RECOMMENDATION ITU-R S.1554

Methodology for determining the overall accuracy of epfd↓ measurements

(Question ITU-R 236/4)

(2002)

The ITU Radiocommunication Assembly,

considering

a) that the World Radiocommunication Conference (Istanbul, 2000) (WRC-2000) adopted a combination of single-entry validation, single-entry operational and, for certain antenna sizes, single-entry additional operational equivalent power flux-density (downlink) (epfd↓) limits, contained in Article 22 of the Radio Regulations (RR), along with the aggregate limits in Resolution 76 (WRC-2000), which apply to non-geostationary fixed-satellite service (non-GSO FSS) systems, that protect GSO networks in parts of the frequency range 10.7-30 GHz;

b) that compliance of a non-GSO FSS system with the single-entry operational epfd↓ limits is not subject to verification by the Radiocommunication Bureau;

c) that administrations with assignments to GSO FSS and/or broadcasting-satellite service (BSS) networks that have been brought into use, as well as administrations with assignments to non-GSO FSS systems that have been brought into use, require reliable means of ascertaining that non-GSO FSS systems are in compliance with the single-entry operational limits referred to in *considering* a);

d) that epfd↓ levels may have to be measured at operational GSO earth stations in order to determine if the operational limits are exceeded,

noting

a) that Recommendation ITU-R S.1558 is being developed to provide a method for measuring epfd↓ levels,

recommends

1 that the methodology described in Annex 1 can be used to determine the accuracy of the measurement procedure.

ANNEX 1

Methodology for determining the overall accuracy of epfd↓ measurements

1 Introduction

WRC-2000 adopted operational epfd limits to protect GSO FSS links from suffering loss of synchronization or degraded performance due to non-GSO systems and to protect GSO FSS systems employing adaptive coding in 30/20 GHz bands.

The non-GSO satellites, due to the geometry of their orbits with respect to the GSO ground antennas, may exceed the operational limits for only short periods of time (s). The operational limits could be measured at earth station locations that suffer loss of synchronization events or degraded performance at an unexpected time (e.g. not obviously caused by a very high rain fade, a sun outage event, or an event caused by equipment failure and/or associated with switch over).

The GSO satellite operator would determine whether the loss of synchronization or degraded performance was due to in-line interference from a non-GSO FSS system into the GSO network. If there is perceived to be a correlation between loss of synchronization or degraded performance and a non-GSO system in-line event, a measurement system would be used at the GSO receive earth station site incurring the losses of synchronization or degraded performance to measure the level of non-GSO interference being experienced by the GSO earth station.

The preferred embodiment of the measurement procedure requires a well-calibrated carrier system monitoring (CSM) earth station in the same beam as the affected earth station. The CSM station provides a calibrated reference level for the affected earth station. It allows the expertise required to perform calibration to be centralized. Additionally, it is desirable to set up an automated measurement system at the affected earth station to reduce the probability of human error affecting the results.

In this Annex the overall accuracy of operational measurements of non-GSO interference is calculated for the preferred measurement procedure.

Acronym list

AWG: additive white Gaussian

B: bandwidth

CSM: carrier system monitoring

DSP: digital signal processing

IOT: in-orbit test

LNA: low noise amplifier

RSS: root squared sum

S/N: signal-to-noise ratio

T: time (s)

