculating interference from GPS alone consists of:

– calculating co-channel self-interference using a more precise analytical model which includes the dependence of the interference power on various factors such as relative Doppler and code delays among the desired and the interfering signals, code cross-correlation and receiver non-linear effects;

– using a constellation model to model the variations in the received signal from both the desired and the interfering sources and antenna gain variations as a function of the user elevation angle;

– conducting a global search to establish the location(s) at which the expected C/N_0 is minimum; and

– computing C/N_0 at these locations as a function of time computed to determine the duration of this minimum C/N_0.

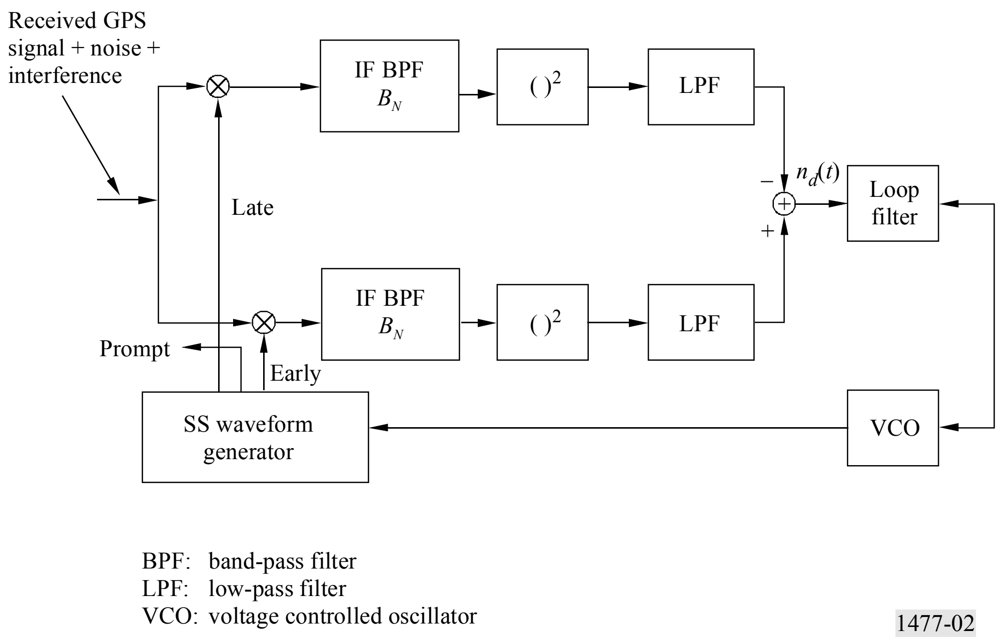
Using this methodology, a realistic baseline is established for C/A-code co-channel self-interference to which external sources of interference can be added for analysis. The comparison of these minimum C/N_0 points to a predefined threshold (34 dB(Hz) for acquisition and 30 dB(Hz) for code tracking) will determine if the added interference causes loss of GPS service.

3.1 Analysis of GPS co-channel self-interference

The model of the non-coherent delay-lock tracking-loop used in the analysis is shown in Fig. 2.

FIGURE 2

Non-coherent code tracking-loop



The total signal received by the GPS receiver channel is the sum of the signals received from the GPS satellite being tracked and from other GPS satellites (L) in view of the receiver. An expression for the total signal environment at the input of the tracking-loop can be written as:

$$r(t) = \sqrt{2G_0 P_0}\, d(t - \tau_0(t))\, c_0\,(t - \tau_0(t)) \cos(\omega_c t + \omega_0^d t + \varphi_0) + \sum_{i=1}^{L} \sqrt{2G_i P_i}\, d_i(t - \tau_i(t))\, c_i(t - \tau_i(t)) \cos(\omega_c t + \omega_i^d t + \varphi_i) + n(t) \quad (1)$$

where:

P_0:	average power received from the GPS satellite that is being tracked
P_i:	average power from the i-th GPS satellite in view of the GPS receiver
G_i:	gain including the antenna effects in the direction of i-th GPS satellite
$c_0(t)$:	spreading code for the GPS satellite being tracked
$c_i(t)$:	spreading code for the i-th satellite
$d(t)$:	data bit (±1 with a period T) for the GPS satellite being tracked
$d_i(t)$:	data bit (±1 with a period T) for the i-th satellite
$n(t)$:	additive white Gaussian noise
$\tau_0(t)$:	path delay from the GPS satellite being tracked including code Doppler effect
$\tau_i(t)$:	path delay from the i-th satellite to the receiver including code Doppler effect
φ_0:	random carrier phase of the signal from the GPS satellite being tracked
φ_i:	random carrier phase of the signal from the i-th satellite
ω_c:	GPS carrier frequency (rad/s)

ω_0^d: carrier Doppler frequency of the satellite being tracked (rad/s)

ω_i^d: carrier Doppler frequency of the i-th interfering satellite (rad/s).

A simplifying assumption is made in the expression for the auto- and cross-correlation functions of the codes, and that is that the Doppler can be handled separately from the spreading code term. This condition is found to be true for low relative Doppler frequency between satellites. It has also been found that the worst-case interference happened when the relative Doppler frequency between satellites is low.

From the received signal of equation (1) the co-channel self-interference ($n_d(t)$) from other GPS satellites in view but not tracked, at the input of the loop filter is given by:

$$\begin{aligned} n_d(t) \;=\; & \frac{1}{2} K_1 \sum_{i=1}^{N} P_i \, D_{0i}^I(\xi_{0i}) \;+\; K_1 \sum_{i=1}^{N} \sqrt{P_0 \, P_i} \, D_{0i}^c(\xi_{0i}) \cos[\omega_{i0}^d t \;+\; \Delta_{\varphi i0} \;+\; \Delta\theta_{d_{i0}}(t)] \;+ \\ & K_1 \sum_{j=1}^{N} \sum_{i=j+1}^{N} \sqrt{P_j \, P_i} \, D_{ij}^c(\xi_{i0}, j_{i0}) \cos[\omega_{ij}^d t \;+\; \Delta\varphi_{ij} \;+\; \Delta\theta_{ij}(t)] \end{aligned} \tag{2}$$

where:

K_1:	mixer loss or gain
$\Delta\theta_{d_{ij}}(t) = \theta_{d_i}(t) - \theta_{d_j}(t)$:	data modulation phase difference between the i-th and the j-th GPS satellites
$\Delta\varphi_{ij} = \varphi_i - \varphi_j$:	random phase difference between the signals from the i-th and the j-th GPS satellites
$\omega_{ij}^d = \omega_i^d - \omega_j^d$:	differential carrier Doppler frequency shift between the i-th and the j-th satellites.

