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Application of EMF Emission Measurement Techniques to Wireless Communications Systems for Compliance With Directive 2004/40/EC

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Europe is the only region in the world with common legislative acts regulating exposure to electromagnetic fields (EMF) for both the general public and workers. Council Recommendation 1999/519/EC deals with the limitation of exposure of the general public to EMF (0 Hz—300 GHz). Directive 2004/40/EC regulates the minimum health and safety requirements regarding the exposure of workers to the risks arising from EMF. This paper discusses the general application of existing standards and recommendations in measurement techniques for determining compliance of measured exposure limit values and action values with those defined in 2004/40/EC.

compliance   measurement techniques   wireless communications systems
2004/40/EC Direcive

1. INTRODUCTION

The recently published Directive 2004/40/EC [1] introduces the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents. The Directive requires compliance with the exposure limit values and action values in all European Union countries. This paper presents the highlights of the Directive specifically related to measurements, differences between emissions and exposure standards, the basics of standardization, and physical characteristics of the fields produced by wireless communications systems. The measurement requirements for wireless communications systems are discussed, followed by conclusions that show that application of the Directive requires a thorough knowledge of electromagnetics, instrumentation and various measurement standards.

2. DIRECTIVE 2004/40/EC

The intent of Directive 2004/40/EC [1] is to create minimum protection bases for all workers. The two well-known approaches, proactive and retroactive, apply. The proactive approach includes incorporating preventive measures into the design of work environments, and by selecting work equipment and work methods. The retroactive approach consists of exposure evaluation of workers, and the use of protective suits. An example highlighting the two approaches is the situation of maintenance workers on a tower containing many

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antennas operating in various wireless systems and service. The workers typically perform tasks related to only one wireless service. Obviously this exposure situation is quite complex, and it is mostly impractical to directly measure a worker's total exposure. The proactive protection approach is oriented towards future tower designs. The design should support simple human exposure evaluations, e.g., using greater distances between antennas for any single wireless service. A retroactive approach has application in the considered situation. In present practices it is very difficult to co-ordinate a deactivation of the other wireless services on a tower while doing maintenance on only one system. Therefore, the retroactive approach includes human exposure estimation by a combination of measurement and calculation methods and, for protection measures, the use of protective suits for the workers. The Directive defines exposure limit and action values based on known short-term adverse effects to the human body. Since most present wireless communications systems operate in frequency bands above 110 MHz, the physical quantity used for compliance evaluation against exposure limits is the rate of energy absorption.

The Directive [1] defines two levels for radiofrequency (RF) exposure purposes: exposure limit values and action values. Exposure limit values are limits on exposure to electromagnetic fields (EMF) that are based directly on established health effects and biological considerations. Compliance with these limits will ensure that workers exposed to EMF are protected against all known adverse health effects (i.e., the already mentioned short-term adverse effects). In the considered frequency spectrum for wireless communications systems, the relevant quantity is the Specific Absorption Rate (*SAR*). *SAR* is defined for use between 100 kHz and 10 GHz, and it means that exposure limit values on *SAR* provide prevention of whole-body heat stress and excessive localized tissue heating. *SAR* is not a directly (in situ) measurable parameter. Thus action values are given in terms of the magnitude of directly measurable parameters, i.e., electric field strength (E), magnetic field strength (H), magnetic flux density (B) and equivalent plane–wave power density (S). Action values are obtained from the exposure limit values according to the rationale used by the International Commission on Non-ionizing Radiation Protection (ICNIRP) in its guidelines [2]. Compliance with the action values will ensure compliance with the relevant exposure limit values.

The aim of the Directive [1] is to oblige the employer to evaluate workers' exposure. The evaluation[1] is performed either by measurement and/or calculation of the directly-measurable action values, or by measurement and/or calculation of indirectly-measurable exposure limit values. This paper considers only measurements of action values.

In practice, action values are averaged in time and space. Time averaging of any of the action values (equivalent plane–wave power density, electric field strength, magnetic field strength, and magnetic flux density) in the frequency band between 100 kHz and 10 GHz is performed over any 6-min period. Above 10 GHz, averaging of the same action values is performed over any $68/f^{1.05}$-min period, where frequency (f) is given in gigahertz. In addition, spatial averaging is performed over the entire body of the exposed individual. This is discussed in more detail in section 7 on measurement procedures.

