

Measurement and Exposure Assessment for Standard Compliance

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1. Introduction

The use of sophisticated wireless communications devices has been increasing exponentially over the past decades, with a corresponding public perception of increase in ambient background of radio frequency (RF) or high-frequency (HF) radiation in the environment. This perception has developed into a public concern, thus requiring an engagement of public health authorities to quantify these fields by measurements, in order to estimate a potential health risk to general public as well as possible occupational hazards. This article will focus on the issue of high-frequency measurements, that should enable exposure assessment for compliance with existing standards and guidelines in non-ionizing radiation protection, more specifically with those relevant to high-frequency electromagnetic fields. Article contains description of basic properties of electromagnetic fields, presentation of high-frequency measurement techniques, requirements for measurement instrumentation, and an example of measurements for compliance with existing guidelines and standards.

2. Standards and Guidelines

Currently existing standards and guidelines (e.g. ICNIRP, IEEE C95.1) take a rate at which RF electromagnetic energy is absorbed in the body, i.e. Specific Absorption Rate (SAR) as a dosimetric quantity. For a pulsed environment an absorbed energy density (Specific Absorption - SA) is applied only for special kinds of exposure: it is either an exposure to a single pulse or when there are less than five pulses with a pulse-repetition period of less than 100 ms (IEEE C95.1, 1991), or to pulses of duration less than 30 μ s. If the unit SAR is to be applied, measurement results have to be averaged over 6 minutes. In practice, it is impossible to perform direct measurements of SAR. Therefore, recommended measurement practice introduced exposure levels in terms of unperturbed electric and magnetic field strength in the near field and power density in the far field, in addition to absorbed energy units. Since the guidelines and standards have been developed on the basis of bioelectromagnetic research in the field of thermal effects, the spatial and time-averaged values are to be measured.

3. Basic Properties of Electromagnetic Field

The behavior of electromagnetic field is described by Maxwell's equations. It follows that from a source emitting electric field, a magnetic field is being induced. That magnetic

field further on induces electric field, thus developing electromagnetic field, which is propagating through the medium. Elementary dipole equations enable us to see what is depicted in Fig. 1. Namely, three main zones can be distinguished: reactive near field, radiating near field and far field zone. Biggest antenna dimension is marked as D , distance $L1$ is a boundary far-field/near-field, distance $L2$ is a boundary of reactive near-field/radiating near-field. In the space immediately surrounding the antenna electromagnetic energy does not radiate in the main direction, but it is stored. Therefore, it is called reactive near-field region. The components of the field vary very much with distance and they do not follow the inverse law with distance from the antenna. As the distance from the antenna increases, there is a part of the energy which propagates, but still there is no real plane-wave radiation. This zone is called radiating near-field region. Finally, only in the far field region the field strength follows the rule of inverse field strength with distance, which proves the real plane-wave character.

Fig. 1 Near and far field region

The theoretical distance to the far-field zone is usually taken as the $L1 = 2D^2/\lambda$, where D is the largest dimension of the antenna. However, for large antennas (largest dimension greater than the wavelength - e.g. parabolic reflectors, arrays and horn antennas) it is practically taken as $0.5D^2/\lambda$.

The radiating near-field region may not exist if the greatest dimension of the antenna is much smaller than the wavelength (small antennas - e.g. resonant dipoles). If it exists, in this region measurements can be made with a probe or receiving antenna small compared to the source if the radiation and if any scattering objects are in the far field of the receiving antenna (which depends on the dimension of the antenna), if the main beam of the receiving antenna contains the radiation source, as well as any source of multipath scattering and if there is enough distance (several largest dimensions of the radiating portion of the source) between the receiving antenna and the radiation and any scattering sources.

The reactive near field region is characterized by its reactive character, which means that the term of radiating power density does not have physical meaning. Therefore, in this region the electric or magnetic field should be measured with the probe or receiving antenna small compared to the source.

4. Measurements Considerations

Carefully done measurements made in free space or in an anechoic chamber with calibrated equipment can give very accurate results, because an influence of a probe or instrument or human presence is negligible. However, human exposure assessment (meaning

the whole space occupied by a person, but measured without presence of a human body) often times requires performing measurements under non-ideal conditions, which means enclosed space, i.e. in buildings. Conditions are non-ideal, because the resultant electromagnetic field has not only incident, but also reflected component, thus meaning that a standing wave has to be taken into account. Therefore, in order to obtain accurate results, it is critical to focus on a measurement protocol, which incorporates choice of methods and instrumentation.