The discriminator functions in equation (2) are defined by:

$$D_{0i}^I(\xi_{0i}) = R_{c_{0i}}^2\left[\left(\delta - \xi_{0i} + \frac{\Delta}{2}\right)T_c\right] - R_{c_{0i}}^2\left[\left(\delta - \xi_{0i} - \frac{\Delta}{2}\right)T_c\right] \tag{3a}$$

$$D_{0i}^c(\xi_{0i}) = R_{c_{00}}\left[\left(\delta + \frac{\Delta}{2}\right)T_c\right] R_{c_{0i}}\left[\left(\delta - \xi_{0i} + \frac{\Delta}{2}\right)T_c\right] - R_{c_{00}}\left[\left(\delta - \frac{\Delta}{2}\right)T_c\right] R_{c_{0i}}\left[\left(\delta - \xi_{0i} - \frac{\Delta}{2}\right)T_c\right] \tag{3b}$$

$$D_{ij}(\xi_{0i},\xi_{0j}) = R_{c_{0i}}\left[\left(\delta - \xi_{0i} + \frac{\Delta}{2}\right)T_c\right] R_{c_{0j}}\left[\left(\delta - \xi_{0j} + \frac{\Delta}{2}\right)T_c\right] - R_{c_{0i}}\left[\left(\delta - \xi_{0i} - \frac{\Delta}{2}\right)T_c\right] R_{c_{0j}}\left[\left(\delta - \xi_{0j} - \frac{\Delta}{2}\right)T_c\right] \tag{3c}$$

In equations (3a) to (3c):

$\xi_{0i}(t) = \dfrac{\tau_0(t) - \tau_i(t)}{T_c}$:	normalized differential delay between the satellite being tracked and the i-th GPS satellite in view of the GPS receiver
δ:	tracking error
$R_{c_{0i}}(\tau) = \dfrac{1}{T}\displaystyle\int_0^T c_0(t)\, c_i(t + \tau)\, \mathrm{d}t$:	code cross-correlation between the 0-th code and the i-th code.

When $i = 0$ equation (3a) results in the well known tracking-loop discriminator S-curve and the contribution from equations (3b) and (3c) is zero. When i is not equal to zero (index corresponding to the satellite being tracked) all the three equations (3a) to (3c) contribute to the noise in the tracking-loop. To compute the co-channel interference power, we obtain the psd.

$I_0(f, f_{ij}^d, \tau_{ij})$, as a function of the differential carrier Doppler (f_{ij}^d) and the differential path delay (τ_{ij}) between the i-th and j-th satellites by taking the Fourier Transform of equation (2). The psd for the co-channel self-interference can be written as in equation (4).

$$
\begin{aligned}
I_0(f,\, f_{ij}^d,\, \tau_{ij}) = {} & \frac{K_1^2}{4\,P_0} \sum_{i=1}^{N} P_i^2 \left| D_{0i}^{IF}\ (f/\nu_{i0}^n) \right|^2 + \\
& \frac{K_1^2}{4\,P_0 T} \sum_{i=1}^{N} P_0\, P_i\, \tau_{i0}^2 \left\{ \left| D_{0i}^{CF}\ (f/\nu_{i0}^n) \right|^2 * \left[\left[\frac{\sin \pi (f - f_{i0}^d)\, \tau_{i0}}{\pi (f - f_{i0}^d)\, \tau_{i0}} \right]^2 + \left[\frac{\sin \pi (f + f_{i0}^d)\, \tau_{i0}}{\pi (f + f_{i0}^d)\, \tau_{i0}} \right]^2 \right] \right\} + \\
& \frac{K_1^2}{4\,P_0 T} \sum_{j=1}^{N} \sum_{i=j+1}^{N} P_j\, P_i\, \tau_{ij}^2 \left\{ \left| D_{ij}^{F}\ (f/\nu_{ij}^n) \right|^2 * \left[\left[\frac{\sin \pi (f - f_{ij}^d)\, \tau_{ij}}{\pi (f - f_{ij}^d)\, \tau_{i0}} \right]^2 + \left[\frac{\sin \pi (f + f_{ij}^d)\, \tau_{ij}}{\pi (f + f_{ij}^d)\, \tau_{ij}} \right]^2 \right] \right\}
\end{aligned} \tag{4}
$$

where the symbol $*$ denotes a convolution operation. f_{ij}^d and τ_{ij} are related to the range rate difference ($\dot{\rho}_i - \dot{\rho}_j$) and the range difference ($\rho_i - \rho_j$) between the i-th and the j-th satellite as follows:

$$
\begin{aligned}
f_{ij}^d &= v_{ij}^n \times f_c \\
&= \frac{v_{ij}}{c} \times f_c \\
&= \frac{\dot{\rho}_i - \dot{\rho}_j}{c} \times f_c
\end{aligned}
$$

$\tau_{ij} = \dfrac{(\rho_i - \rho_j)}{c}$; c is the speed of light. (In the evaluation, the magnitudes of the differential delays are restricted to less than 20 ms.)

The first term in equation (4) is similar to the expression one can obtain for the psd of co-channel self-interference in a linear correlator with data modulation removed. The second and third terms in equation (4) results because of the squaring done in the tracking-loop. The second term corresponds to the interference from the i-th satellite including the data modulation and the third term is due to the intermodulation products of i-th and j-th satellite signals falling within the loop bandwidth. It should be noted that all the terms in equation (4) are functions of Doppler effects and the second and third terms are functions of relative delays as well, among the satellites in view. Also, since the third term is a function of both differential Doppler and delay of all the satellites in view, other than the satellite being tracked, taken in pairs it is also difficult to determine a reasonable worst case to evaluate this term. However, it is believed that the contribution of this term in most of the practical scenarios is insignificant and thus not included in the results presented here. Due to the above-mentioned simplification, the results presented here are somewhat optimistic.