Action values are defined in terms of unperturbed rms field values. When dealing with systems that emit high peak power, conversion from peak to rms values is needed. For systems using frequencies between 10 MHz and 300 GHz, peak action values are calculated by multiplying the relevant rms values by 32 for field strengths and by 1000 for the equivalent plane–wave power density.

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[1] In the available literature the wording "human exposure assessment" is widely used. Assessment is maybe a somewhat inappropriate word choice, because it could indicate a certain, higher amount of uncertainty. There is an opinion that many presently used measurement and calculation methods give a smaller amount of uncertainty; thus, a better word choice could be "human exposure evaluation."

3. TYPES OF STANDARDS

Standards usually specify either limits on human exposure (exposure standards), emissions from a device (emissions standards), or compliance evaluation techniques and protocols (compliance standards).

Exposure standards define limits on human exposure from all devices that emit EMF into living or working environments. These standards define maximum levels to which whole or partial body exposure is permitted from any number of radiation emitting devices. The most important "backbone" standard is ICNIRP [2], which is the basis for the two most important regionally-applied European exposure standards, the Directive [1] and the Recommendation [3]. Limits in exposure standards are defined for the general public [3], or for specific populations such as workers [1], medical patients, military personnel, children, or the elderly.

Emissions standards define limits on EMF emissions from devices. The limits are generally based on engineering criteria for minimization of electromagnetic interference with other equipment. The most important emission standards in Europe are those of the Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunications Standards Institute (ETSI).

Compliance standards define compliance evaluation techniques and protocols for checking the characteristics of devices and environments relative to the exposure or emissions standards. The most important international and European compliance standards are those of CENELEC and International Electrotechnical Commission (IEC).

CENELEC is the most important European body in the areas of emissions and compliance standards. It is composed of the national electrotechnical committees of 28 European countries. CENELEC prepares voluntary electrotechnical standards for electrical and electronic goods and services in Europe. The CENELEC subcommittee CLC/TC 106X, "Electromagnetic fields in the human environment," specializes in human exposure evaluation. Because this is a fast-paced and fast-growing field, given the many new applications of emerging wireless technologies, a primary focus of this group is preparation of a generic standard for workers' environment, prEN 50XXX, with other specific standards developed for different technologies. At present specific standards exist, or are under preparation, for the following areas:

- wireless systems: base stations and hand-held (telecommunications), broadcast transmitters;
- industry applications: industrial heating;
- radio frequency identification (RFID): low power devices, cordless audio and video;
- medical devices: active implantable medical devices;
- transport: trains.

Another important standards body—also mandated by the European Commission—is the European Committee for Standardization (CEN), which, among others, has the objective to promote voluntary standards for the safety of workers and consumers, interoperability of networks and environmental protection.

ETSI is an independent, non-profit organization, with a mission to produce telecommunications standards. In recent years ETSI has entered the standards exposure evaluation arena and published a guide to the methods of measurement of RF fields, produced under the electromagnetic compatibility and radio spectrum matters (ERM) committee [4].

The work of Technical Committee TC 106: "Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure" of IEC is based on five Working Groups (WG); each WG oversees one or more Project Teams:

WG1:	Measurement and calculation methods for low frequency (0 to approximately 100 kHz) electric and magnetic fields and induced currents,
WG2:	Characterization of low frequency electric and magnetic fields produced by specific sources,
WG3:	Measurement and calculation methods for high frequency (approximately 100 kHz to 300 GHz) electromagnetic fields and specific absorption rate (*SAR*),

WG4: Characterization of high frequency electromagnetic fields and *SAR* produced by specific sources,
WG5: Generic standards: general application and common practices.

4. PHYSICAL CHARACTERISTICS OF FIELDS GENERATED BY WIRELESS COMMUNICATIONS SYSTEMS

The antenna of any wireless communications system generates field components in the reactive near-field, reactive-radiative near-field, radiating near field (the so-called Fresnel) and far-field regions. An important parameter that differentiates near- and far-field regions is the phase difference between signals from the antenna tip ($r + \lambda$) and those from the centre (r). The phase difference is a function of the path difference (λ). According to the Rayleigh criterion, if the difference is larger than $\lambda/16$, the signal level at the observation (measurement) point[2] will be significantly modified.