2 Measurement procedure realization using a DSP, spectrum analyser or power meter

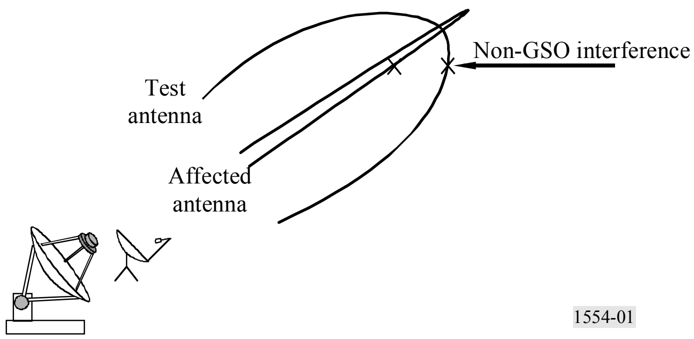
The critical concern in accurately measuring the non-GSO interference is system calibration. The calibration equipment may be integrated into the earth station affected by non-GSO interference; calibration can be performed remotely from a CSM station, or a well-calibrated portable system can be brought to the affected earth station site. Additionally, the portable system could be implemented using a scanning antenna. Each system design involves its own set of trade-offs.

In order to measure epfd↓ accurately, one of the straightforward approaches could be to integrate the measurement and calibration equipment into the earth station receiving the interference. However, this approach will require disruption of the GSO service, while the system is integrated and calibrated. Service may be disrupted for several hours. Additionally, service would presumably be disrupted again if the measuring equipment is needed at another earth station site.

A self-contained, portable, test set-up may be the most cost-effective approach. The system would not disrupt GSO operations and calibration measurements could be performed ahead of time. The portable test set-up may require a smaller antenna than the earth station affected by the interference. In this case the wider beamwidth test antenna could receive higher epfd levels from the non-GSO system compared to the affected antenna at small off-axis angles, as shown in Fig. 1.

FIGURE 1

Measurements with a small test antenna and a large earth station antenna



There are two solutions to the problem in Fig. 1. If the direction of the non-GSO interference is known, then the gain difference between the test antenna and affected earth station antenna can be accounted for if the respective antenna patterns are accurately known. Alternatively, the test antenna could track the non-GSO satellite. Additionally, if a large enough tracking antenna is used it will provide discrimination between the GSO signal and the non-GSO interference under test until the non-GSO is in the main lobe of the GSO antenna.

Using a smaller test antenna will yield a lower S/N relative to a larger antenna that is receiving the same signal strength. The lower the received S/N the longer the measurement time required to get the same level of accuracy. Table 1 shows the half power beamwidths and S/N (assuming a receiver temperature of 200 K), for several different antenna sizes. The S/N correspond to signal levels equal to the operational limit values for a 3 m (–161.25 dB(W/(m^2 · 40 kHz))) and 10 m (–166 dB(W/(m^2 · 40 kHz))) antenna, respectively.

TABLE 1

Measurement characteristics for different size earth station antennas

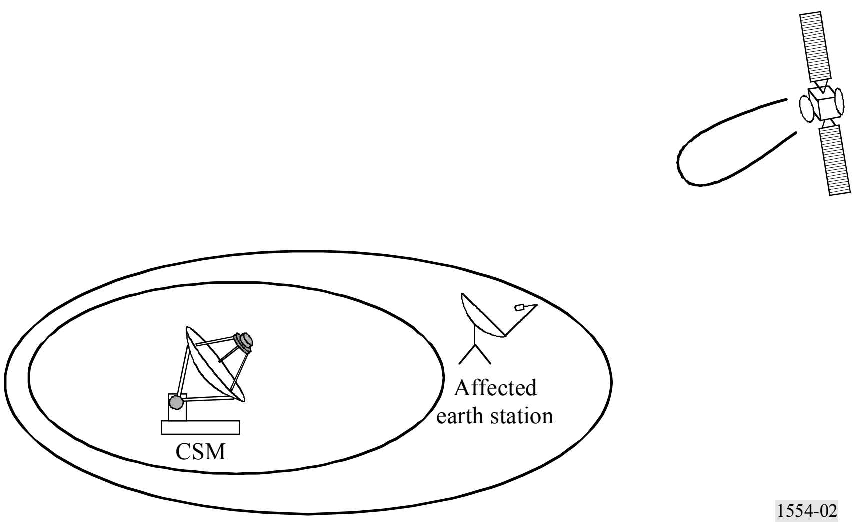
Antenna diameter (m)	**Half power beamwidth (degrees)**	**(Signal level = –161.25 dB(W/(m^2 · 40 kHz))) S/N (dB)**	**(Signal level = –166 dB(W/(m^2 · 40 kHz))) S/N (dB)**
2	1.75	1.4	–3.3
3	0.58	4.5	–0.2
10	0.175	15	10.3

Finally, if a calibrated CSM earth station is available in the same beam as the affected earth station then it can perform the calibration for the affected earth station. The CSM station is very accurately calibrated and can be used to determine the received signal level at the affected earth station.

