Title	**Uncertainty of Measurement of Radiofrequency Electromagnetic Fields – Measurement Equipments.**
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Date	2006-04-10
Version	3
Distribution	Various
Document	Ext_Tec_0406_03_UnMeasEquip
Abstract	This document describes the rules for expressing and evaluating the uncertainty of measurement. It also exemplifies the use of those rules by estimating the uncertainty related with several commercial available equipments for radiofrequency electromagnetic fields evaluation.

Document History

Date	Version	Comment	Version Editor
2006-03-27	01	First version	Gonçalo Carpinteiro
2006-04-10	02	Comments to previous version	Luis M. Correia
2006-05-12	03	Final corrections	Carla Oliveira

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1. INTRODUCTION

The main purpose of the extensive measurements programme conducted within the scope of the **monIT** Project [1] is to assess compliance against exposure to radiation thresholds [2] of locations near mobile communications base stations (BSs) antennas. The extensive nature of this task requires the definition of adequate measurement procedures as well as the use of certified equipment, in order to allow a reliable estimation of exposure levels.

There are a number of measurement procedures that can be used. However, the **monIT** Project adopts the CEPT[1] recommendation ECC/REC/(02)04 [3], which specifies in-situ measurement procedures to assess electromagnetic (EM) fields in the frequency range from 9 kHz to 300 GHz. Generally, the proposed method defines three measurements setups, each one requiring the operation of different measurement equipments with adequate characteristics.

Like any other physical quantity measurement, EM field measurements require a quantification of results quality, which is accomplished by estimating the uncertainty of the measurement. Without such estimation, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard. In fact, the uncertainty calculation provides an interval that contains, with a certain level of confidence, a large fraction of the values that can be reasonably assigned to the measured quantity.

There are several factors to take into account while estimating the uncertainty of EM field measurements. Besides all the environment related factors (*e.g.*, multipath, reflections, and moving objects), there is the uncertainty related with the measurement equipment, which is the main focus of the present document.

All the equipment related parameters that affect the overall value of uncertainty must be combined using the rules defined in [4]. This way, Section 2 describes the most important characteristics of the required equipment, while Section 3 describes the rules for uncertainty calculation. Moreover, Section 4 exemplifies this calculation using the available information for several devices. The document ends with some conclusions, in Section 5.

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[1] European Conference of Postal and Telecommunications Administrations.

It is important to mention that all uncertainty estimations are obtained in a worst-case perspective. In other words, the considered values for all involved parameters are the ones that lead to the highest possible value of uncertainty.

2. INSTRUMENTATION

The measurement procedure that is mentioned in Section 1 requires the use of two types of measurement equipment. Both are intended to measure radiofrequency (RF) EM field strengths, allowing the comparison of the obtained values with reference levels [2].

The first required type is a broadband radiation meter, to be used with an isotropic field probe. This configuration must be able to measure the effective value of the field strength, also known as the root mean square (RMS) value, in order to assess the general radiation level in a broad frequency range and on a specific location.

Conversely, the other required type of equipment must be frequency selective, providing EM field levels by frequency. The most common configuration is a spectrum analyzer, which should be portable and capable of software control, used in conjunction with a selective probe. Although allowing a simple operation during measurements, the use of selective isotropic probes is not mandatory. Sometimes, it is necessary to use different antennas or probes to cover the desired frequency range.

The remaining of the present Section describes the main characteristics of these two types of equipment, emphasizing the ones that are most important to assess measurement uncertainty. Section 2.1 describes broadband equipment, while Section 2.2 focuses on frequency selective equipment.

2.1 Broadband Equipment

The basic components of broadband instruments are: a sensor (antenna), a detector, the necessary electronic circuitry, and a readout device. Figure 1 shows a possible configuration to combine these and other components. The sensor/detector element is responsible for the generation of an electrical signal proportional to the field strength or to the square of the field strength. The detected signal is then carried to the conditioning circuitry by a high impedance connection that minimizes coupling with the field, isolating the sensor/detector from the subsequent elements. The functions performed by the conditioning circuitry include filtering, amplification, digitizing and others signal processing operations. Note that the combination of the sensor/detector, high impedance connection and conditioning circuitry is often referred to as the probe. The connection between the conditioning circuitry and the readout device is performed by an interconnection cable, which is either optical or conductive. The readout device is responsible to display field strength information in an adequate way. Thus, it may include logging, averaging, or other data conditioning capabilities. Finally, there is also the possibility to have an external device performing some specific function, as for instance a remote readout or a data logging function.