TABLE 1. Characteristics of the Near and Far Field

Physical Quantity	Reactive Near Field	Reactive-Radiating Near Field	Radiating Near Field	Radiating Far Field
Inner boundary	0	λ	$3\ \lambda$	Max ($3\ \lambda$; $2\ D^2/\lambda$)
Outer boundary	λ	$3\ \lambda$	Max ($3\ \lambda$; $2\ D^2/\lambda$)	4
Equivalent plane–wave power density	$S \leq \lvert E\rvert \lvert H\rvert$	$S \leq \lvert E\rvert \lvert H\rvert$	$S \leq \lvert E\rvert \lvert H\rvert = \lvert E\rvert^2/Z_0$	$S \leq \lvert E\rvert \lvert H\rvert = \lvert E\rvert^2/Z_0$
Wave impedance	different from Z_0	different from Z_0	equal to Z_0 locally	equal to Z_0

Notes. λ—wavelength, *D*—maximum dimension of the antenna, *S*—equivalent plane–wave power density, *E*—electric field strength, *H*—magnetic field strength, Z_0—free-space impedance.

Table 1 highlights the basic characteristics of the four defined field regions. The reactive near field departs from the antenna and is characterized by reactive field components that do not contribute to the radiation of energy, but can couple into nearby materials and thus produce energy absorptions. The wave impedance in the near field differs significantly from the far-field wave impedance, because the three components of the electric field in general are not perpendicular to the three components of the magnetic field. The usual power density ($\underline{E} \times \underline{H}$) is thus not a relevant quantity, since in this region the field does not really propagate, but rather changes between a predominantly electric and a predominantly magnetic field with each cycle of the time-harmonic signal. All field components need to be measured to evaluate human exposure in the near field. A specific problem in this field region is that the presence of the measuring probe can cause serious perturbations in the reactive fields (changes in the source antenna impedance, power output, and radiation pattern), which makes meaningful measurements with typical instruments difficult or impractical. The near-field "zone" extends from the source to approximately one wavelength away. The next zone is the reactive-radiating near field, with an inner boundary at one wavelength and the outer boundary at three wavelengths from the source/antenna. In this region the near-field components slowly transition away from being exclusively reactive and begin to prepare for the propagating characteristic of the next field zone. In the third zone, the radiating near field behaves locally like the far field: its inner boundary is three wavelengths from the source, whereas the outer boundary depends on the antenna type and dimensions. For larger antennas, the far-field distance is defined with the relation $2\ D^2/\lambda$, with D the maximum dimension of the antenna, which makes the outer boundary, where far-field characteristics begin, predominate. Otherwise, for typical short antennas, the radiating near field has

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[2] Also called Point Of Investigation (POI).

the same inner and outer boundaries, 3 λ, which means that actually the third field region does not exist, but is within the second, reactive-radiating near field zone. The mentioned local far-field behavior of the third zone relates to the wave impedance that is defined locally as free-space impedance. This means that electric and magnetic fields are locally, i.e., only at certain locations, perpendicular. The radiating far-field region begins at the outer boundary of the third zone, and in the ideal case it extends to infinity. The electric and magnetic field strengths each have only one field component, which are mutually perpendicular. Furthermore, both components are perpendicular to the direction of energy propagation.

In conclusion, in the reactive near field zone, it is necessary to measure all six components of field strengths (three electric and three magnetic field components). Power density is not a relevant physical parameter. The much simpler relationships in the far field means it is possible to get an exact result by measuring one component only. The basic relationship between electric field strength, magnetic field strength, wave impedance (Z_0), and the power density of the equivalent plane wave (S) is described with Equation 1:

$$S_{\text{eq}} = E \times H = \frac{E^2}{Z_0}. \tag{1}$$

Electric field strength can be calculated from magnetic field strength and wave impedance by knowing transmitted power (P) and antenna numeric gain (G), which depends on elevation (θ) and azimuth (ϕ) angles, and distance (r) from the point of investigation as

$$E = Z_0 H = \frac{\sqrt{30 P G(\Theta, \phi)}}{r}. \tag{2}$$

5. WIRELESS COMMUNICATIONS SYSTEMS: EMF MEASUREMENT REQUIREMENTS

As mentioned, this paper focuses on wireless communications systems operating above 110 MHz. Compliance is defined with respect to three zones surrounding a transmitter antenna:

