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Radiocommunication Sector of ITU

Recommendation ITU-R SM.1753-1

(04/2010)

Methods for measurements of radio noise

SM Series

Spectrum management

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 SM.1753-1

Methods for measurements of radio noise

(2006-2010)

Scope

For radio noise measurements there is a need to have a uniform, frequency-independent method to produce comparable, accurate and reproducible results between different measurement systems. This Recommendation provides a set of processes or steps that need to be integrated in a measurement procedure resulting in these comparable results.

The ITU Radiocommunication Assembly,

considering

a) that, due to the introduction of many types of electrical and electronic equipment (producing radio noise) and radiocommunication networks (e.g. ultra-wide band (UWB), power line telecommunication (PLT) and computers), the radio noise levels stated in Recommendation ITU-R P.372 might increase;

b) that, for efficient spectrum management, administrations need to know the exact noise levels;

c) that there is a need to harmonize the measurement methods for noise measurements to achieve reproducible results that can be mutually compared;

d) that, for noise measurements, certain minimum equipment specifications are required,

recommends

1 that measurements of radio noise should be carried out as described in Annex 1.

Annex 1

Methods for measuring radio noise

1 Introduction

This annex describes methods for measuring and evaluating radio noise in practical radio applications.

2 Sources of radio noise

- radiation from lightning discharges (atmospheric noise due to lightning);
- aggregated unintended radiation from electrical machinery, electrical and electronic equipments, power transmission lines, or from internal combustion engine ignition (man-made noise);
- emissions from atmospheric gases and hydrometeors;
- the ground or other obstructions within the antenna beam;
- radiation from cosmic radio sources.

While noise due to natural causes is unlikely to change significantly over long periods of time, man-made noise (MMN) is often dominant in some parts of the radio spectrum and the intensity may change with increasing density of use of electrical and electronic devices, with the introduction of new types of device, and with changes in measures intended to improve electromagnetic compatibility. Thus man-made noise is the type that is mainly of interest when performing radio noise measurements.

TABLE 1

Importance of radio noise sources per frequency range

Noise source	Frequency range of importance
Atmospheric noise due to lightning	9 kHz to 30 MHz
Cosmic noise	4 MHz to 100 MHz
Man-made noise	9 kHz to 1 GHz
Emissions from atmospheric gases, etc.	Above 10 GHz

3 Components of radio noise

Using the definition given in Recommendation ITU-R P.372, radio noise is the aggregate of emissions from multiple sources that do not originate from radiocommunication transmitters. If at a given measurement location there is no dominance of single noise sources, the characteristic of the radio noise often has a normal amplitude distribution and can be regarded as white Gaussian noise.

However, with the high density of noise emitting devices especially found in cities and residential areas, it is virtually impossible to find a location that is not at least temporarily dominated by noise or emissions from a single source. These sources often emit impulses or single carriers. Since radiocommunication equipment has to operate in such an environment, it may be unrealistic to exclude these components from radio noise measurements.

TABLE 2

Components of radio noise

Noise component	Properties	Sources (examples)
White Gaussian noise[(1)] (WGN)	Uncorrelated electromagnetic vectors Bandwidth equal to or greater than receiver bandwidth Spectral power level increases linear with bandwidth	Computers, power line communication networks, wired computer networks, cosmic noise
Impulsive noise (IN)	Correlated electromagnetic vectors Bandwidth greater than receiver bandwidth Spectral power level rises with square of bandwidth	Ignition sparks, lightning, gas lamp starters, computers, ultra wideband devices
Single carrier noise (SCN)	One or more distinct spectral lines Bandwidth smaller than receiver bandwidth Spectral power level independent of bandwidth	Wired computer networks, computers, switched mode power supplies

(1) In the context of this annex to Recommendation ITU-R SM.1753, WGN is considered to represent a continuous noise signal which exhibits a nearly flat power spectral density in the frequency ranges around the measurement bandwidth.

While the WGN component is sufficiently characterized by the r.m.s. value, this is much more difficult for the IN. Modern digital communication services almost always apply error correction, making it more immune especially against impulsive noise. However, when certain pulse lengths and repetition ratios are reached, IN can significantly interfere with the operation of such a service.

It is therefore desirable to measure radio noise in a way that gives not only the level of IN but also certain information about the statistical distribution of pulse parameters.

Single carrier noise (SCN) is only detected as such when it comes from a single source near the measurement location. Multiple sources emitting single carriers quickly add up to a noise-like spectrum as their numbers increase. Recommendation ITU-R P.372 defines radio noise as the aggregated unintended radiation from various sources and specifically excludes emissions from single, identifiable sources. It is therefore necessary to select measurement locations and/or frequencies that are not dominated by emissions from these single sources which makes further consideration of SCN unnecessary in the context of MMN measurements.

4 Key parameters

The measurement procedures described here will deliver results for the following parameters of radio noise:

WGN:

– r.m.s. level, presented as a single value or hourly medians over the day

IN:

– Peak level, presented as a distribution

– Impulse/burst lengths, presented as a distribution
– Impulse/burst period, presented as a distribution.

5 Measurement principles

The White Gaussian noise component (WGN) can be measured using an r.m.s. detector. This measurement method is herein referred to as the "r.m.s.-method". Using the 20% reduction described in § 10.3, it is possible to obtain the r.m.s. noise value directly from a frequency scan, even if some of the frequencies are occupied with wanted signals.

IN, however, can only be measured by fast sampling of the momentary RF amplitude values. These values are stored for off-line evaluation to obtain the impulse parameters. The measurement is preferably done on a single frequency that is free of wanted signals and continuous carriers. The maximum time between two consecutive samples is:

$$Ts \leq \frac{1}{2 * RBW} \tag{1}$$

where:

Ts: time between two consecutive samples

RBW: filter bandwidth used for measurement.

This measurement method is herein referred to as the "raw data sampling method".

6 Measurement type

Determining the true MMN level and characteristics including IN for all frequency ranges can be a very time consuming complex measurement task. However, when only the WGN component is of interest, or only certain frequency ranges have to be investigated, the measurements can be simplified significantly without losing important information or reducing accuracy. For this reason, the following three different methodologies are recommended when performing radio noise measurements:

Type A: WGN only. This Type delivers only WGN levels, disregarding IN. It only requires measurements of the remaining r.m.s. level on a "free" frequency. Both r.m.s. and raw data sampling methods can be applied. Evaluation of data is relatively simple.

Type B: WGN and IN. This Type delivers WGN levels and characteristics of the important IN parameters of radio noise. It requires fast data sampling (raw data sampling method). Data evaluation is more complex and requires extensive post-processing, most of which can only be performed by computers.

Type C: WGN, IN and separation of MMN. In addition to WGN level and IN characteristics, this Type separates MMN, IN from atmospheric noise to a large extent which may be important in the HF frequency range. The measurement process is equal to measurement Type B, but it has to be performed at two different locations and the equipment of both locations has to be time synchronized.

The selection of the adequate measurement Type depends on the requirements, environmental category and frequency range. If measurement results should be for general use, the recommended Type is underlined.

TABLE 3

Recommended measurement Types

Frequency range	Outdoor measurements	Indoor measurements
9 kHz – 300 kHz (LF)	A, B	A, B
300 kHz – 3 MHz (MF)	A, B, C	A, B
3 MHz – 30 MHz (HF)	A, B, C	A, B
30 MHz – 300 MHz (VHF)	A, B	A, B
300 MHz – 3 GHz (UHF)	A, B	A, B
> 3 GHz (SHF)	A	A

7 Equipment specifications

7.1 Receiver and preamplifier

The measurement receiver should be a standard transportable measurement receiver or spectrum analyser and any additional pre-amplification such as LNA must exhibit a low equipment noise figure together with high gain stability which is essential for the performance of noise measurements.

To guarantee an acceptable measurement accuracy it is required to keep the measured noise at least 10 dB above the equipment noise floor if an r.m.s. detector is used. An external low noise amplifier (LNA) can assist in this goal. It is essential for frequencies > 20 MHz.

Care should be taken to use a measurement receiver with a built-in correction for the error that is imposed on the result when measuring at low *S*/*N* ratios. If this noise correction is switchable, it can be turned on. However, in this case no additional correction as described in § 10.2 is applicable.

The requirements for the measurement system are given in Table 4 which does not describe a new set of measurement receivers or LNA specifications but only points out the additional or specific requirements necessary for a receiver and LNA used for noise measurements. Also the frequency band designations are based on the practical implementation of a noise measurement system and do not point to a specific receiving system.

TABLE 4

Noise measurement system (receiver/LNA) requirements

Function	Frequency range		
Frequency range	9 kHz – 30 MHz	30-500 MHz	0.5-3 GHz
Input (antenna input) VSWR	50 Ω, nominal < 1.5		
3rd order intercept	≥ 20 dBm (> 3 MHz)	≥ 10 dBm	≥ 0 dBm
2nd order intercept	≥ 60 dBm (> 3 MHz)	≥ 50 dBm	≥ 40 dBm
Preselection	Set of sub-octave band filters or tracking filter	Tracking or fixed filter Low pass/high pass filter	
Total noise figure	≤ 15 dB (> 2 MHz)	≤ 2 dB(1) (> 20 MHz)	≤ 2 dB(1)

TABLE 4 (*end*)

Function	Frequency range		
IF rejection	> 80 dB	> 90 dB	> 100 dB
Image rejection	> 80 dB	> 90 dB	> 100 dB
LNA gain	≤ 18 dB	≤ 25 dB	≤ 25 dB
LNA gain stability	≤ 0.7 dB at 20-30°C		
LNA gain flatness over the frequency range of interest	< 0.4 dB	< 0.4 dB	< 0.5 dB
AGC	Measurement outputs should have no AGC applied		
Electromagnetic compatibility of the measurement set-up including computers and interface	All interference produced and received by the set-up should be > 10 dB below the average noise to be measured		

(1) This noise figure applies to the LNA.

When an LNA is used, the requirements in Table 4 have to be met by the whole combination of receiver and LNA. The system noise figure of the combination is dominated by the noise figure of the LNA.

Care should be taken not to overload the receiver or the LNA. An external band pass filter has to be applied to prevent overloading. Below 30 MHz, signals with the highest input level originate from broadcast stations. The attenuation of the band pass filter throughout the broadcast bands should be at least 20 dB.