The equivalent C/N_0 can be written as:

$$C/N_0 = 10 \log (P/(N_0 + I_0 (f, f_{ij}^d, \tau_{ij}))) \tag{5}$$

where :

N_0: single sided thermal noise spectral density

$I_0 (f, f_{ij}^d, \tau_{ij})$: psd of the GPS co-channel self-interference.

In the evaluation of the C/N_0 as a function of satellite geometry, the magnitude of the co-channel interference is found in general to diminish rapidly as the relative Doppler frequency between satellites increases. This supports the assumption made in deriving equation (2).

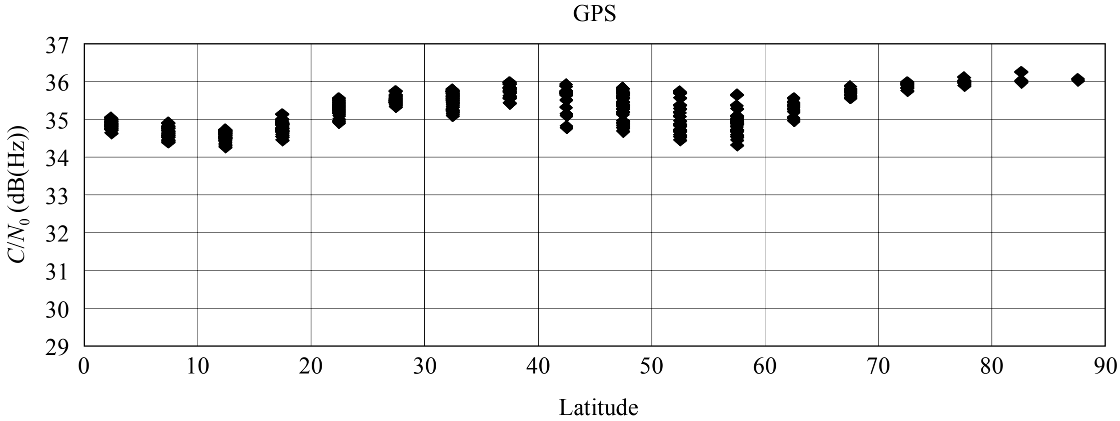
3.2 Sample results

The results presented here consider only the GPS co-channel self-interference. The thermal noise level used into the receiver is assumed to be –201.5 dB(W/Hz). The specified GPS signal power for the C/A-code into a 0 dBic gain antenna is –160 dBW. (No allowance is made for correlator loss.) The GPS antenna model used assumes a minimum gain at 5° elevation angle of – 4.5 dB and a maximum gain at zenith of 3 dB. The C/N_0 associated with acquisition (assured initial or re-acquisition of a GPS satellite signal in a timely manner) is 34 dB(Hz). A GPS constellation-driven model of the satellite orbits and an antenna specification mentioned earlier are used to model all, including short duration, effects of interference. The differential Doppler shifts, differential delays and the received power levels from all the GPS satellites in view are obtained from the constellation-driven model and are used in conjunction with equation (5) to determine the resulting C/N_0.

In Fig. 3, the minimum C/N_0 available at the receiver as a function of user's latitude and longitude is plotted. This data was generated using a five degree-latitude, equal-area approximate grid over the northern hemisphere, using a two-minute temporal time-step over a 24-h period. Also note that due to the inherent symmetry, the data for the southern hemisphere is approximately identical to that of the northern hemisphere. For each ground point, only the minimum (worst case) C/N_0 over all satellites in the 24-h period is recorded. Each minimum is plotted against the corresponding latitude of the ground point. Thus, the dispersion of points at equal latitudes represents the variation in the minimum received C/N_0 experienced by receivers with differing longitudes. The results show that the minimum C/N_0 level for GPS operation (without any interference from other signal sources) is adequate to meet the criteria for both acquisition and tracking.

FIGURE 3

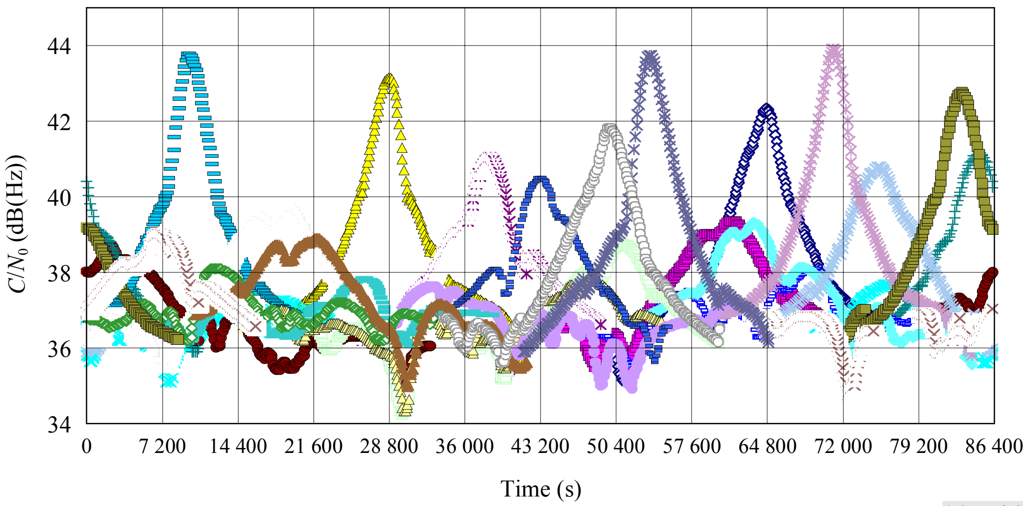
Worst-case C/N_0 for a global simulation of GPS co-channel self-interference as a function of user latitude



The C/N_0 available to a GPS receiver as a function of time over a 24-h period is plotted in Fig. 4 for a user located in the vicinity of 12.5° latitude and –96° longitude (worst case from Fig. 3). Multiple plots in this Figure represent the C/N_0 of different GPS satellites visible from that location.

