Measuring Non-Ionizing Electromagnetic Fields from a Specific Direction

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Abstract: - The apparatus used for broadband radiation hazard evaluation usually measures and displays the total electric field strength (RMS value) over a frequency bandwidth. However, given that the reference levels (RL), according to the ICNIRP Guidelines or other specific legislations, are frequency dependent, the compliance of a particular RF or microwave transmitter and its contribution to the total received electromagnetic energy at a given measurement location it is not easily identifiable.

On the other hand, narrowband measurements using appropriate antennas and spectrum analyzers, make determinable the power level from every single transmitter. However, in this case, and given that the antennas used are directional and linearly polarized, a large number of measurements has to be taken in order to obtain the total electric field strength and consequently to check for compliance with the legislation limits.

In this work a method is presented for determining: the total electric field from a particular direction to a specific point of a measurement location (e.g. from a mobile base station mast), the angle of maximum incident electric field and the total exposure quotient from the sources laying at that particular direction in a given frequency band.

Key-Words: - Non-ionizing Electromagnetic Fields, Electromagnetic Radiation, Electromagnetic Spectrum, Multiple Sources Coefficient, Reference Levels, Compliance estimation

1 Introduction

The increased need for fast, reliable and always handy communications boosted the evolution of modern communication systems such as mobiles, broadcasting and wireless networking. To support them, a large number of antenna stations have been installed in residential areas.

These systems operate at the non-ionizing electromagnetic radiation bands (NIER) (0 Hz – 300 GHz). Several studies concerning the effects of NIER on the humans have been recently conducted. For the general population protection, basic restrictions (BR) and reference levels (RL) concerning electric field strength - E, magnetic field strength - H, magnetic flux density – B, equivalent plane wave power density - S, specific absorption rate - SAR, current density - J, etc have been established by International Organizations, e.g. ICNIRP [1], the European Council [2] and several countries.

Therefore, it is necessary that some of the above electromagnetic quantities (E, H, S) are measured at places of interest, in order to estimate the compliance with the established RL.

2 Estimation of the total electric field strength arriving from a specific direction.

Consider an electromagnetic wave propagating in the direction of the Z axis. The electric field E at a frequency f_i is represented by a vector $\vec{E}_i$ perpendicular to the Z axis at a random angle with respect to the horizontal axis (perpendicular to the direction of propagation).

The magnitude of electric strength, $\left|\vec{E}_i\right|$, can be estimating by performing two measurements with a linear polarized antenna i.e. one at horizontal (H) and one at vertical (V) polarization (Fig.1):

$$\left|\vec{E}_i\right| = \sqrt{E_{H,i}^2 + E_{V,i}^2} \qquad (1)$$

where $\mathbf{E_{H,i}}$ and $\mathbf{E_{V,i}}$ are the measurement of the components of $\mathbf{E_i}$ at H and V polarizations respectively. It can be easily shown, that equation (1) is valid for every pair of measurements as long as they are performed in pairs of perpendicular at each other polarizations (Fig.2). Therefore:

$$\left|\vec{E}_i\right| = \sqrt{E_{H,i}^2 + E_{V,i}^2} = \sqrt{E_{\theta,i}^2 + E_{(\theta-90),i}^2} \qquad (2)$$

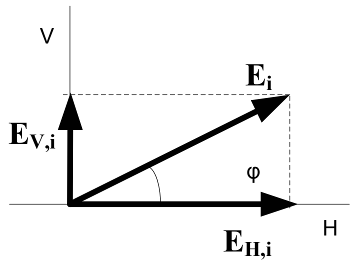

Figure 1. $\mathbf{E_i}$ Horizontal and Vertical components

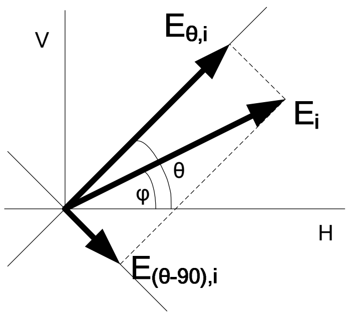

Figure 2. $\mathbf{E_i}$ arbitrary perpendicular directions components

On a multiple transmitter problem the magnitude of the total electrical field arriving from a specific direction can be estimated by the means of RMS calculation value of $\mathbf{E_i}$:

$$\left|\vec{E}\right| = \sqrt{\sum_i \vec{E}_i^2} = \sqrt{\sum_i \left(E_{H,i}^2 + E_{V,i}^2\right)} =$$

