FREQUENCY-SELECTIVE ANALYSIS OF THE ISOTROPIC BEHAVIOUR AND MEASUREMENT UNCERTAINTY OF THE FIELD STRENGTH MEASUREMENT SYSTEM FIELD NOSE

A. Kriz and W. Müllner
ARC Seibersdorf research GmbH
Electromagnetic Compatibility and RF-Engineering, A-2444 Seibersdorf
E-mail: alexander.kriz@arcs.ac.at

Abstract: A rigorous analysis of uncertainties involved with frequency-selective field-strength measurements of the radio frequency emissions from mobile communications base stations using the innovative Field Nose system is presented. The analysis is based on measurements and numerical simulations. The contributions from antenna patterns, antenna factor calibration, test receiver calibration, temperature coefficients, standing waves and cable losses are considered. An expanded uncertainty (k=2; 95 %) between 2.9 dB (80 MHz) and 2.3 dB (2.5 GHz) is found. The most important uncertainty contribution at lower frequencies (< 900 MHz) is standing waves. At higher frequencies the isotropy becomes significant.

I. INTRODUCTION

With the boost of mobile phones also public concerns regarding health and safety aspects are increasing. Therefore safety guidelines for the protection of the population from frequency radiation have been defined. In order to check the adherence to these legal limits adequate measurement systems are necessary.
There are certain requirements for performing precise and reproducible evaluations: The measurement system must consider incident waves from all directions in the same way (isotropy). A further requirement is the frequency selectivity in order to compare the measurement result with the frequency-dependent limits given in the national standards. Here the band selectivity, which is needed to differ between broadcast and mobile phone signals, is as necessary as a fine selectivity, to distinguish the channels of the mobile phone providers. Finally, also a high sensitivity of the measurement system is necessary in order to measure field strength values correctly which are often far below the limits. For the practical application the knowledge of the measurement uncertainty of the applied measurement system is necessary.

II. MEASUREMENT PROCEDURE

Three different measurement techniques are applied for the measurement of radio frequency electromagnetic fields of broadcast and mobile phone stations. The simplest procedure uses field probes where the simple handling and the good isotropy is an advantage. The low sensitivity and the missing frequency selectivity are disadvantages.
The application of a directional antenna and a spectrum analyser is an alternative procedure. The problem of the missing isotropy because of the radiation pattern of the antenna is obvious. A manual search of the maximum field strength for each emitter and each frequency is necessary for a correct measurement. This procedure is extremely time intensive when performed carefully.
The Field Nose system combines the advantages of both above mentioned procedures. It fulfils the requirements regarding isotropy, frequency selectivity, sensitivity, and time efficiency, see Table I.

Table I - Evaluation of the measurement procedure

	Field probe	*Antenna*	*Field Nose*
isotropic	✓	-	✓
frequency-selective	-	✓	✓
sensitive	-	✓	✓
time efficient	✓	-	✓

The Field Nose system measurement procedure is called Add3D. This method is based on the addition of three separately measured orthogonal E-field components. The principle of three orthogonal measurements was already applied by Tofani [1] in order to measure the field strength of broadcast and TV stations. With a field probe the E-field components are measured at the same time by the use of three orthogonal short dipoles. Whereas the dipoles in the field probe have a very high resistance in order to avoid the mutual influence, the measurement dipole used for Add3D has a low impedance (50 Ohm system), thus achieving a higher sensitivity in comparison to field probes.
The field strength E [dB µV/m] results from the three voltage measurements U [µV] with orthogonal orientation of antennas and application of the antenna factor AF [dB/m] according to the Equation 1.

$$E = AF + 20 \cdot \log\left(\sqrt{U_x^2 + U_y^2 + U_z^2}\right) \qquad (1)$$

The direction of the incident field vector is in general unknown. The radiation pattern of the Hertzian dipole shows a sinusoidal behavior in the E-plane according to Equation 2.

$$f_x = \sin\varphi$$
$$f_y = \sin(\varphi + 90°) = \cos\varphi \qquad (2)$$

For the explanation of the method we look at a special case where the H-vector of the electromagnetic field is oriented in z-direction.

