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Alternative Approach Leading to Reduction in Measurement Instrument Uncertainty of EMI Measurement

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Abstract: Even in the field of electromagnetic compatibility, low measurement uncertainty means high measurement quality. Although there are standardized procedures for obtaining the uncertainty of such a measurement, which facilitate uncertainty estimation, modern approaches show further reduction possibilities. The paper presents an alternative approach to reducing measurement instrument uncertainty in the case of electromagnetic interference measurement based on many years of our experience and a large number of measurements in this field. In the paper, two different methods of uncertainty reduction are described. The first method is based on a detailed analysis of the sources of uncertainty and the subsequent division of the analyzed frequency band into more subranges. Another method uses the choice of the antenna factor, which also contains information about the test site where the measurement is carried out. In this way, despite a lengthy analysis, it is relatively easy to achieve a measurement instrument uncertainty that is below the maximum measurement uncertainty given by the CISPR standard.

Keywords: EMI measurement, measurement instrument uncertainty, electromagnetic compatibility, hybrid antenna, reduction of uncertainty.

1. INTRODUCTION

The key element for correct measurements in the field of electromagnetic compatibility (EMC) today is the control not only of the measurement results, but also of the measurement uncertainty. Test engineers should be equally experienced to understand such complex measurements as electromagnetic interference (EMI) measurement is. The EMI levels measured by an accredited test laboratory must have measurement uncertainties below a certain level to be acceptable. EMC measurements typically have large uncertainties of at least several decibels, so it is not surprising that current international EMC standards define the level of measurement instrumentation uncertainty (MIU), which should be considered when determining compliance or non-compliance with a standard limit, as ±6.3 dB [1]. This level is valid for disturbances from 30 MHz to 1 GHz in open-area test sites and semi-anechoic chambers, based on the previous research. However, a large uncertainty can lead to over-design and additional expense of a product to achieve EMC or to under-design and failure of EMC requirements [2], [3]. As a result, it is important to have a good understanding of the EMI measurement principles and their uncertainties to minimise the MIU as much as possible.

Currently, there are several guides on how to quantify uncertainties of EMC measurements [1], [4], [5]. All guides are based on the document Guide to the Expression of Uncertainty in Measurement [6] and the theory of probability statistics. Unlike common measurements [7], the theories and mathematical apparatus are also valid for EMC measurements when we get the results in decibels. The analysis in [8] shows that neglecting the logarithmic character of measured values when expressing uncertainty leads to a small error that can also be neglected. This is applicable only to a model with additive data when the resulting variable Y is given by the equation:

$$Y_{\mathrm{dB}} = X_{1\mathrm{dB}} + X_{2\mathrm{dB}} + \cdots + X_{m\mathrm{dB}}. \tag{1}$$

This fact is confirmed by the existence of a lognormal distribution. The lognormal distribution was developed to analyze lognormally distributed multiplicative data, see Fig. 1. The lognormal distribution has no zero or negative values. Its transform converts multiplicative data into additive data that can then be used with the normal distribution:

$$X_{\mathrm{dB}} = 8.687\ \ln X = 20\ \log_{10} X. \tag{2}$$

The importance of the lognormal distribution lies in the fact that it is correct to use logarithmic terms, in decibels, for the statistical analysis of EMC data. Therefore, the equations applied in uncertainty analysis of the EMC measurement are the same as for the common measurement.

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In recent years, the uncertainty of EMI measurements has received less attention. We find mention of the inclusion of TDEMI measuring devices in the measurement chain [9], [10], [11], the evaluation of variations due to tolerances, temperature and frequency response of the measurement system [12], or the influence of RBW on the accuracy of the measurement [13]. Discussions about the measurement result close to the specification limits can be found in [14], [15].

In this paper, we will show how we can reduce the estimate of the EMI measurement instrument uncertainty in a relatively simple way. Through a complex analysis, we can determine the frequency dependence of the individual uncertainty contributions and then use the division of the frequency band into sub bands, similar to the research in [16], [17]. Another way to reduce the uncertainty is to choose a suitable antenna factor [18]. Also, considering correlations between given parameters in the antenna factor measurement can affect the MIU value, as some EMI measurement contributions are interdependent.