FIGURE 4

GPS co-channel self-interference at the worst-case location as a function of time

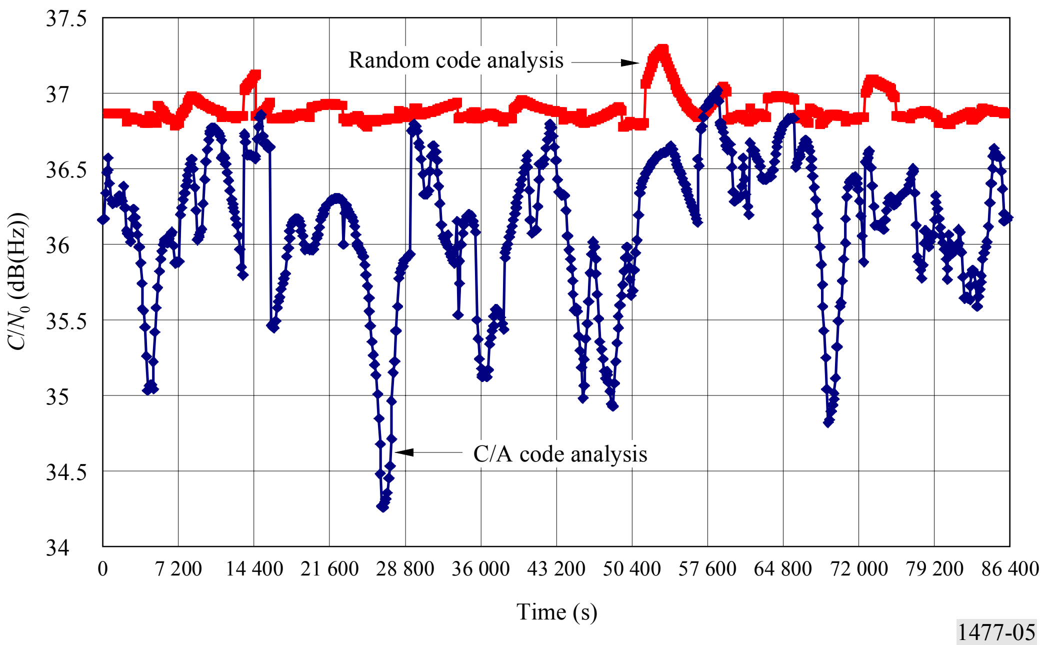


From Figs. 3 and 4 it can be seen that despite the fact that co-channel self-interference from all the visible GPS satellites is included the minimum C/N_0 for all the user locations on the globe and for all time is above the acquisition threshold C/N_0 of 34 dB(Hz). Furthermore, an examination of Fig. 4 indicates that there are two occurrences of minimum C/N_0 being within 1 dB of acquisition threshold (34 dB(Hz)). This indicates a potential for loss of acquisition capability, for at least one satellite, in the presence of additional interference from external sources. Each occurrence lasts for a period of 10 to 15 min. In the first occurrence, time around 30 000 s, two or possibly three of the eight satellites visible fall within this range and in the second occurrence, around 72 000 s, one of the seven visible satellites fall within this range. For a different user location, the time and duration of this event may vary, although the variation is not expected to be very large.

For the sake of comparison, the envelope of minimum C/N_0 for the satellites in view, based on both the random code as well as the exact C/A-code, are plotted in Fig. 5. The curve corresponding to the random code analysis is nearly constant since it is based on the –61.5 dB interference level with respect to the carrier power as discussed earlier. The slight variation seen in this plot is due to antenna gain changes with the changing lines-of-sight to the satellites as a function of time. In contrast, the curve corresponding to the C/A code analysis includes all the effects of differential Doppler, differential delays, data modulation and antenna gain changes as a function of time resulting in a reduction of minimum C/N_0 ranging from 0 dB to 2.5 dB. Results presented in Figs. 4 and 5 clearly indicate the difference in minimum C/N_0 with and without including differential Doppler and delay effects in the analysis can be considerable. Therefore, in any interference analysis performed in consideration of frequency sharing must include all the signal effects as described in this Annex.

FIGURE 5

Comparison of co-channel self-interference for random and C/A-code signals



4 Conclusion

The analysis methodology described in this Annex incorporates a more accurate description of C/A-code co-channel self-interference than that using a random code model. Both methods of analysis show that GPS service is available at all times. The effect of this worst-case analysis is that there are limited location and time dependent effects that may reduce the margin for external sources of interference. (The applicability of this model to high-availability safety-of-life uses of GPS is contrasted with other users of GPS, such as spaceborne platforms, for which an analysis using an average level of co-channel self-interference may suffice.) A sample case is presented showing that, for the worst-case location, there are two instances when the noise effect on one or two satellites is within 1 dB of the acquisition threshold.

Annex 2

Characteristics of the RNSS receivers operating in the GLONASS system and its augmentations

This Annex describes several types of current and prospective aeronautical receivers of the GLONASS system. Each of them could be modified for terrestrial or maritime applications.

The receiver of the first type is designed for operation in the civil aviation for en-route navigation and Category I approach stages. The receiver is intended to operate using the GLONASS system standard accuracy signals (SAS) transmitted at frequencies $K = –7, ..., 0, 1, ..., 12$.

The receiver of the second type is designed for operation in the civil aviation for en-route navigation and Category I approach stages. The receiver is intended to operate using the GLONASS system SAS signals transmitted at frequencies $K = –7, ..., 0, 1, ..., 4$.

The receiver of the third type is designed for operation in the civil aviation for en-route navigation and Category I approach stages using the SBAS-GLONASS (see Note 1) system. The receiver is intended to operate using the GLONASS system SAS signals transmitted at frequencies $K = –7, ..., 0, 1, ..., 4$ and with SAS-signals from satellites of the SBAS-GLONASS system, those signals would be transmitted at frequencies $K = 5, ..., 9$.

NOTE 1 – SBAS: Satellite-based augmentation system. A wide coverage augmentation system in which the user receives augmentation information directly from a satellite-based transmitter. The SBAS-GLONASS system SAS signals are expected to be transmitted from geostationary satellites after 2005 in the frequency band 1 605-1 607.5 MHz.

The receiver of the fourth type is designed for operation in the civil aviation for en-route navigation and Category I/II/III approach stages using the SBAS-GLONASS and GBAS (see Note 2) systems. The receiver is intended to operate using the GLONASS system SAS signals transmitted at frequencies $K = –7, ..., 0.1, ..., 4$, SAS signals from the SBAS-GLONASS system to be transmitted at frequencies $K = 5, ..., 9$ and SAS signals transmitted at frequencies $K = -12, ..., – 8$ from pseudolites (see Note 3).

NOTE 2 – GBAS: Ground-based augmentation system. An augmentation system in which the user receives augmentation information directly from a ground-based transmitter.