The IF selectivity between 6 and 60 dB should be accurately known to calculate the equivalent noise bandwidth when measurements with different IF filters have to be compared. If specified, the noise bandwidth can be taken out of the receiver specifications. This is the bandwidth of a (theoretical) rectangular filter that passes the same noise power as the filter of the receiver or analyser.

7.2 Antennas

According to Recommendation ITU-R P.372, the noise level is stated as a noise figure (in dB above thermal noise) rather than field strength. This noise figure is per definition referenced to a "lossless" antenna. Regarding noise sources that are evenly spread over the horizontal plane or that are received under relatively small vertical angle, the closest fit to a lossless antenna is a vertical tuned dipole. It is therefore recommended to use such a dipole for noise measurements above 30 MHz.

Below 30 MHz, vertical dipoles are not practical as they become too big in size. Also, they are only ideal if they are far enough away from the ground which again would be hard to realize. Recommendation ITU-R P.372 therefore uses a short vertical monopole on perfectly conducting ground as a reference antenna for frequencies below 30 MHz. It is recommended to use a short vertical monopole with a height of less than one tenth of the wavelength as the measurement antenna. This short monopole, however, has to be electrically matched to the input impedance of the receiver (usually 50 Ω). This matching is usually done with active elements. It is important that no extra amplification is included in the antenna as this would make the antenna subject to overloading from strong broadcast signals.

Applying the model that noise sources are received uniformly from all angles, a possible directivity of the measurement antenna does not have to be corrected. Even most directive antennas like Yagis only achieve their gain in the preferred direction by suppressing signals from other directions accordingly, so the average gain for the noise environment is zero. It is therefore possible to use directional antennas for the measurements in circumstances where noise is expected to be uniformly distributed as long as they are matched.

For the calculation of the external noise figure it is necessary to know the antenna factor that can be used to calculate the field strength from measured antenna voltage. Often this figure is given by the manufacturer, but the following issues have to be considered carefully:

– If the antenna is directive, the antenna factor given by the manufacturer only applies to the direction of the main beam. However, for the calculation of noise field strength only the average[1] antenna factor from signals coming in from any direction has to be used.
– Especially at low frequencies it is important that the conditions are met under which the manufacturer states the antenna factor. Things like distance of the antenna from the ground, obstructions in close vicinity of the antenna and earthing can significantly alter the antenna factor.

When the antenna factor is not known, it may also be measured using a reference antenna with known antenna factor, but the above considerations always apply. A practical way to determine the antenna factor is to compare the levels from measurement and reference antenna for a large number of emissions from random directions and average the results for each frequency band.

With regards to the reference antennas in Recommendation ITU-R P.372 and to match with practical receiving situations, the feeding point of the measurement antenna should be on or close to the ground for frequencies up to 60 MHz, and at least 5 m above the ground for higher frequencies.

8 Uncertainty analysis

The end result of the measurement should reflect a real value that can be reproduced even when another measurement set-up is used. Not only the average accuracy but also the limits in which the values can change are required. An uncertainty budget containing all contributors to the total uncertainty should be made for each measurement. Information about this can for example be found in the ISO "Guide to the Expression of Uncertainty in Measurements".

9 Measurement process

9.1 Selecting measurement locations

Even on one frequency the radio noise level, especially when dominated by MMN, varies depending on the time and location. In frequency bands below 30 MHz, noise levels mainly change over time due to propagation conditions. Therefore, in general multiple measurements at different locations have to be made. Recommendation ITU-R P.372 defines four different location

[1] Where the noise sources are uniformly distributed, the noise power received by a directive measurement antenna and by a theoretical isotropic antenna will be the same. This, in this context, the average antenna factor is obtained by applying an appropriate correction for the antenna gain in the specific direction.

categories. To reflect the resulting differences in MMN level, measurement sites should be selected according to their categories. However, for the benefit of more detailed evaluation it is recommended to classify noise measurements in the following categories:

TABLE 5

Selection criteria for outdoor measurement locations

Category	Definition
Remote rural	No obvious civilization, no buildings, no traffic, no electrical installations within 5 km
Rural	Open countryside with largely agricultural activity, building density < 1/ha, no major roads, no electrified railways
Residential	Villages and pure residential areas with no commercial or industrial activities. No electrified railways and no major roads and no high voltage overhead lines or facilities within 1 km
Urban	Dense residential buildings including minor commercial or industrial activities and shops. No electrified railways, major roads and high voltage overhead lines or facilities within 500 m
City	Dense commercial or industrial buildings and offices. Major roads and railways can be in the vicinity, but should not be dominating
Industrial area	Areas with dense factory sites and heavy industry
Railway	Locations with dominant electrified major railways
Road	Locations with dominant road traffic, e.g. highway

Measurement results should be evaluated separately for each location category. To allow a reasonable statistical statement about the radio noise level, measurements should be made on at least 10 locations per category.

All of the above measurement locations should be outdoor. To estimate the average radio noise level from multiple sources indoor, the results from measurements taken outdoor can be reduced by the expected building attenuation for the respective frequency.

Experience shows, however, that indoor noise levels tend to be even higher than those measured outdoor. This is due to the domination of a few single noise sources coming from inside the building where the measurement is taken. If this environment is to be investigated, the location categories in Table 5 are not applicable since it is not important whether the building is in a city, residential or rural surrounding. Instead, the different categories of buildings as shown in Table 6 are recommended:

It should be noted that indoor measurements always measure the sum of noise and interference from single sources. In most cases emissions from single sources inside the house will be dominant. According to current definitions in Recommendation ITU-R P.372, these emissions are not MMN. However, radiocommunication services have to cope with all unwanted signals, whether it is noise or interference, to function properly. For practical reasons it may therefore be desirable to measure the sum of both.

TABLE 6

Selection criteria for indoor measurement locations

Category	Definition
Domestic	Single house or flat with typical electrical and electronic appliances for private use
Office	Electrical and electronic appliances for business use, IT and telecommunication equipment, e.g. computers, printers, local area networks
Shopping centre	Locations with shops and supermarkets
Railway station	Major railway stations inside roofed platform area
Airport terminal	Major airports, inside terminal building
Factory	Inside factory buildings dominated by electrical machinery
Hospital	Locations dominated by medical appliances

9.2 Frequency selection

It is possible to perform measurements on one single frequency (channel) or in a certain frequency band (e.g. 100 kHz) these observations can be made automatically and the results processed according to a pre-defined protocol.

In the HF frequency band it is virtually impossible to find a frequency that is free of wanted emissions for the whole 24 h measurement period. The simplest way to find a suitable frequency or band is to use information from test measurements or historical data. However, it is not guaranteed that all measurement samples can be used because unforeseen occupancy could occur during the actual survey. Instead of selecting a fixed frequency or band for the measurement, it is therefore desirable that a scan over the band of interest is made to determine the WGN level. The frequency that had the lowest level in the scan range should then be measured in single frequency mode for a time of at least 0.5 s to determine the IN level. Especially in the frequency range below 30 MHz with varying occupancy over the day, it is recommended to repeat this frequency selection before each measurement.

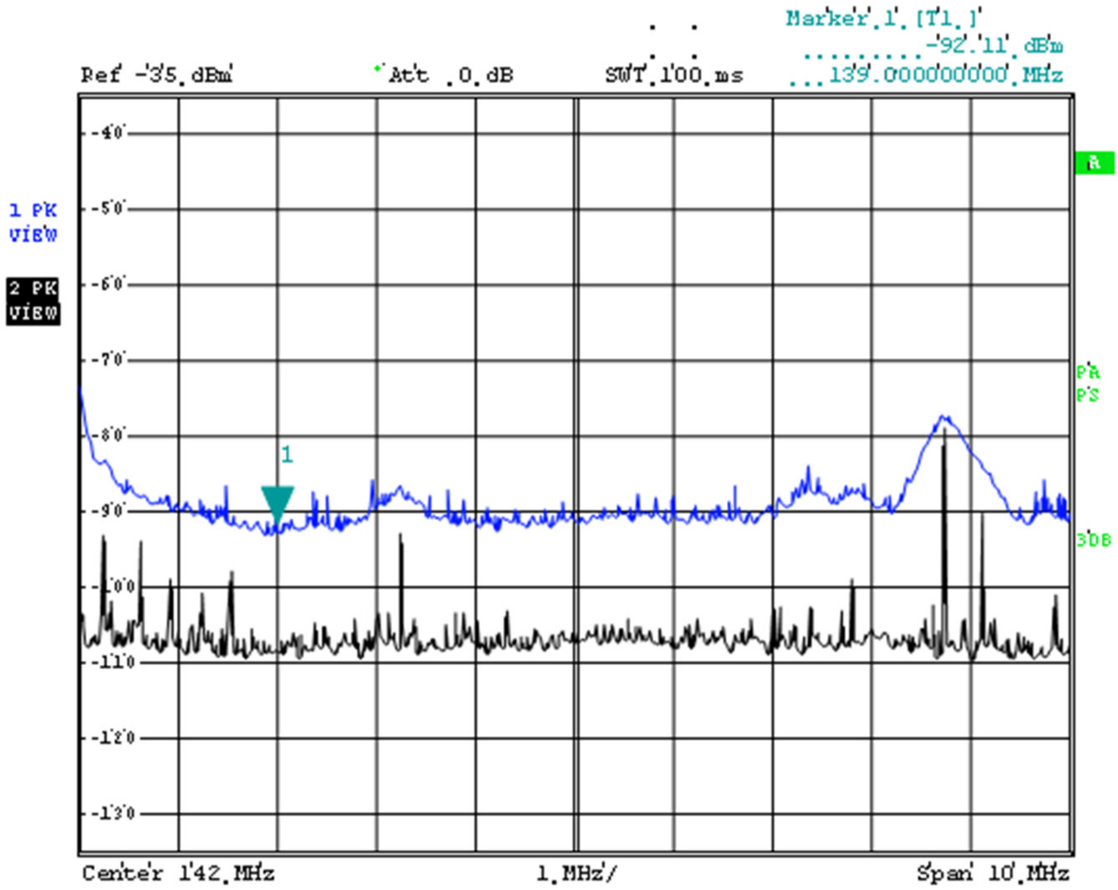
In the frequency range above 30 MHz, wanted emissions usually come from national sources and occupancy is known. In this case, a fixed frequency with no active assignments can be used.