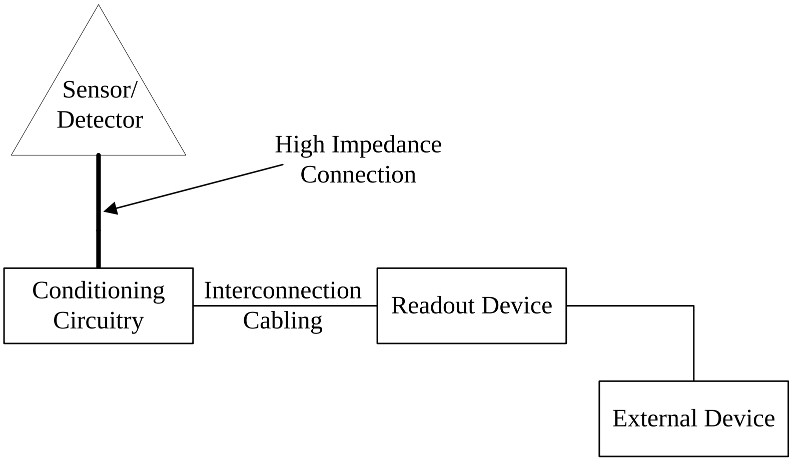

Figure 1 – Basic components of a broadband RF instrument (adapted from [5]).

The design and characteristics of the probe determine to a great extent the performance of the entire unit. So, it is important to describe the most important probe elements (sensor and detector) in more detail.

The sensor or antenna that is used depends on which field component one is interested in. It is possible to use either a combination of dipoles, which responds to electric field strength (E), or a combination of loops, which responds to magnetic field strength (H). It is well known [6] that the voltage at dipole terminals is proportional to the tangential component of the incident E field; similarly, the voltage at loop terminals is proportional to the perpendicular component of the incident H field. This way, the adequate summation of the outputs of an arrangement of three mutually orthogonal dipoles/loops provides a value that is independent from the device orientation, being called isotropic. In order to achieve a uniform response over a wide range of frequencies, the physical size of the dipole/loop must be small compared to the wavelength at the highest frequency to be measured. The small dimension of the sensor is also advantageous, in the sense that the field to be measured will be less perturbed.

In order to provide useful information, the output of the dipoles/loops must be processed in a such manner that the value of the measured parameter can be displayed on a readout device.

This function is accomplished by the detector, which can be either a diode or a thermocouple, the diode being the most common one. A diode is a nonlinear device with output voltage proportional to the square of the input voltage and consequently to the square of E or H.

Due to the characteristics of broadband instruments previously described, there is a number of parameters that contribute to the worst-case overall uncertainty that can occur when this type of instrument is used, namely:

- Absolute error – This parameter is important only when an estimation of an absolute value is required, as in the case of EM field measurements for comparison with exposure thresholds.
- Instrument linearity.
- Amplitude modulation response.
- Flatness.
- Out-of-band response.
- Near field response – To be considered only in the case of near field measurements.
- Isotropy.
- EM interference.
- Temperature response.
- Supply voltage response.
- Stability.

Some of these parameters are corrected by applying a correction factor obtained during a calibration process. The estimation of correction factors is mandatory for frequency response, linearity and isotropy. The existing calibration methods, [7], are based on the establishment of a known EM field for comparison with the value measured by the equipment.

2.2 Frequency Selective Equipment

Frequency selective or narrowband instruments are able to provide the level of the field at each frequency measured separately, allowing the identification of all EM radiation sources in the analysed frequency band that contribute to the total exposure level. Although the operation of such instruments is not as straightforward as the case of broadband equipments, the provided information can be very useful when assessing compliance with frequency dependent exposure thresholds.

Basically, frequency selective instruments consist of an antenna that acts as the sensor element, a spectrum analyser and all the necessary interconnection cables.