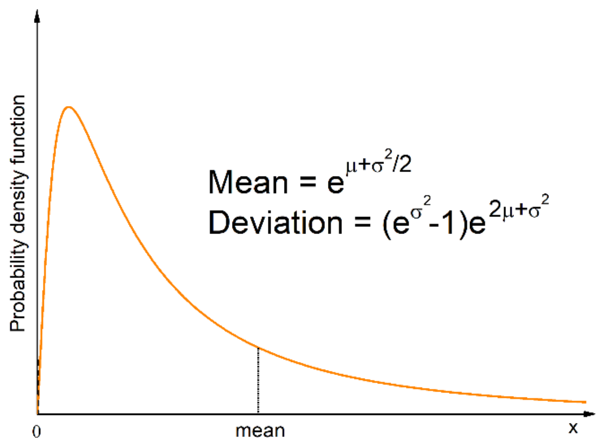


Fig. 1. Lognormal probability distribution.

2. SUBJECT & METHODS

The principle of the EMI measurement is described in the international standard [19], the measurement facility is shown in Fig. 2. The intensity of the interfering electric field E, expressed in decibels, is measured and is given by the following equation:

$$E(\mathrm{dBm}) = V_{\mathrm{r}}(\mathrm{dBm}) + F_{\mathrm{a}}(\mathrm{dB}), \tag{3}$$

where V_{r} is the voltage measured on the antenna output and F_{a} is the antenna factor of the measuring antenna.

The EMI of an equipment under test (EUT), placed on a non-conductive table 80 cm above a ground plane and arranged to represent the traditional operating conditions, is to be measured at a given distance. As is evident from Fig. 2, the measuring antenna can receive not only the direct wave incident on the antenna, but also the wave reflected from the reference ground plane - a conductive metal area plane of sufficient size placed on the ground between the EUT and the measuring antenna. Since the direction of maximum radiation from the EUT is unknown and reflections from the ground plane affect the electromagnetic field distribution, the EUT shall be rotated in azimuth and the antenna height shall be varied within the range of 1 to 4 m above the ground plane. Furthermore, the measurements must be performed with both horizontal and vertical polarisation of the measuring antenna. EMI should be scanned in a given frequency range (usually from 30 to 1000 MHz) and must be measured with an EMI receiver.

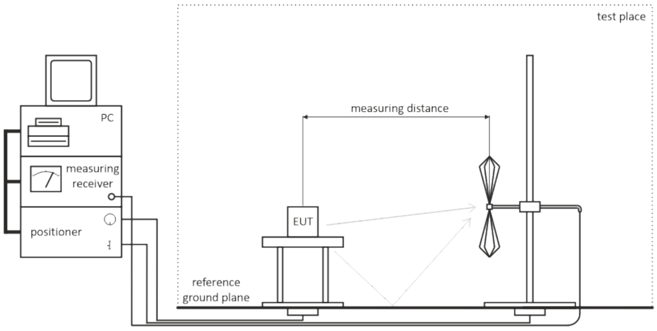


Fig. 2. Measurement facility for EMI measurement [17].

As mentioned before, the guide on how to identify and quantify the uncertainty contribution of such a measurement can be found in [1]. The sources affecting the measurement result and uncertainty can be:

- EMI receiver and its characteristics,
- properties of the measuring antenna,
- the transmission path (between antenna and EMI receiver),
- test site and its arrangement,
- impact of ambient conditions,
- EUT arrangement and operation.

The effects of these sources are not equivalent, some of them can even be neglected under certain circumstances. Due to the complexity of the measurement, it is quite difficult to determine the influence of these factors on the measurement uncertainty using a statistical analysis, a Type A evaluation. Therefore, a Type B evaluation is applied based on scientific judgement using all relevant information. If we do not have the necessary documentation, the uncertainty needs to be estimated using other information. Only the upper and lower limits of the uncertainty can be estimated, so the uncertainty calculation method is given by [7].

Table 1 shows the identified uncertainty contributions and their estimated value according to [1]. The worst case is presented: measurement in a semi-anechoic chamber, measuring distance of 3 m and using a vertically polarized hybrid antenna. Based on this identified uncertainty budget, equation (3) is extended to:

$$E = V_{\mathrm{r}} + a_c + F_{\mathrm{a}} + \delta V_{\mathrm{sw}} + \delta V_{\mathrm{pa}} + \delta V_{\mathrm{pr}} + \delta V_{\mathrm{nf}} + \delta M + \delta F_{\mathrm{af}} + \delta F_{\mathrm{ah}} + \delta F_{\mathrm{adir}} + \delta F_{\mathrm{aph}} + \delta F_{\mathrm{acp}} + \delta F_{\mathrm{abal}} + \delta A_{\mathrm{N}} + \delta d + \delta A_{\mathrm{NT}} + \delta. \tag{4}$$

The MIU shall be evaluated for this measurement taking into account each of the contributions listed in Table 1 [1].

The coverage factor $k = 2$ yields approximately a 95% level of confidence for the normal distribution, which is typical for most measurement results. However, receiver readings are expressed with a standard uncertainty given by the experimental standard deviation of the mean ($k = 1$) [4].