The example in Fig. 1 shows the spectrum around 142 MHz with a few emissions from frequency users, recorded MaxHold with two different RBWs (upper trace: 300 kHz, lower trace: 10 kHz). The marked frequency is selected for noise measurements as it is assumed to be free from emissions and far enough away from used channels.

Especially when performing unattended automatic survey and frequency selection, it cannot always be assumed that the selected frequency contains only noise. Selecting a frequency band which mostly consists of background noise having Gaussian amplitude distribution enhances the accuracy of the measurement of the noise power level. The most reliable way to prove whether a frequency (band) contains only WGN is to apply the mathematical concept of singular value decomposition (SVD). This method includes constructing an autocorrelation matrix estimate from the received signal and then evaluating the results obtained from the application of SVD to the estimated autocorrelation matrix.

FIGURE 1

Selection of a single frequency



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The most practical way to select a proper frequency (band) is to first find a possible candidate band by scanning the desired frequency range and identify the frequency (band) with the lowest level. The usability of this frequency (band) can be verified by applying the SVD process. If the SVD reveals that the scan contains mostly WGN, the measurement can be used. If not, an alternative frequency (band) has to be selected.

The details of the SVD method are described in Appendix 1.

9.3 Analyser/receiver settings

Recommended equipment settings are given in Table 7:

TABLE 7

Analyser/receiver settings

Measurement time	It is practical to produce a result every 10 to 30 s. For WGN measurements with an r.m.s. detector a sweep time or scan time of 10 to 20 s is useful. For raw data sampling it is practical to run one scan of at least 0.5 s length every 10 to 30 s. During the scan, sample amplitudes have to be taken at a very fast rate (sampling frequency at least 1/RBW).
Frequency range	The observation frequency range depends fully on the use of the chosen frequency band; this frequency band can even be split in sub bands or frequencies depending on the frequency band.

TABLE 7 (*end*)

RBW	If the frequency band scanning is used, the bandwidth of the applied filter depends on the frequency span divided by the required resolution. The raw sampling principle dictates a RBW of half of the sampling frequency. The shape factor of the filter should be determined to make it possible to compare measurement results from different receivers. For recommended RBW values, see Table 8.
Detector	For WGN measurements a true r.m.s. detector is necessary, any other detector is unsuitable. Some manufacturers also label this detector as average (r.m.s.). It is important that the detector averages power, not voltage. These detectors are generally based on a sampler of which the sampling rate is based on the filter bandwidth. The r.m.s. power is calculated from these samples over a defined time period. This time period is the measurement period. When a non sampling r.m.s. detector is used the integration time of this detector has to be $10/2B_N$ (kHz) if 1% uncertainty is expected. So, if the noise bandwidth B_N is 500 Hz, the minimum integration time has to be 10 s. Special attention to this has to be given when receivers of an older generation are used. When the measured values are less than 10 dB above the equipment noise floor this detector requires a custom calibration. The raw data principle has to use a sample detector because the processing including r.m.s. calculations are done afterwards.
Attenuator	3 dB An external attenuator between antenna and LNA is recommended to set a defined receiver/LNA input impedance to guarantee a low measurement uncertainty. If it can be assured that the antenna exactly matches the input impedance of the LNA, the additional attenuation is not needed.
Pre-selector	On (if switchable)

TABLE 8

Measurement bandwidths

Frequency range	RBW for measurement Type A (WGN only)	RBW for measurement Types B and C (WGN and IN)
300 kHz – 30 MHz	100 Hz	10 kHz
30 MHz – 450 MHz	1 kHz	100 kHz
450 MHz – 1 GHz	1 kHz	300 kHz
1 GHz – 3 GHz	10 kHz	5 MHz
> 3 GHz	10 kHz	10 MHz

In this context, RBW is the equivalent noise bandwidth of the nominal 3 dB bandwidth.

Using larger RBWs as indicated in Table 8 produces larger amounts of data to be processed because of the higher necessary sampling speed. However, IN may be seen more clearly. If measurement Types B and C are performed it is still recommended to use the narrower bandwidth for the WGN measurement and the higher bandwidth for the IN measurement only.

9.4 Measuring period

The measuring period should be chosen considering the time in which significant changes in the measured noise can be expected. For example to include day and night differences of HF propagation and temporarily used equipment the standard measuring period should be 24 h. To take into account variation due to seasons HF measurements may be repeated a number of times each year. For frequencies above 30 MHz, a minimum survey period of 10 h during working daytimes is recommended.

9.5 Separation of man-made and atmospheric noise (measurement Type C only)

Below 30 MHz, significant parts of the IN component can originate from atmospheric noise such as lightning. If measurements are to determine only the MMN, the atmospheric noise would have to be subtracted from the measurement result. This, however, is only possible for IN. To identify the origin of IN it is necessary to measure at two different locations at the same time:

– the measurement location; and

– the reference location.

The distance between both locations should be more than the range of typical MMN emissions but close enough to assume the same skywave propagation conditions (recommended: 500 m to 10 km).

The measurement equipment from both locations has to be exactly time-synchronized (maximum offset: 100 ms). Examples on how to achieve exact time synchronization are:

– Periodically switching the measurement receiver to a standard time signal (e.g. DCF77)

– Using the time signal from an attached GPS receiver.

The transmitted time can be used to adjust the internal processor’s clock or an offset between processor’s clock and the transmitted real time can be calculated and used to correct the time stamp that has to be stored with every measurement scan.

By means of these time stamps each scan can later be compared with the respected scan at the other location. If a signal shows up on both measurement locations it is assumed to be atmospheric noise or a wanted emission received via the skywave and is eliminated from the results before further processing. Signals that are only received at the measurement location are assumed to be MMN from nearby sources.

9.6 Data collection and post processing

9.6.1 WGN measurements with r.m.s. detector (Measurement Type A)

A spectrum analyser scans a frequency band in a number of steps (frequency bins). A normal number of bins with modern spectrum analysers is 500-10 000. If the scan time for instance is 10 s the results of the measurements is a database (matrix) of $500 \times 8\ 600$ to $10\,000 \times 8\ 600$ measurement samples per day. To have the possibility to exclude certain parts of the measurement and to apply different statistical methods, this database should be processed afterwards with dedicated software.

9.6.2 WGN + IN measurements with raw data sampling (Measurement Types A, B and C)

To allow a complete evaluation of impulses, it would be necessary to sample so fast that each single pulse is captured at least once. However, this would result in a very large amount of data to be stored. For a statistical evaluation, continuous observation of the frequency range is not necessary. Instead, the survey can be divided into individual scans (of one frequency or one band). One scan should be at least 0.5 s long during which the momentary signal level is captured as fast as possible ($Ts \leq 1/RBW$). Then, a pause of a few seconds can be introduced during which nothing is measured, until the next scan starts. This method still produces many million samples per survey that have to be statistically evaluated by dedicated software.

10 Data processing

10.1 Overview

Table 9 presents the different processing steps for the different measurement principles.

TABLE 9

Processing steps

Processing step	r.m.s.-WGN measurement	Raw data sampling
Correction for equipment noise	x	x
Determination of the WGN level using the “20% method”	x	
Validation of the 20% cut-off value	x	
Plotting the amplitude probability distribution (APD) of the raw samples		x
Calculation of F_a	x	x
Separation of IN samples from WGN		optional
Combination of impulse trains to bursts		optional
Separation of MMN pulses from atmospheric noise		optional
Calculation of pulse parameter distribution		optional

10.2 Correction for equipment noise

The signals we measure are in fact signals superimposed on the equipment noise. To determine the difference between external and equipment noise, a manual measurement can be performed to determine the correction as follows:

a) using an r.m.s. detector on a currently “free” frequency, measure the level of the WGN;

b) replace the antenna with a 50 Ω load and measure the sum of the system noise and load thermal noise, using the same settings as before.

If the result difference of from measurement a) and b) is K dB or more, no additional correction for the equipment noise is necessary. If it is less, the equipment noise from measurement b) has to be linearly subtracted from all external noise values:

$$p_{WGN} = p_a - \frac{f-1}{f} p_b \qquad (2)$$

where:

p_a: noise level from the measurement a) in linear units

p_b: noise level from the measurement b) in linear units

f: equipment noise factor.

The coefficient K can be calculated as:

$$K(\text{dB}) = 10 \log \frac{11(f-1)}{f} \tag{3}$$

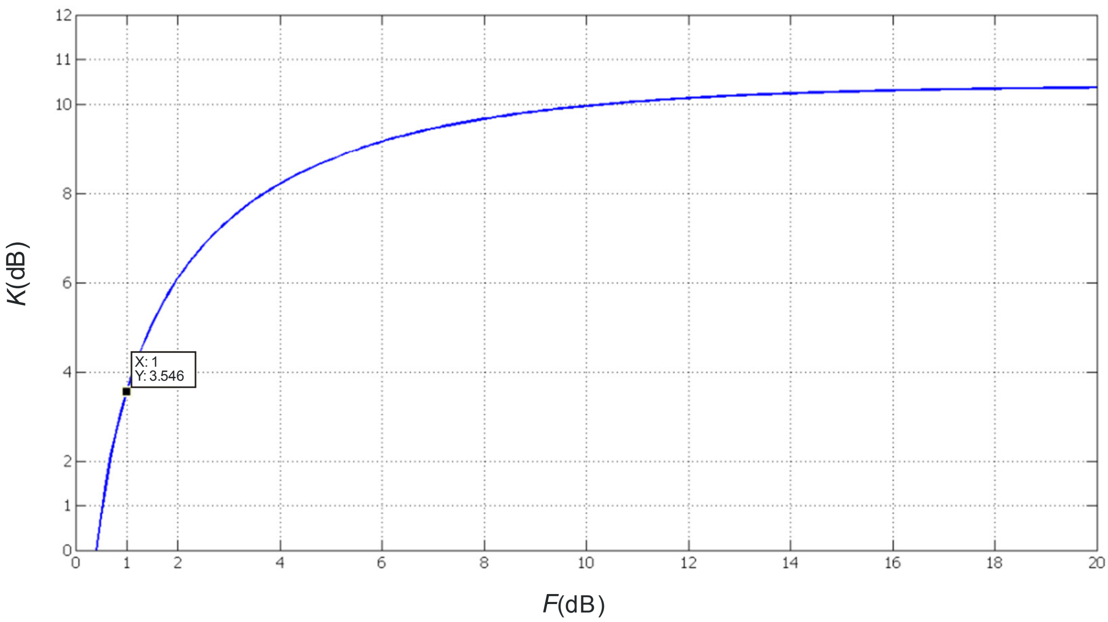
Equipment specifications usually provide a noise figure F. Because this is the noise factor expressed in decibels, the noise factor f can be calculated as follows:

$$f = 10^{\left(\frac{F}{10}\right)} \tag{4}$$

The calculated curve in Fig. 2 gives the value of K as a function of the noise figure.

