RECOMMENDATION ITU-R SA.1157-1

Protection criteria for deep-space research

(1995-2006)

Scope

This Recommendation specifies the protection criteria needed to success fully control, command and operate manned and unmanned research satellites in deep space, that is, satellites conducting their assigned missions in the volume of space more distant from Earth than 2 million km.

The ITU Radiocommunication Assembly,

considering

a)	that manned deep-space research has unique requirements for extreme reliability of radiocommunications so as to ensure safety of life;

b)	that both manned and unmanned deep-space research have unique requirements for extreme reliability of radiocommunications so as to ensure successful reception of valuable scientific data collected at particular critical times, and that repeated transmission of these data is often not possible;

c)	that the extreme sensitivity of deep-space earth stations results in unusually low levels of permissible interference;

d)	that protection criteria have been derived as shown in Annex 1 for deep-space research earth stations and for stations in deep-space;

e)	that interference susceptibility has been derived as shown in Annex 2,

recommends

1	that protection criteria for deep-space research earth stations should be established as follows:

-222 dB(W/Hz) in bands near 2 GHz,

-221 dB(W/Hz) in bands near 8 GHz,

-220 dB(W/Hz) in bands near 13 GHz,

-217 dB(W/Hz) in bands near 32 GHz;

2	that protection criteria for stations on spacecraft in deep-space should be established as follows:

-193 dB(W/20 Hz) in bands near 2 GHz,

-190 dB(W/20 Hz) in bands near 7 GHz,

-186 dB(W/20 Hz) in bands near 17 GHz,

-183 dB(W/20 Hz) in bands near 34 GHz;

3	that calculation of interference that may result from atmospheric and precipitation effects should be based on weather statistics that apply for 0.001% of the time (see § 2.3 of Annex 1).

Annex 1

Protection criteria for deep-space research

1   Introduction

This Annex establishes protection criteria for deep-space research. These criteria may be used in calculations of coordination distance and for other analysis. The protection criteria are also relevant to studies of sharing within the space research service. Potential interference with other services is considered and conclusions are drawn about the feasibility of sharing. Future relay satellites for use in deep-space missions are not considered in this Annex.

The protection criteria are based on the susceptibility of receivers typically used for deep-space research, as described in Annex 2.

1.1   Interference effects and consequences

The consequence of interference that impairs the proper functioning of an earth-station or space-station receiver can be a reduction or interruption in the ability to navigate and control a spacecraft, and in the ability to receive scientific and engineering data sent by a spacecraft.

The receiver contains several synchronization loops, each of which locks to, and tracks, a particular signal component. With sufficiently strong interference, one or more of the several loops will lose lock on the desired signal. Momentary interference can also cause this unlocking and it may take several minutes in the case of the weakest signals to regain lock. During the critical periods that occur during most deep-space missions, it is essential to transmit and receive scientific data without error or interruption. Loss of lock during these periods results in irretrievable data loss. It is this characteristic that leads to such severe requirements for protection from interference. In contrast, the data communicated by some other radio services are often available for retransmission.

For some modes of operation, the loop bandwidths are unusually narrow. A particular example is the carrier tracking loop in the earth-station receiver. This bandwidth may be as narrow as 1 Hz, and in special circumstances less (300 mHz). It might be concluded that it would be unlikely that an interfering signal would lie exactly within that bandwidth, but it must be remembered that the frequency of the desired signal is Doppler shifted as a result of Earth rotation. For example, an 8.4 GHz signal will be shifted ±11 kHz when received by an earth station located at a latitude of 35°. An interfering signal with a fixed frequency that is anywhere within the Doppler-shifted range of the deep-space signal will sweep through the carrier tracking loop bandwidth, and unlocking can result. In addition, interference does not have to be exactly within the loop bandwidth in order to affect the loop. As long as the interference frequency is near the loop bandwidth, and has sufficient power, severe degradation is possible. Interference that is remote from the loop bandwidth can also cause degradation through other mechanisms, such as maser saturation.

1.2   Development of protection criteria

To ensure the proper operation of the entire receiving system, each of the four subsystems must be protected against interference. A protection criterion specifies the amount of interference power that will result in a maximum acceptable degradation of performance. The maximum acceptable degradation for each subsystem is given in Table 1. Using these values, the corresponding maximum allowable interference may be determined.

In the following sections of this Annex, protection criteria are developed. For each of the several receiver subsystems, there is a maximum acceptable performance degradation as caused by interference. The amount of interference that can cause such degradation is presented in Annex 2. The receiver subsystem that is most sensitive to interference determines the maximum allowable interference. This amount is the protection criterion for the receiver. Greater interference is harmful.