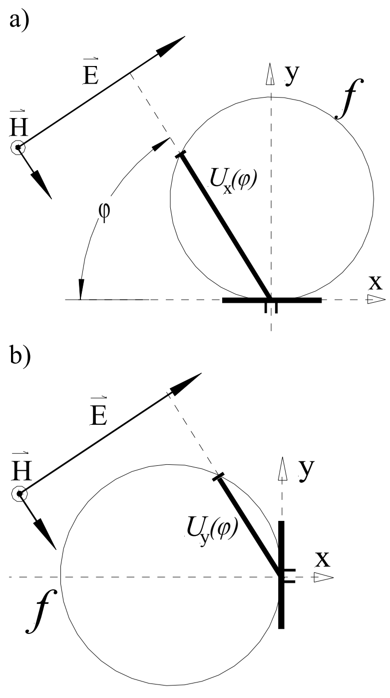

Fig.1 - Measurement of the field strength components $U_x(\varphi)$ in a) and $U_y(\varphi)$ in b).

In Fig. 1 you can see the measurement of both voltages $U_x(\varphi)$ and $U_y(\varphi)$. As a first step the dipole is positioned parallel to the x axis and the voltage $U_x(\varphi)$ is measured. Then the dipole is turned 90° (parallel to y axis) and $U_y(\varphi)$ is measured. Finally the components are summarized. Equation 3 shows how one can derivate a field strength proportional voltage U which is not anymore dependent on the incident angle of the wave. This principle will only work perfectly if the radiation pattern of the antenna comes up to the one of a Hertzian dipole.

The description of the radiation pattern in the three-dimensional case takes place in the spherical coordinate system according to Fig. 2. Here the radiation pattern of the antenna is described as polarization dependent with $f_\upsilon(\upsilon,\varphi)$ and $f_\varphi(\upsilon,\varphi)$. An additional index describes the orientation of the dipole in the Cartesian coordinate system (x,y,z). So e.g. $f_{\upsilon,x}(\upsilon,\varphi)$ is for the orientation of the dipole in x direction. The radiation pattern of the vector addition of the three separate measurements in spherical coordinates is demonstrated in Equation 4. Generally, all radiation patterns are linear and normalized to the maximum value of 1.

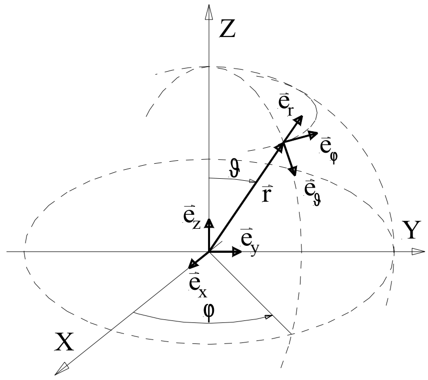

Fig.2 - Spherical coordinates

$$f_\vartheta(\vartheta,\varphi) = \sqrt{f_{\vartheta,x}(\vartheta,\varphi)^2 + f_{\vartheta,y}(\vartheta,\varphi)^2 + f_{\vartheta,z}(\vartheta,\varphi)^2} \le 1$$
$$f_\varphi(\vartheta,\varphi) = \sqrt{f_{\varphi,x}(\vartheta,\varphi)^2 + f_{\varphi,y}(\vartheta,\varphi)^2 + f_{\varphi,z}(\vartheta,\varphi)^2} \le 1 \qquad (4)$$

Perfect isotropy is achieved by the Hertzian dipole:

$$f_{\vartheta,ideal}(\vartheta,\varphi) = f_{\varphi,ideal}(\vartheta,\varphi) = 1 \qquad (5)$$

III. FREQUENCY-SELECTIVE ANALYSIS OF THE FIELD NOSE SYSTEM

The Hertzian dipole was used for the explanation of the Add3D method. For the measurement uncertainty analysis of the measurement procedure a real antenna is used. We use a conical dipole antenna PCD 8250 from ARC Seibersdorf research for the frequency range from 80 MHz to 2.5 GHz. For this frequency range also a measurement uncertainty calculation is performed according to the GUM [2]. Therefore it is necessary to have a closer look at the uncertainty contributions.