FIGURE 2

Threshold for equipment noise correction



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10.3 Determination of the WGN level using the "20% method" (r.m.s.-WGN measurement only)

Especially below 30 MHz it cannot be assumed that the measurement frequency (or range) is free for the whole measurement period. It is therefore recommended to do a scan over a small frequency range instead of measuring on one frequency alone. Unwanted occupancies can be eliminated from the result by using only the samples with the lowest 20% levels and discard the other 80%. This, however, also discards some noise containing samples and would therefore result in too low noise levels unless a correction is applied. The necessary correction is determined by connecting a white noise source to the receiver, take some measurement samples and determine the average r.m.s. level from all (100%) samples. Then the upper 80% are cut off and the average r.m.s. level from the lowest 20% samples is calculated. The correction to be applied is the difference between both average r.m.s. levels (100% and 20%).

10.4 Validation of the 20% cut-off value (r.m.s. WGN measurements only)

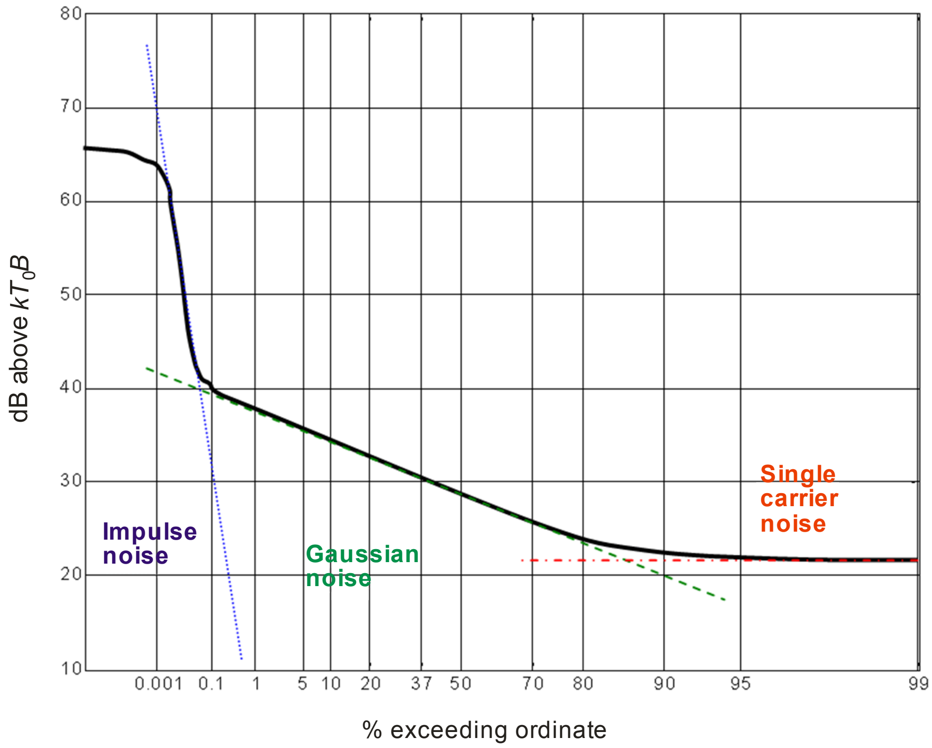
For HF 20% of the lowest values is a practical value to determine the noise level. For other frequency ranges it may be checked whether this 20% value is correct or should be changed to another value. Some methods to validate the cut-off value are described in Appendix 2.

10.5 Plotting of the APD (raw data sampling only)

If raw data sampling is used to determine the WGN, the r.m.s. level can theoretically be determined by linear averaging the power levels of all samples measured in a certain (integration) time. However, this is only correct if nothing else than WGN was present during the measurement. Especially in HF, this can often not be assumed. In these cases, the r.m.s. level of WGN can be determined by plotting the raw data in a so called "Amplitude Probability Distribution" graph: This graph shows the percentage of measurement samples that exceed a certain amplitude (see Fig. 3).

FIGURE 3

Typical amplitude probability distribution



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The x-axis of the APD graph has a Rayleigh scaling. With this scaling, it is easy to separate the different types of noise: White noise shows up as a straight sloping line (in the middle of the graph). It can be shown mathematically that the gradient of this line is −10 when both scales are converted to linear. This means that the line falls by 10 dB between 0.1%, 37%, 90% and 99%.

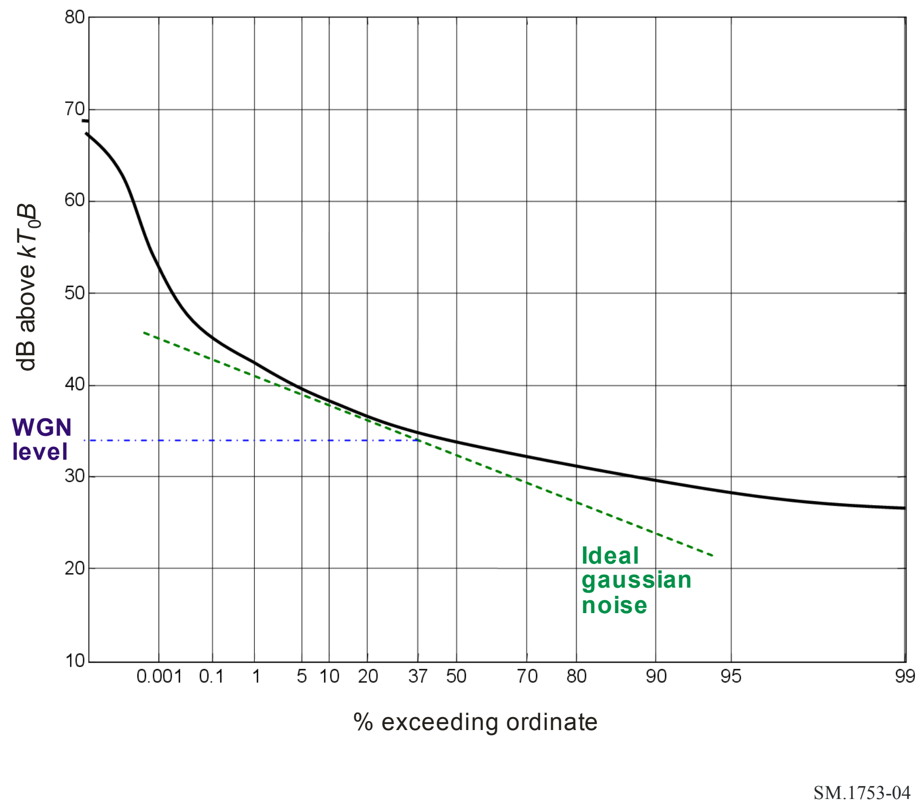
The rising edge to the left indicates impulsive noise, the levelling out towards the right side is due to single carriers from nearby sources and the lower level indication limit of the measurement receiver.

When no single carriers or narrowband wanted emissions are present, the overall r.m.s. level is the value at the point where the curve crosses 37% on the abscissa.

However, the presence of carriers and wanted emissions not only produce a rise towards the right end of the APD but also raises the whole curve including the 37% value, and produces a concave curve instead of a straight line in the mid part of the graph, like in Fig. 4.

FIGURE 4

APD graph in the presence of carriers and/or wanted signals



In this case, the level of the WGN is determined by fitting a straight line with the slope of ideal WGN to the curve. The r.m.s. WGN level is where this tangent crosses the 37% value on the abscissa.

To enhance accuracy, measurement values taken over time can be transformed into the frequency domain by applying a Fourier Transform. A second APD graph is built from the resulting frequency domain values and again a tangent is fitted to the middle part of the graph. The r.m.s. level of the WGN is also the 37% value of the frequency domain APD. When wanted signals or single carriers were present during the measurement, only one of the two APD graphs is raised, depending on the nature of the signals. The exact overall WGN is then the lower of both 37% values. This evaluation method is especially necessary when noise measurements are taken inside frequency bands occupied by wanted signals. When frequencies are selected so that no dominant carriers and wanted emissions are present, the FFT transform is usually not necessary.

10.6 Calculation of F_a

In line with Recommendation ITU-R P.372, the noise level is expressed as a noise figure of a lossless antenna due to external noise F_a in dB above thermal noise.

The thermal noise can be calculated as:

$$P_0 = 10 \log(K * t * b) \tag{5}$$

where:

K: Boltzmann constant $1.38*10^{-23}$ (J/K)

t: ambient temperature (K)

b: noise equivalent bandwidth of the measurement filter (Hz).

At a reference temperature t_0 of 290 K (17°C), P_0 becomes −174 dBm in 1 Hz bandwidth.

The measured noise level is the sum of external noise and noise originating from the measurement system, mainly consisting of receiver noise and, in case an LNA is used, of the noise from the LNA. The external noise factor f_a can be calculated using the equations in Recommendation ITU-R P.372. In real measurement environments it is realistic to assume that the temperature of all parts of the measurement system is equal. Furthermore, it can be set to the reference temperature t_0 of 17°C without introducing a considerable error except for special cases with extreme temperatures. Under these assumptions, the key equation that can be used for the calculation of f_a is:

$$f_a = f - f_c f_t f_r + 1 \tag{6}$$

where:

f: measured total noise factor in linear units (p_{meas}/p_0)

f_c: noise factor associated with antenna (antenna output/available input power)

f_t: noise factor associated with transmission line (cable input/output power)

f_r: noise factor of the receiving system (receiver and LNA, if used).

All lower-case parameters are given in linear units, not dB. To arrive at the more commonly used logarithmic units, it should be noted that all parameters are power levels, so for the conversion the rule:

$$F_a \text{ (dB)} = 10 \log(f_a) \tag{7}$$

applies.