TABLE 1

Maximum acceptable degradation of receiving subsystems

Receiving subsystem	Maximum acceptable degradation
Maser pre-amplifier	1 dB gain compression
Carrier tracking	10° loop static phase error or peak phase jitter
Telemetry	1 dB equivalent reduction in symbol energy to noise spectral density ratio ($\Delta E/N_0 = -1$ dB)
Ranging	1 dB equivalent reduction in symbol energy to noise spectral density ratio ($\Delta E/N_0 = -1$ dB)

2   Protection criteria for deep-space earth stations

There are four receiver subsystems that are sensitive to interference: maser pre-amplifier, carrier tracking loop, telemetering subsystem and ranging subsystem.

2.1   Maximum acceptable performance degradation

The gain of a maser pre-amplifier is reduced as a function of the input power for very strong signals or interference. This gain compression results in non-linear operation. Strong interference can thus produce non-linear effects on the desired signal, including generation of spurious signals. The maximum acceptable gain compression is considered to be 1 dB. The use of gain compression as a measure of non-linear effects is common practice.

The response of the carrier tracking loop to interference is an increase in phase error and jitter. Sufficiently strong interference can cause loss of lock. The maximum acceptable degradation is considered to be a 10° increase in static phase error or a 10° increase in peak phase jitter.

The degradation of telemetry bit error performance and ranging accuracy as a result of interference can be expressed in terms of a corresponding reduction in signal-to-noise ratio. The maximum acceptable degradation for the telemetry and ranging subsystems corresponds to a 1 dB reduction in the symbol energy-to-noise spectral density ratio.

The maximum allowable interference for each receiver subsystem is derived from the corresponding maximum acceptable degradation. The protection criterion for the entire receiver is the maximum allowable interference for the most sensitive subsystem.

Table 1 summarizes the maximum acceptable performance degradation for each of the four receiver subsystems.

2.2 Interference levels corresponding to maximum acceptable performance degradation

2.2.1 Maser pre-amplifier

Table 2 shows the interference power that causes a 1 dB gain compression in the maser pre-amplifier. The data source is found in Annex 2.

TABLE 2

Maximum allowable interference power for 1 dB gain compression in maser pre-amplifier, 8.4 GHz

Interference type	Data source	Interference for 1 dB gain compression
Continuous wave (CW)	Fig. 2	–114 dBW
Noise (40 MHz bandwidth)	Fig. 2	–190 dB(W/Hz)

2.2.2 Carrier tracking, telemetry and ranging subsystems

2.2.2.1 Interference ratios for carrier tracking, telemetry and ranging

Table 3 shows the interference-to-carrier ratio (I/C) interference-to-signal ratio (I/S) or interference-to-noise ratio (I/N) that corresponds to the acceptable degradation of the carrier tracking, telemetry and ranging subsystems. The ratios are found as follows:

For CW interference, the allowable interference ratio for each subsystem may be found directly from curves given in Annex 2.

For noise-like interference to the carrier tracking loop, Fig. 8 shows that a reduction in carrier margin from 10 dB (the typical minimum operating point) to 5.5 dB results in an additional 10° of phase jitter. The corresponding I/N ratio is given by:

$$I_0/N_0 \;=\; 10 \log \left(10^{(CM_0/10)}/10^{(CM_i/10)} \;-1\right) \qquad \text{dB}$$

where:

$\quad I_0/N_0$: ratio of interference noise spectral density to receiver noise spectral density

$\quad CM_0$: carrier margin (dB) without interference

$\quad CM_i$: carrier margin (dB) with interference.

and carrier margin is the ratio of carrier-power-to-noise-power in the carrier tracking loop.

For noise-like interference to the telemetry and ranging subsystems, the allowable I/N is given by:

$$I_0/N_0 \;=\; 10 \log \left(10^{(\Delta E/N_0)\,/\,10} \;-\; 1\right) \qquad \text{dB}$$

where:

$\quad I_0/N_0$: ratio of interference noise spectral density to receiver noise spectral density

$\quad \Delta E/N_0$: criterion given in Table 1 and the reduction in equivalent symbol energy-to-noise spectral density ratio or signal-to-noise ratio.

TABLE 3

Maximum allowable *I*/*C*, *I*/*S* or *I*/*N* for CW and noise-like interference

Subsystem (criterion)	Interference type	Data source	Maximum interference ratio
Carrier tracking (10° added peak phase jitter)	CW	Fig. 3	$I/C = -15$ dB
	Noise-like	Fig. 8 and calculation	$I_0/N_0 = +2.6$ dB
Telemetry (1 dB reduction in E/N_0 from interference in carrier tracking loop)	CW	Fig. 5	$I/C = -1.5$ dB
Telemetry (1 dB reduction in E/N_0 from interference in telemetry detection bandwidth)	CW	Fig. 4	$I/S = -11$ dB
	Noise-like	Calculated	$I_0/N_0 = -5.9$ dB
Ranging (1 dB reduction in E/N_0 from interference in carrier tracking loop)	CW	Fig. 6	$I/C = -5$ dB
Ranging (1 dB reduction in E/N_0 from interference in range estimator bandwidth)	CW	Fig. 7	$I/S = -7.1$ dB
	Noise-like	Calculated	$I_0/N_0 = -5.9$ dB

2.2.2.2 Maximum allowable interference for carrier tracking, telemetry and ranging

For CW interference, the maximum allowable interference depends upon the *I*/*C* (*I*/*S*) and the minimum carrier (signal) level determined by the receiver design point. If it is assumed that the carrier, telemetry and ranging signal powers are equal, Table 3 shows that the maximum allowable CW interference is dictated by the carrier tracking loop because it requires the smallest *I*/*C*.