III.1 Isotropy

The radiation pattern of the measurement antenna was simulated with Numerical Electromagnetic Code. (NEC). By applying the calculated radiation pattern of the measurement antenna the radiation patterns of the

$$U(\varphi) = \sqrt{U_x^2(\varphi) + U_y^2(\varphi)} = \sqrt{\frac{E^2 \cdot f_x^2}{AF^2} + \frac{E^2 \cdot f_y^2}{AF^2}} = \frac{E}{AF}\sqrt{\sin^2\varphi + \cos^2\varphi} = U \qquad (3)$$

addition of the three single components are calculated for the selected frequencies. The results are shown in Fig. 3 a) to f). At a frequency of 80 MHz no deviation of the spherical shape is recognizable, at 900 MHz it is recognizable, and at 2.5 GHz it is clearly seen in both polarizations.
The relative measurement error F is expressed as difference between measurement value and true value, referred to the true value. By taking Equation 5 into consideration we can say

$$F(\vartheta,\varphi) = \frac{f(\vartheta,\varphi) - f_{Ideal}(\vartheta,\varphi)}{f_{Ideal}(\vartheta,\varphi)} = f(\vartheta,\varphi) - 1 \quad (6)$$

Applying the realistic view that the incident angle and the polarization of the E-field are totally random you can receive the possible measurement uncertainty ISO(AFAntenna) by averaging the squares of the error over the sphere (Equation 7).

$$ISO(AF_{Antenna}) = 20 \cdot \log\left(\sqrt{\frac{\iint F(\vartheta,\varphi)^2 d\vartheta d\varphi}{4\pi}}\right) \quad (7)$$

From the Equations 4 and 6, it is recognizable that the measurement error can never be positive. It consequently shows an unsymmetrical interval (systematic error). The measurement uncertainty can be reduced by introducing a correction factor. It is called Isotropy Factor IF and is equal to the average of the radiation pattern over the sphere.

$$IF = 20 \cdot \log\left(\frac{\iint f(\vartheta,\varphi) d\vartheta d\varphi}{4\pi}\right) \quad (8)$$

In this case the reduced isotropy uncertainty, which is used for the calculation of the measurement uncertainty, can be quoted according to Equation 9.

$$ISO(AF_{Add3D}) = 20 \cdot \log\left(\sqrt{\frac{\iint (f(\vartheta,\varphi) - IF)^2 d\vartheta d\varphi}{4\pi}}\right) \quad (9)$$

Please remind that $f(\upsilon,\varphi)$ is the simulated pattern, and the integrals can not be solved analytically.

III.2 Impact of standing waves

As a consequence of the mismatch between antenna and receiver there are standing waves on the measurement cable which influence the result. The uncertainty is calculated according to EA-02/04 from the two reflection factors according to Equation 12.

$$MIS = 20 \cdot \log\left(1 + \frac{2|\Gamma_1||\Gamma_2|}{\sqrt{2}}\right) \quad (10)$$

III.3 Sensitivity to non-orthogonality

An error occurs if the angles between the measurement axes are not exactly 90°. The error can be estimated by using Equation 4, 6 and 7. We examined the influence to the isotropy when using a Hertzian dipole, which results to 0.06 dB/°.

III.4 Temperature coefficient

The temperature coefficient of the cable and the antenna is measured by using a network analyzer and a temperature controlled chamber. The measured influence of the temperature is very low only 0.7 dB/100°and 0.6 dB/100°.

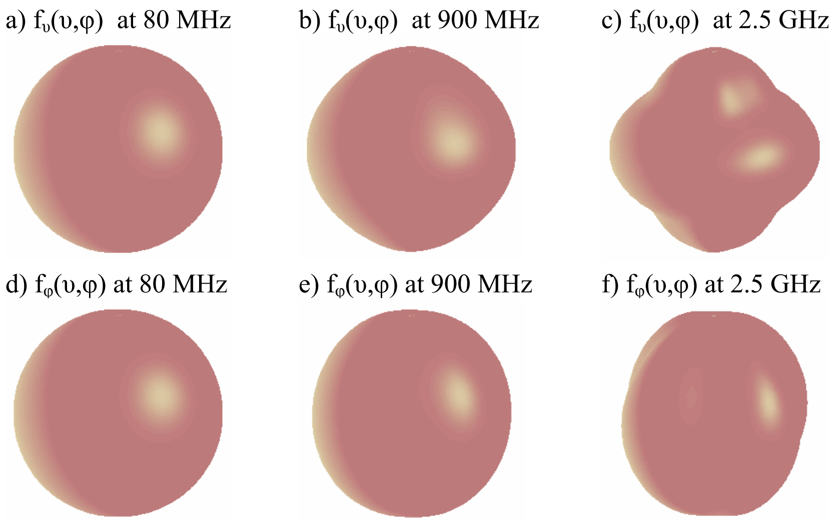

Fig.3 - Isotropy of the Add3D procedure using simulated radiation patterns of the PCD 8250 antenna