In some practical measurement situations the following assumptions can be made:

– The antenna can be regarded as lossless ($f_c = 1$), especially when matched antennas are used (e.g. tuned dipoles for frequencies above 30 MHz).

– The transmission line loss can be neglected ($f_t = 1$), especially for frequencies below 30 MHz.

– The receiver noise can be neglected ($f_r = 1$) when the measured noise power is at least 10 dB above the receiver noise (see § 10.2).

In these cases the measured noise power is practically equal to the external radio noise power.

When measured in dBm, the noise figure F_a in dB can then be calculated to:

$$F_a = P_n - P_0 \tag{8}$$

where:

P_0: the thermal noise power (dBm)

P_n: external noise power (dBm).

For frequency ranges above 60 MHz, when a vertical tuned dipole is used, F_a can indeed be calculated as stated above. For lower frequencies, however, it is usually not be possible to use a lossless antenna.

In this case, the external noise figure can be calculated when applying the average antenna factor (see § 7.2):

$$E = U + AF \qquad \text{dB}(\mu\text{V/m}) \tag{9}$$

where:

E: field strength dB(μV/m)

U: antenna terminal voltage dB(μV)

AF: antenna factor (dB)[2].

When AF is known, F_a can be calculated from the measured noise level as follows:

$$F_a = P + AF - 20\log(f) - 10\log(b) + 202.5 \qquad \text{dB} \qquad (10)$$

where:

F_a: antenna noise figure due to external noise (dB)

P: r.m.s. level of the WGN (dBm)

AF: antenna factor (dB)

f: measurement frequency (MHz)

b: measurement bandwidth (Hz).

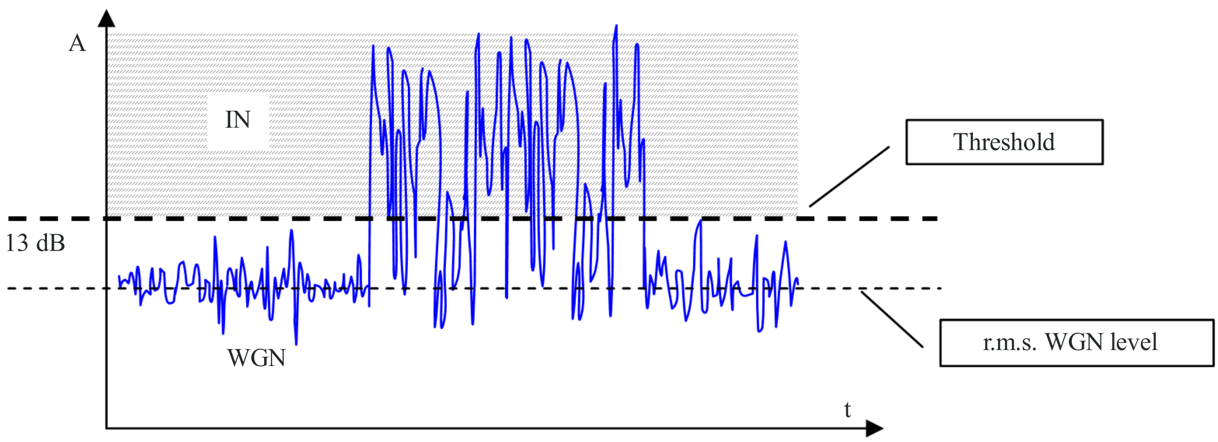
The above formula was developed using formula (7) of Recommendation ITU-R P.372 for a short vertical monopole as a reference antenna, formula (9) above and assuming a 50 Ω measurement system with P (dBm) = U (dB(μV)) −107 dB.

10.7 Separation of IN samples from WGN (measurement Types B and C only)

Experience shows that the IN from MMN does not fit properly in one of the mathematically described models. When sampled sufficiently fast, WGN also may have short peaks that extend well above the average level. To extract only those samples originating from IN, a threshold has to be applied that is well above the WGN peaks. This threshold is set to 13 dB above the r.m.s. WGN level as this is the usual CREST factor (difference between r.m.s. and peak value) for WGN. All measurement samples above the threshold are treated as IN.

FIGURE 5

Separation of IN and WGN



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[2] The antenna factor is usually simply given as a and is usually expressed in dB. It is recognized that this is dimensionally incorrect, but reflects usual engineering practice.

10.8 Combining impulse trains to bursts (measurement Types B and C only)

When examining the RF amplitude of real pulses vs. time it can be seen that most pulses are in fact a series of short peaks or "pulse trains". Because measuring pulse levels for MMN focuses on the interference potential of a pulse it is necessary to integrate the peaks of a pulse train to a single event that is called a "burst". This integration is done as long as at least 50% of the measurement samples are above the threshold.

The length of each burst in a record is calculated in a way that the following conditions are met for all pulses received throughout the complete record:

1 the sample directly following a burst start point always exceeds the threshold, the sample directly following a burst end point always falls below the threshold;

2 at least 50% of samples between burst start and burst end exceed the threshold.

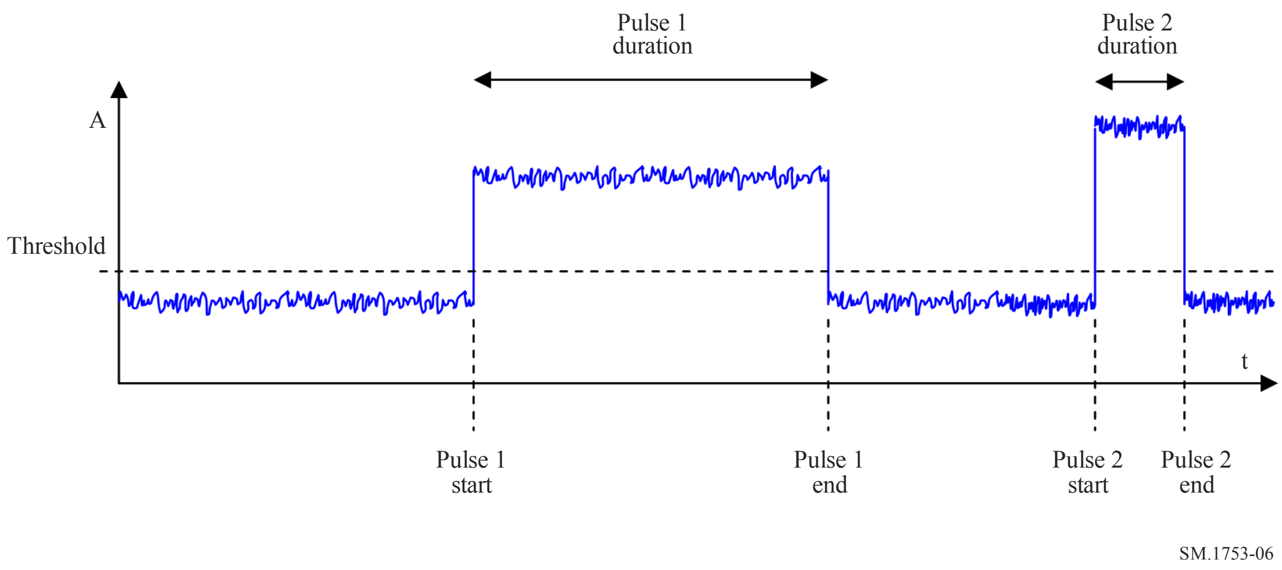
For a time of at least 25% of the burst length all samples in front of the burst start and after the burst end fall below the threshold.

The consequence of these conditions is that certain peaks within irregular pulse trains are combined to one single, long burst.

The following figures show some examples:

FIGURE 6

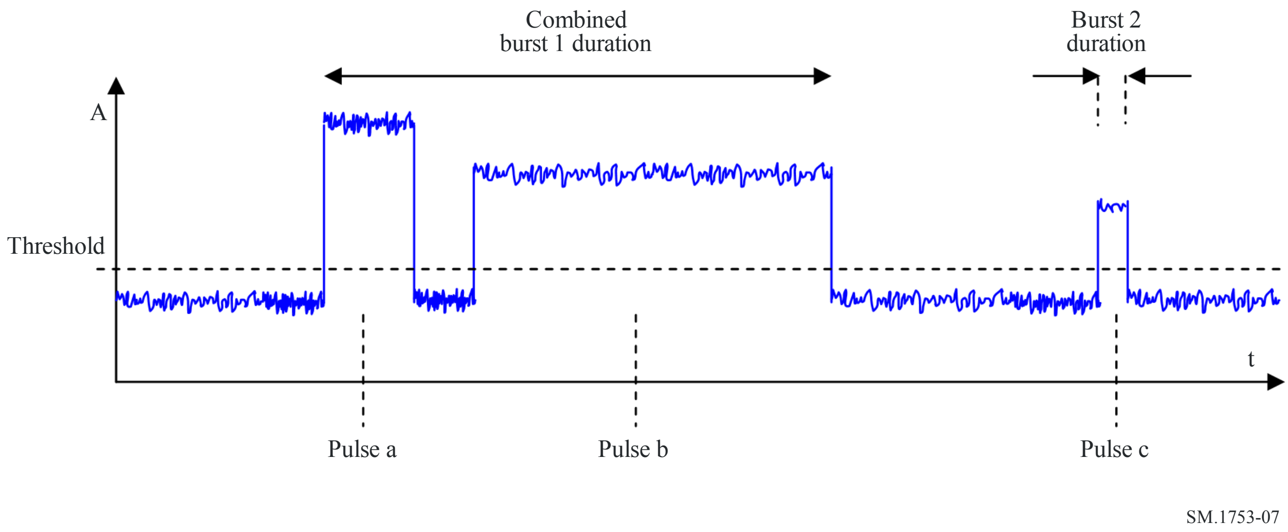
Determination of burst start and end points



Counting from the centre of pulse 1 in Fig. 6, the "gap" between pulse 1 end and pulse 2 start is more than 25% of the length of pulse 1, so the second peak is interpreted as a separate pulse.