Figure 2 shows the CSM station and the affected earth station. Notice that the CSM receives the same signal from the satellite as the affected earth station but with a different satellite gain. Since the relative satellite antenna gains in the direction of both earth stations are known (IOT measurements) the CSM station can calibrate the affected earth station receive signal level. This reference level can then be used by the affected earth station to determine its noise and interference levels.

FIGURE 2

CSM configuration providing calibration to an affected earth station



This Annex focuses on the accuracy of the approach where a CSM station is used to calibrate the affected earth station receive signal level. The measurement procedure is as follows:

– Both the CSM and affected earth station could measure the satellite beacon. The beacon measurement provides a stable well-known signal level that can be used for calibration at the CSM station. It also provides an estimate of the differential between the atmospheric losses at the affected earth station compared to the CSM station.

  If the variations in the beacon level due to stability and measurement error are greater than the variation due to atmospheric changes then the beacon measurement may not be valuable. The rest of this Annex assumes that interference measurements are performed in clear sky and the beacon measurements are not factored into the overall accuracy estimate.

  It should be noted, however, that in the case of a low Earth orbit (LEO) system where the significant interference occurs near an in-line event the fading on the non-GSO signal can be assumed to be close to that of the GSO system. This implies that the carrier-to-interference level for the link is approximately the same in clear sky and during rain. Thus the true non-GSO interference level should take into account the fade level.

– At the CSM station measure a reference signal. Two sources for the reference signal have been investigated:

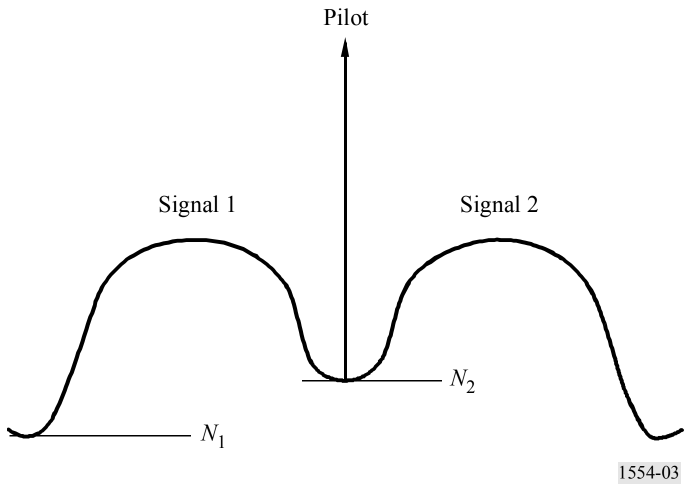
  – the reference signal is the earth station carrier affected by interference,

  – the reference signal is a pilot signal transmitted in the guardband adjacent to the affected signal.

  Fig. 3 shows the affected signal under test. The guardband shows the pilot that can be used as the CSM reference signal.

FIGURE 3

In-band versus out-of-band noise levels



Notice that because of the filter skirts the noise level in the guardband can be different than the noise at the signal frequency. This can cause an error if the affected earth station signal is used as the CSM reference. When the affected earth station signal is the reference it is used to determine noise level N_1. However, the interference is measured relative to noise level N_2. Therefore, if the affected earth station signal is used as a reference then the measured interference can be in error by the difference between noise levels N_1 and N_2.