For carrier tracking, the minimum carrier-to-noise ratio is 10 dB. The corresponding maximum allowable interference power for noise-like interference is:

$$P_i = N_0 + 10 \log B + 10 + I/C$$

where:

P_i: maximum allowable interference power for carrier tracking (dBW)

N_0: receiver noise spectral density, given in Table 4 (dB(W/Hz))

B: carrier tracking loop bandwidth, taken as 1 Hz

I/C: interference-to-carrier ratio as given in Table 3 (dB).

The results of these calculations are summarized in Table 4.

TABLE 4

Maximum allowable interference power to earth-station receivers

Band (GHz)	Receiver noise spectral density (dB(W/Hz))	Maximum CW interference power (dBW)	Maximum noise-like interference power spectral density (dB(W/Hz))
2.29-2.30	–216.6	–221.6	–222.5
8.40-8.45.	–215.0	–220.0	–220.9
12.75-13.25	–214.6	–219.6	–220.5
31.8-32.3	–211.4	–216.4	–217.3

2.3   Protection criteria for deep-space earth-station receivers

Table 5 gives the maximum allowable interference that will not cause more than the acceptable degradation of earth-station receiver performance. These values are the protection criteria for a deep-space earth-station receiver at the receiver input terminals: greater interference is harmful. Also shown is the corresponding power spectral flux-density at the aperture of a 70 m diameter reflector antenna. The antenna has approximately 70% area efficiency for the lower bands and 40% at 32 GHz.

TABLE 5

Interference protection for deep-space earth-stations

Band (GHz)	Maximum allowable interference power spectral density (dB(W/Hz))	Maximum allowable interference power spectral flux-density (dB(W/m$^2 \cdot$ Hz))
2.29-2.30	–222.5	–257.0
8.40-8.45	–220.9	–255.1
12.75-13.25	–220.5	–254.3
31.8-32.3	–217.3	–249.3

To protect earth-station receivers, the power spectral density of noise-like interference, or the total power of CW interference, should not be greater than the amount shown in Table 5.

To obtain the coordination area surrounding an earth station, propagation due to fluctuating weather conditions must be considered. To limit service outage due to enhanced trans-horizon propagation to less than 5 min during any day of the year, it is necessary to allow for propagation during the worst weather hour in the year and the worst 5 min within that hour. This condition is taken as 0.001% of the time.

Appendix 7 to the ITU Radio Regulations shows application of the 0.001% weather condition leads to a slightly increased coordination distance compared to that necessary for a service able to tolerate greater service outage.

3   Protection criteria for space stations in deep space

Space station and earth-station receivers for deep-space research function in a similar manner, except that the space station does not include a maser. Space stations are susceptible to interference in ways similar to those described earlier for earth stations.

The criterion for protection of deep-space station receivers is that interference power must be no stronger than receiver noise power. Compared to deep-space earth station criteria, this is less severe and is a consequence of generally larger performance margins on the Earth-to-space link. For protection of stations on spacecraft in deep space, the power spectral density of wideband interference, or the total power of CW interference in any 20 Hz band should be no larger than the amount shown in Table 6, at the receiver input terminals: greater interference is harmful. The 20 Hz bandwidth specification is the carrier tracking loop bandwidth of the spacecraft transponder operated with threshold signal strength. The values of noise temperature shown in Table 6 are estimates of currently practical systems that could be used in deep space.

TABLE 6

Interference protection for receivers on spacecraft in deep space

Band (GHz)	Receiver noise temperature (K)	Maximum allowable interference power spectral density (dB(W/20 Hz))
2.11-2.12	200	−192.6
7.145-7.190	330	−190.4
16.6-17.1	910	−186.0
34.2-34.7	2 000	−182.6

Annex 2

# Interference susceptibility of receiving systems for deep-space research

1   Introduction

This Annex presents information on the interference susceptibility of receiving systems used for radiocommunications associated with deep-space research. Two classes of interference are considered: CW and noise-like interference. The particular receiving systems that have been analysed are those of the Deep Space Network (DSN) operated by the United States of America.

2   The receiving system

The receiving system includes four major elements, each of which must be protected from interference: the maser pre-amplifier, the carrier tracking loop, the telemetry subsystem, and the ranging subsystem. The interference susceptibility of each of these will be discussed in § 4 below. A simplified block diagram of the receiving system is shown in Fig. 1.

