CALCULATION OF THE MEASUREMENT UNCERTAINTY FOR THE FIELD STRENGTH MEASUREMENT SYSTEM FIELD NOSE[1]

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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 high-precision measurements. 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 %) of 2.5 dB (2.5 GHz) is found at the worst case frequency.

Key words: measurement uncertainty, frequency selective, omni-directional, isotropy, field strength

1. Introduction

In this paper, we show a rigorous analysis of the measurement uncertainties involved in monitoring RF fields using the innovative Field Nose measurement system recently developed by Seibersdorf research. The analysis is based on precise measurements. The calculation of the overall uncertainty is done according to the "Guide to the Expression of uncertainty in Measurement (GUM) [1] and related documents [2][3].

2. The Field Nose System

Field Nose is an automatic, isotropic, frequency-selective measurement system for electrical equivalent field strength in the frequency range from 80 MHz to 2.5 GHz. It is intended primarily for autonomous monitoring of the fields generated by mobile communications base stations. Field Nose is based on the "Add3D" method [4] developed by Seibersdorf research. This method uses three mutually orthogonal, electrically short broadband dipoles. In contrast to classical field probes that detect just the field-strength integrated over all frequencies, Add3D uses a spectrum analyser to detect the voltages at each dipole in a frequency-selective way.

The equivalent field strength E [dBμV/m] results from the three voltage measurement sweeps U [μV] with orthogonal orientation of antennas and application of the antenna factor AF [dB/m] according to Equation 1 [5].

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

A spherical coordinate system is used to describe the polarization dependent radiation pattern $f_\varphi(\vartheta,\varphi)$ and $f_\vartheta(\vartheta,\varphi)$ of the measurement procedure. An additional index denotes the orientation of the dipole in the Cartesian coordinate system (x, y, z). The radiation pattern of the vector addition of the three separate measurements in spherical coordinates is demonstrated in Equation 2.

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

For the Hertzian dipole perfect isotropy results.

$$f_{\vartheta,ideal}(\vartheta,\varphi) = f_{\varphi,ideal}(\vartheta,\varphi) = 1 \qquad (3)$$

3. Uncertainty Calculation

When calculating the measurement uncertainty according to the GUM a model function is required. This function describes the behaviour of the system and allows one to calculate how sensitive the system reacts on each contribution. For the Field Nose system the model function is given in Equation 4, the parameters are described in Table 1.

$$\begin{aligned} E &= AF + IF + ISO + 20 \cdot \log\left(\sqrt{U_X^2 + U_Y^2 + U_Z^2}\right) \\ &+ MIS + CL + \sqrt{6} \cdot ORTHO \cdot \Delta\varphi + (TCC + TCA) \cdot \Delta T \end{aligned} \qquad (4)$$

3.1 Antenna Factor Calibration

The antenna has to be calibrated under free-space conditions. When the calibration is performed by an accredited calibration laboratory the typical uncertainty in the antenna factor is 1 dB (k=2; 95 %).

3.2 Isotropy of the Field Nose system

The isotropy is determined by measurements of the 3D pattern of the Seibersdorf PCD 8250 by using a two axis antenna-positioner and an error analyses which is based on statistical methods.

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[1] Field Nose is a registered trademark of ARC Seibersdorf research GmbH

Symbol	Unit	Explanation	Source	Chapter
E	dB µV/m	Equivalent electric field strength	Result	
AF	dB/m	Antenna factor calibration of main lobe	Calibration sheet	3.1
IF	dB	Isotropy factor	Computer simulation	3.2
ISO	dB	Residual non-isotropy after correction	Computer simulation	3.2
U_x, U_y, U_z	µV	Voltage measurement with test receiver	Calibration sheet	3.6
MIS	dB	Mismatch between antenna and test receiver	Measurement	3.5
CL	dB	Cable loss calibration	User calibration	3.4
ORTHO	dB/°	Sensitivity to non-orthogonality	Computer simulation	3.3
$\Delta\varphi$	°	Angle error due to tripod	Measurement	3.3
TCC	dB/°	Temperature coefficient cable	Measurement	3.7
TCA	dB/°	Temperature coefficient antenna	Measurement	3.7
ΔT	°C	Change of temperature	Datasheet	3.7