FIGURE 7

Combining pulses



In Fig. 7, all three conditions as defined above are met for pulse a) in order to qualify it as a complete burst. However, for pulse b) the condition that at least 25% of the measurement samples in front of the sub-pulse start have to fall below the threshold is not fulfilled unless pulse a) is included and a combined pulse (burst) is formed. The time between the end of this burst 1 and the start of pulse 3 is more than 25% of the burst 1 length. Pulse c) is therefore not included but kept as a separate pulse.

10.9 Separation of MMN pulses from atmospheric noise (measurement Type C only)

As said earlier, this separation is only possible if method 3 with time-synchronized measurement at two locations is applied. IN from atmospheric noise (mainly thunderstorms) will be received at both measurement and reference location, so the aim is to detect this kind of signals in the measurement results.

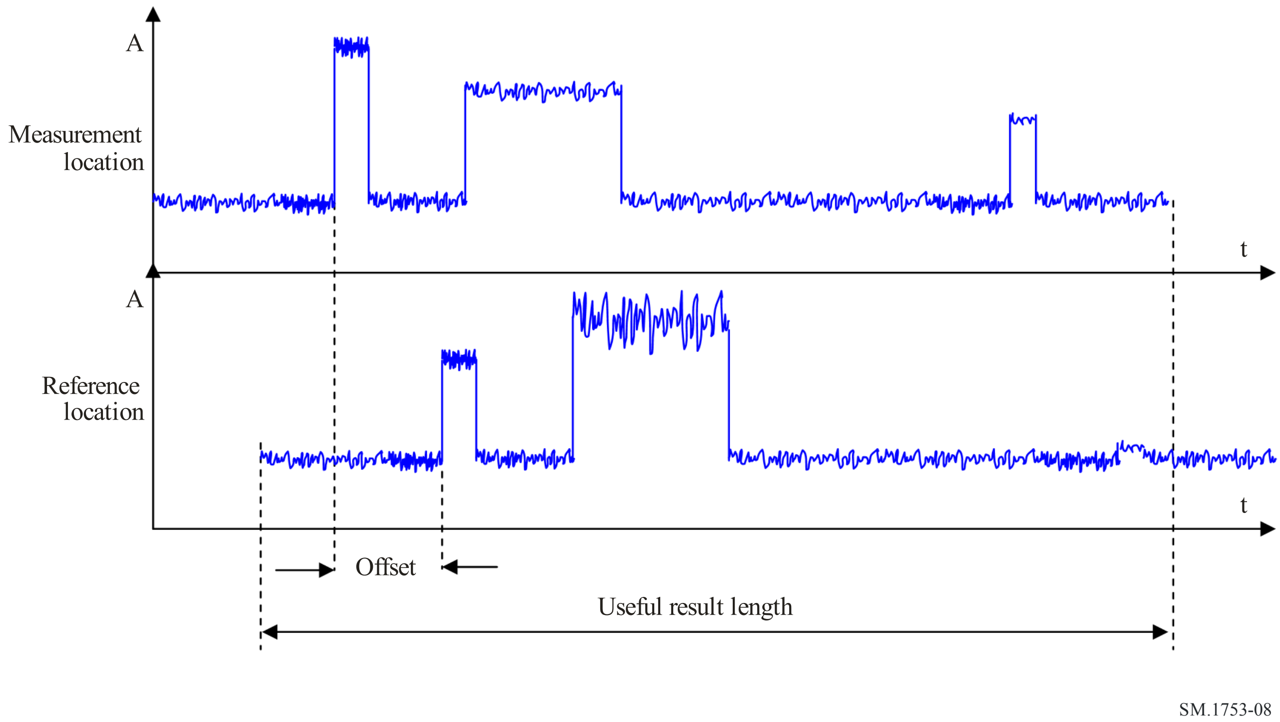
Because the time synchronization of the measurement equipment will never be as accurate as one sample, the exact time offset between both locations has to be determined first. This is done by comparing the start and end times of all impulse/burst samples from the measurement and reference location with each other and calculating a correlation value. Then all samples from the measurement location are shifted in time by one sample and the correlation value is calculated again and so on. The position with the highest correlation defines the exact time offset between both measurements. The following evaluation steps are applied only to those samples that have been measured at both locations (useful result length).

Example: The maximum correlation is achieved at an offset of +100 ms applied to the reference location. The measurement (scan) time was 1 s. The useful result length is then from 0.1 s to 1.0 s of the reference location and 0 s to 0.9 s of the measurement location (see Fig. 8)

Inside the useful result length, the impulse/burst start samples are investigated: If, for each impulse/burst, they occur within a tolerance of 50% of the impulse/burst length at both measurement and reference location, the impulse/burst is deleted from the results as it is assumed to be received over the skywave and therefore most probably of atmospheric nature. If a pulse/burst start point occurs only at the measurement location, it is kept for the IN processing.

FIGURE 8

Determination of time offset between measurement locations



10.10 Calculation of pulse parameter distribution (measurement Types B and C only)

As said earlier, to fully characterize IN, the following parameters are required:

– Impulse/burst level

– Impulse/burst length

– Impulse/burst repetition frequency or period

– Total impulse/burst time.

Because the first three parameters change randomly, their values have to be presented as a distribution plot.

10.10.1 Impulse/burst level

The total impulse/burst level (IN level) can only be measured correctly for Impulse/burst lengths of at least 1/RBW. Since an impulse/burst can only interfere with a modern digital communication system when it is at least as long as the symbol time, choosing an RBW according to Table 8 already results in measurement values that represent true interference potential. The IN level, however, is still dependant of the RBW. Therefore, the used RBW has to be stated when IN levels are presented. To be independent of the measurement bandwidth it is recommended to normalize the measured results to the RBW used and state the IN level as a level density. The y axis of the IN APD in then labelled in dB(μV/MHz). To convert a measured IN value into IN level density, the following formula is applied:

$$Wg = U + 20\log(1/b) \qquad \text{dB}(\mu\text{V/MHz}) \qquad (11)$$

where:

Wg: spectral density dB(μV/MHz)

U: measured noise voltage from a lossless antenna dB(μV)

b: noise bandwidth (MHz).

In case the antenna cannot be regarded lossless, the adequate correction to the measured noise voltage according to § 10.6 has to be applied.

There will be one IN distribution plot per frequency and location class according to Tables 5 and 6.

10.10.2 Impulse/burst length and period

Once impulse/burst start and end samples are identified, the length of each impulse/burst is calculated as:

$$N_1 / f_s \tag{12}$$

where:

N_1: number of samples between impulse/burst start and end

f_s: sampling frequency.

The impulse/burst period is calculated as:

$$N_2 / f_s \tag{13}$$

where:

N_2: number of samples between consecutive impulse/burst start points

f_s: sampling frequency.

10.10.3 Total impulse/burst time

The total impulse or burst time is given as a percentage of the total survey time:

$$i = (Ni / N) * 100 \tag{14}$$

where:

Ni: number of samples above the IN threshold

N: total number of measurement samples.

11 Result presentation

11.1 WGN measurements

Besides the presentation in terms of F_a, it is also common to give the noise level in terms of field strength, especially below 30 MHz. For this type of presentation it is necessary to convert the measured noise power using the following equation from Recommendation ITU-R P.372:

$$E_n = F_a + 20 \log(f / \text{MHz}) + B + 95.5 \tag{15}$$

where:

F_a: noise figure due to external noise (F_a = 10 log(f_a))

f: measurement frequency (MHz)

B: logarithmic noise equivalent measurement bandwidth (B = 10 log(b).

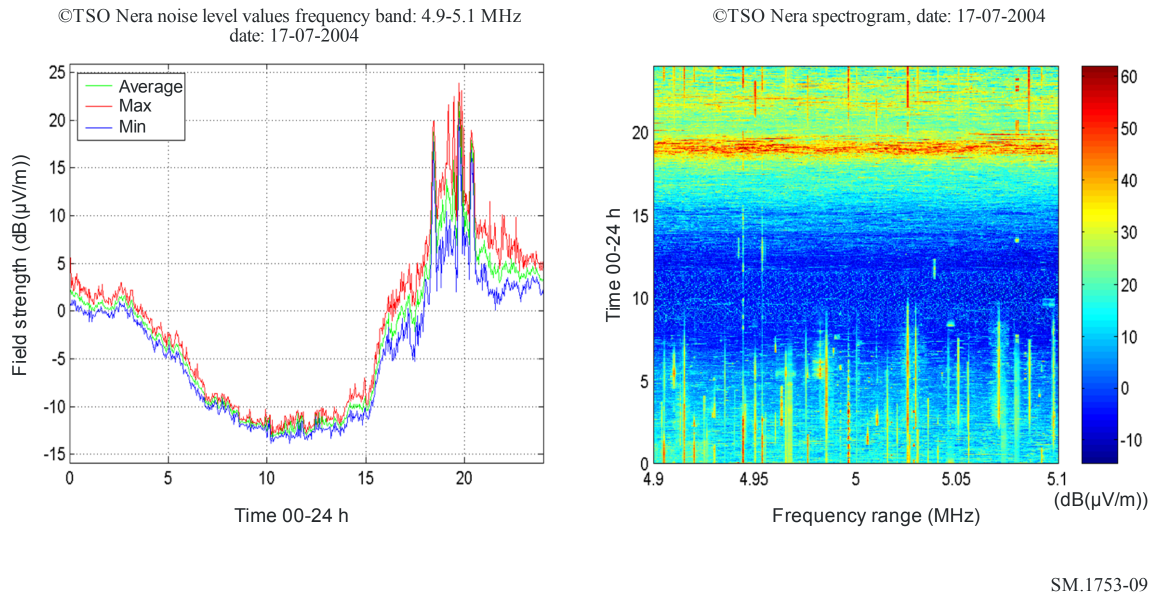
Equation (15) is valid for short vertical monopoles. For matched dipoles, the value 95.5 has to be replaced by 99.0.

In frequency ranges below 30 MHz, the radio noise significantly changes over the time of day. Therefore the calculated results should be presented over 24 h.

Figure 9 shows an example of measurement results at 5 MHz (4.9-5.1 MHz). The maximum, average and minimum values over 24 h can be seen in the left hand plot and the spectrogram, containing all the scans over 24 h on the right side.