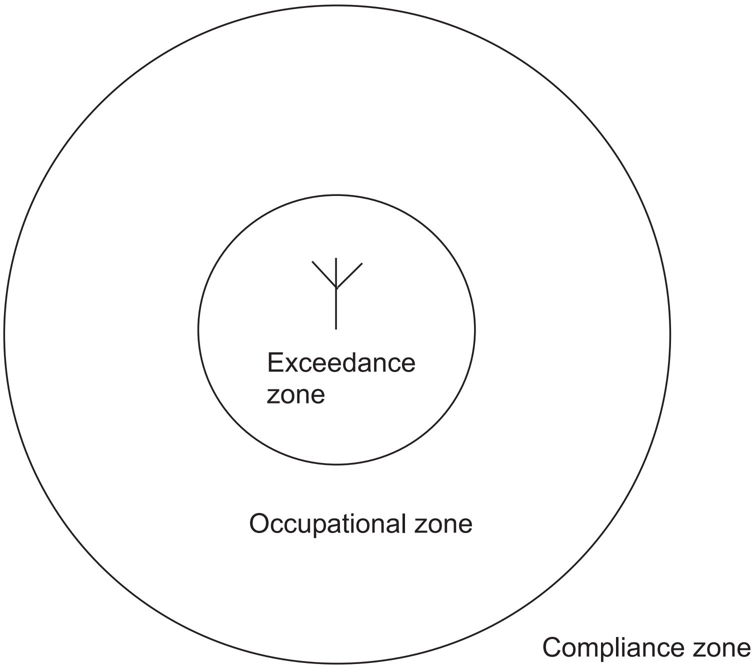

Figure 1. Definition of compliance, occupational, and exceedance zones.

compliance, occupational, and exceedance (non-compliance), as shown in Figure 1 and in Gajšek and Šimunić [5]. The compliance zone is surrounded by a compliance boundary that is valid for both occupational and general public exposure types.

The compliance boundary defines the volume outside which exposure levels do not exceed the basic restrictions, which is called a compliance zone. It is irrespective of the duration of exposure, and is determined via a procedure with a sufficient number of measurement points. The required measurements are either *SAR* (exposure level) or EMF (action values). The compliance boundary zone must comply at low, middle, and high frequencies in each frequency band.

The occupational zone is a zone bound on its outer side by the compliance boundary, while the inner boundary is determined by values higher than for occupational exposure levels.

The exceedance zone is a zone that has values higher than permitted for occupationally-exposed people. Only very limited access or no access is allowed in the exceedance zone.

Typical measurement situations/objectives encompass three known cases. In the first one, the objective is to determine the compliance zone for a known source, where all other sources are considered negligible. The second case requires determination of the compliance zone for the known source in a particular location. This requires a survey of all EMF, including those operating at out-of-band frequencies. This survey should provide an answer whether the other electromagnetic sources can be neglected. The third situation requires determining compliance in a particular location which has unknown source(s). According to the measuring protocol, total fields have to be measured for the whole frequency spectrum. If the results show non-compliance only, the relative contribution from each source to the non-compliance condition must be determined.

Exposure Level Evaluation is performed under the worst emission conditions of exposure field strength. The exposure field strength measurand is defined for the entire space which persons may occupy, but as measured without any human body present (the so-called unperturbed EMF).

The worst emission conditions encompass the simultaneous presence of several EMF sources, even operating at different frequencies. The first step is to determine exposure field strength (E) (Equation 3), in the whole space from a single incident electromagnetic wave:

$$E = \sqrt{E_x^2 + E_y^2 + E_z^2}. \tag{3}$$

Next E_i from each other single wave is determined and then summed up to give composite field strength (E_c):

$$E_c = \sqrt{E_1^2 + E_2^2 + E_3^2 + \ldots}. \tag{4}$$

Exposure ratio (*ER*) is the assessed exposure parameter at a specified location for each operating frequency of a radio source, expressed as a fraction of the related limit. For reference levels at wireless communications systems frequencies *ER* at each operating source frequency is defined as follows:

$$ER = \max\left[\left(\frac{E}{E_1}\right)^2, \left(\frac{H}{H_1}\right)^2\right] \text{ or } ER = \left(\frac{S}{S_1}\right). \tag{5}$$

E, H, and S are the measured values and E_1, H_1, and S_1 are the investigation E-field limits at frequency f, defined in the corresponding national law or international guidelines [6].