The pilot signal may provide a slightly more accurate measurement than using the affected earth station signal as the reference. The accuracy estimate calculated in this Annex does not address the error that may occur if the affected earth station signal is used as the CSM reference.

– At the affected earth station measure interference plus noise and noise. The interference plus noise measurement is performed in the guardband next to the affected carrier. The noise level can also be measured in the guardband, but just before and after the interference event.

All the measurements must be performed close together in time so that the values do not have a chance to change. Additionally, the interference is present only for a short time, which limits the measurement time and accuracy.

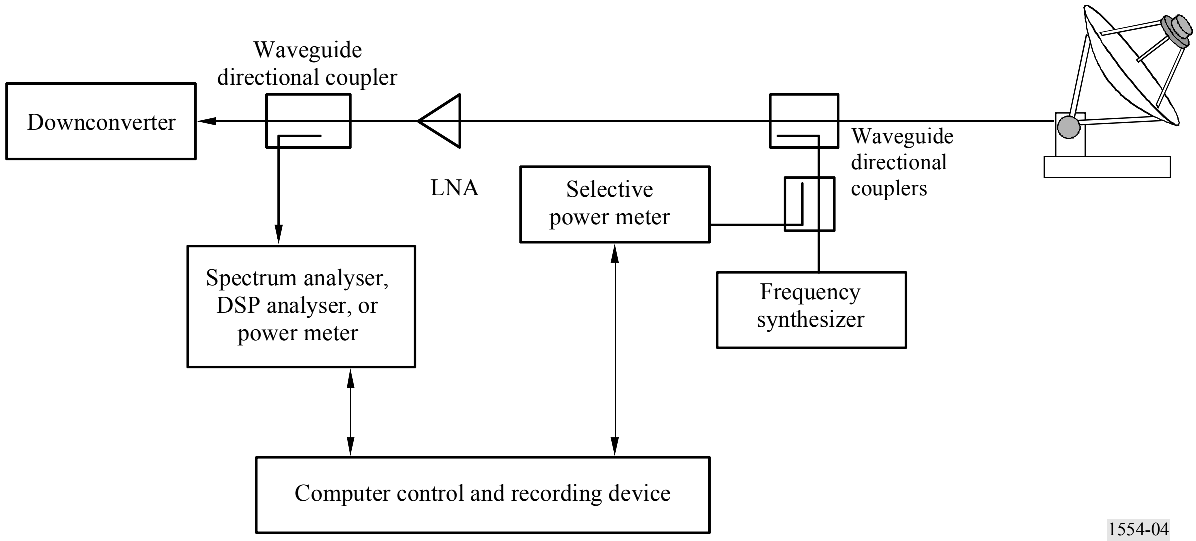
An automated procedure can be used to make the measurements. The set-up would require a measurement instrument (power meter, spectrum analyser, DSP) at the affected earth station. The output of the measurement device would be attached to a computer which stores the spectrum under test. An interference pulse would trigger interference plus noise and noise measurements on the stored data. At the same time a signal could be sent automatically to the CSM in order to request a measurement of the reference carrier as soon as possible (more study is needed on the procedure to be employed here, and on the potential contribution to the error budget of any significant delay).

3 Calibration of the CSM RF path

The measurement procedure relies on the accuracy of the CSM system. Fig. 4 shows a block diagram of a CSM station with the calibration equipment integrated directly into the RF path of the earth station.

FIGURE 4

CSM block diagram



The measuring instrument consists of a spectrum analyser, DSP analyser or power meter connected through a waveguide directional coupler after the LNA. Calibration equipment consists of a frequency synthesizer and power meter for calibrating the measurement equipment.

The equipment is controlled from a computer interface. The computer controls measurement parameters, calibration times, and the recording of the measurement information. The frequency synthesizer provides a reference calibration signal. This is needed to minimize the effects of equipment drift and random variations on the measurements.