Table 1: Measurement uncertainty contributions

3.2.1 Error Analysis

The relative measurement error F is expressed as difference between measurement value and true value, referred to the true value. By taking Equation 3 into consideration we can say

$$F(\vartheta,\varphi)=\frac{f(\vartheta,\varphi)-f_{Ideal}(\vartheta,\varphi)}{f_{Ideal}(\vartheta,\varphi)}=f(\vartheta,\varphi)-1 \qquad (5)$$

Applying the realistic view that the incident angle and the polarisation of the E-field are totally random you can receive the possible measurement uncertainty ISO($AF_{Antenna}$) by averaging the squares of the error over the sphere (Equation 6).

From the Equations 2 and 5, graphically displayed in Figure 4a, it is recognisable that the measurement error can never be positive.

$$ISO(AF_{Antenna})=20\cdot\log\left(\sqrt{\frac{\iint F(\vartheta,\varphi)^2\,d\vartheta d\varphi}{4\pi}}\right) \qquad (6)$$

It consequently shows an unsymmetrical interval (systematic error). The measurement uncertainty can be reduced by introducing a correction factor, see Figure 4b. It is called Isotropy Factor IF and is equal to the average of the radiation pattern over the sphere.

$$IF=20\cdot\log\left(\frac{\iint f(\vartheta,\varphi)\,d\vartheta d\varphi}{4\pi}\right) \qquad (7)$$

The Isotropy Factor can be included in the antenna factor of the Add3D procedure as in Equation 8.

$$AF_{Add3D}=AF_{Antenna}+IF \qquad (8)$$

From Equation 1 and 8 you can derive Equation 9, which is essential for the Field Nose system.

$$E=AF_{Add3D}+20\cdot\log\left(\sqrt{U_x^2+U_y^2+U_z^2}\right) \qquad (9)$$

In this case the reduced isotropy uncertainty can be quoted according to Equation 10.

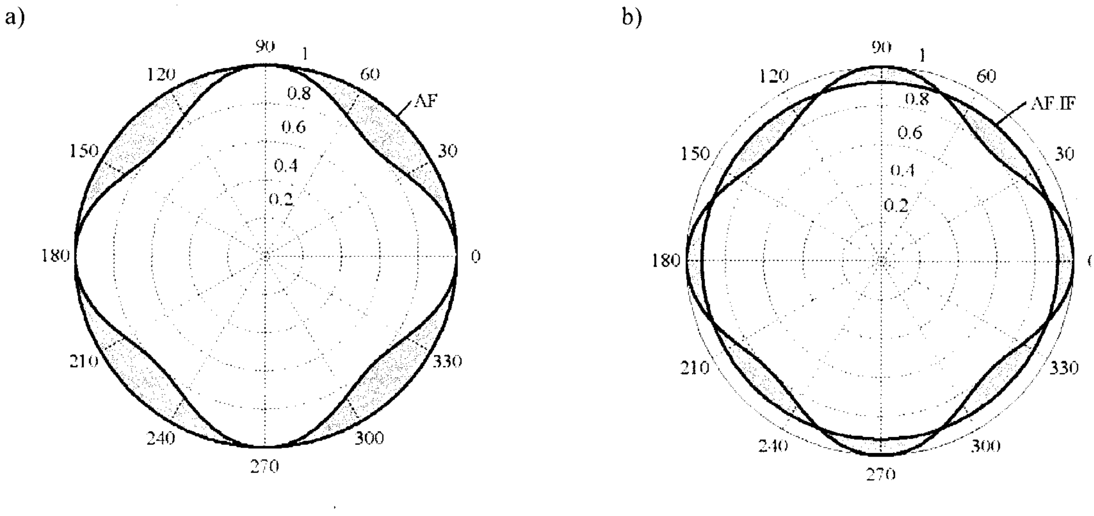
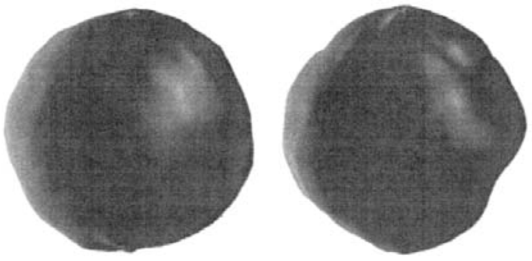