There are several types of antennas that can be used together with a spectrum analyser. Depending on which type is being used, the voltage appearing at the antenna terminals is proportional to the tangential component of the incident $\boldsymbol{E}$ or to the perpendicular component of the incident $\boldsymbol{H}$. The proportionality factor, named antenna factor (A_f), is obtained by means of measurements or calculations, being provided by the antenna supplier. Thus, performing the adequate operations with the signal at antenna terminals and given A_f, which is frequency dependent, it is possible to obtain the field value. As in the case of broadband equipment, it is very useful to combine three mutually orthogonal antennas with small dimensions to form an isotropic, wideband sensor. Nevertheless, in many cases, the use of one sensor is not enough to cover the desired frequency range, and it is necessary to use a combination of several antennas with adequate frequency bands.

Essentially, there are two types of spectrum analysers that can be used to perform RF EM field measurements:

- Real time analysers – All the frequency range is simultaneously sampled. However, they have important limitations regarding frequency range.
- Swept-tuned analysers – The input signal is swept through the selected frequency span, sampling all signal components successively in time. These are the most common spectrum analysers, the superheterodyne analyser being the most well-known example.

A detailed explanation of spectrum analysers operation is out of the scope of this document. Information on this subject can be found, for example, in [8].

In the case of frequency selective instruments, the most important parameters to consider in an uncertainty evaluation are:

- Antenna factor calculation.
- Cable correction factor calculation.
- Absolute amplitude error.
- Flatness.
- Linearity.

The last three parameters are directly related with the spectrum analyser characteristics.

3. EXPRESSION OF UNCERTAINTY

The term uncertainty of measurement refers to a parameter, associated with the result of a given measurement, that characterizes the dispersion of the values that could reasonably be associated to the measurement, [4]. Generally, the result of a measurement is only an estimation of the value of the measured quantity, and it is only complete when accompanied by a statement of uncertainty.

An evaluation of uncertainty is particularly important when considering EM field measurements to assess compliance with exposure thresholds. Actually, due to the special requirements of this situation, it is strictly necessary to provide an interval around the measured value, containing a large fraction of the values that could reasonably be associated to the exposure levels.

In practice, there are many possible parameters that affect the measurement, contributing to the overall uncertainty. As referred in Section 1, uncertainty calculations in this document only take into account the parameters related with measurement equipment. These parameters are mentioned in Section 2, which describes the instrumentation used for RF EM fields measurements. The remaining of this section describes the rules to combine all the parameters that contribute to the uncertainty of the measurement, based on the methodology defined in the “Guide to the Expression of Uncertainty in Measurement”, [4].

All the uncertainty components are grouped into two categories: type A and type B. Note that this classification does not intend to indicate any specific difference in the nature of a component. Instead, it indicates a difference in the way that uncertainty is evaluated. Both types of evaluation are based on probability distributions, and uncertainty components resulting from either type are quantified by variances or standard deviations.

In a type A evaluation, the estimated variance of a generic quantity X_i, $u^2(x_i)$, is equal to the statistical variance (s^2) of a series of independent observations. Then, the estimated standard deviation, $u(x_i)$, is the square root of the estimated variance, and it is usually referred to as the type A standard uncertainty.

When it is not possible to perform a type A experimental evaluation, a type B evaluation must be considered. In this case, $u^2(x_i)$ and $u(x_i)$ are evaluated by scientific judgment based on all of the available information on the possible variability of X_i. Examples of possible sources of information are:

- Previous measurement data.
- Manufacturer’s specifications.
- Calibration certificates.

For convenience, $u(x_i)$ evaluated this way is called a type B standard uncertainty.

The several standard uncertainties, resulting from a type A or a type B evaluation, are combined to obtain the combined standard uncertainty, u_c. Thus, the combined standard uncertainty of the measured value y, which is a estimation of the measurement Y, results from the combination of the several standard uncertainties of the estimated x_i values of the N X_i considered parameters,

$$u_c\left(y\right)=\sqrt{\sum_{i=1}^{N}\left(c_i\cdot u\left(x_i\right)\right)^2} \tag{1}$$

where,

c_i is the sensitivity coefficient, which describes how output estimate y varies with changes in the values of the input estimates x_i.

In addition to the calculation of $u_c(y)$, it is often necessary to obtain an additional measure of uncertainty that meets the requirement of providing an interval about the measurement result that may be expected to encompass a large fraction of the distribution of values that could reasonably be associated to the measurement. This additional measure is termed expanded uncertainty and is denoted by U. The expanded uncertainty is obtained by multiplying $u_c(y)$ by a specific coverage factor k,

$$U=k\cdot u_c\left(y\right) \tag{2}$$

The result of a given measurement is then expressed as $Y = y \pm U$. This expression means that the best estimate of Y is y, and that the interval $y - U$ to $y + U$ is expected to contain a large fraction of the values that could be associated to Y. The fraction of values can be quantified by the level of confidence p of the interval.