NOTE 3 – Pseudolites are terrestrial transmitters to transmit SAS signals with the GLONASS-type signal characteristics.

The receiver of the fifth type is designed for operation in the civil aviation for en-route navigation and Category I/II/III approach stages using the SBAS-GLONASS and GBAS (ground-based) systems. The receiver is intended to operate using the GLONASS system of precision (high) accuracy (navigation) signals (PAS) being transmitted at frequencies $K = –7, ..., 0, 1, ..., 4$, the SBAS-GLONASS system SAS signals to be transmitted at frequencies $K = 5, ..., 9$ and SAS signals transmitted at frequencies $K = –12, ..., –8$ from pseudolites.

To meet the accuracy requirements imposed by the approach stage of flight in civil aviation the GLONASS receivers are fitted with correlators having narrow gates (strobes) and gates of special form.

TABLE 4

The GLONASS system receivers of the first type

L1 carrier frequencies	$F_{K1} = f_{01} + K\,\Delta f_1$ where: f_{01} = 1 602 MHz Δf_1 = 0.5625 MHz K = –7, ..., 12
Code chip rate in the GLONASS SAS-signal	511 kbit/s
Navigation data rate in the GLONASS system	50 bit/s
Minimum received power level of SAS signal at antenna input	–161 dBW
Minimum antenna gain towards satellite at 5° elevation	–4.5 dBic
Maximum antenna gain in the upper hemisphere	+7 dBic
Antenna gain in the lower hemisphere	–10 dBic
Frequency bandwidth of RF filter at 3 dB level with centre at 1 603.406 MHz	25.1 MHz
Frequency bandwidth of pre-correlator filter at 3 dB level with centre at 1 603.406 MHz	20.91 MHz
Overload recovery time	1-5 μs
Receiver noise temperature	400 K
Receiver aggregate narrow-band interference threshold in track mode(1), (2)	–149 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(1), (2)	–155 dBW
Receiver aggregate wideband interference threshold in track mode(1), (2)	–146 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(1), (2)	–152 dB(W/MHz)

(1) The interference threshold already takes into account the effects of GLONASS intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

(2) For GLONASS receivers the resistance to interference is measured with respect to the following performance parameters: tracking error (1 σ) 0.8 m, word error rate 1 in 10^4 words. This tracking error does not include contributions due to signal propagation as multipath, tropospheric and ionospheric effects as well as ephemeris and GLONASS satellite clock errors.

TABLE 5

The GLONASS system receivers of the second type

L1 carrier frequencies(1)	$F_{K1} = f_{01} + K\,\Delta f_1$ where: f_{01} = 1 602 MHz Δf_1 = 0.5625 MHz K = –7, ..., 4
Code chip rate in the GLONASS SAS-signal	511 kbit/s
Navigation data rate in the GLONASS system	50 bit/s
Minimum received power level at antenna input in the GLONASS system	–161 dBW
Minimum antenna gain towards a GLONASS satellite at 5° elevation	–4.5 dBic
Maximum antenna gain in the upper hemisphere	+7 dBic
Antenna gain in the lower hemisphere	–10 dBic
Frequency bandwidth of RF filter at 3 dB level with centre at 1 601.156 MHz	19.69 MHz
Frequency bandwidth of pre-correlator filter at 3 dB level with centre at 1 601.156 MHz	16.41 MHz
Overload recovery time	1-5 μs
Receiver noise temperature	400 K
Receiver aggregate narrow-band interference threshold in track mode(2), (3)	–149 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–155 dBW
Receiver aggregate wideband interference threshold in track mode(2), (3)	–146 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–152 dB(W/MHz)

(1) The presented receivers are intended for reception of GLONASS SAS-signals at frequencies K = –7, ..., 0, 1, ..., 4.

(2) The interference threshold already takes into account the effects of GLONASS intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

(3) For GLONASS receivers the resistance to interference is measured with respect to the following performance parameters: tracking error (1 σ) 0.8 m, word error rate 1 in 10^4 words. This tracking error does not include contributions due to signal propagation as multipath, tropospheric and ionospheric effects as well as ephemeris and GLONASS satellite clock errors.

TABLE 6

The GLONASS system receivers of the third type

L1 carrier frequencies(1)	$F_{K1} = f_{01} + K\,\Delta f_1$ where: f_{01} = 1 602 MHz Δf_1 = 0.5625 MHz K = –7, ..., 9
Code chip rate in the GLONASS SAS-signal	511 kbit/s
Code chip rate in SAS-signal of the SBAS-GLONASS system	511 kbit/s
Navigation data rate in the GLONASS system	50 bit/s
Navigation data rate, SBAS-GLONASS, with FEC, rate 1/2	500 symbols/s
Word error rate (1 word is equal to 250 information bits) for the SBAS-GLONASS system	1×10^{-3}
Minimum received power level at antenna input in the GLONASS system	–161 dBW
Minimum received power level at antenna input in the SBAS-GLONASS system	–161 dBW
Minimum antenna gain towards a GLONASS satellite at 5° elevation	–4.5 dBic
Minimum antenna gain towards an SBAS-GLONASS satellite at 5° elevation	–4.5 dBic
Maximum antenna gain in the upper hemisphere	+7 dBic
Antenna gain in the lower hemisphere	–10 dBic
Frequency bandwidth of RF filter at 3 dB level with centre at 1 601.156 MHz	19.69 MHz
Frequency bandwidth of pre-correlator filter at 3 dB level with centre at 1 601.156 MHz	16.41 MHz
Overload recovery time	1-5 µs
Receiver noise temperature	400 K
Receiver aggregate narrow-band interference threshold in track mode(2), (3)	–149 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–155 dBW
Receiver aggregate wideband interference threshold in track mode(2), (3)	–146 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–152 dB(W/MHz)

(1) The presented receivers are intended for reception of GLONASS SAS-signals at frequencies K = –7, ..., 0, 1, ..., 4 and SBAS-GLONASS SAS-signals at frequencies K = 5, ..., 9.

(2) The interference threshold already takes into account the effects of GLONASS intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

(3) For GLONASS receivers the resistance to interference is measured with respect to the following performance parameters: tracking error (1 σ) 0.8 m, word error rate 1 in 10^4 words. This tracking error does not include contributions due to signal propagation as multipath, tropospheric and ionospheric effects as well as ephemeris and GLONASS satellite clock errors.

