Radiation Protection Dosimetry Advance Access published May 28, 2010

Radiation Protection Dosimetry (2010), pp. 1–5 doi:10.1093/rpd/ncq158

EVALUATION OF UNCERTAINTY IN THE MEASUREMENT OF ENVIRONMENTAL ELECTROMAGNETIC FIELDS

B. Vulević[1,]* and P. Osmokrović[2]

[1]Radiation and Environmental Protection Laboratory, 'VINČA' Institute of Nuclear Sciences, PO Box 522, 11001 Belgrade, Serbia

[2]Faculty of Electrical Engineering, University of Belgrade, Bulevar Kralja Aleksandra 73, PO Box 3554, 11000 Belgrade, Serbia

*Corresponding author: banevul@vinca.rs

Received October 12 2009, revised April 25 2010, accepted April 28 2010

With regard to Non-ionising radiation protection, the relationship between human exposure to electromagnetic fields and health is controversial. Electromagnetic fields have become omnipresent in the daily environment. This paper assesses the problem of how to compare a measurement result with a limit fixed by the standard for human exposure to electric, magnetic and electromagnetic fields (0 Hz–300 GHz). The purpose of the paper is an appropriate representation of the basic information about evaluation of measurement uncertainty.

INTRODUCTION

The use of devices emitting electromagnetic fields (EMF) ranging from static to microwave frequencies has significantly increased in the past two decades. Their presence has affected almost every aspect of living (home, travelling, school, college, work…). In the case of low-frequency fields (0 Hz–100 kHz), attention is focused on the systems for transmission, distribution and use of the electrical energy. For the high-frequency range (100 kHz–300 GHz), the main sources up to now have been Radio and TV transmitters and the cellular mobile communication systems. Their functions will be enlarged by additional services (mobile video and television) in the future. Generally, new artificial sources include different exposure scenarios with regard to the body site, duration of use, target population and also owing to simultaneous exposure to complex multiple frequencies spread over a potentially large frequencies range(1).

Significant public and media concerns are expressed about increases in EMF exposure of people and its potentially adverse effects on health, particularly health of children. These associations are not explained by any confirmed biological mechanism and there are doubts as to their causal nature, as the available evidence is inadequate to make sound scientific conclusions. Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) point out that scientific studies still fail to provide support for an effect of EMF on self-reported symptoms, but indicate that the expectation or belief that something is harmful may play a role in symptom formation. Further, epidemiological and laboratory investigations are needed(2).

In order to evaluate population exposure, knowledge of the field levels is very important. Measurements are basic both for the verification of the results obtained through the use of numerical models, and for the evaluation of the field levels when the sources are unlikely to be simulated because of their number, working condition and complex distribution. The result of a measurement, given by the indication of the instrument, is only an estimate of the measurand (the subject to measurement) and thus it is complete only if associated to a statement of the uncertainty parameter that characterises the dispersion of the values that could be reasonably attributed to the measurand. All the components giving an uncertainty contribution should then be identified with reference both to the measuring instruments used and to the measurement procedures and conditions; that cannot be a priori dismissed(3). The evaluation of uncertainty becomes crucial when comparing a result of measurement with a field limit value fixed by a standard(4).

Besides the uncertainty associated with the use of a field meter, other contributions also have to be considered when evaluating uncertainty of a field measurement. These contributions depend both on the measurement procedures and conditions and on the characteristics of the field source.

STANDARDISATION OF EMF MEASUREMENTS

One has to differentiate between low- and high-frequency EMF field measurements. The range for low-frequency measurements is from 0 Hz to 100 kHz and the range for high-frequency measurements is from 100 kHz up to 300 GHz. For meaningful EMF measurements to be carried out, the following information is needed[5]:

(1) the type of field source, e.g. supply current and voltage, radiated power;
(2) the characteristics of the source of field e.g. frequency, operational behaviour, modulation, duty cycle;
(3) the measuring instruments and their characteristics e.g. measurement principle;
(4) the evaluation bases such as standards, limit values etc.;
(5) the uncertainty of the measurements.

The International Electrotechnical Commission (IEC) promotes international co-operation on all questions concerning standardisation in electrical and electronic fields. IEC collaborates closely with the International Organisation for Standardisation (ISO), in accordance with conditions determined by the agreement between the two organisations.

In accordance with the document of the IEC technical committee 106, 'Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure', the standardisation of EMF measurements includes[6]:

(1) characterization of the electromagnetic environments with regard to human exposure;
(2) measurement methods, instrumentation and procedures;
(3) assessment methods for the exposure produced by specific sources;
(4) basic standards for the other sources;
(5) assessment of uncertainties.