Table 1. Uncertainty contributions in the measurement of EMI (vertically polarised hybrid antenna at a distance of 3 m) [1].

Input quantity	Symbol	Uncertainty estimation in dB	Probability distribution function
Receiver reading	V_r	±0.1	normal; k=1
Attenuation: antenna – receiver	a_c	±0.2	normal; k=2
Hybrid antenna: antenna factor	F_a	±2.0	normal; k=2
Receiver correction: sine wave voltage	δV_{sw}	±1.0	normal; k=2
Receiver correction: pulse amplitude response	δV_{pa}	±1.5	rectangular
Receiver correction: pulse repetition rate response	δV_{pr}	±1.5	rectangular
Receiver correction: noise floor proximity	δV_{nf}	+0.5/0.0	rectangular
Mismatch: antenna – receiver	δM	+0.9/-1.0	U-shaped
Hybrid antenna correction: antenna factor frequency interpolation	δF_{af}	±0.3	rectangular
Hybrid antenna correction: antenna factor height deviation	δF_{ah}	±0.3	rectangular
Hybrid antenna correction: directivity difference	δF_{adir}	±3.2	rectangular
Hybrid antenna correction: phase centre location	δF_{aph}	±0.3	rectangular
Hybrid antenna correction: cross-polarisation	δF_{acp}	±0.9	rectangular
Hybrid antenna correction: balance	δF_{abal}	±1.0	rectangular
Site correction: site imperfections	δA_N	±4.0	triangular
Site correction: separation distance	δd	±0.3	rectangular
Site correction: table material and setup	δA_{NT}	±0.5	rectangular
Site correction: table height	δh	±0.1	normal; k=2
Expanded uncertainty		*±6.3*	

While all sensitivity coefficients are uniform the combined standard uncertainty $u_c(E)$ of the measured EMI is calculated.

$$u_c(E) = \sqrt{\sum_i \frac{u_i^2}{\chi_i^2}}, \tag{5}$$

where u_i is an estimate of the uncertainty of the i-th input quantity and χ_i is a coefficient related to the given probability distribution function. The MIU of the test laboratory is then given as the expanded uncertainty for the EMI measurement.

$$U_{lab} = 2\, u_c(E). \tag{6}$$

Hence, the MIU for the EMI measurement for the mentioned setup is 6.3 dB, which is also the U_{CISPR}, the expanded uncertainty value evaluated with respect to the EMI measurement and given by [1].

3. Results

The common practise in test laboratories is to estimate the MIU according to the guide in [1], also using mostly the same values. Our approach requires a more detailed analysis of the measurement itself, which is time-consuming.

A. Analysis of uncertainty sources

Different approaches were chosen to analyse the uncertainty sources.

The discussion about the analysis of the test receiver and its uncertainties took place a long time ago [20], [21]. In addition to the sources of uncertainty listed in Table 1, other sources are considered, resolution of the reading, level measurement and its thermal stability, attenuation measurement, detector linearity measurement, frequency response measurement and its interpolation and/or gain measurement at bandwidths. However, these additional sources only have a minimal impact on the overall uncertainty of the test receiver reading and can be neglected. Then, as an estimate of the uncertainty of the reading of the receiver reading, we get a value of 1.4 dB, which is essentially frequency independent.

In case of attenuation and mismatch between the measuring antenna and the receiver, we have to start from the measured values. The attenuation of the measurement chain can be determined quite simply by a transmission measurement, where the antenna is replaced with a generator. At higher frequencies, we assume a significant increase in the measurement chain attenuation, as cable losses increase, and there is also a decrease in amplification of pre-amplifiers if used.

The most problematic part in terms of impedance mismatch is the measuring antenna, especially if a broadband antenna is used. After all, the input impedance of the broadband antenna changes significantly with frequency. Despite the different balanced/unbalanced networks used in antennas, there is a problem in achieving the desired impedance, especially with a biconical antenna and antennas derived from it, like hybrid antennas. The measurement is affected by another error δM [1]:

$$\delta M = 20.\log[(1 - \Gamma_a S_{11})(1 - \Gamma_b S_{22}) - S_{21}^2 \Gamma_a \Gamma_b], \tag{7}$$

where Γ_a and Γ_b are the reflection coefficients of the antenna and test receiver, respectively. S-parameters (S_{11}, S_{21} and S_{22}) represent the parameters of a two-port network of a transmission path between the antenna and the receiver. These values should be obtained by a vector circuit analyzer.