4.1 Measurement Protocol

A specific behaviour of high-frequency fields (e.g. existence of reradiating surfaces, elliptical polarization when penetrating human body) requires careful planning of measurement protocols that should incorporate both spatial and time averaging. As a first step, it is necessary to completely analyse the ambient electromagnetic environment, which could otherwise become a source of error. Effects of sensor (i.e. receiving antenna) size with respect to characteristics such as frequency of the RF source, as well as measurement distance are also of considerable importance.

Selection of the method and instrumentation depends on the frequency, output source power, modulation type, type of exposure (continuous or pulsed), spurious frequencies including radiated harmonics and number of radiating sources. Before starting the measurements, the items that have to be addressed include the check of the previously mentioned source characteristics and the check of propagation characteristics, such as a distance of source to test site, type of antenna and properties including gain, beam width, orientation, eventual scanning program, physical size with respect to the distance to the area being surveyed, polarization of the E- and H-fields, existence of absorbing or scattering objects likely to influence the field distribution at the test site, as suggested in (IEEE C95.3-1991, 1992). Finally, it is unavoidable to be aware of characteristics of measuring device, given in the next chapter, as well as of quantities and values given in guidelines and standards that are followed.

In a special case, when performing near field measurements or measurements inside buildings due to the presence of the standing wave, care should be taken of two important points, i.e. spacing between measurements, which should be relatively small, if all minima and maxima are to be taken into account and presence of operator or probe close to the radiation source, which could cause serious disturbances of the reactive fields.

4.2 Time and Spatial Averaging

Spatial averaging is carried out over an area equivalent to the vertical cross-section of the human body. Field probes should be placed at least 0.2 m from any object or person. The grid of values should be established on the basis of width of 0.35 m and height of 1.25 m perpendicular to the ground and respecting the rule of at least 0.75 m from the ground. For

the space inside buildings, it is recommended that the field is measured at least at 1.5 m from the ground. If measurements are performed with an isotropic construction of three dipoles, which is necessary because of the complex environment inside buildings, it is necessary first to calculate the exposure field strength E_i at one position as:

$$(1)$$

Once having isotropic values, obtained either through three dipoles or directly through a field meter with three orthogonal dipoles, it is necessary to measure the field at at least three places in the room of interest. Thus, the spatially averaged value of the electric field is calculated from the following formula:

$$(2)$$

Of course, if the values are read in terms of power P (i.e. read by power meter or spectrum analyzer), then it is necessary first to calculate power density w from power for every measured component via:

$$w_i = P_i / A_e \quad (3)$$

where A_e is effective antenna area. For the dipole it is related to wavelength λ as:

$$A_e = 0.13 \lambda^2 \quad (4)$$

In that case isotropic value of power density w is:

$$(5)$$

and the spatially averaged value of power density is:

$$(6)$$

where w_i is power density measured at the specific i -th location.

Many guidelines specify the permissible values of RF field strength or power density as averaged over 6 minutes. Single measurement is sufficient unless significant changes (more than 20 %) occur within a period of 6 minutes. By performing multiple measurements, time-averaged RMS electric / magnetic field can be calculated from:

$$(7)$$

and the time-averaged power density:

$$(8)$$

where E_i and w_i are the measured rms electric field and power density in the i -th period, the Δt_i is the time duration in minutes and n is number of time periods within 6 minutes. The sum of the time duration should always be 6 minutes.

4.3 Multiple Frequency Environment

If measured in a closed environment, it is necessary to establish the electromagnetic field components by a set of corresponding antennas and spectrum analyzer. Usual practice, especially when assessing exposure of cellular personal communications systems, gives a number of components, which can be recorded during the measurements by a spectrum analyzer. Namely, it is necessary to determine which are the most significant components. The ratio of the measured power density value at each frequency and the limit value at that frequency has to be determined, and the sum of all ratios at what is considered the most significant components should not exceed unity when averaged spatially and over time.

$$(9)$$

If the measurements are performed in the far-field zone, both kinds of probes - electric and magnetic field will give the accurate value of power density. However, this is valid only for continuous wave exposure, where electric and magnetic field are related to the power density by a simple equation:

$$(10)$$

where H is magnetic field strength (Am^{-1}) and Z_0 is free-space impedance (376.6Ω).

Generally, for a pulsed environment diode-based electric field measurement instrumentation will display the value with certain errors (Simunic and Koren, 1997). The measured value in case of multiple sources generating multiple frequencies will include errors, as well (Randa et Kanda, 1985). Even greater error will occur in the real urban electromagnetic environment with multiple pulsed sources, generating multiple frequencies. In order to be aware of the "instrument factor", the instrument should be simulated for the simpler case of the pulsed environment, and the results should be verified with measurements. Therefore, before making measurements, it is necessary to have a

comprehensive handbook of measurement instrument, that would include clear performance statement, including restrictions in the near field and multiple sources environment.