Figure 4: Radiation pattern at 2.5 GHz; the grey areas indicate the measurement error caused by non-isotropy a) without Isotropy Factor: error interval [+0...-0.2] b) Isotropy Factor applied: error interval [-0.1...+0.1]

$$ISO(AF_{Add3D}) = 20 \cdot \log\left(\sqrt{\frac{\iint (f(\vartheta,\varphi) - IF)^2 d\vartheta d\varphi}{4\pi}}\right) \quad (10)$$

3.2.2 Measurements of the antenna pattern

The three dimensional pattern of a Seibersdorf PCD 8250 antenna is measured with a two axis antenna-positionier. This data were used to calculate the isotropy, which are shown in Figure 5. The isotropy decreases with higher frequencies, due to pattern degeneration with increasing frequency.



a) at $f_\varphi(\vartheta,\varphi)$ 900 MHz b) $f_\varphi(\vartheta,\varphi)$ at 1.8 GHz

c) at $f_\varphi(\vartheta,\varphi)$ 2.5 GHz

Figure 5: Isotropy of the Add3D procedure using measured radiation patterns of the PCD 8250 antenna

The Isotropy Factor, the uncertainty contribution ISO($AF_{Antenna}$) and the residual uncertainty contribution ISO(AF_{Add3D}) are shown in Table 2.

f [MHz]	IF [dB]	ISO ($AF_{Antenna}$) [dB]	ISO (AF_{Add3D}) [dB]
900	-0.84	0.81	0.28
1800	-1.28	1.17	0.44
2500	-2.10	1.78	0.79

Table 2: Isotropic behavior of the Field Nose system from measured data

3.3 Angle Error in orthogonal positioner

An error occurs, because the antenna is not positioned perfectly in three orthogonal directions. A three dimensional pattern has three degrees of freedom, one for rotation around each axis. So in each of the three orthogonal positions we have three angle errors Δφ. This leads to a formula with three different sensitivity coefficients, see Formula 11.

We examined the influence to the isotropy when using a Hertzian dipole. The pattern of the Hertzian dipole is toroidal and symmetrically when turning around one axis. When using this assumption following relations can be derived

$$\begin{aligned} ORTHO_Z &= 0 \\ ORTHO_X &= ORTHO_Y = ORTHO \end{aligned} \quad (12)$$

So Equation 11 is simplified to Equation 13 if statistical independence between the angle errors Δφ is valid.

$$Angle\_Error = \sqrt{6} \cdot ORTHO \cdot \Delta\varphi \quad (13)$$

The sensitivity factor ORTHO is determined by turning one of the pattern in Equation 2 by Δφ. The resulting pattern is analysed by Equation 6, which leads to 0.016 dB/°.

Due to the mechanical precision of the Field Nose rotator a maximum deviation of ± 2° can be measured. So Δφ is assumed to be 2°.

3.4 Cable Loss Calibration

It is very simple to perform a precise cable loss calibration even without vector network analyzer. If padding attenuators are used to reduce the influence of standing waves it is no problem to reach a low measurement uncertainty in a range of less then 0.4 dB (k=2; 95 %).