$$= \sqrt{\left(\sqrt{\sum_i E_{H,i}^2}\right)^2 + \left(\sqrt{\sum_i E_{V,i}^2}\right)^2} =$$

$$= \sqrt{E_{H,rms}^2 + E_{V,rms}^2} \qquad (3)$$

Using eq. 2 in 1 we have:

$$\left|\vec{E}\right| = \sqrt{\sum_i \vec{E}_i^2} = \sqrt{\sum_i \left(E_{\theta,i}^2 + E_{(\theta-90),i}^2\right)} =$$

$$= \sqrt{\sum_i E_{\theta,i}^2 + \sum_i E_{(\theta-90),i}^2} =$$

$$= \sqrt{\left(\sqrt{\sum_i E_{\theta,i}^2}\right)^2 + \left(\sqrt{\sum_i E_{(\theta-90),i}^2}\right)^2} =$$

$$= \sqrt{E_{\theta,rms}^2 + E_{(\theta-90),rms}^2} \qquad (4)$$

where $E_{H,rms}$, $E_{V,rms}$, $E_{\theta,i}$ and $E_{(\theta-90),i}$ are the RMS values of the components $E_{H,i}$, $E_{V,i}$, $E_{\theta,i}$ and $E_{(\theta-90),i}$ given by:

$$\left|\vec{E}_{H,rms}\right| = \sqrt{\sum_i E_{H,i}^2}, \qquad (5)$$

$$\left|\vec{E}_{V,rms}\right| = \sqrt{\sum_i E_{V,i}^2}, \qquad (6)$$

$$\left|\vec{E}_{\theta,rms}\right| = \sqrt{\sum_i E_{\theta,i}^2}, \qquad (7)$$

$$\left|\vec{E}_{(\theta-90),rms}\right| = \sqrt{\sum_i E_{(\theta-90),i}^2} \qquad (8)$$

Consequently, in order to estimate the total electric field arriving from a particular direction, e.g. from a mobile base station mast, using a directional antenna and an appropriate receiver, e.g. a spectrum analyzer (SA), two measurements at perpendicular polarizations suffice. Usually the horizontal and vertical polarizations of the receiving antenna are used with an appropriate azimuth and tilt to the desired direction.

3 Compliance estimation with respect to the reference levels.

To estimate compliance to RL for thermal effects consideration and for electromagnetic fields received from a specific direction at a specific location, using a spectrum analyzer as a receiving device, it is necessary to set up the appropriate SA settings (frequency span, start frequency, stop frequency, resolution bandwidth, video bandwidth, sweep time, sweep points, input attenuation, reference level, scale type etc for the used SA model) and treat measurement traces correctly ([3],[4],[5] and [6]).

The rest of the parameters (antenna factor/gain, cable and connector losses, and instruments specifications) are already known from the respective manufacturer's data sheets and they must be input to the software used, for every measurement. Moreover, the overall uncertainty of the measurements according to [7] and [8] can be estimated using those parameters.

Therefore and given that a SA usually records the received power in dBm over a frequency band of interest, it is necessary to transform the power obtained in the SA output to power density, electric field strength, magnetic flux density and magnetic field strength in the input of the measuring system, and to compute the appropriate summation of exposure quotients or in other words the multiple sources coefficient (MSC), over the frequency band of interest. If the result is less than unity, then according to legislation [10][11] and standardization guidelines [12] compliance is achieved.

Summation of exposure quotients for frequencies above 100 KHz is expressed by:

$$\sum_{i=100KHz}^{1MHz}\left(\frac{E_i}{c}\right)^2+\sum_{i>1MHz}^{300GHz}\left(\frac{E_i}{E_{L,i}}\right)^2\leq 1 \qquad (9)$$

$$\sum_{i=100KHz}^{150KHz}\left(\frac{H_i}{d}\right)^2+\sum_{i>150KHz}^{300GHz}\left(\frac{H_i}{H_{L,i}}\right)^2\leq 1 \qquad (10)$$

where $\boldsymbol{i}$ refers to a specific frequency $\boldsymbol{f_i}$, index $\boldsymbol{L}$ refers to the RL of the corresponding quantity at frequency $\boldsymbol{f_i}$, $\boldsymbol{E}$ is electric field strength, $\boldsymbol{H}$ is magnetic field strength, $\boldsymbol{c} = 87/f^{0.5}\, V/m$ and $\boldsymbol{d} = 0.73/f\ A/m$.