In order to comply with guidelines and standards, for a pulsed wave average power P_{av} has to be calculated from the peak power P_{peak} and duty cycle DC as:

$$P_{av} = P_{peak} \cdot DC \quad (11)$$

Similar formula is valid for average power density w_{av} (Wm^{-2}) for a pulsed wave:

4.4 Properties of Measurement Device

Measurement devices for field strength or power density measurements consist of three main parts: probe, connecting leads and instrumentation. The probe includes field sensing elements: for an electric field it is a dipole and for a magnetic field it is a loop. Isotropic probe comprises three field sensing elements.

The questions to be asked before making a decision whether a measurement device is appropriate are related to the isotropicity of the instrument (is response directional or polarized?); to the probe response (is it responding only to a specific parameter, i.e. only electric or only magnetic field; is it responding to other radiation, such as ionizing radiation, artificial light, sunlight or corona discharge; is the response time, i.e. the time required for the instrument to reach 90% of its value when exposed to a step function of continuous wave energy known; is out-of-band response known?); to the frequency selectivity of the instrument; to the measured value (is it a peak or RMS value - the very important comment is that the peak values should be added linearly and the RMS values geometrically); to the stability of the instrument; to the dynamic range of the instrument; to the probe dimensions (are they less than $\lambda/10$ at highest operating frequency, in order not to perturb the original field); to the leads from the sensor to the meter (do they significantly perturb the field at the sensor?); to the question whether is the whole instrument producing significant scattering of the electromagnetic field; to the separate calibration of the instrument with the particular probe for the electric and for the magnetic field; and finally to the instrument supply with a comprehensive handbook which includes a clear statement of the performance, with a special attention to any restrictions in its application (e.g. pulsed fields, multiple frequency sources, near-field measurements)?

4.5 Antenna Considerations

Antenna or probe should be placed as far as possible from all metal objects. If measurements are performed indoors, the dimensions of the antenna are very important, concerning the available space. The effects of building structure on penetration of remotely generated signals should be assessed (e.g. magnitude of building attenuation as a function of

frequency, materials used in building construction, location within a building, already existing field components). The ideal position of the antenna is at approximate center of a room and certainly at least 1.5 m above the floor, in order to avoid reflections from the floor. As mentioned above, the result of reflections indoors could be a standing wave phenomenon. In order to estimate the maximum of the standing wave, the position of the antenna should be varied in small steps (less than 0.25 wavelength). This consideration is also valid for the outdoor measurements, if not in free space, and if there is a possibility of establishing standing waves, easily recognizable by a great variation of field intensity. Antenna should be oriented according to the antenna type and the required field information. For instance, rod antennas should be oriented vertically; loop antennas in three orthogonal positions; dipoles in three orthogonal positions or at least in horizontal and vertical positions; log-periodic, horns and dishes in horizontal and vertical at desired elevation and azimuth angle - spectrum should be scanned in each polarization.

At frequencies higher than 100 MHz it is recommended to use monopole or half-wave dipole adjusted for each frequency. Commercially available directional antennas (e.g. horn antennas) should not be used, except in the case where source locations have been well defined.

Recommended antennas and probes, depending on the frequency range are given in Table 1.

Table 1 Recommended antennas and probes

Loop antenna, which is shielded and unbalanced with respect to ground, is recommended for magnetic field strength measurements from 30 Hz to 30 MHz. Half-wavelength dipole antenna are used from 30 MHz to 1 GHz. Its length is adjusted for resonance at specific frequency. Therefore, the dipole is practical only for surveying specific frequency region. Also, the specifics of the dipole is its impedance, influenced by its distance from nearby reflecting surfaces and the earth. Broadband dipole antenna can be applied over a wide frequency range, from 30 MHz to 200 MHz. Log-periodic antenna is used in the frequency range from 200 MHz to 10 GHz when the radiation source is distributed over a very large angle, compared to the antenna beamwidth or for the known source location. Planar log-periodic antennas are used for measuring both the orthogonal components of elliptically or linearly polarized waves. Conical log-spirals are used for circularly polarized fields. Pyramidal horn antennas are used in the frequency region 1 GHz - 10 GHz. There is a clear relation between power density of the source and a total power in the far field. If higher gains are required, dish antenna can be used in the same frequency range.

4.6 Electric and Magnetic Field Probes

Both types, electric and magnetic field probes can be used for measurement of power density. This is valid for far field, and for radiating near field, if the conditions mentioned above are satisfied. Electric field probes usually use three orthogonal short dipoles. The

frequency range is from 10 MHz to 20 GHz. Magnetic field probes use a combination of three orthogonal small loops, with a much narrower frequency range of 10 MHz to 300 MHz.