FIGURE 9

Mean, maximum and minimum values and spectrogram over 24-hour period

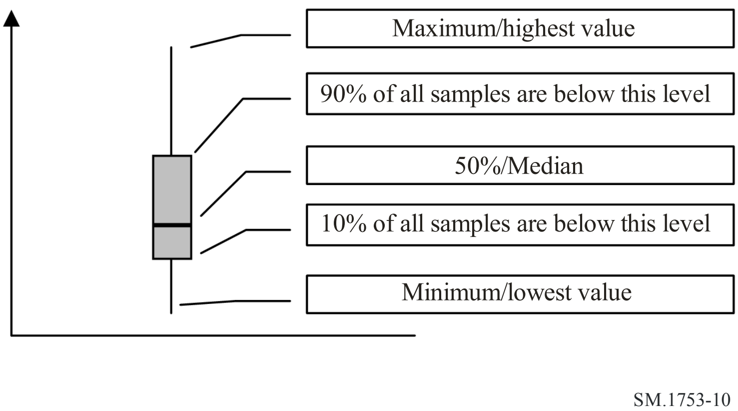


The results can also be integrated over periods of 1 h and presented in tabular form (one value every hour).

An alternative way to present the WGN results is the so called boxplot. For every hour, the maximum, upper 90%, median, lower 10% and minimum values are calculated and shown in a box.

FIGURE 10

Principle of a boxplot

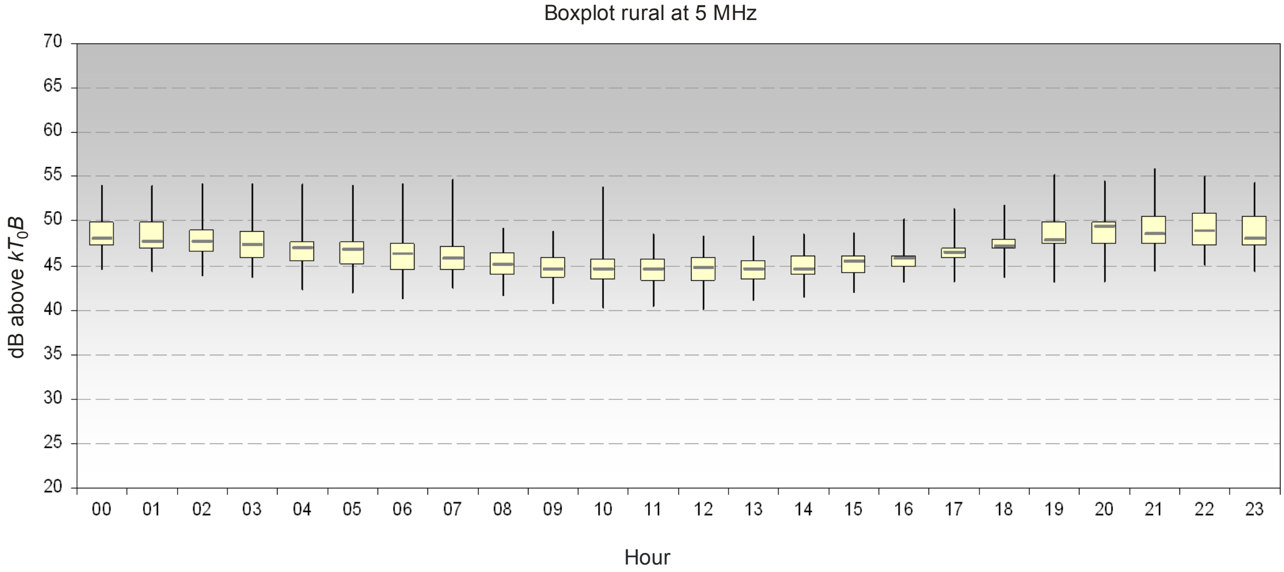


The boxplot is particularly useful to present the results from multiple measurements in just one diagram.

Figure 11 shows a boxplot summarizing 23 measurements done at rural locations.

FIGURE 11

r.m.s. WGN results presented as a boxplot



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11.2 IN measurements

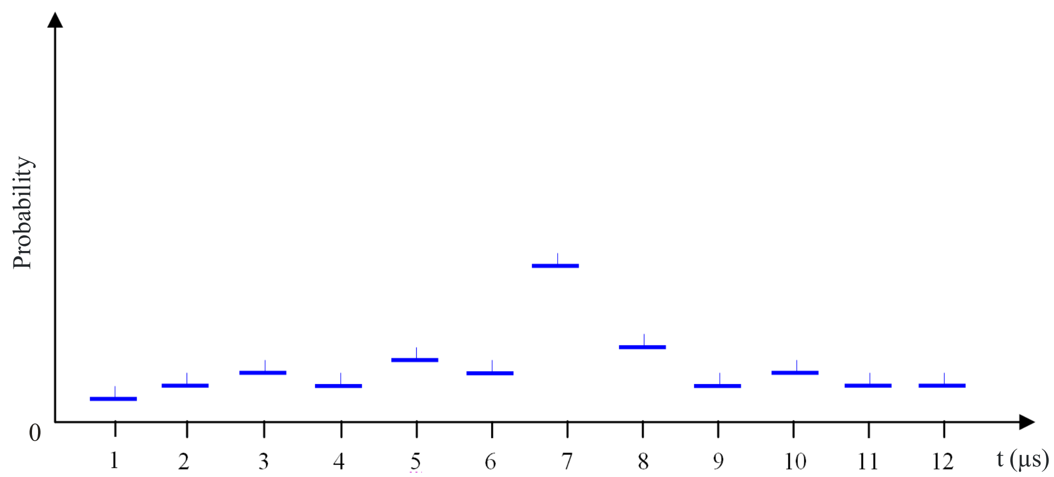
The impulse/burst level statistics are best presented as an APD graph like in Fig. 3. If all measurement samples are included in the APD (IN and WGN samples), the relative amount of impulses can be derived from the graph directly by reading the value where the graph leaves the straight line to the left. In the example of Fig. 3 this would be at 0.1%.

However, more detailed information about the level distribution of impulses can be taken from an APD that is produced from IN samples only and converted into level densities (see § 10.10.1).

The distribution of impulse/burst length and period can best be presented as a graph indicating the relative probability against the length or period itself, like in the Fig. 12.

FIGURE 12

Example of impulse/burst length distribution



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The example shows that most of the impulses have a length of 7 μs.

The time resolution of this graph is equal to the sampling rate.

12 Limitations

The described approach to separate IN from WGN and calculate its key values result in the following limits for IN parameters:

TABLE 10

Limitations for measurable IN

Parameter	Value
Lowest IN level	13 dB above WGN level
Shortest pulse length	1/sampling frequency
Longest pulse length	For measurements with sweep analysers: sweep time For continuous measurements: measurement time
Lowest PRF	For measurements with sweep analysers: 1/sweep time For continuous measurements (e.g. FFT): 1/acquisition time
Highest PRF	Sampling frequency/2

Appendix 1

Verification of WGN frequency selection using SVD

SVD is an analytic method to determine if the noise measured is non-Gaussian. In general, SVD is a matrix approximation technique which filters out zero values and works with the singular values of the matrix. Matrices are related to signals and SVD separates efficiently the noise data from the signal data.

The application of the SVD to determine the Gaussian noise is a three step procedure:

Step 1: Using the I and Q measured signal values form a complex value $x(n)$ with the length of N, an autocorrelation sequence (ACS) estimate with the length of M and an autocorrelation with that sequence are constructed with the measured signal values as follows:

First the order p of the size of the autocorrelation matrix R_x is determined. This size depends on the available data samples. If an ACS with the length of M has been calculated with N measured samples in a scan, the size of the autocorrelation matrix is $(p + 1)*(p + 1)$ where $M = p + 1$. A number as low as $p = 19$ can be used, but in principle, a higher value for p results in a better classification.

Then the (generally complex) autocorrelation matrix estimate $\hat{R}_k$ is constructed:

$$\hat{R}_x = \begin{bmatrix} \hat{r}_x(0) & \hat{r}_x^*(1) & \hat{r}_x^*(2) & \cdots & \hat{r}_x^*(p) \\ \hat{r}_x(1) & \hat{r}_x^*(0) & \hat{r}_x^*(1) & \cdots & \hat{r}_x^*(p-1) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \hat{r}_x(p) & \hat{r}_x(p-1) & \hat{r}_x(p-2) & \cdots & \hat{r}_x(0) \end{bmatrix} \in \mathbf{C}^{(p+1)\times(p+1)} \tag{16}$$

where:

$$\hat{r}_x(m) = \frac{1}{N-m} \sum_{n=0}^{N-m-1} x(n+m)x^*(n) \tag{17}$$

The * denotes a conjugate value. Note that since R_x is an autocorrelation matrix, $p + 1$ unique ACS values are used to fill the matrix. The unique values are constructed through equation (17). Each of these values uses up to N measurements.

Step 2: In this step, the singular values of the matrix of equation (16) are evaluated by application of SVD. From the SVD of $\hat{R}_k$, two auxiliary unitary matrices U, V and a diagonal matrix $\sum$ of the same size are computed:

$$\hat{R}_x = U\Sigma V^H \tag{18}$$

There are $p + 1$ singular values σ_k of the matrix Σ which are either zero or positive. Note since Σ is a diagonal matrix, the singular values are simply the diagonal values.

Step 3: Evaluation of quantities based on the singular values as a metric to decide if the noise is Gaussian. Specifically, a metric $\nu(k)$ and its index k are calculated using equation (19):

$$\nu(k) = \frac{\left\|\hat{R}_k^{(k)}\right\|_F}{\left\|\hat{R}_k\right\|_F} = \left[\frac{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_k^2}{\sigma_1^2 + \sigma_2^2 + \ldots + \sigma_{p+1}^2}\right]^{\frac{1}{2}} \tag{19}$$

where $\left\|\hat{R}_k\right\|_F$ is the Frobenius norm of a matrix $\hat{R}_k$.

Note that the Frobenius norm corresponds to the norm of a vector that results when stacking the columns of the matrix on top of each other.

The final step is to determine the reference index value k which satisfies $\nu(k) = 0.95$. Depending on the required confidence level, other values than the value 0.95 may be used. The confidence level increases as the value comes closer to 1. From the experiments 0.95 is recommended as a practical value.

If $k > \frac{p+1}{2}$, then only WGN exists in the measurement samples, otherwise signal(s) plus noise exist.