The relation between incident power density $\boldsymbol{S_{in,i}}$, electric field strength and magnetic field strength at a given frequency $\boldsymbol{f_i}$ is given by:

$$\left|\vec{S}_{in,i}\right|=\left|\vec{E}_i\times\vec{H}_i\right|=\frac{\vec{E}_i^2}{\eta}=\eta\cdot\vec{H}_i^2 \qquad (11)$$

where $\boldsymbol{n = 120\cdot\pi}$ is the characteristic resistance of free space. Of course for the calculation of the total field arriving from a specific direction:

$$\vec{S}=\left|\vec{E}\times\vec{H}\right|=\frac{\vec{E}^2}{\eta}=\eta\cdot\vec{H}^2 \qquad (12)$$

The above equations are valid for the far field region of an antenna i.e when:

$$r>\max(3\lambda,\frac{2D^2}{\lambda}) \qquad (13)$$

where $\boldsymbol{D}$ is the maximum linear dimension of the antenna, $\boldsymbol{\lambda}$ is the free-space wavelength and $\boldsymbol{r}$ is the distance.

The computation of S, E and H in the input of the measurement system can be carried out using the appropriate formulas described at [6] and [9] by which the trace points are corrected for the equivalent noise bandwidth imposed by intermediate frequency filter (RBW filter), and then taking into account the frequency dependent loss of each component of the measurement system (cables, connectors, external attenuators e.t.c.) and the antenna factor/gain at $\boldsymbol{f_i}$ (Antenna factor, cable and other losses or frequency depended gains can be directly taken from manufacturers data sheets using appropriate interpolation methods [9]).

Using equation (11) the electric and magnetic field strength at the input of the measuring system at $\boldsymbol{f_i}$ is computed by:

$$E_{in}(f_i)=\sqrt{120\cdot\pi\cdot S_{in}(f_i)} \qquad (14)$$

and $$H_{in}(f_i)=\sqrt{\frac{S_{in}(f_i)}{120\cdot\pi}} \qquad (15)$$

For far field conditions and for frequencies over 10MHz using (9) through (12) it can be easily proved that the MSC is given by:

$$MSC=\sum_{i\geq 10MHz}^{300GHz}\left(\frac{E_i}{E_{L,i}}\right)^2=\sum_{i\geq 10MHz}^{300GHz}\left(\frac{H_i}{H_{L,i}}\right)^2=$$

$$=\sum_{i\geq 10MHz}^{300GHz}\frac{S_{in}(f_i)}{S_{L,i}} \qquad (16)$$

where $\boldsymbol{S_{L,i}}$, $\boldsymbol{E_{L,i}}$ and $\boldsymbol{H_{L,i}}$ are the reference levels at $\boldsymbol{f_i}$ for power flux density, electric field strength and magnetic field strength respectively.

Suppose now that two measurements in perpendicular polarizations of the receiving antenna are taken in a frequency band above 10MHz and below 300GHz (i.e at $\boldsymbol{f_{Low}}$ and $\boldsymbol{f_{High}}$). Without loss of generality let us assume that horizontal and vertical polarizations are employed. Then the MSC for the horizontal (MSC_H) and for the vertical polarization (MSC_V) of the receiving antenna will be:

$$MSC_H=\sum_{i\geq f_{Low}}^{f_{High}}\left(\frac{E_{H,i}}{E_{L,i}}\right)^2 \qquad (17)$$

$$MSC_V=\sum_{i\geq f_{Low}}^{f_{High}}\left(\frac{E_{V,i}}{E_{L,i}}\right)^2 \qquad (18)$$

Adding (20) and (21) and using (1) we take:

$$\mathrm{MSC_H} + \mathrm{MSC_V} = \sum_{i \ge f_{Low}}^{f_{High}} \left(\frac{E_{H,i}}{E_{L,i}} \right)^2 + \sum_{i \ge f_{Low}}^{f_{High}} \left(\frac{E_{V,i}}{E_{L,i}} \right)^2 =$$

$$= \sum_{i \ge f_{Low}}^{f_{High}} \frac{\left(E_{H,i}^{\ 2} + E_{V,i}^{\ 2} \right)}{\left(E_{L,i}^{\ 2} \right)} = \sum_{i \ge f_{Low}}^{f_{High}} \left(\frac{E_i}{E_{L,i}} \right)^2 = MSC \quad (19)$$

Thus computing the MSC_H and MSC_V from the respective traces of the SA we can compute the total MSC originated from sources at a particular frequency band from a given direction at a specific measurement position. Likewise, we can compute all the electromagnetic quantities (S, E, H and MSC) for a given direction using appropriate equations.