4.7 Detector Types

There are four basic types of envelope detectors that can be used for performing RF measurements, namely: average power, quasi-peak voltage, peak voltage, and average voltage detectors. The choice of detector will depend on approximate knowledge of signal environment. Insofar, the detectors showing average power have been the most desirable, because of the existing standards and recommendations (Johnston R. et al., 1999). Of course, the properties of ideal measurement device are well-known: fast response (at least order of microsecond), isotropic response, showing peak electric field and simultaneous measurement of electric and magnetic field for near field (Simunic, 1999).

4.8 Calibration

It is of utmost importance to calibrate measuring equipment and especially antennas. The recommended antenna system calibration is given elsewhere (De Leo et al, 1994; IEEE SCC 28, 1999).

5. Experimental Results

Figure 2 shows the basic measurement set-up for measuring multiple frequency environment, especially focusing on GSM downlink frequency band, for measuring radiation from base stations. The set-up consists of spectrum analyzer and a dipole antenna. Measurements are taken in three orthogonal polarizations (a, b, and c) at different locations, if measured inside the buildings and at different frequencies of GSM downlink frequency band. Also, it is necessary not only to perform spatial, but also time-averaging.

Fig. 2 Basic measuring set-up

As an example, results of measurements around GSM base stations taken in May of 2001 in the town of Zagreb are given here. Measurements were initiated by Croatian Ministry of Health, due to citizen complaint. Base stations antennas are approximately 100 m from the residential neighbourhood. The environment can be characterized as light urban with two-stories buildings.

Measurements were taken at three positions for three polarizations in the whole GSM downlink band (Fig. 3).

Fig. 3 Example of GSM base stations measurements

The most significant values ("worst-case") could be seen at three GSM frequencies at position 1 (near the window), written in Table 2. Consistently low values in one of the polarizations indicate that the environment can be characterised as a Line-Of-Sight with insignificant local scattering (which is exactly the case, because the base stations antennas could be seen from the window).

| Polarization | a | b | c |
|-----------------------------------|---------|---------|---------|
| Measured power at $f_1 = 937$ MHz | -36 dBm | -37 dBm | -45 dBm |
| Measured power at $f_2 = 957$ MHz | -38 dBm | -33 dBm | -45 dBm |
| Measured power at $f_3 = 959$ MHz | -42 dBm | -36 dBm | -45 dBm |

Table 2 Measured power values at three most significant frequencies

As stated in the above text, it is necessary to convert these values to power density, according to (3). Since the values are measured with a dipole antenna, we use (4) for calculation of A_e . The corresponding power densities are given in Table 3:

| Polarization | a | b | c |
|---|-------------------------|-------------------------|-------------------------|
| Measured power density at $f_1 = 937$ MHz | 0.028 mW/m ² | 0.022 mW/m ² | 0.003 mW/m ² |
| Measured power density at $f_2 = 957$ MHz | 0.018 mW/m ² | 0.029 mW/m ² | 0.004 mW/m ² |
| Measured power density at $f_3 = 959$ MHz | 0.007 mW/m ² | 0.029 mW/m ² | 0.004 mW/m ² |

Table 3 Measured power density values at three most significant frequencies

It is necessary to take cable losses in the account. In this particular case, they are 1.7 dB.

The next step is to calculate isotropic values, and it is done by (5):

$$\begin{aligned}
 f_1 = 937 \text{ MHz} & \quad w_1 = 0.053 \text{ mW/m}^2 \\
 f_2 = 957 \text{ MHz} & \quad w_2 = 0.051 \text{ mW/m}^2 \\
 f_3 = 959 \text{ MHz} & \quad w_3 = 0.040 \text{ mW/m}^2
 \end{aligned}$$

Application of formula (9) will give comparison of the data to recommended values in guidelines. If reference values are taken from ICNIRP guidelines (in the frequency band from 400 to 2000 MHz power density reference level for the whole body is $f/200$ W/m²), the exposure limit values for this example at $f_1 = 937$ MHz , $f_2 = 957$ MHz and $f_3 = 959$ MHz are

4.685, 4.785 and 4.795, respectively. This means that in this example formula (9) gives the value of 0.00003, or in other words the measured total value of power density is 100000 times smaller than the one given in ICNIRP guidelines.

6. Conclusion

It is very important to perform measurements for exposure assessment very carefully, because of a number of possible errors due to the various reasons: measurement position, instrument showing different value than expected, dimensions of the probe, environmental conditions, operator's presence, etc. Due to possible non-thermal interaction of various equipment of emerging technology, encompassing variety of sources, with human beings, it is crucial to define the values that have to be measured (spatial- and time-average electric and magnetic field, averaging time, peak power density, average power density). As it has been attempted to show in this paper, measurements are a very challenging task. However, with the well-defined quantities to be measured and by planning measurements very carefully, it is possible to perform them and to estimate their error.

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