The maximum possible value of k is $p + 1$. Note that as k increases in equation (19), $\nu(k)$ converges to 1. Figure 13 shows an example of this graph for a signal that contains only noise samples.

Figure 14 shows an example of a scan that contains noise mixed with some weak carriers.

FIGURE 13

Graph of ν(*k*) for WGN

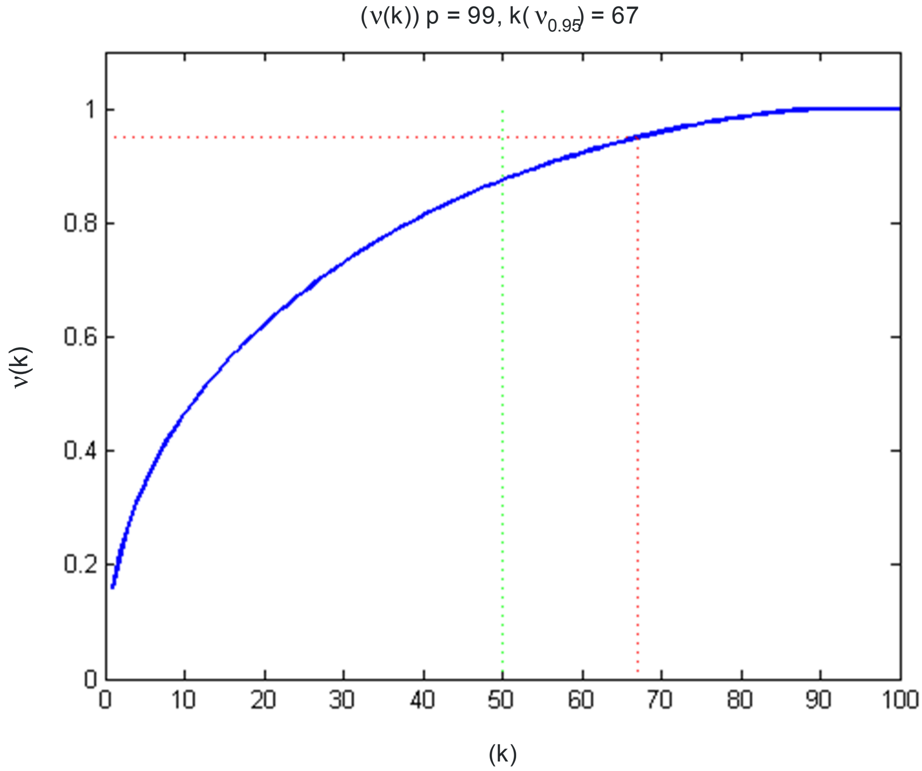

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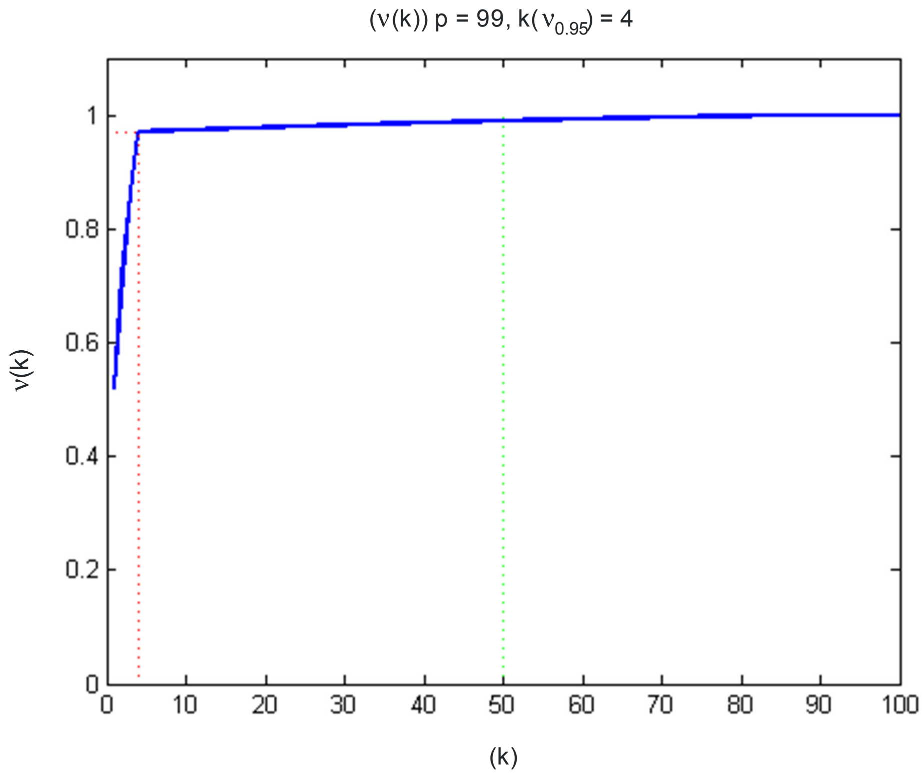
FIGURE 14

Graph of ν(*k*) for the case of four multi-carriers (channel power is −97 dBm)



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It can be seen that although the S/N of the injected carries is very low (the APD shows virtually a straight line), the $\nu(k)$ curve shows a complete different behaviour compared to when only noise is present. The SVD method is therefore much more sensitive that purely evaluating the APD.

The method is also applicable to real value measurements.

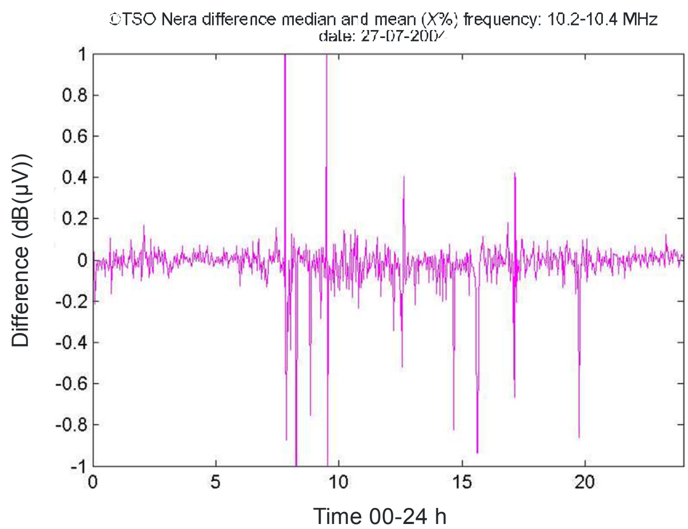
Appendix 2

Verification of the cut-off value when using direct r.m.s. measurements

It is assumed that X% of the measurement values from a scan contain noise samples only. If the correct percentage of values are excluded from the evaluation process, the median and mean value of the remaining noise samples should be the same. A practical test is to plot the difference between the mean and median value, which is obviously influenced by non-noise signals.

FIGURE 15

Difference between mean and median values (20% selection)



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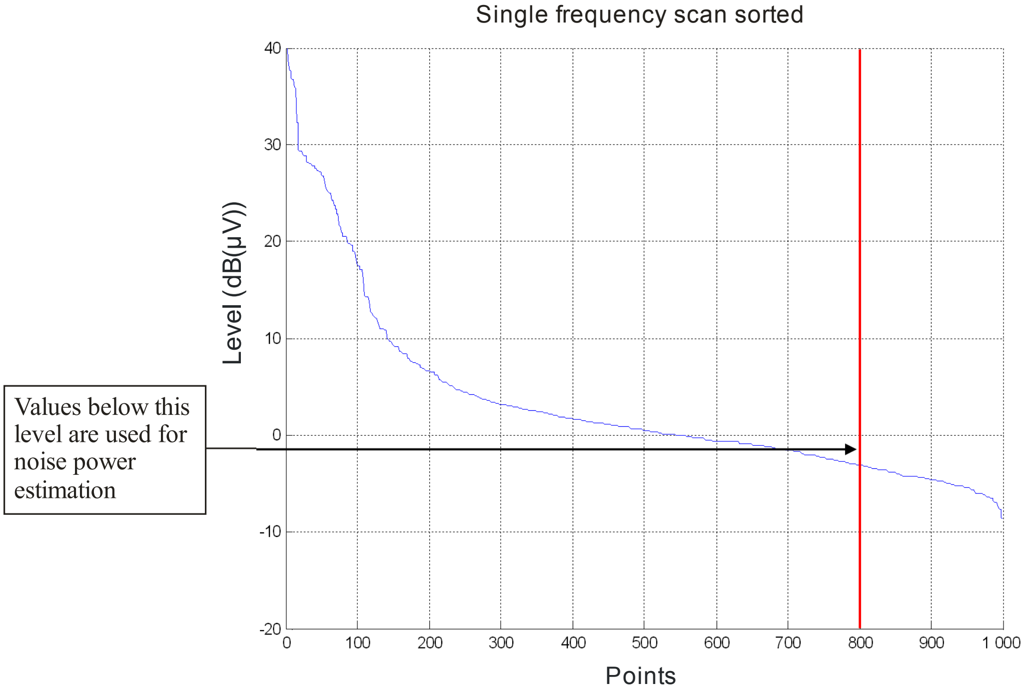
As an example the graph in Fig. 15 shows the difference between mean and median values with a fixed percentage of 20% for all scans. The observation period is 24 h (00:00 to 23:59). During the hours 07:00 to 20:00 thunderstorms cause the distribution of the 20% selection to have large slopes and thus large differences between the median and mean power values.

Another test would be to plot the number of measurement samples of a certain level versus that level and check whether the curve at the right side of the "X%" cutoff point is smooth and has a small slope. An example is given in Fig. 16.

FIGURE 16

Randomly chosen scan with sorted values



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The selected cut-off value (vertical line) is at 800 out of 1 000 measurement samples which correspond to 20%. It can be seen that in this example the selection of the cut-off value is not critical: any value between 70% and 10% (300 and 900 samples) could have been chosen as this is the range where the curve has a steady slope.

Both test methods require some *a priori* calibration. Also a meaningful number of samples need to be used in the calculation, for example a single sample cannot be used in this Type of test.

References

Recommendation ITU-R P.372 − Radio noise

Report ITU-R SM.2055 − Radio noise measurements

Report ITU-R SM.2155 − Man-made noise measurements in the HF range

Report ITU-R SM.2157 − Measurement methods for power line high data rate telecommunication systems.