Excluded are:

(1) the establishment of exposure limits;
(2) mitigation methods which have to be dealt with by the relevant product committees.

Actual IEC TC 106 standards and projects for the low- and high-frequency range are shown in Table 1. Meaningful comparison is possible only between the result of EMF measurements obtained following these methods on the one hand, and the reference levels and basic restrictions of contemporary safety standards (i.e. IEEE C95.1) and guidelines from the International Commission on Non-Ionising Radiation Protection (ICNIRP).

Table 1. Standards and projects IEC TC 106.

EMF measurement		
	Basic standard	Specific sources
Low-frequency range (0 Hz–100 kHz)	IEC 61786:1998	Household appliances Standard 62233 Power Lines Project 62110 *Industrial equipment* *Railways*
High-frequency range (100 kHz–300 GHz)	Project 62334	Handheld devices Standard 62209 Base station Project 62232 Short range devices Project 62369 *Broadcast emitter,* *Radar, etc.*

Note: The items in italics are part of the scope of TC 106 but are not covered by existing standards or projects[6].

THE EVALUATION OF THE MEASUREMENT UNCERTAINTY

Uncertainty in the scientific or technical context has a very specific meaning. If one makes a measurement many times, a range of results which are close to the 'true' value is obtained. This spread in measured results can stem from differences in the exact measurement position, statistical variation in the response of the measurement instrument or differences in the way that different people read the instrument display. The uncertainty of the used measuring equipment has to be known and considered in the final assessment.

The evaluation of uncertainty should be performed following the ISO/IEC Guide[7]. The European Committee for Electrotechnical Standardisation (CENELEC) issued the standard EN 50413[5], where useful information can be found about identification of the uncertainty components.

Low-frequency range

The electric and magnetic fields in the low-frequency range (up to 100 kHz) are mainly independent from each other and shall both be assessed, when measurement is to be made. For a given exposure scenario, the electric field strength depends only on the voltage used, whereas the magnetic field strength or magnetic flux density depends only on the electric currents.

Listed are some factors that can significantly contribute to the total uncertainty when measuring low-frequency electric or magnetic fields[3]:

(1) The uncertainty associated with the use of the field meter, which includes the components due to calibration, stability and bandwidth (in relation to the characteristics of the field generated by the source);
(2) The spatial non-uniformity of the field to be measured with respect to the probe dimensions

and, if an isotropic probe is used, to the arrangement of the three single-axis probes;
(3) The temporal variation of the measured field, in relation to the time constant of the field meter;
(4) The uncertainty in the evaluation of the distance of the probe from the field source;
(5) The environmental conditions such as humidity, temperature etc.;
(6) The short-term repeatability of the measurements.

In the case of electric field measurements, it may be necessary to consider[3]:

(a) The proximity effects, owing to the perturbation of the field because of the presence of the operator.
(b) The presence of a low-frequency magnetic field, for example, when performing a measurement in proximity to an overhead power line, and the immunity to electromagnetic interference.

As to the magnetic field measurement, contributions can stem from[3]:

(a) Perturbation of the field to be measured due to the presence of ferromagnetic or conductive objects in the proximity of the probe.
(b) Influence of an external low-frequency electric field.
(c) Uncertainty associated to the value of the load of the source, if a field value normalised to the rated conditions is calculated from the measured value.
(d) Presence of an ambient field, which may be comparable to that generated by the source to be investigated.

From the analysis of the literature[3], it is clear that the most significant contributions are due to errors in positioning of the probe and the non-uniformity of the field in relation to the probe dimensions. The resulting uncertainty is strongly dependent on the measurement point and it becomes more critical in close proximity to the source, because of the strong non-uniformity of the field distribution.

High-frequency range

In the high-frequency range (Radio Frequencies–RF: 100 kHz–300 GHz), several field types exist, which should be assessed differently depending on the distance r from and the biggest dimension D of the radiating source. Table 2 indicates whether to measure electric (E) or magnetic (H) field strength, or both, at different distances from the field source.

Reliable assessment procedures have to be able to distinguish between the contributions from different RF sources and also to estimate individual exposure. Possible dosimetric approaches are the use of frequency selective monitoring equipment to assess variation versus time, and of frequency selective equipment like dosemeters to assess individual exposure. Procedures based on the use of broadband measurement equipment are suitable for epidemiological studies if one source is dominant or if other reliable procedures, such as analytical calculations, are applied, that make it possible to distinguish between the contributions from different sources[8].