TABLE 7

The GLONASS system receivers of the fourth type

L1 carrier frequencies[1]	$F_{K1} = f_{01} + K\,\Delta f_1$ where: f_{01} = 1 602 MHz Δf_1 = 0.5625 MHz K = –12, ..., 9
Code chip rate in the GLONASS SAS-signal	511 kbit/s
Code chip rate in SAS-signal of the SBAS-GLONASS system	511 kbit/s
Code chip rate in SAS-signal from pseudolites	511 kbit/s
Navigation data rate in the GLONASS system	50 bit/s
Navigation data rate, SBAS-GLONASS, with FEC, rate 1/2	500 symbols/s
Word error rate (1 word is equal to 250 information bits) for the SBAS-GLONASS system	1×10^{-3}
Navigation data rate in the pseudolite	50 bit/s
Minimum received power level in the GLONASS system at antenna input	–161 dBW
Minimum received power level in the SBAS-GLONASS system at antenna input	–161 dBW
Minimum received power level from pseudolites at antenna input	–161 dBW
Minimum mean power level of signals from pseudolites at antenna input	–140 dBW
Minimum antenna gain towards a GLONASS satellite at 5° elevation	–4.5 dBic
Minimum antenna gain towards an SBAS satellite at 5° elevation	–4.5 dBic
Minimum antenna gain towards a pseudolite	–21 dBic
Maximum antenna gain in the upper hemisphere	+7 dBic
Antenna gain in the lower hemisphere	–10 dBic
Frequency bandwidth of RF filter at 3 dB level with centre at 1601.156 MHz	19.69 MHz
Frequency bandwidth of pre-correlator filter at 3 dB level with centre at 1601.156 MHz	16.41 MHz
Overload recovery time	1-5 µs
Receiver noise temperature	400 K
Receiver aggregate narrow-band interference threshold in track mode[2], [3]	–149 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode[2], [3]	–155 dBW
Receiver aggregate wideband interference threshold in track mode[2], [3]	–146 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode[2], [3]	–152 dB(W/MHz)

(1) The presented receivers are intended for reception of GLONASS SAS-signals at frequencies $K = -7, ..., 0, 1, ..., 4$, SBAS-GLONASS SAS-signals at frequencies $K = 5, ..., 9$ and pseudolite SAS-signals at frequencies $K = -12, ..., -8$.

(2) The interference threshold already takes into account the effects of GLONASS intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

(3) For GLONASS receivers the resistance to interference is measured with respect to the following performance parameters: tracking error (1 σ) 0.8 m, word error rate 1 in 10^4 words. This tracking error does not include contributions due to signal propagation as multipath, tropospheric and ionospheric effects as well as ephemeris and GLONASS satellite clock errors.

TABLE 8

The GLONASS system receivers of the fifth type

L1 carrier frequencies(1)	$F_{K1} = f_{01} + K\,\Delta f_1$ where: f_{01} = 1 602 MHz Δf_1 = 0.5625 MHz K = –12, ..., 9
Code chip rate in the GLONASS PAS-signal	5.11 Mbit/s
Code chip rate in SAS-signal of the SBAS-GLONASS system	511 kbit/s
Code chip rate in SAS-signal from pseudolites	511 kbit/s
Navigation data rate in the GLONASS system	50 bit/s
Navigation data rate, SBAS-GLONASS, with FEC, rate 1/2	500 symbols/s
Word error rate (1 word is equal to 250 information bits) for the SBAS-GLONASS system	1×10^{-3}
Navigation data rate in the pseudolite	50 bit/s
Minimum PAS received power level in the GLONASS system at antenna input	–161 dBW
Minimum SAS received power level in the SBAS-GLONASS system at antenna input	–161 dBW
Minimum SAS received power level from pseudolites at antenna input	–161 dBW
Minimum mean power level of signals from pseudolites at antenna input	–140 dBW
Minimum antenna gain towards a GLONASS satellite at 5° elevation	–4.5 dBic
Minimum antenna gain towards an SBAS satellite at 5° elevation	–4.5 dBic
Minimum antenna gain towards a pseudolite	–21 dBic
Maximum antenna gain in the upper hemisphere	+7 dBic
Antenna gain in the lower hemisphere	–10 dBic
Frequency bandwidth of RF filter at 3 dB level with centre at 1 601.156 MHz	19.69 MHz
Frequency bandwidth of pre-correlator filter at 3 dB level with centre at 1 601.156 MHz	16.41 MHz
Overload recovery time	1-5 μs
Receiver noise temperature	400 K
Receiver aggregate narrow-band interference threshold in track mode(2), (3)	–149 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(2), (3)	–155 dBW
Receiver aggregate wideband interference threshold in track mode(2), (3)	–146 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(2), (3)	–152 dB(W/MHz)

(1) The presented receivers are intended for reception of GLONASS PAS-signals at frequencies K = –7, ..., 0, 1, ..., 4, SBAS-GLONASS SAS-signals at frequencies K = 5, ..., 9 and pseudolite SAS-signals at frequencies K = –12, ..., –8.

(2) The interference threshold already takes into account the effects of GLONASS intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

(3) For GLONASS receivers the resistance to interference is measured with respect to the following performance parameters: tracking error (1 σ) 0.8 m, word error rate 1 in 10^4 words. This tracking error does not include contributions due to signal propagation as multipath, tropospheric and ionospheric effects as well as ephemeris and GLONASS satellite clock errors.

Annex 3

E-NSS-1 receiver characteristics

Table 9 provides characteristics of radionavigation-satellite receivers for use in the band 1 559-1 610 MHz with the planned E-NSS-1 system for aeronautical, maritime and land applications.

These receivers are also planned for operation in the 1 215-1 260 MHz band.