FIGURE 1
**Simplified functional block diagram for a typical
deep-space network receiving system**
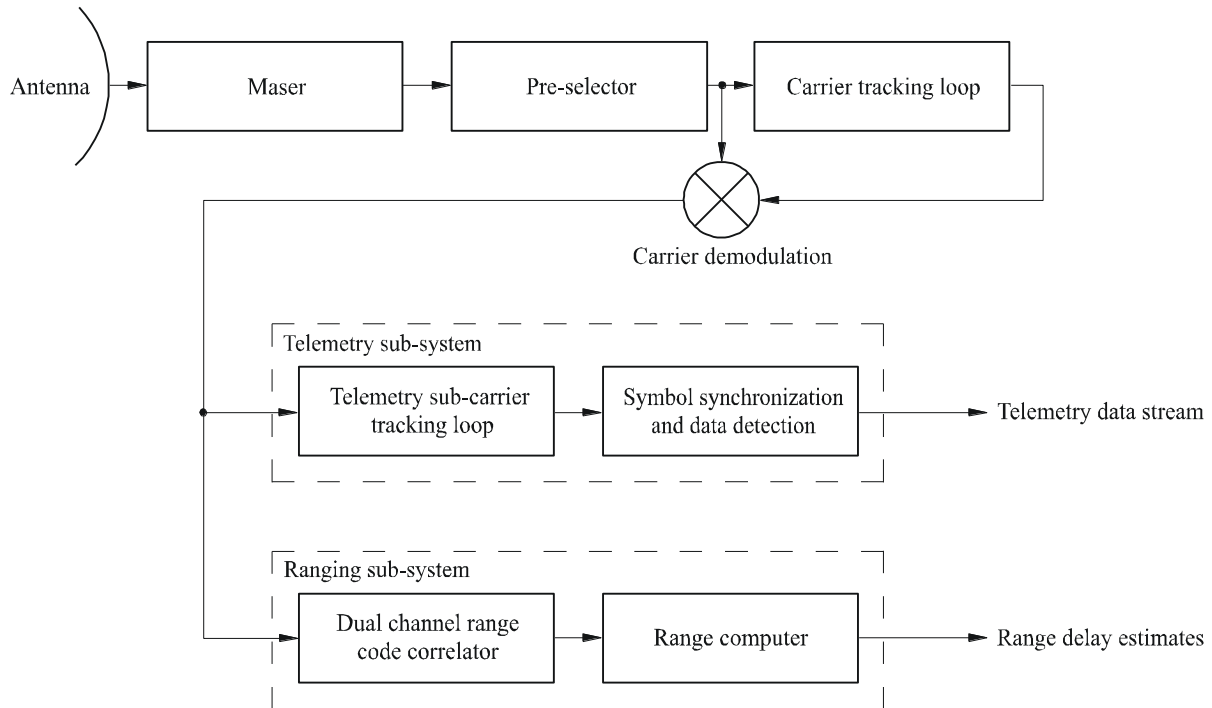
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3   Results of interference

Interference can result in performance degradation, non-linear operation or loss of data. The effect of the interference depends on its strength and separation in frequency from the wanted signal.

At weak-to-moderate power levels, co-channel interference can increase the static phase error and phase jitter of the carrier tracking loop, increase the telemetry bit error ratio, or reduce the accuracy of the range estimate. This performance degradation can generally be expressed as an equivalent reduction in signal-to-noise ratio and can, in theory, be compensated by increasing the power level of the wanted signal. In practice, the power of the wanted signal is usually not adjustable.

Strong interference having a large frequency separation from the wanted signal can result in a performance degradation and simultaneously drive one or more of the receiver components into a non-linear region, resulting in gain compression and the generation of harmonics, spurious signals, and intermodulation products. These non-linear effects are collectively referred to as saturation effects. Unlike performance degradation, saturation effects generally cannot be compensated even if the power level of the wanted signal is increased.

Strong interference having a small frequency separation from the wanted signal can cause the receiving system to lose lock or synchronization, resulting in a total loss of data.

4   Effects of CW interference

The specific interference effects are to be discussed in the following subsections for each of the four receiving subsystems. Although the receiving system is most sensitive to co-channel interference, adjacent-channel interference and even out-of-band interference can sometimes cause detrimental

effects. A co-channel interference is one whose frequency is in the passband of the subsystem. The frequency of the interference signal is assumed to be fixed unless specified otherwise.

4.1 Interference susceptibility of the maser pre-amplifier

The principal interference susceptibility of a maser is saturation (gain compression) by strong signals. The maser is most sensitive to interference that has a frequency in or near the maser passband, or the maser idle frequencies. Interference power that causes 1 dB maser gain compression is shown in Fig. 2 for a typical maser operating in the 8.4 GHz band.