In this way the contribution of the electromagnetic field arriving from a specific direction, to total field at the measurement position, can be computed by comparing the above electromagnetic quantities to the ones measured using an isotropic receiver (e.g. an isotropic field probe in conjunction with a field meter or an isotropic antenna and a SA).

In addition, the angle of the maximum incident electric field ($\theta_{E,max}$) from a given direction at a given frequency band can be obtained using the formula:

$$\theta_{E,max} = \tan^{-1} \left(\frac{\left| \vec{E}_{V,rms} \right|}{\left| \vec{E}_{H,rms} \right|} \right) = \tan^{-1} \left(\frac{\sqrt{\sum_i E_{V,i}^2}}{\sqrt{\sum_i E_{H,i}^2}} \right) \quad (20)$$

4 Experimental results

Electromagnetic Radiation Measurements Laboratory (ERML) of the Department of Applied Informatics and Multimedia of the Technological Educational Institute of Crete has applied the above described methodology to carry out electromagnetic field measurements in the area of Crete Island.

These measurements follow the necessary measurement protocol [14] in the RF region in order to comply with the Greek Legislation or other national and international recommendations and standards [10]-[13]. Moreover, the ERML has developed special purpose software [17] in order to automate the measurement procedures. This software is used on the one hand to facilitate the measurement procedure and on the other hand to certify that the measurements are in accordance with the necessary protocol. This software uses standard SCPI commands [16] and operates together with Agilent E4407B SA to record and process electromagnetic field measurements at various frequency bands of interest.

As an example, the results from two pairs of perpendicular measurements for the incident electric field strength are presented in figure 3 (θ=45°). These measurements were taken in the vicinity of GSM900 mobile base station in its downlink band. The calculation of RMS value for the electric field strength from the spectral components in that frequency band, and of respective MSC's are given in table 1.

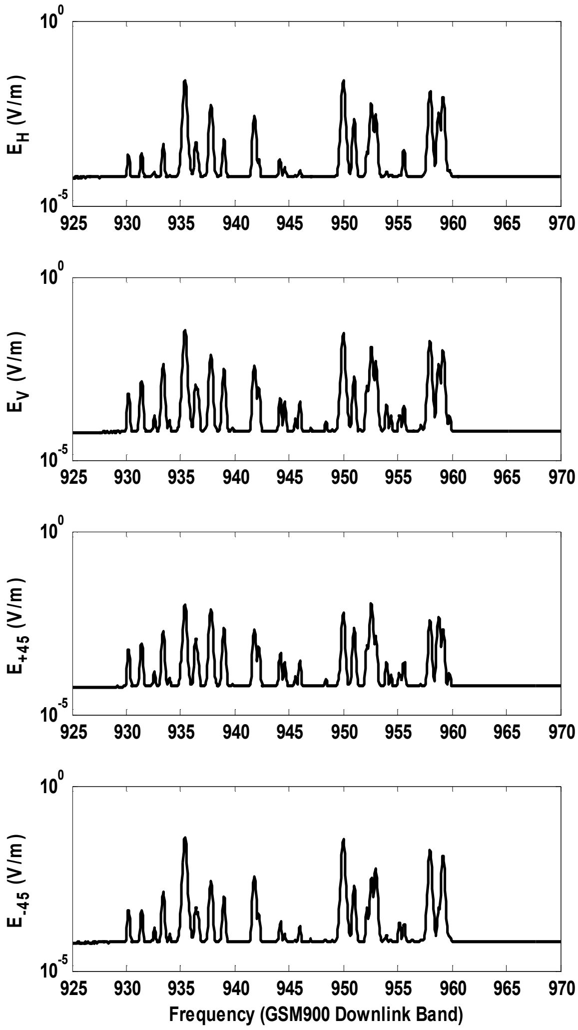

Figure 3. Computed electric field strength in the input of the receiving antenna for four different polarizations, H, V, +45° and -45°.