We know from experience that the most significant source of uncertainty in EMI measurement is the measuring antenna. Its properties, except for the measurement of the antenna factor itself, can only be analyzed using numerical simulations, and therefore it is necessary to create a suitable antenna model. In our case, this is a hybrid Bilog antenna; see Fig. 3, where the creation of the model is described in [22]. The most important parameter in terms of analysis is the antenna factor F_a:

$$F_a = E/_V. \tag{8}$$

It can be obtained in two steps. First, it is necessary to create a planar electromagnetic wave at the place where the investigated antenna should be located. The best way is to place a short dipole radiating at a sufficient distance from the point of observation [23]. In the first step, the electric field strength E is obtained at the location of the antenna. Next, the antenna is placed at the point of investigation and the voltage V at the antenna terminals is calculated. Similarly, we can quantify almost all sources of uncertainty related to the antenna factor.

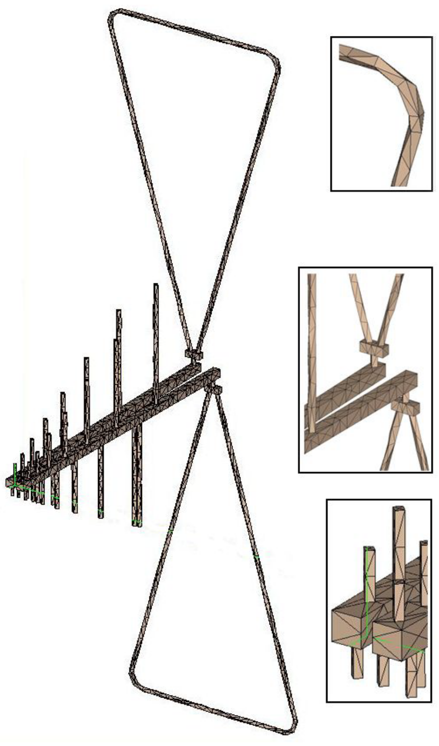


Fig. 3. Model of a hybrid Bilog antenna and its details.

If another antenna is used instead of a half-wave dipole antenna, there is an effect of a directivity error δF_{adir}. To express this error, the antenna factor of the analyzed antenna has to be determined as a function of the angles of the spherical coordinate system (Θ, Φ). This can be done by rotating the field source around the analyzed antenna so that the electromagnetic wave propagates at the required angles (Θ, Φ). The directivity error can then be expressed as:

$$\delta F_{adir} = F_a(\Theta, \Phi) - F_{adip}(\Theta, \Phi), \tag{9}$$

where F_a is the antenna factor of the analysed antenna and F_{Ad} is the antenna factor of the half-wave dipole at the same angles of incidence (Θ, Φ). The presence of a perfectly conductive ground plane near the antenna changes the input impedance, but at the same time affects the directional characteristics of the antenna. Although this influence is negligible at low frequencies, at higher frequencies there is a significant deformation of the main lobe of the antenna's radiation pattern, see Fig. 4 [24].

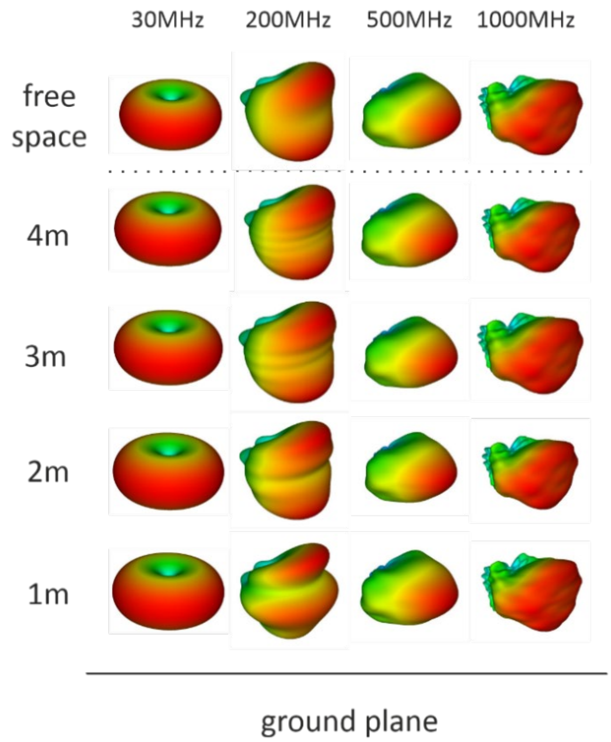


Fig. 4. Influence of the ground plane on the directional characteristics of the Bilog antenna for a vertical polarization.