These are some of the uncertainty contributions[3,9]:

(a) Probe calibration, which should be carried out in an accredited laboratory;
(b) Frequency interpolation, due to the fact that the probe calibration curve is determined for discrete frequencies of the reference EMF;
(c) The measuring procedure followed to estimate the measured quantity and differences due to different staff carrying out the same type of measurement;
(d) The effects of environmental conditions (i.e. temperature, humidity) in the measurement set-up.

Table 2. Evaluation parameters for high-frequency range[5].

	Reactive near field	Radiating near field	Far field
Distance (r)	$r < \lambda$	$\lambda < r < 2D^2/\lambda$	$r > 2D^2/\lambda$
$E,H \sim 1/r$	No	No	Yes
$Z_0 = E/H$	$\neq Z_0$	$\approx Z_0$	$=Z_0$
To measure	E and H	E or H	E or H

Note: D, biggest dimension of the radiating structure; i.e. diameter of a parabolic antenna.

In Table 3, an example from CENELEC standard EN 50413 is reported for electric field strength measurements performed with a broadband measurement system. Relative combined standard uncertainty was calculated following the ISO/IEC Guide[7]:

$$u_c = \left(\sum_{i=1}^{N} (c_i\, u(x_i))^2\right)^{1/2},$$

where the sensitivity coefficient–$c_i = \pm 1$, resulting from the presumption of the case where the measurand is already a linear function of the quantities on which it depends. The relative expanded uncertainty is obtained by multiplying the relative combined standard uncertainty by the coverage factor $k = 1.96$; the confidence level is $\sim$95 %.

For comparison of a measurement result and a 'limit' fixed by the standard for human exposure

Table 3. Example of an uncertainty budget for field strength measurement using a broadband measurement system[5].

Influence factor	Reference	Specified uncertainty (%)	Distribution	Division factor	Standard uncertainty $u(x_i)$ (%)
Frequency response	Calibration report	15	Rectangular	1.73	8.7
Uncertainty of frequency response	Calibration report	14	Normal ($k = 2$)	2	7
Linearity deviation	Calibration report	3	Rectangular	1.73	1.7
Uncertainty of linear deviation	Calibration report	2.5	Normal ($k = 2$)	2	1.3
Isotropic deviation	Data sheet	12.2	Rectangular	1.73	7
Modulation response	Data sheet	5	Rectangular	1.73	2.9
Temperature response	Data sheet	3.5	Rectangular	1.73	2
Repeatability	Measuring series	15	Normal ($k = 1$)	1	15
	Combined standard uncertainty/u_C (%)/				20.4
	Expansion factor/k/				1.96
	Expanded uncertainty/U (%)/				40.0

Table 4. Example of an expanded uncertainty for electric field strength measurement EMR-300, E-Probe: Type 8.3 (100 kHz–3 GHz).

Input quantity	Relative uncertainty (dB) (conf. interval of 95 %)	Relative uncertainty (num.) (conf. interval of 95 %)	Relative standard uncertainty (conf. interval of 66 %) $u\ (x_i)$
(A) (0.6–1.25 V/m; 100 MHz–3 GHz) Temperature: 25°C			
Isotropy	1	0.12	0.06
Linearity	3	0.41	0.21
Flatness	2.4	0.32	0.16
Temperature	0.2	0.02	0.01
Combined standard uncertainty	$u_c = \sqrt{\sum_{i=1}^{n} (c_i\, u_{xi})^2} = 0.27$		27 % (2.1 dB)
Expanded uncertainty (95 %)	$U = 1.96,\ u_c = 0.53$		53 % (3.7 dB)
(B) (1.25–2.5 V/m; 100 MHz–3 GHz) Temperature: 25°C			
Isotropy	1	0.12	0.06
Linearity	1	0.12	0.06
Flatness	2.4	0.32	0.16
Temperature	0.2	0.02	0.01
Combined standard uncertainty	$u_c = 0.18$		18 % (1.4 dB)
Expanded uncertainty (95 %)	$U = 1.96,\ u_c = 0.35$		35 % (2.6 dB)
(C) (2.5–400 V/m; 100 MHz–3 GHz) Temperature: 25°C			
Isotropy	1	0.12	0.06
Linearity	0.5	0.06	0.03
Flatness	2.4	0.32	0.16
Temperature	0.2	0.02	0.01
Combined standard uncertainty	$u_c = 0.17$		17 % (1.4 dB)
Expanded uncertainty (95 %)	$U = 1.96,\ u_c = 0.33$		33 % (2.5 dB)

Note: Input quantity data are used from Operating Manual in ref. (10).
Conversion: $X\ (\mathrm{dB}) = 20\ \log((x\%/100) + 1)$.
Conversion: $x\ (\%) = (10^{(X\,\mathrm{dB}/20)} - 1) \cdot 100$.

to electric, magnetic and electromagnetic fields, 'the total value' (the measured values plus the expanded uncertainty) is needed. On the basis of ref. (3), levels of field intensity measured with a relative uncertainty within 3 dB (41 %) can be directly compared.