3.5 Standing Waves

As 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 [3] from the two reflection factors according to Equation 14.

$$MIS = 20 \cdot \log\left(1 + \frac{2|\Gamma_1||\Gamma_2|}{\sqrt{2}}\right) \quad (14)$$

f [MHz]	VSWR receiver	VSWR PCD 8250	Γ_1	Γ_2	MIS [dB]
900	1.5	1.4	0.2	0.17	0.40
1800	1.5	1.1	0.2	0.05	0.11
2500	1.5	1.4	0.2	0.17	0.40

Table 3: Uncertainty terms due to standing waves

In Table 3 the uncertainty term MIS is calculated supposing a typical receiver VSWR and the measured VSWR of the antenna.

$$Angle\_Error = \begin{aligned} &ORTHO_X \cdot \Delta\varphi_{X_X} + ORTHO_Y \cdot \Delta\varphi_{Y_X} + ORTHO_Z \cdot \Delta\varphi_{Z_X} + \\ &ORTHO_Z \cdot \Delta\varphi_{X_Y} + ORTHO_X \cdot \Delta\varphi_{Y_Y} + ORTHO_Y \cdot \Delta\varphi_{Z_Y} + \\ &ORTHO_Y \cdot \Delta\varphi_{X_Z} + ORTHO_Z \cdot \Delta\varphi_{Y_Z} + ORTHO_X \cdot \Delta\varphi_{Z_Z} \end{aligned} \quad (11)$$

3.6 Receiver Calibration

The receiver must have a valid and traceable calibration to national and international standards. The measurement uncertainties achieved reach from 1 dB (k=2; 95%) for high performance desktop devices to 3 dB (k=2; 95%) for cost efficient handheld devices.

3.7 Temperature Influences

For outdoor measurements we assume a temperature range from 0 °C up to 40 °C. We have determined the temperature coefficients of the receive cable and the PCD 8250 antenna. For that purpose we placed the cable and the antenna in a climate controlled chamber and recorded the change of the loss. The temperature coefficients are shown in Table 4.

f [MHz]	TC Cable Loss [dB/100°C]	TC Balun Loss [dB/100°C]
900	0.30	0.34
1800	0.47	0.47
2500	0.60	0.72

Table 4: Temperature coefficients (TC)

The impact of temperature change to the test receiver depends strongly on the used type. The examination of this influence should be included to the calibration sheet.

3.8 Total Combined Uncertainty

After building the model function the sensitivity coefficients are determined through derivation. Now the frequency dependent uncertainty budget can be calculated, see Table 6 for 1800 MHz. 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.

The expanded uncertainty (k=2, 95% coverage probability) for field strength measurements with the Field Nose system is calculated for some frequencies of interest in Table 5. The measurement uncertainty is 2.55 dB and below.

f [MHz]	**900**	**1800**	**2500**
U [dB]	1.84	1.90	2.55

Table 5: Expanded measurement uncertainty of the Field Nose system

4. Conclusions

In this paper we present a comprehensive uncertainty analysis of the frequency selective field strength measurement system Field Nose in the frequency range from 80 MHz to 2.5 GHz. The determination of the isotropic behaviour by measurements is an important part of the uncertainty calculation. The estimated expanded uncertainty of maximum 2.55 dB makes the system perfectly suited for traceable EMF measurement and monitoring applications. The calculation of the uncertainty is transparent for the user so it is possible to estimate the impact if one of the components is changed.

References

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Quantity X_i	**Standard uncertainty $u(x_i)$**	**Probability distribution**	**Sensitivity coefficient c_i**	**Uncertainty Contribution $u_i(y)$**
AF	0.5 dB	normal	1	0.5 dB
ISO	0.44 dB	normal	1	0.44 dB
Ux	0.5 dB	normal	0.58	0.5 dB
U_y	0.5 dB	normal	0.58	0.5 dB
U_z	0.5 dB	normal	0.58	0.5 dB
MIS	0.11 dB	U-shaped	1	0.11 dB
CL	0.2 dB	rectangular	1	0.2 dB
$\Delta\varphi$	2°	rectangular	0.06 dB/°	0.12 dB
ΔT	40°C	rectangular	0.0095 dB/°C	0.5 dB
U			**(k=1)**	**0.95 dB**

Table 6: Uncertainty budget for 1800 MHz