ER for n sources is a sum of all *ER*s:

$$ER = \sum_{i=1}^{n} ER_i. \tag{6}$$

The next step is to determine the parameters essential for choosing the kind of measurement. The two main groups of parameters are distinguished as source-related and environmental. The source-related parameters are characteristics of the source:

- maximum EIRP (Equivalent Isotropically Radiated Power) and antenna gain G of the antenna system, including maximum gain and beam width;

- field polarization, frequency, type of modulation of the source(s);
- direction of energy propagation from the source (antenna location, antenna height, beam direction, beam tilt).

The environmental parameters are the characteristics of the surroundings. A few are immediately obvious: direction, distance and relative orientation of the source(s), and prominent features of the physical environment with respect to the field point. Also, in real measurement situations, it is often unavoidable to perform many measurements in near fields and/or in reflective environments in the presence of standing waves. These situations require larger sampling of accessible space, preferably extending at least half a wavelength horizontally and vertically, i.e., in all directions. The test equipment and/or personnel for monitoring EMF strength introduce perturbations in the radio-frequency field distributions. Therefore, it is desirable to perform independent measurements of both electric and magnetic fields at all frequencies. Finally, nowadays it is routinely expected to measure at sites with multiple sources and frequencies, thus requiring frequency selective measurements.

The measuring instrumentation can be defined according to its type as broadband (usually a wideband antenna with a spectrum analyzer, or an isotropic hand-held instrument), and narrowband (usually a frequency-selective antenna with a spectrum analyzer).

The choice of proper instrumentation is determined by the standard with which compliance is being evaluated (frequency-dependent limits), by the number and characteristics of EMF sources, and by the field zone (i.e., reactive near field, radiating near field, far field).

Existence of comprehensive operating instructions is another necessary requirement for the measuring instrument. The instrument consists of three basic parts: sensor, leads, and metering instrumentation. The sensor is usually an antenna combined with a detector; the leads carry the signal response to the metering instrument with signal-conditioning circuitry and a display device. It is a requirement that the probe responds only to one particular field component and does not have significant spurious responses; for instance, E-field instruments should pick-up only E-field without an H-field response. The probe/sensor itself should have an isotropic response i.e., non-directional and non-polarized. Any leads from the sensor to the meter should not significantly perturb the field at the sensor or couple energy from the field, which is accomplished by using highly-resistive partially-conducting material. The dimensions of the probe sensor should preferably be less than $\lambda/10$ in the surrounding medium at the highest operating frequency, in order to avoid strong perturbations of the field distribution. Finally, the probe should not produce significant scattering, which means that housing materials must be carefully chosen.

6. MEASUREMENT CHECKLISTS

Before performing the measuring procedure, it is important to complete three checklists, namely for the instrument, the source, and the field propagation characteristics.

The checklist for the measuring instruments includes ensuring that a suitable far-field reading on a known radiation source can be obtained. The reading of the instrument has to be checked with isotropic and linear probes, especially with respect to identifying possible dependences of probe orientation. The direction of the sensor leads should be changed, while keeping the probe stationary, to check for unwanted pickup on the leads. A comparison of the readings should be performed with an available second calibrated instrument. Also, the reading values should be compared with the expected (or calculated) field strengths. These tests have to be performed before the measurements, and after the survey these should be repeated.

The checklist for the source consists of checking generator types and generated power; carrier frequency or frequencies; modulation characteristics; polarization; duty factor, pulse width and repetition frequency, if applicable; type of antenna (except for leakage sources) and properties such as gain, physical dimensions and radiation pattern, etc. This list also contains the number of sources, including any out-of-band signals that might affect the measurements.

The checklist for propagation characteristics requires knowledge of the distance from source to test site or measuring point, and an inventory of absorbing, scattering, or reflecting objects likely to influence field strength at the measuring point.

In situations when source characteristics are not well-defined (if there is a leakage source), a number of exploratory measurements must be performed around the test site, scanning a wide frequency range until some positive response is found by a sensitive probe with non-directional and non-polarized sensor. The range settings should support a gradual approach towards the likely leakage source(s). Only after the location of the leakage has been confirmed, can the range be set higher.

Issues that have to be considered when performing measurements are related to the fact that field strength levels are quoted for unperturbed fields. In practice, local reflections are present even without people present (the so-called multi-path propagation). Near metallic objects the edge of the probe should be at least three probe lengths away from the object. The compliance zone boundaries have to be accurately determined and sufficiently close to one another. The expected time variability of the source has to be taken into account by performing measurements over an extended period. In this period the peak usage of the wireless systems has to be monitored. For the case of GSM, e.g., one parameter to follow would be channel variability.