Table 4 presents the results of measurement uncertainty determination for the isotropic electric field probe (Type 8.3) of EMR-300 RF radiation meter[8,10,11]. Case A in the table is not in line with the qualification.

DISCUSSION

With the introduction of the new concept of the measurement uncertainty, all errors were defined as stochastic variables and, consequently, a practicable measuring method was created, suitable for efficient application in all sorts of experimental measurements[12–14].

Field levels obtained with instruments having a relative uncertainty >3 dB are to be considered only informative. In this case, if the total value is still lower than the limit, there is a strong probability that the 'presumed' field level is below the limit. In other cases, a decision cannot be taken and it is necessary to repeat the measurement with an instrument that can ensure greater accuracy.

The importance of calibration for evaluation of uncertainty in measurements is generally enormous. Calibration in domain of high-frequency range has a number of 'open questions'. Some of them are:

(1) What reference signals shall be used for calibration?
(2) Are continuous wave reference signals always adequate?

Future work will focus on a detailed answer to questions on traceable calibration.

FUNDING

The Republic of Serbia Ministry of Science and Technological Development supported this work under contract 141046.

REFERENCES

1. ICNIRP. *ICNIRP statement on EMF-emitting new technologies.* Health Phys. **94**(4), 376–392 (2008).
2. European Commission, SCENIHR. *Health Effects of Exposure to EMF.* Available on http://ec.europa.eu/health/ph_risk/committees/04_scenihr/docs/scenihr_o_022.pdf (2009).
3. Borsero, M., Crotti, G., Anglesio, L. and d'Amore, G. *Calibration and evaluation of uncertainty in the measurement of environmental electromagnetic fields.* Radiat. Prot. Dosim. **97**(4), 363–368 (2001).
4. Vulević, B. Assessment of ELF magnetic field levels in residence areas near power plants. CD Proceedings of Cigre International Colloquium, Power Frequency Electromagnetic Fields ELF EMF, Session 4, Sarajevo, Bosnia and Herzegovina (2009).
5. CENELEC EN 50413:2008. *Basic standard on measurement and calculation procedures for human exposure to electric, magnetic and electromagnetic fields (0 Hz–300 GHz)*, European Committee for Electrotechnical Standardization CENELEC (2008). Available at www.cenelec.eu.
6. IEC/TC 106, SMB/3857/R. *Strategic policy statement*. The International Electrotechnical Commission (IEC), Secretariat Canada, (2008).
7. ISO/IEC Guide 98–3:2008. *Uncertainty of measurement, Part 3: guide to the expression of uncertainty in measurement (GUM:1995)*, International Organization for Standardization (ISO) (2008). Available at www.iso.org.
8. Vulević, B. *Determination of radiofrequency radiation levels in area of GSM base stations.* Master Thesis (in Serbian), University of Belgrade, Faculty of Electrical Engineering (2006).
9. Stratakis, D., Miaoudakis, A., Kadsidis, C., Zacharopoulos, V. and Xenos, T. *On the uncertainty estimation of electromagnetic field measurements using field sensors: a general approach*. Radiat. Prot. Dosim. **133**(4), 240–247 (2009).
10. Freeden, J. von. *EMR-200/300 radiation meters operating manual, BN 2244/98.22* (2001).
11. Electronic Communications Committee (ECC). *ECC recommendation (02)04 (revised Bratislava 2003, Helsinki 2007): measuring non-ionizing electromagnetic radiation (9 kHz–300 GHz)*, Edition 060207 (2007).
12. Stankovic, K., Arandjic, D., Lazarevic, Dj. and Osmokrovic, P. *Expanded and combined uncertainty in measurements by GM counters.* Nucl. Technol. Radiat. Prot.–2/2007. **Vol. XXII**, No. 2, 64–70 (2007).
13. Stankovic, K. and Vujisic, M. *Influence of radiation energy and angle of incidence on the uncertainty in measurements by GM counters.* Nucl. Technol. Radiat. Prot.–1/2008. **Vol. XXIII**, No. 1, 41–42 (2008).
14. Stankovic, K., Vujisic, M. and Dolicanin, E. *Reliability of semiconductor and gas-filled diodes for over-voltage protection exposed to ionizing radiation.* Nucl. Technol. Radiat. Prot.–2/2009. **Vol. XXIV**, No. 2, 132–137 (2009).