III.3 Estimation of the expanded uncertainty of measurement

When calculating the measurement uncertainty according to the GUM a model function is required which contains all significant contributions.

$$E = AF + IF + ISO + 20 \cdot \log\left(\sqrt{U_X^2 + U_Y^2 + U_Z^2}\right) + MIS + CL + ORTHO \cdot \Delta A + (TCC + TCA) \cdot \Delta T \quad (11)$$

This function describes the behavior of the system and allows one to calculate how sensitive the system reacts on each contribution [2]. Table II lists the contributions and its estimates.
After building the model function the sensitivity coefficients are determined through derivation. Now the uncertainty budget can be calculated for each frequency of interest, for 900 MHz see Table III. It is assumed that the three orthogonal voltages are approximately equal, which leads to a sensitivity factor of 0.58. If one of the voltages is much smaller than the other two its sensitivity factor decreases and the sensitivity factor of the other two voltages increases. The overall measurement uncertainty is not depended from the ratio of the three components.

Table III - Uncertainty budget for 900 MHz

Quant. Xi	*Stand. Uncert. (xi)*	*Prob. Distr.*	*Sens. Coeff. ci*	*Uncert. Contr. ui(y)*
AF	0.5 dB	normal	1	0.5 dB
ISO	0.16 dB	normal	1	0.16 dB
Ux	0.5 dB	normal	0.58	0.29 dB
Uy	0.5 dB	normal	0.58	0.29 dB
Uz	0.5 dB	normal	0.58	0.29 dB
MIS	0.4 dB	U-shap	1	0.4 dB
CL	0.2 dB	rectang.	1	0.2 dB
ΔA	2 °	rectang.	0.06	0.12 dB
ΔT	40 °C	rectang.	0.013	0.52 dB
U			(k=1)	1 dB

Table IV - Expanded measurement uncertainty of the Field Nose system

f [MHz]	*80*	*450*	*900*	*1800*	*2500*
U [dB]	2.9	2.5	2	2.2	2.3

The expanded uncertainty (k=2, 95% coverage probability) of the Field Nose system for some frequencies of interest is calculated, see Table IV. The measurement uncertainty in the electric field strength measurement by using the Add3D method with a PCD8250 antenna and a typical measurement receiver is around 2.5 dB and below.

IV. CONCLUSION

A rigorous calculation of measurement uncertainty for the frequency-selective field-strength measurement systems Field Nose system is presented. Numerical simulations and measurements had been performed to gather input estimations for the calculation. The contributions from antenna patterns, antenna factor calibration, test receiver calibration, temperature coefficients, standing waves and cable losses are considered. An expanded uncertainty (k=2; 95 %) between 2.9 dB (80 MHz) and 2.3 dB (2.5 GHz) is found. In the future we will refine our calculation by replacing calculated pattern data by measured pattern data.

REFERENCES

[1] S. Tofani, P. Ossola: "Accuracy in Outdoor Isotropic Measurements of Multiple-Source, Multiple-Frequency EM Fields", IEEE Transaction on EMC, Vol. 34, No. 3, August 1992

[2] EA-02/04: "Expression of the Uncertainty of Measurement in Calibration", EA European co-operation for Accreditation, Dec. 1999

[3] A. Kriz, W. Müllner: "Calculation of the Measurement Uncertainty for the Field Strength Measurement System Field Nose" 2004 International Symposium on Electromagnetic Compatibility, Sendai, June 2004

Table II - Measurement uncertainty contributions

Symbol	*Unit*	*Explanation*	*Source*	*Estimates*
AF	dB/m	Antenna factor calibration of main lobe	Calibration sheet	1 dB (k=2)
IF	dB	Isotropicity factor	Simulation	Chapter III.1
ISO	dB	Residual non-isotropicity after correction	Simulation	Chapter III.1
Ux, Uy, Uz	µV	Voltage measurement with test receiver	Calibration sheet	1 dB (k=2)
MIS	dB	Mismatch between antenna and test receiver	Measurement	Chapter III.2
CL	dB	Cable loss calibration	User calibration	0.4 dB (k=2)
ORTHO	dB/°	Sensitivity to non-orthogonality	Simulation	Chapter III.3
ΔA	°	Angle error due to tripod	Measurement	±2°
TCC	dB/°C	Temperature coefficient cable	Measurement	Chapter III.4
TCA	dB/°C	Temperature coefficient antenna	Measurement	Chapter III.4
ΔT	°C	Change of temperature	Datasheet	0°C to 40°C