FIGURE 2

Signal level required to reduce the gain of a 8.45 GHz maser

by 1 dB, versus frequency
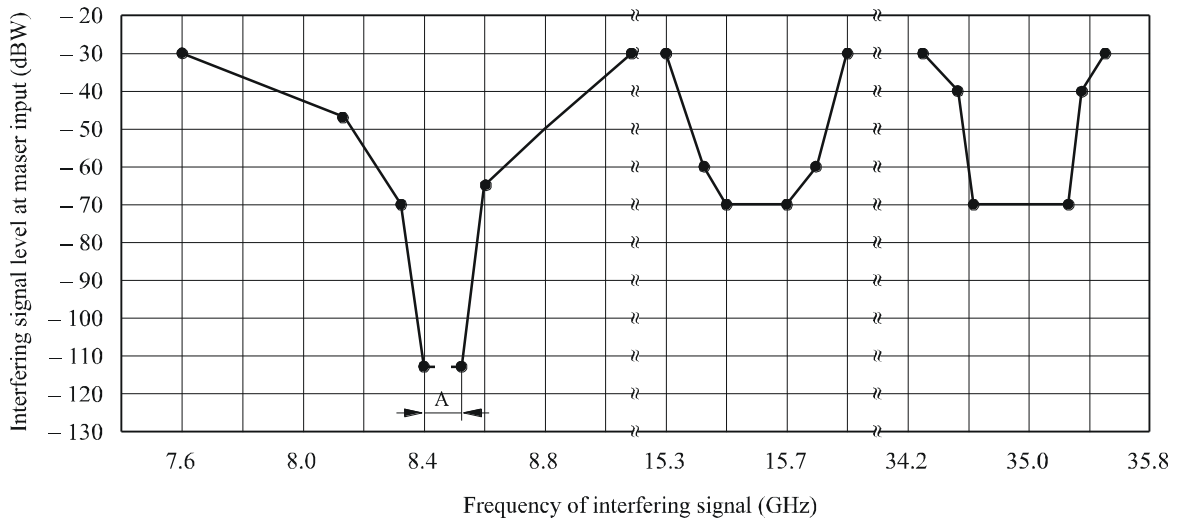
RFI type: CW
A: maser signal bandpass

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4.2 CW RFI susceptibility of the carrier tracking loop

The carrier tracking loop is a double heterodyne tracking loop which incorporates a synchronous-detector automatic gain control (AGC) loop and second-order phase-locked loop preceded by a bandpass limiter.

Strong interference can cause the loop to lose lock to the wanted signal, and the loop may lock to the interference. Both fixed frequency and sweeping (changing frequency) CW interference can result in this effect. If the interference is changing in frequency, the loop may first lose lock to the wanted signal and then lock to the interference as it moves close to the frequency of the wanted signal. As the interference moves through and away from that frequency, the loop then loses lock to the interference and may later re-lock to the wanted signal. The time it takes for the loop to re-lock to the wanted signal depends on the signal strength, the interference strength and the sweep rate. It may vary from seconds to minutes. If the interference is fixed in frequency, re-locking to the wanted signal may not be possible.

At a weaker level, interference can increase the static phase error and the phase jitter in the loop. This is true for both fixed and sweeping interference.

Figure 3 shows peak jitter as a function of CW *I/C*.

FIGURE 3

Peak phase jitter I/C ratio
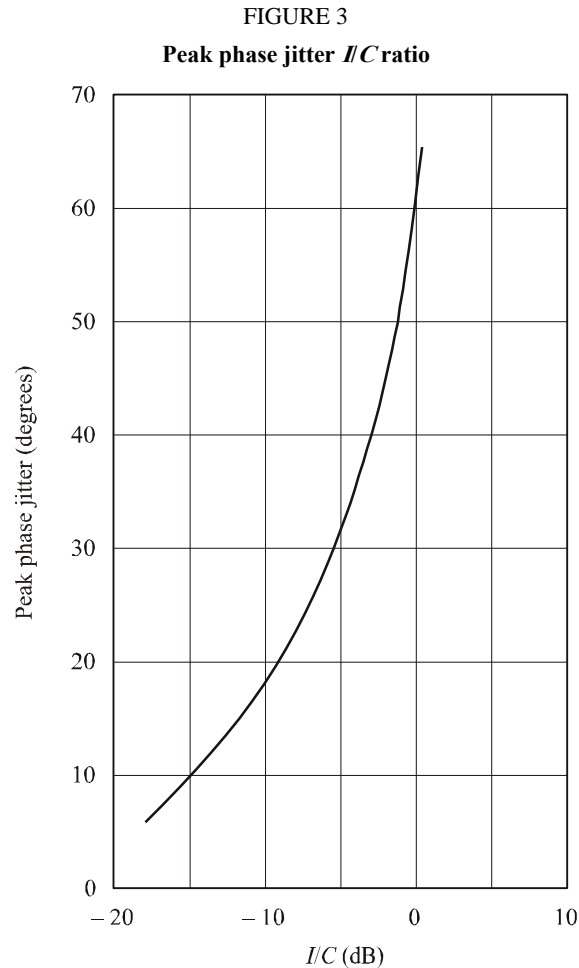
RFI type: CW

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### 4.3 CW RFI susceptibility of the telemetry subsystem

Telemetry degradation can be expressed as an equivalent reduction in symbol energy-to-noise spectral density ratio, $\Delta E/N_0$, which is defined as the amount by which the E/N_0 spectral density ratio would have to be reduced in the case of no interference in order to obtain a symbol error ratio equal to that in the presence of interference.