The value of k is chosen on the basis of the level of confidence required for the interval $y \pm U$.

For instance, a factor of 1.96 provides a level of confidence of 95 %, given that measured values follow a normal distribution.

4. EVALUATION OF MEASUREMENT EQUIPMENT UNCERTAINTY

In order to illustrate the calculation of the uncertainty of measurement related with the measurement equipment, this section considers several instruments that are of common use for measuring EM fields. All the considered equipments are designed to the specific purpose of performing measurements in order to assess compliance with exposure to radiation thresholds.

Section 4.1 considers 4 broadband instruments, while Section 4.2 considers 3 frequency selective instruments.

4.1 Broadband Equipment

From all the equipments that are commercially available, a set of 4 broadband instruments was selected in order to represent the most common configurations, Table 1. All of them consist on an isotropic field probe and on a portable field meter containing all the necessary electronic and interfaces.

Table 1 – Broadband equipment for uncertainty calculation.

Reference	**Field Meter**	**Isotropic Probe**		
		Model	**Measured Quantity**	**Frequency Range**
BB1	PMM 8053 [9]	EP 33M	*E*	700 MHz – 3 GHz
BB2	PMM 8053A [9]	EP 330	*E*	100 kHz – 3 GHz
BB3	Narda EMR-300 [10]	E-field type 8	*E*	100 kHz – 3 GHz
BB4	Narda EMR-300 [10]	H-field type 14	*H*	100 MHz – 1 GHz

A type B evaluation was performed considering all the available data in equipments data-sheets and calibration certificates. Nevertheless, the necessary information about the parameters described in Section 2.1 is not always available. The approach to overcome this problem is to consider only the available information and state that the remaining parameters are not significant to the overall uncertainty. In the particular case of the equipment listed in Table 1, information about the following parameters is available:

- Absolute error.
- Flatness.
- Isotropy.
- Instrument linearity.
- Temperature response.
- Calibration process.

One of the considered parameters is the uncertainty related to the calibration process. During calibration, an estimation of several correction factors that will affect the measurement result is performed. Depending on the equipment, the correction factors are related to linearity, flatness or both.

The calculation of the combined standard uncertainty and of the expanded uncertainty for those equipments is summarized in Table 2.

Table 2 – Combined standard uncertainty and expanded uncertainty calculation for the broadband equipment.

Parameters	**BB1**		**BB2**		**BB3**		**BB4**	
	Value	**$u(x_i)$**	**Value**	**$u(x_i)$**	**Value**	**$u(x_i)$**	**Value**	**$u(x_i)$**
Absolute error	1 dB	0.07	0.8 dB	0.06	1 dB	0.07	1 dB	0.07
Flatness	1.5 dB	0.11	1.5 dB	0.11	2.4 dB	0.18	1.5 dB	0.11
Isotropy	1 dB	0.07	1 dB	0.07	1 dB	0.07	1 dB	0.07
Instrument linearity	-	-	-		3 dB	0.24	1 dB	0.07
Temperature response	1 dB	0.07	0.1 dB	0.01	1.5 dB	0.11	0.8 dB	0.06
Calibration	15 %	0.08	15 %	0.08	0.5 dB	0.03	0.5 dB	0.03
$u_c(y)$ [dB]	**1.44**		**1.29**		**2.52**		**1.40**	
U [dB] **(k = 1.96)**	**2.63**		**2.38**		**4.40**		**2.57**	

The calculations in Table 2 assume independency between parameters and a sensitivity coefficient of 1, which means that the combined standard uncertainty is linear dependent on the standard uncertainty of each parameter.

4.2 Frequency Selective Equipment

To illustrate the uncertainty calculation related with frequency selective equipments, two systems are considered: the COMOBASE system [12], from Antennessa, and the SRM 3000 system [12], from Narda.

The COMOBASE system is a combination of several independent elements that were adapted for the purpose of performing EM field measurements to assess compliance with exposure to radiation thresholds. The basic components are an isotropic wideband sensor (80 MHz – 3GHz), three shielded cables, an RF switch, a spectrum analyser ANRITSU MS2711B [13], a laptop and a software tool to control the entire system. The available information allows a type B evaluation of the following parameters:

- Antenna factor calculation.
- Cable correction factor calculation.
- Sensor Isotropy.
- Spectrum analyser total uncertainty.