TABLE 9

Frequency range	1 587.696-1 591.788 MHz (E1) 1 559.052-1 563.144 MHz (E2)
Carrier frequencies	1 589.742 MHz (E1) 1 561.098 MHz (E2)
PN code rates	3.069 Mchip/s (E1 and E2)
Antenna coverage	Hemispherical
Antenna peak gain (zenith)	3 dBi
Antenna minimum gain (5° elevation)	–4.5 dBi
Receiver system noise temperature	350 K
Minimum received signal power at antenna output	–157.3 dBW
C/N_0 required for precision navigation	41.2 dB(Hz)
Receiver aggregate wideband interference threshold[(1)]	–141.3 dBW in any 1 MHz
Receiver aggregate narrow-band interference threshold[(1)]	–151.3 dBW

[(1)] The interference threshold already takes into account the effects of E-NSS-1 intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

Annex 4

LSATNAV/MSATNAV receiver characteristics

The LSATNAV constellation is based on a combination of two types of satellites: the main constellation is a constellation of low-Earth orbit (LEO) satellites which is augmented by GSO satellites. Similarly, the MSATNAV architecture comprises a constellation of medium-Earth orbit (MEO) satellites which could be augmented by GSO satellites. These GSO satellites can be, on the one hand, satellites currently used in SBASs (GPS-like signals at 1 575.42 MHz GPS frequency, modulated with data using a symbol rate of 500 bit/s), or on the other hand, LSATNAV/MSATNAV dedicated GSO satellites (signal at LSATNAV/MSATNAV frequency modulated with data using a symbol rate of 500 bit/s).

A LSATNAV/MSATNAV receiver is basically composed with:

– an omnidirectional antenna able to receive all visible LSATNAV/MSATNAV satellite signals and L1-GPS-SBAS;

– a receiver/signal processor;

– a navigation processing and input/output devices.

The operational requirements need to meet ICAO SARPs and are, in the first case, equivalent to those of SBAS-GPS receivers. These SBAS receivers are land, maritime and aeronautical receivers designed to provide basic level of service.

In the second case, the operational requirements are required to meet ICAO SARPs and are equivalent to those of GBAS-GPS receivers. However, the GBAS receivers characteristics are not included in this Annex.

In both cases, in order to provide the expected accuracy, the receiver/signal processing must be able to process dual frequency measurements for ionospheric corrections, and must be able to process a narrow chip-spacing correlation in code tracking loop.

In this Annex the technical characteristics of SBAS LSATNAV/MSATNAV receiver are detailed.

In Table 10 description power levels at the antenna input refer to the power that would be received by an isotropic, circularly polarized antenna of the proper polarity, while power levels at the antenna output refer to the power levels that account for the antenna gain in the direction of the specific signal or interference source.

TABLE 10

SBAS LSATNAV/MSATNAV air navigation receiver, basic level of service

L1 carrier centre frequency	1 575.420 MHz 1 589.742 MHz 1 561.098 MHz
L2 carrier centre frequency	1 216.347 MHz 1 217.370 MHz 1 258.290 MHz
C/A code chip rate	1.023 Mbit/s
Navigation data rate, GPS	50 bit/s
Navigation data rate, SBAS, with FEC, rate 1/2	500 symbols/s
Minimum received power level at antenna input (SBAS)	–161 dBW
Minimum antenna gain towards satellite at 5° elevation	– 4.5 dBic
Maximum antenna gain in upper hemisphere	+7 dBic
Assumed antenna gain in lower hemisphere	–10 dBic
Receiver noise figure	4.4 dB
Receiver aggregate narrow-band interference threshold in track mode(1)	–150.5 dBW
Receiver aggregate narrow-band interference threshold in acquisition mode(1)	–156.5 dBW
Receiver aggregate wideband interference threshold in track mode(1)	–140.5 dB(W/MHz)
Receiver aggregate wideband interference threshold in acquisition mode(1)	–146.5 dB(W/MHz)

(1) The interference threshold already takes into account the effects of LSATNAV/MSATNAV intra-system interference based on random code analysis. The threshold must account for all other aggregate interference.

Annex 5

Margin for safety of life radionavigation applications

1 Introduction

There is a long history of reserving a portion of the interference link budget for a margin in order to ensure that the radionavigation service is protected. These margin values typically lie in the range of 6 to 10 dB, or more. Furthermore, there is ample precedent for a safety margin for radionavigation safety services in the ITU, e.g. a former ITU-R Report stated:

"Regardless of the original intentions of radio spectrum planners, there can be no doubt that the pressure on the radio spectrum for additional allocations to the various radio communication services can result in aeronautical protection criteria being effectively regarded as non-aeronautical sharing criteria. As a consequence, a safety service must take considerable precautions to ensure that any radio service sharing the same radio band is constrained sufficiently to leave an adequate margin under all likely circumstances so that the aggregate harmful interference never exceeds the required protection criteria."

Also, Recommendation ITU-R M.1318 – Interference protection evaluation model for the radionavigation-satellite service in the 1 559-1 610 MHz band, contains, in its Annex 1, a model for the evaluation of radionavigation-satellite interference. That model specifies the need for a factor called: extra margin of protection (dB). Its description states Extra margin to ensure protection against factors like multipath.

2 Purpose of safety margin

A safety margin, (which may also be called a public safety factor), is critical for safety-of-life applications in order to account for risk of loss of life due to radio-frequency interference that is real but not quantifiable. To support safety of life applications, all interference sources must be accounted for.

3 Applications of safety margin

The utilization of safety margins in navigation systems is well established. ICAO Annex 10 (Attachment G, Table G-2) specifies a safety margin for the microwave landing system (MLS) of 6 dB. The instrument landing system (ILS) applies a safety margin of 8 dB (see Recommendation ITU-R SM.1009, Appendix 3 to Annex 2). In each case the margin is defined with respect to the navigation system carrier power. That is, to test system performance for these systems, the signal power is reduced from the nominal level by the safety margin, then tested to determine whether the system provides the required performance in the presence of interference. In other words, the manufacturer must design the equipment to handle the highest anticipated interference level while receiving a desired signal level lower (by the safety margin) than would be otherwise received. With GNSS this approach is not possible, because reducing the carrier power by 6 dB or more below the designed power would result in satellites being dropped in the tracking algorithm of the receiver. This is because the received GNSS satellite power is relatively fixed, and thus terrestrial receivers operate over a small dynamic range.

As with MLS and ILS, the approach used by GNSS defines a level of interference that the manufacturer must be able to handle within the performance specifications, and defines a level less than this by the safety margin that is the highest anticipated interference level.

For GNSS, the critical receiver performance term is the C/N. It is the ratio of the carrier power C (dBW) to the total noise power spectral density N_T (dB(W/Hz)). For the GNSS, the resulting improvement in the C/N is much less than the safety margin itself. For example, a safety margin as defined for GNSS of 6 dB (i.e. the interference must be reduced by 6 dB) results in a C/N increase of only 2.48 dB. In comparison, for MLS and ILS the increase in C/N would be equal to the safety margin, i.e. 6 dB in this case.