The $\Delta E/N_0$ ratio resulting from CW interference that is within the telemetry detection bandwidth is given in Fig. 4.

Telemetry performance can also be degraded by CW interference that falls within the carrier loop bandwidth. Figure 5 shows $\Delta E/N_0$ ratio as a result of carrier loop phase jitter versus I/C, for a 10 Hz frequency offset and for a typical receiving mode operating in the 8.4 GHz band.

FIGURE 4

Equivalent reduction in telemetering E/N_0 as a result of interference in the telemetering channel, versus I/S, for selected values of probability of symbol error, P_0
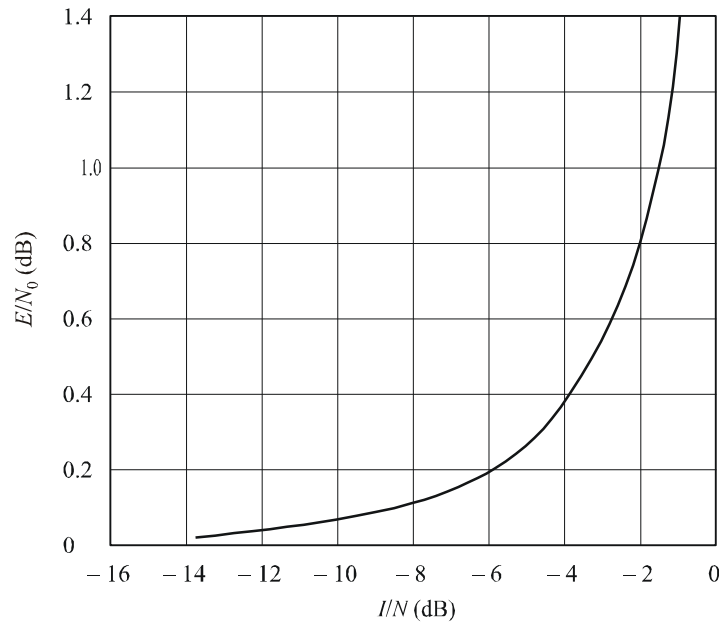

$P_0 = 10^{-5}$

10^{-4}

10^{-3}

E/N_0 (dB)

I/S (dB)
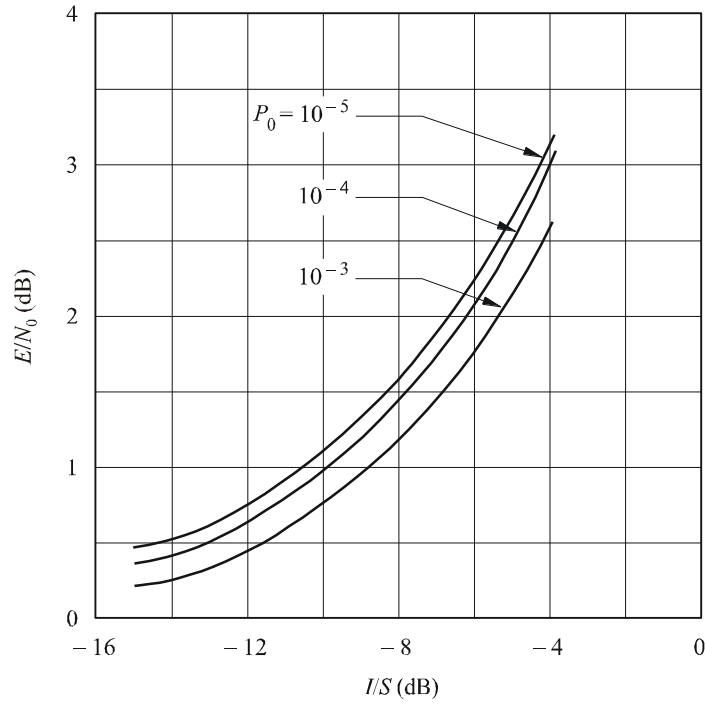
RFI type: CW
P_0: probability of symbol error

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FIGURE 5

Equivalent reduction in telemetering E/N_0 as a result of carrier loop phase error and jitter, versus I/N

E/N_0 (dB)

I/N (dB)