Polarization	Erms	MSC
H	$7.62 \cdot 10^{-2}$	$5.42 \cdot 10^{-6}$
V	$10.23 \cdot 10^{-2}$	$9.79 \cdot 10^{-6}$
+45°	$3.89 \cdot 10^{-2}$	$1.42 \cdot 10^{-6}$
-45°	$11.64 \cdot 10^{-2}$	$1.27 \cdot 10^{-5}$

Table 1: RMS electric field strengths and MSC's for figure's 3 measurements

Using equations 3 and 4 and the data of the above table we take two values for the incident electric field from the direction of the mobile base station:

$$\left|\vec{E}_{H,V}\right| = \sqrt{0.0762^2 + 0.1023^2} = 0.13\frac{V}{m}$$

$$\left|\vec{E}_{+45,-45}\right| = \sqrt{0.0389^2 + 0.1164^2} = 0.12\frac{V}{m}$$

Accordingly using equations (17) through (19) the resultant MSC from H and V polarizations of the receiving antenna is:

$$MSC_{H,V} = 5.42\times 10^{-6} + 9.79\times 10^{-6} = 1.52\times 10^{-5}$$

and the resultant MSC from +45^o and -45^o polarizations of the receiving antenna is:

$$MSC_{+45,-45} = 1.42\times 10^{-6} + 1.27\times 10^{-6} = 1.41\times 10^{-5}$$

Using equation 20 the angle of maximum incident electric field is computed as:

$$\theta_{E,max}=53.36^o\approx 53^o$$

The computed electric field strength in the input of the receiving antenna from the measurement at that angle is shown in figure 4.

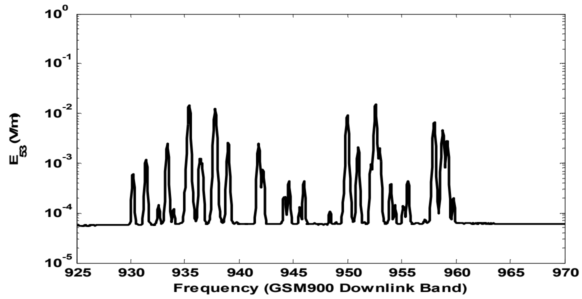

Figure 4. Computed electric field strength in the input of the receiving antenna for approximately 53^o polarization.

For the last polarization example the RMS value of the incident electric field is:

$$\left|\vec{E}_{+53}\right| = 0.12\frac{V}{m}$$

whereas the corresponding MSC is:

$$MSC_{+53} = 1.31\times 10^{-5}$$

As we can see from these results, there is a small difference computing the total incident electric field and computing the sums of exposure quotients with pairs of perpendicular measurements. This is due to the non ideal alignment of the receiving antenna to the emitting source(s) at the different polarizations and due to the different instantaneous power of the base station(s) at each time of measurements. The latter can be eliminated using a large number of power averages for each individual measurement.

5 Conclusions

In this work a method of measuring the incident electric field, magnetic field and power density from a given direction at a given frequency band is presented. The proposed method can be used to estimate the summation of exposure quotients and find out if the emissions from that particular direction are compliant with ICNIRP guidelines or other countries legislation.

The basic characteristics and advantages of this method are:

- It requires only one pair of measurements at perpendicular polarizations using a directional antenna and a narrowband receiver to estimate all the necessary electromagnetic quantities from transmitters at a given direction. In that way the transmitter(s) compliance with the restrictions imposed by the legislation acts or guidelines for non-ionizing electromagnetic exposure to the human laying at the place of measurements can be examined. Of course spatial averaging is needed for more reliable results.
- Using this method, the knowledge of accurate direction of the incident maximum electric field is not needed as this method compensates for direction errors. The measurement error which can be introduced by inaccurately finding the direction of maximum exposure manually (when an operator of the measurement system rotates the receiving antenna and another operator watching if the spectrum analyzer trace reaches a maximum value) is minimized. Additionally the presence of the antenna operator close to the antenna in order to find the maximum received power perturbs incoming electric field resulting in additional inaccuracies. However with the proposed method the only accuracy needed is to use a pair of exactly perpendicular polarized measurements.
- The time needed to obtain the results for MSC is minimized, since the work of the antenna operator is eliminated.
- Reflections or emissions from other directions than the desired one are kept to a minimum because of the directional antenna characteristics.

- The whole mathematical procedure can be easily implemented using a computer connected to the spectrum analyzer. This has the benefit of eliminated the operator errors during set up the measuring system. Thus in a very short time which depends mostly on the analyzer settings (sweep time, number of averages, RBW filter) the MSC and the other electromagnetic quantities for a given direction at a given frequency band can be computed with high accuracy.
- Finally the proposed method can be used to estimate the contribution of the spectral components originating from a specific direction to the total field in the same or a wider frequency band. This is very useful in order to estimate the contribution to the total exposure from a mobile base station at a specific location, which is of a great importance especially for the public living in the vicinity of that base station.

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