4 GNSS safety margin

The allowable non-aeronautical interference level must be significantly below the design interference threshold by the safety margin. A safety margin of 5.6 dB was used in the development of the –70 dB(W/MHz) limit adopted in Recommendation ITU-R M.1343. However, for general application this margin is adjusted slightly to 6 dB, which brings it into the range of safety service margins which have been adopted by the ITU-R for other safety-of-life applications, as highlighted above. Specifically, interference to GNSS SBAS is accounted for in the following way:

For Category I precision approach SBAS air navigation receivers (see Annex 1) the interference threshold is −140.5 dB(W/MHz). The components of the interference threshold include: receiver thermal noise and satellite intra-system interference based on random code analysis. A safety margin is then included to account for aeronautical design uncertainties; future GNSS self-interference (e.g. pseudolites); unknown interference sources (e.g. industrial RF interference (RFI)); and intra-system based on analysis of specific codes. Based on the interference threshold and the safety margin the allowable interference is –146.5 dB(W/MHz). This value must protect against aggregate non-aeronautical interference.

In case there is a potential for more than one source of interference at the same time, it will be necessary to apportion the –146.5 dB(W/MHz) among the potential interference sources. Considering the situation where a GNSS receiver is subject to the maximum interference caused by an MSS MES at a separation distance of 30 m (as was assumed when developing Recommendation ITU-R M.1343), there is no room left for additional interference. This single MES provides for the maximum aggregate interference at the GNSS receiver input.

In the case of the situation above, when additional non-transient interference sources are limited to a value of 10 dB below –70 dB(W/MHz), the aggregate interference to GNSS will increase with a value of 0.5 dB.

When the GNSS receiver is in the acquisition mode it is 6 dB less immune to interference. The permissible aggregate interference level must be reduced correspondingly to protect this mode of operation. In setting the maximum levels for unwanted emissions from MESs operating in non-GSO mobile-satellite systems, only the tracking mode was considered as the effects of interference from these MESs were considered to be transitory.

It is noted that GNSS receivers require an additional protection of 10 dB when the interfering signal is 700 Hz or less in bandwidth.

An aeronautical safety margin of at least 6 dB is required to protect the safety-of-life applications of GNSS. Additional margins may be required, depending on:

– the operational requirements for RNSS including accuracy, availability, continuity and integrity;
– operational environment including terrain and weather;
– the configuration of RNSS including augmentations;
– the effects of the statistics on all parameters used in interference analyses unless the worst-case conditions are assumed; and

– RFI sources that are not specifically included in the interference analysis but that may have a potential to contribute to the interference of GNSS.

5 Interference risk allocation

Interference analyses employed for communications networks which are based on service unavailability are not applicable for safety-of-life services because an outage for such a service is not acceptable if it is in excess of a rate of 1×10^{-6}/h (see below). In addition, they do not address the effects on spurious emissions, of aging or malfunctioning equipment, and unit-to-unit performance variations. Also, there is the temptation to discount the impact of interference sources that do not routinely occur. However, the aeronautical community attempts to quantify the risks associated with events that could cause outages or misleading information, even those which may be considered very unlikely.

Aeronautical equipment must be designed to handle very rare events on the assumption that they will indeed occur. Given the millions of flight hours flown by civil aircraft each year, the probability of a very rare (1×10^{-6}/h) event occurring somewhere during the year is a virtual certainty. It is important to recognize that the risk created by interference must be assessed when conducting interference analyses.

The ICAO standards for GNSS SBAS and GBAS airborne receivers require the annunciation of a navigation alert when the RFI receiver susceptibility level is exceeded. The GNSS risk analysis allocates a 1×10^{-5} per approach loss of continuity for non-GNSS interference for Category I approaches. The intent of the continuity requirement is to limit the RFI events to one in 100 000 approaches. During precision approaches the 6 dB aeronautical safety margin may be consumed by variations in the GNSS *C*/*N*, as indicated in § 2. Therefore any increase in the aggregate non-aeronautical interference above the –146.5 dB(W/MHz) limit (from the example used in § 4) would cause a loss of continuity event at the GNSS receiver. Similarly any increase in the GNSS intra-system interference such that the 6 dB safety margin is exceeded, would also cause a loss of continuity event at the GNSS receiver in the presence of an RFI signal at the interference threshold. Precedence for this interpretation is the ITU margin definition given for ILS in § 2. As stated there, the RFI is evaluated at minimum *C*/*N* conditions at selected spatial points in the ILS coverage volume. In other words, no credit is assigned the interfering signal because of the existence of the safety margin.

6 Compliance considerations

Any proposal to share an ARNS/RNSS band must include consideration of the failure modes of the proposed service. The proposal must identify any faults that might present a threat to the native safety service and describe how such modes would be detected. It must also discuss how users of the safety service will be notified and analyse the time-to-alarm of such notification. The proposal must also describe how the salient features of any relevant failure will be archived for later analysis. Such faults would include excursions in the radiated inband or out-of-band power. They would also include deviations in the radiated spectrum –narrow-band versus wideband, for example.

The proposal must also detail how the proposed safety margin would be maintained through all relevant operational scenarios. These analyses would include path loss calculations from the proposed service to all users of the safety service. These analyses would need to consider all likely proximities of the proposed service to aircraft, ships and land emergency users of the safety service. They would also need to reasonably consider the possible multiplicity of interference sources. The proposal must also consider the likely proximity of the proposed service to fixed radio assets used by the safety service.

Finally, the proposal would need to consider the impact on recent or planned additions to the safety service.

7 Conclusions

7.1 The 6 dB GNSS safety margin results in only a 2.48 dB *C*/*N* margin based on a receiver noise figure of 4.4 dB. This *C*/*N* value is less than the safety margins for other ICAO defined navigation systems, but within the range of margins accepted within the ITU-R for safety services.

7.2 The safety assessment by the radionavigation services requires that the probability of a non-aeronautical RFI source exceeding its protection limit should be less than one in 100 000 Category I approaches. This loss-of-continuity risk is not included in the GNSS safety margin.

7.3 The allowable level of non-aeronautical interference is a fixed number, and represents the aggregate interference from all known sources. If new services are established, their emissions must be restricted in order not to exceed the allowable aggregate level.