RFI type: CW
Band = 8.45 GHz
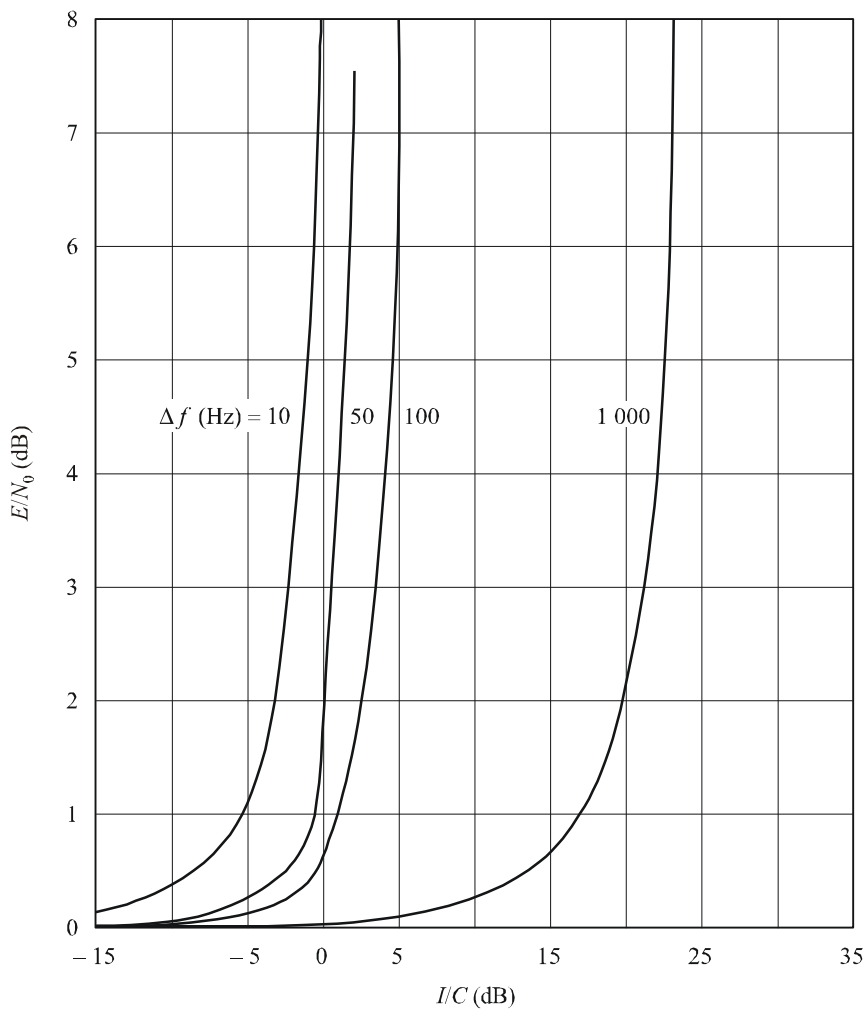Frequency offset = 10 Hz

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4.4   CW RFI susceptibility of the ranging subsystem

Interference can degrade the performance of the ranging subsystem by increasing the variance of the range delay estimates. The degradation can be expressed in terms of an equivalent reduction in the effective ranging signal-to-noise ratio.

CW interference in the carrier tracking loop bandwidth affects the ranging system performance, as shown in Fig. 6. The effect of CW interference in the ranging signal bandwidth is shown in Fig. 7. The *I/S* ratio refers to the ratio of the interference power to the ranging signal power.
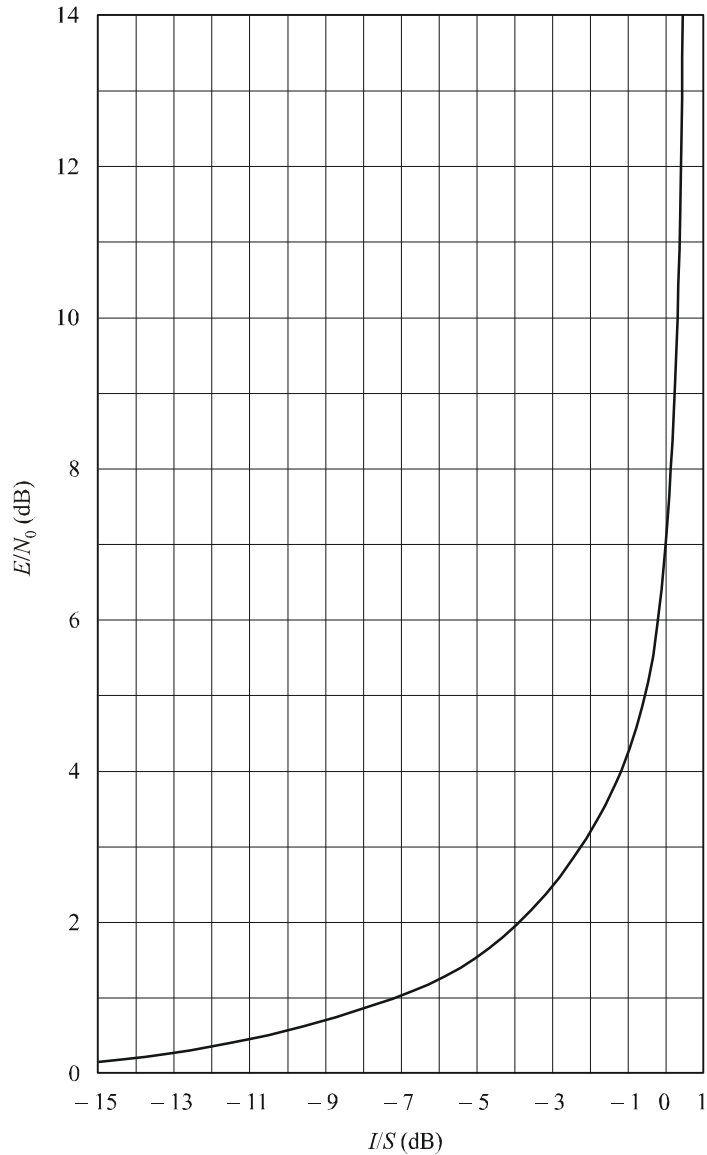
FIGURE 6