Human error can be a significant source of error in setting up the calibration process, depending on the expertise of the earth station staff. The monitoring system has to first be calibrated off-line. These calibrations remain static during operation. The second type of calibration is automatic and is performed during operation. Both types of calibration data are required to meet accuracy requirements.

Off-line the instrumentation (i.e. power meters, analysers, synthesizers), antenna, and components (i.e. waveguides, couplers, measurement filter, and LNA) are calibrated. These calibrations may be accomplished periodically, using standard laboratory procedure. Data files are maintained that include calibrations over a frequency range depending on how the measurements are made. The frequency synthesizer and power meters are checked at regular intervals to ensure the accuracy of the calibration equipment.

Two automatic gain calibration measurements (G_C and G_n) of the receive downlink chain from the antenna headend to the measuring device must be performed periodically. A frequency synthesizer injects a signal into the LNA input. Accurate power meter measurements verify the signal level. The synthesizer level is constantly checked by a separate power meter measurement.

The gains G_C and G_n are both measured at the non-GSO beacon frequency between the antenna feed and the measuring device. The choice of the injected carrier-to-noise ratio should be greater than 25 dB to allow the noise power to be neglected.

The earth station receiver gain equation is given by:

$$G_C = G_n = \frac{1}{L_C(CW)}\left(\frac{P_m}{P_I L_{Cal}}\right) \tag{1}$$

where:

P_m: power at the power meter

P_I: injected power

$L_C(CW)$: loss of the measurement filter for the reference carrier

L_{Cal}: calibration error between the reference carrier and the receive waveguide at the antenna feed.

In Table 2 there is a breakdown of the error standard deviations associated with equation (1). These uncertainties are assumed to be Gaussian random variables. A Monte Carlo statistical evaluation of equation (1) by computer, using the uncertainties in Table 2, yields the receive gain uncertainty of ±0.34 dB.

TABLE 2

Earth station receive gain errors

Item	Error (dB)	Comments
P_I	±0.2	Single power measurement using an accurate power meter
P_m	±0.2	Single power measurement using an accurate power meter
L_C		Variation assumed to be negligible
L_{Cal}	±0.2	Power measurement and temperature variations
G_C, G_n	±0.34	Evaluation of equation (1) using the uncertainties above

If the noise and signal measurements are performed at approximately the same frequency then only one calibration is necessary.

4 Accuracy of the interference and noise measurements at the affected earth station

The overall measurement accuracy is dependent on the accuracy of the power measurement. This includes both the internal accuracy in the measurement device and the variations in the measurements due to noise. As an example, the HP8566A spectrum analyser has an internal amplitude measurement accuracy of about ±0.3 dB.

The accuracy due to noise is directly related to the duration of the measurement. The measurement device integrates the received power for T seconds. If the input noise is AWG then the output of the integrator will be chi-squared distributed. The mean, m_n, and variance, σ^2, for the noise only measurement and for the signal plus noise measurement are:

$$\text{Noise only:} \quad m_n = 2\,M \text{ and } \sigma^2 = 4\,M \tag{2}$$

$$\text{Signal plus noise:} \quad m_n = M\,S/N + 2\,M \text{ and } \sigma^2 = 4\,M\,S/N + 4\,M \tag{3}$$

where:

$M = BT$

B: measurement bandwidth (Hz)

S/N: received signal-to-noise ratio.

Since BT is large the chi-squared distribution approaches a normal distribution by the central limit theorem. The equation for calculating the confidence level in the power measurements is:

$$P_{conf} = \frac{1}{\sqrt{2\pi\,\alpha^2}} \int_{m_n(1-\Delta)}^{m_n(1+\Delta)} e^{\frac{-(q-m_n)^2}{2\sigma^2}}\, \mathrm{d}q \tag{4}$$

where P_{conf} is the probability that you are within Δ of the measured power and q is the dimentionless variable. The measurement accuracy in dB is approximately:

$$\mathit{measurement\ accuracy} \cong \pm 10 * \log(1 + \Delta) \qquad \text{dB} \tag{5}$$