Table 3 summarizes the calculations for the COMOBASE system.

Table 3 – Combined standard uncertainty and expanded uncertainty calculation for the COMOBASE system.

Parameters	**Source of Information**	**Supplied Uncertainty**			**Standard Uncertainty, $u(x_i)$**
		Value [dB]	**Value [%]**	**Distribution**	
Antenna Factor	Calibration Certificate	1.25	0.15	Normal (1.96)	0.08
Cable Correction Factor	Additional Information	0.5	0.06	Normal (1.96)	0.03
Isotropy	Specifications	2	0.26	Normal (1.96)	0.13
Spectrum Analyser	Specifications	2	0.26	Rect. ($\sqrt{3}$)	0.13
Combined Standard Uncertainty, $u_c(y)$					**0.20 (1.58 dB)**
Expanded Uncertainty, U (k = 1.96)					**0.39 (2.87 dB)**

The SRM 3000 system is a handheld, battery powered selective measuring device with a specific design for safety analysis of EM fields, consisting of a basic unit and a measurement probe. The basic unit contains a spectrum analyser for the frequency range of 100 kHz to 3 GHz, and is usually operated with a triaxial probe that allows isotropic measurements in the range from 75 MHz to 3 GHz. The isotropic probe can be directly connected to the basic unit or using a specific RF cable.

Similar to the other devices evaluated in this document, the available information to calculate the SRM 3000 uncertainty is provided in calibration certificates and data-sheets. However, the value of the expanded uncertainty is already provided, thus, there is no need to perform any calculation. Table 4 reproduces the available data in the product information.

Table 4 – Expanded uncertainty for the SRM 3000 system.

Frequency Range [MHz]	**Expanded Uncertainty, *U* [dB] (basic unit with triaxial probe and a 1.5 m RF cable)**	
	Single-axis Measurement with Isotropic Antenna	**Isotropic Antenna**
75 – 900	+2.5 / -3.5	+2.5 / -3.6
901 – 1400	+2.4 / -3.3	+2.5 / -3.5
1401 – 1600	+2.4 / -3.3	+2.6 / -3.8
1601 – 1800	+1.8 / -2.4	+2.6 / -3.8
1801 – 2200	+1.8 / -2.4	+2.4 / -3.4
2201 – 2700	+2.4 / -3.3	+2.9 / -4.5
2701 – 3000	+2.4 / -3.3	+3.5 / -6.1

Note: Temperature ranges from +15ºC to +30ºC; $k = 2$.

5. CONCLUSIONS

The estimation of any physical quantity by means of a measurement always requires the evaluation of the related uncertainty. This remark is especially important for measurement procedures in order to assess RF EM fields for the purpose of comparison against human exposure thresholds. In fact, the expanded uncertainty provides an interval about the result of a measurement, which can be very important to conclude about the possibility of having a value greater than thresholds.

The measurement procedure defined within the scope of the **monIT** Project requires the operation of specific measurement equipments, which contribute to the overall value of uncertainty. This document describes the rules of expressing and evaluating uncertainty and exemplifies the use of those rules by estimating the uncertainty related with several commercial available equipments. During this analysis, the two major types of equipments to assess EM fields are considered: broadband equipments and frequency selective (narrowband) equipments. The former has values of expanded uncertainty that range from 2.38 dB to 4.40 dB, while the latter varies from 1.8 dB to 6.1 dB.

Besides the inherent importance of these values in providing meaningful measurement results, they can also be used as the rationale for the definition of some decision levels that are of extremely importance for some measurement procedures, namely for [3].

There are other parameters, besides the ones related with measurement equipments that must be addressed for the completeness of measurement uncertainty estimation. Actually, the measurement procedure that has been mentioned requires the identification of the points that represent the highest levels of exposure to which a person might be subjected. The surrounding environment has great influence in the selection of points, which have to be included in the total value of measurement uncertainty. This is a complex issue that has to take in account the whole propagation phenomena, and it will be addressed in future works.

Finally, it is important to mention the difficulties in gathering all the necessary information to perform a correct calculation of the uncertainty related with measurement equipments. This is essentially related to the lack of uniformity among manufacturers on expressing equipment characteristics. Sometimes, a direct contact with manufacturers is required.

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