**Equivalent reduction in ranging E/N_0 as a result of carrier loop phase
error and jitter versus I/C for selected values of frequency offset**

RFI type: CW
Band = 8.45 GHz
Δf: frequency offset

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FIGURE 7

**Equivalent reduction in ranging E/N_0 a result of
interference in ranging channel, versus I/S**

RFI type: CW

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5   Effects of noise-like interference

Noise-like interference can saturate the maser pre-amplifier and can degrade the performance of the carrier tracking loop, the telemetry subsystem and the ranging subsystem. To cause a maser gain compression of 1 dB, the power spectral density of the noise-like interference, I_0, would have to be –190 dB(W/Hz), assuming a maser bandwidth of 40 MHz.

For the carrier tracking loop, the peak phase jitter depends on the carrier margin, as shown in Fig. 8. Noise-like interference reduces the carrier margin and hence increases the phase jitter. The carrier margin is related to I_0/N_0 by the expression:

$$CM_i = CM_0 + 10 \log (1 + I_0/N_0)^{-1}$$

where:

CM_i: carrier margin (dB) in the presence of interference

CM_0:   margin (dB) without interference

I_0/N_0:   ratio of interference noise-spectral density to receiver noise-spectral density.

Given a particular carrier margin without interference, and the acceptable increase in phase jitter, Fig. 8 and the foregoing expression allow the I_0/N_0 to be calculated. For example, at a typical margin of 10 dB, an increase of 10° in peak phase jitter will be caused by interference that reduces the margin to 5.5 dB. The I_0/N_0 for this circumstance is 2.6 dB.

FIGURE 8

Peak phase jitter versus carrier margin

1157-08
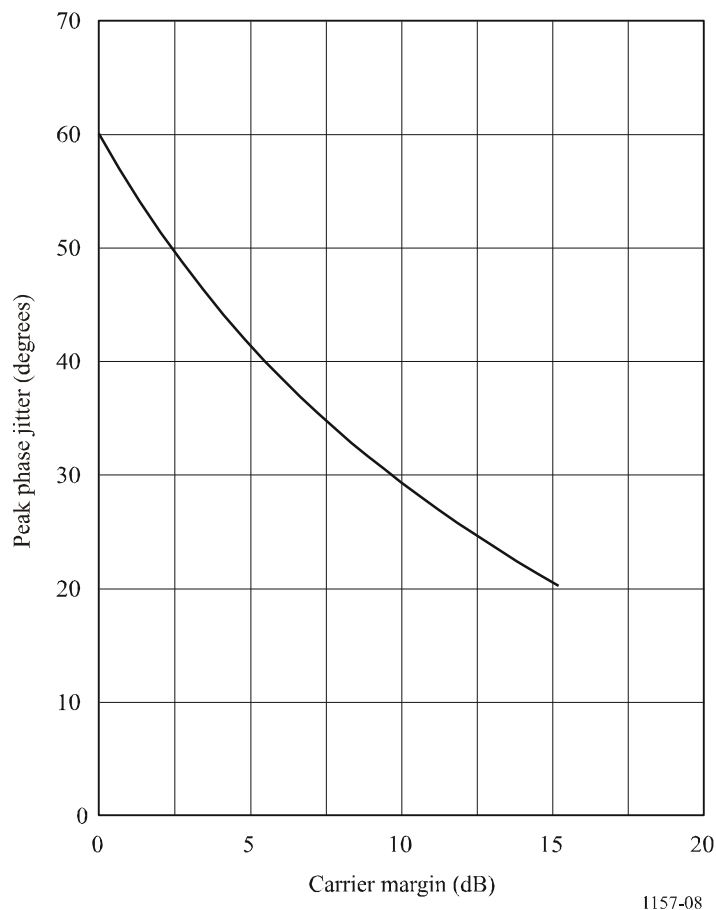
The effect of a noise-like interference on the telemetry and ranging subsystems is to reduce the effective E/N_0 and thereby increase the telemetry error ratio and the range delay estimate variance.

The reduction in equivalent $\Delta E/N_0$ can be expressed as:

$$\Delta E/N_0 = 10 \log (1 + I_0/N_0) \qquad \text{dB}$$

where I_0/N_0 is the interference noise-spectral density to receiver noise-spectral density ratio. Knowing the acceptable reduction of E/N_0, the corresponding I_0/N_0 may be calculated.