Figure 5 shows the accuracy of the noise power measurement using equations (2), (4) and (5). The measurement bandwidth, B, was assumed to be 40 kHz. From the Figure you can see that for a 0.1 s measurement there is 99% confidence that the measurement accuracy is ±0.17 dB. It may be difficult to obtain the required confidence if the measurement time is less than 0.1 s. More accurate results may be obtained by measuring in a wider noise bandwidth if the interference occupies that bandwidth. Accuracy can also be increased by increasing the integration time if the interference pulse is present for the longer duration. However, longer measurement times reduce the flexibility of the measurement system. For example, it may not be possible to check for interference at multiple frequencies or it may be difficult to measure the beam peak.

FIGURE 5

Confidence probabilities as a function of the noise power measurement accuracy and measurement time

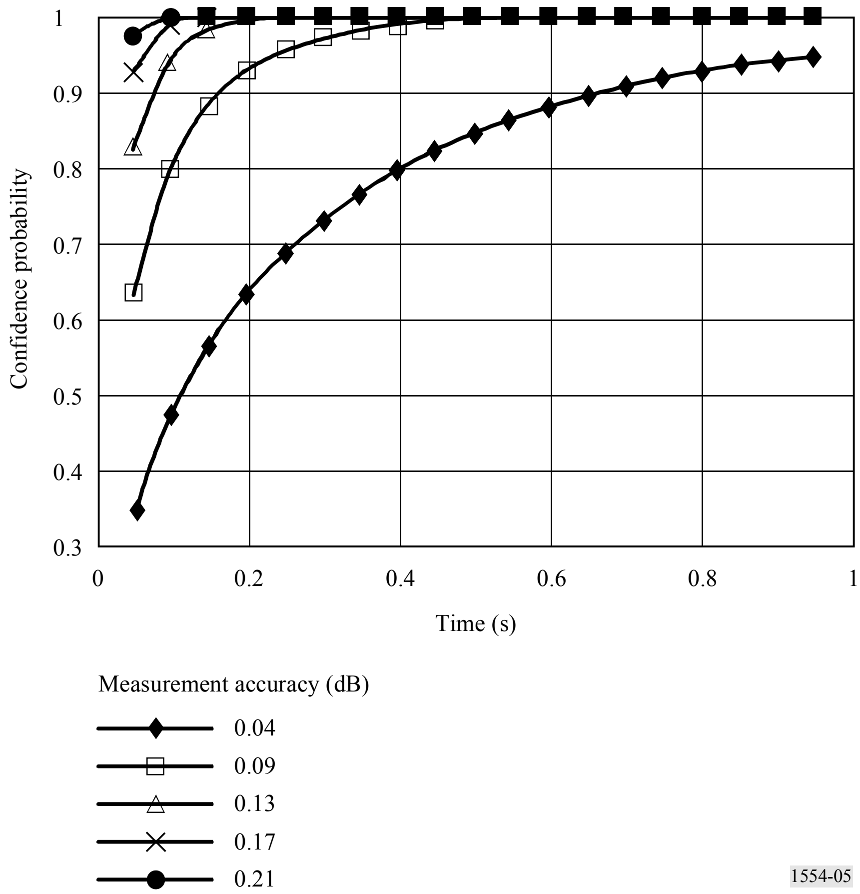


Table 3 shows confidence probabilities for a measurement accuracy of ±0.2 dB for the signal plus noise power measurement, for different *BT* products. Notice that a *BT* product of about 3 000 is required to achieve a measurement accuracy of ±0.2 dB with 99% confidence, even when the *S*/*N* is only −10 dB.