7. MEASUREMENT PROCEDURES

After completing all the necessary checklists, the measurements can begin with the initial procedure. At a height of 1 m above ground level, or 1 m above foot level if the area of interest is above the ground level, or for the case of an elevated antenna, evaluating the fields near the ground, which are dependent on height (ground reflections), a series of measurements throughout a volume area that occupies the entire body of the exposed individual should be performed. In qualitative terms, a human body can be considered to occupy the space and volume roughly equivalent to a parallelepiped having sides of 2 × 1 × 1 m. However, the usual and more applicable principle is based on the evaluation of three heights (1.1, 1.5, and 1.7 m) for each location or Point Of Investigation (POI). POI are selected accessible areas for workers with the maximum step size of either 2 m or *d*/40,[3] where *d* is the distance in meters from the POI to the relevant source. The principle of relevance establishes the conditions for a relevant source: this is in locations where its *ER* is greater than 0.05. The principle is particularly important for application in multi-source environments.

For a single source in the far-field zone, the measurements can be performed in two ways. The first uses a discrete method with multiple points. It is important to choose a sufficient number of points, depending on wavelength, in order to find maxima and minima, especially if the measurements are performed indoors, as in Zrno and Šimunić [7]. The second method is a continuous scan across measurement points, where it is important to choose an appropriate measuring area. In both cases, the measuring operator should avoid reflections or alterations of the field due to support structures, or from the operator's body. Also it is important to maintain cables perpendicular to the direction of the electric field vector [8].

The next case are complex far-field sources [9, 10, 11, 12], which means that there are multiple, distant sources of unknown frequency, polarization, and direction of propagation. This type of measurement requires a broadband isotropic probe, especially due to the presence of standing-wave effects and multiple-field interactions. The volume of space in the zone of interest has to be scanned. The suggested volume is as in the initial procedure.

A final case is consideration of the measurement procedure for near field sources,

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[3] The distance between two POI and the distance to a radio source that results in a 5% change in *ER*.

where accuracy of the measurements depends upon the availability of a probe with electrically small antennas. The instrument should have an isotropic probe that produces minimal perturbation of the FUS (field-under-study), so that even large gradients in near fields can be measured. It is mainly the spatial resolution that is critical; large probes (larger than $\lambda/4$ effective aperture) measure spatially-averaged values. Thus, a series of continuous scans to find the point of maximum intensity should be performed with a special attention paid to reflections from cables, the operator's hands, and the readout meter. Relatively insignificant error contributions occur when objects are separated from the probe sensor by an adequate distance or located farther from the source than the sensor.

In the reactive near field, both E and H components should be measured, but it is much more appropriate to consider evaluation of *SAR*.

Measuring only one E component is permitted if the ratio E/H is larger than free-space wave impedance. These are the high-impedance EMF conditions. If the ratio E/H is smaller than free-space impedance, i.e., in low-impedance EMF conditions, only one H component has to be measured. In the radiating near field, only one E component needs to be measured, and all the other field values can be derived from it and free-space impedance. The resulting differences, if all components have been measured, are small compared with measurement uncertainties. In the radiating far field, only one E component has to be measured.

8. CONCLUSIONS

Applications of the Directive require a thorough knowledge of the theory of EMF and the basics of measuring instrumentation, followed by various measurement standards. The measurement standards for the evaluation of workers' exposure to EMF are produced by CENELEC, which is a body mandated by the European Commission (EC). Since covering all relevant evaluation of EMF situations is a tremendous task, the EC has decided to permit employment of other scientifically based standards until harmonized European CENELEC standards become available. The most important relevant standards development organizations are IEC at the international and CEN and ETSI at the regional (European) level.

The measuring protocols discussed are such that special attention should be paid when measuring multi-source, near-field, and indoor environments. In all these cases, the instruments can easily display values that do not correspond to reality, due mostly to non-ideal responses as well as environmental conditions. The results should present the average value together with the maximum measured value. Thus, it is estimated that the average level of measurement uncertainty is approximately as high as 30%. The uncertainty question leaves an open question about the reliability of the measurement results for the known cases of exceeding the measured action values in the working environment. In these cases, special attention should be directed towards performing as accurate as possible calculations or measurements of exposure limit values. If the results still show exposure standards limits are exceeded, then the compliance boundary around the specific device has to be clearly marked, and the rule of retroactive protection should be applied to workers.

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