TABLE 3

Confidence probabilities for the signal plus noise measurement as a function of the *S*/*N* and measurement *BT* product for a measurement accuracy of ± 0.2 dB

	BT				
***S*/*N* (dB)**	**30**	**99**	**300**	**1 000**	**3 000**
−10.0	0.216	0.382	0.614	0.887	0.994
−1.2	0.224	0.395	0.632	0.888	0.996
1.5	0.236	0.415	0.658	0.889	0.997
3.1	0.249	0.436	0.685	0.891	0.999
4.3	0.262	0.457	0.71	0.893	0.999
5.3	0.275	0.477	0.733	0.896	1
6.0	0.287	0.496	0.755	0.898	1
6.7	0.298	0.514	0.774	0.901	1
7.2	0.31	0.531	0.792	0.904	1
7.7	0.32	0.547	0.808	0.906	1
8.2	0.331	0.562	0.823	0.909	1
8.6	0.341	0.577	0.837	0.912	1
9.0	0.35	0.591	0.849	0.915	1
9.3	0.36	0.604	0.861	0.917	1
9.6	0.369	0.617	0.871	0.92	1
9.9	0.378	0.629	0.881	0.922	1

The RSS of the spectrum analyser calibration accuracy and measurement accuracy define the overall accuracy of the power estimate. The spectrum analyser calibration accuracy is ±0.3 dB. Assuming a power measurement accuracy of ±0.2 dB yields an overall power estimate accuracy of ±0.36 dB.

5 Error budget for total measurement procedure

In this section a calculation of the overall accuracy of the measurement procedure is developed. First the accuracy estimate of the CSM measurement is calculated and this is then combined with the measurements made at the affected earth station. It is recommended that the numerical results should be reviewed after further studies.

Equation (6) shows the reference signal power estimate at the CSM antenna flange. In order to make this estimate the CSM measures the reference signal plus noise and subtracts out the measured noise level. The receiver gain is also included in equation (6). The receive gain calibrations for the reference signal and noise are assumed to be the same (i.e. $G_n/G_C = 1$).

$$P_{Ref}(CSM) = R(CSM) / G_C - N(CSM) \cdot G_n / G_C \qquad (6)$$

P_{Ref} : received reference signal power at the antenna flange

R : received power (reference signal plus noise) input to the measuring device

N : noise power at the antenna flange.

The higher the reference signal-to-noise ratio the lower the impact of the noise measurement on the overall accuracy of P_{Ref}. In this analysis the accuracy calculation is performed assuming a reference S/N equal to 10 dB.

Table 4 shows the standard deviation associated with each parameter in equation (6). Assuming that each parameter is a zero mean Gaussian random variable and Monte Carlo evaluation of equation (6) yields an uncertainty of ±0.45 dB.

TABLE 4

Accuracy of CSM reference signal measurement

Item	**Error (dB)**	**Comments**
G_C , G_n	±0.34	Calculated from equation (1) and Table 2
R	±0.2	Measurement of reference signal plus noise
N	±0.2 ±0.41	Single power measurement using an accurate power meter Accuracy associated with a 10 dB S/N
$P_{Ref}(CSM)$	±0.45	Evaluation of equation (6) using the uncertainties above

The reference signal level calculated at the CSM is translated to a reference level at the affected earth station using equation (7). The equation assumes that accurate IOT measurements are available so that the relative satellite gains at the CSM and affected earth station sites are known.

$$P_{Ref}(ES) = P_{Ref}(CSM) \cdot \Delta G \cdot \Delta L_{FS} \cdot \Delta L_{ATM} \cdot \Delta G_{sat} \tag{7}$$

where:

$P_{Ref}(\mathrm{ES})$: reference signal level at the affected earth station

$\Delta G = \dfrac{G(ES)}{G(CSM)}$: relative antenna gains at the CSM and affected earth station sites

$\Delta L_{FS} = \dfrac{L_{FS}(ES)}{L_{FS}(CSM)}$: ratio of the free space loss in the direction of the affected earth station compared to the CSM site

$\Delta L_{ATM} = \dfrac{L_{ATM}(ES)}{L_{ATM}(CSM)}$: ratio of atmospheric losses at the affected earth station compared to the CSM site

$\Delta G_{sat} = \dfrac{G_{sat}(ES)}{G_{sat}(CSM)}$: relative satellite antenna gains in the direction of the affected earth station compared to the CSM site.

Table 5 shows the standard deviation associated with each parameter in equation (7). Assuming that each parameter is a zero mean Gaussian random variable and simulating equation (7) yields an uncertainty of ±0.56 dB.

TABLE 5

Accuracy of CSM measurements referenced to the affected earth station

Item	**Error (dB)**	**Comments**
$P_{Ref}(CSM)$	±0.45	From Table 4
ΔG	±0.2	Pointing plus antenna calibration errors
ΔL_{FS}	±0.0	
ΔL_{ATM}	±0.1	Measurements are assumed to be performed in clear sky
ΔG_{sat}	±0.2	Assumed to be known from IOT measurements
$P_{Ref}(ES)$	±0.56	Simulating equation (7) using the uncertainties in Table 5 and Table 4

The reference level measured at the CSM station is also measured at the affected earth station. The level measured at the affected earth station is denoted here as $\hat{P}_{Ref}(ES)$.

Equation (8) shows how the measured reference levels are used to calibrate the noise level at the affected earth station site.

$$N_{cal} = N_{meas} \frac{P_{Ref}(ES)}{\hat{P}_{Ref}(ES)} \tag{8}$$

where:

N_{cal}: calibrated noise level at the affected earth station

N_{meas}: noise level measured at the affected earth station.

Table 6 shows the standard deviation associated with each parameter in equation (8). Assuming that each parameter is a zero mean Gaussian random variable and simulating equation (8) yields an uncertainty of ±0.75 dB.

TABLE 6

Accuracy of the noise level estimate at the affected earth station

Item	Error (dB)	Comments
$P_{Ref}(ES)$	±0.56	Calculated in Table 5
$\hat{P}_{Ref}(ES)$	±0.36	Single power measurement made using the HP8566A spectrum analyser
N_{meas}	±0.36	Single power measurement made using the HP8566A spectrum analyser
N_{cal}	±0.75	Simulating equation (8) using the uncertainties above

The final measurement is of interference plus noise at the affected earth station. The calibrated noise level is subtracted from this measurement in order to determine the interference level as shown in equation (9).

$$P_I(ES) = P_{I+N}(ES) - N_{cal}(ES) \tag{9}$$

where:

$P_I(ES)$: interference power at the affected earth station

$P_{I+N}(ES)$: interference plus noise at the affected earth station.

Table 7 shows the standard deviation associated with each parameter in equation (9). The RSS combination of these parameters yields an overall uncertainty of ±0.82 dB.

TABLE 7

Accuracy of the interference level estimate at the affected earth station

Item	Error (dB)	Comments
$N_{cal}(ES)$	±0.75	Calculated in Table 6
$P_{I+N}(ES)$	±0.36	Single power measurement made using the HP8566A spectrum analyser
$P_I(ES)$	±0.82	RSS of above uncertainties

6 Summary

The overall measurement accuracy is estimated in this Annex to be ±0.82 dB.

The following assumptions were made in doing the calculation:

– Non-GSO signal level changes due to traffic variations during the measurement were ignored.

– A CSM site is available in the same beam as the affected earth station. The CSM site is well calibrated with an integrated monitoring system. Calibration errors in the measurement loop have been ignored.

– The reference signal at the CSM site is assumed to be a pilot signal transmitted in the guardband adjacent to the carrier affected by non-GSO interference.

– There is an automated measurement system at the affected earth station. This system detects the non-GSO interference pulse and stores a sufficient amount of data to ensure that the peak interference level can be measured accurately.

– The affected earth station only has to monitor a single frequency. If multiple frequencies have to be monitored then there may not be enough time to make accurate measurements.

– All measurements are made close to the time of the non-GSO interference so that there is no variation of the receiver system noise due to intermods and adjacent satellite interference. This assumption may need to be studied further.