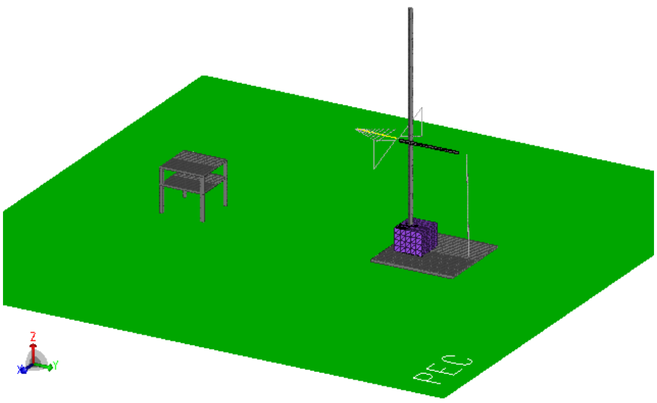


Fig. 5. Model of the test site with auxiliary equipment for EMI measurement.

The test site where the measurements are carried out must meet the ±4 dB criterion [19]. It means that the test site is suitable for EMI measurement if the measured normalised site attenuation (NSA) is within a tolerance of ±4 dB to the theoretical values of the NSA at both antenna polarisations.

Site imperfections are mostly caused by unwanted reflections from auxiliary objects located at the test site. If possible, quantification of these sources of uncertainty can be done by measurements (influence of absorbers and imperfections of the reference ground plane) or by numerical simulations (equipment of a test site such as a non-conductive table, antenna mast, etc.). The numerical analysis shows that objects with the same polarization as the measuring antenna have a noticeable impact on the measurement, see Fig. 5 and Fig. 6.

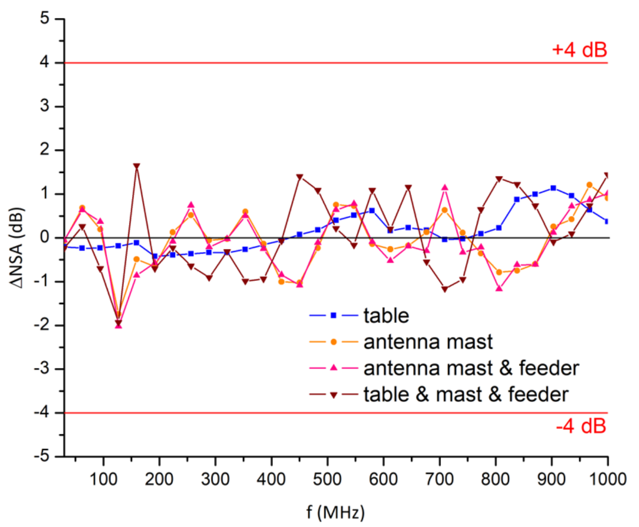


Fig. 6. Error due to imperfections of the test site due to the presence of auxiliary equipment for vertical polarisation of antennas.

Table 2 shows the worst-case analysis of the MIU for the EMI measurement based on the analysis of uncertainty sources for the measurement in a semi-anechoic chamber and using the equipment from the FEI STU EMC laboratory. According to the guide [1], the expanded uncertainty U_{lab} value of the EMI measurement is 7.2 dB for vertically polarized and 6.4 dB for horizontally polarized antennas (MIU for a horizontally polarized EMI measurement is given as 5.2 dB). Although the extended uncertainty is higher than U_{CISPR}, we would have to increase the measured values by (U_{lab}-U_{CISPR}).

B. *Frequency dependent sources*

Many of the uncertainty sources mentioned in the previous chapter are strongly frequency-dependent. For example, the directivity difference of the measuring antenna has its dominant values above 200 MHz, see Fig. 7; while the mismatch error derived from the measurement at the receiving antenna and other parts of the measurement chain has its largest values just at lower frequencies, see Fig. 8. Evident frequency dependence of the uncertainty sources can also be seen in case of antenna factor height deviation or cross-polarization, and all these effects also influence the determination of the antenna factor. Then, it is recommended to divide the frequency range from 30 MHz to 1 GHz into more subranges, and to recalculate the uncertainty only for these subranges to decrease the uncertainty values.

The effect of considering the frequency dependence results in an evident reduction of the extended uncertainty of the EMI measurement, see Fig. 10 (orange line). In the case of a vertically polarised antenna, U_{lab} is equal to 5.9 dB; in the case of a horizontally polarised antenna, it is only 4.7 dB, which is already sufficiently below the U_{CISPR} level.

Table 2. Uncertainty contributions at EMI measurement (vertically polarized hybrid antenna at a distance of 3 m) in analyzed test site.

Input quantity	Symbol	Uncertainty estimation in dB	Probability distribution function
Receiver reading	V_r	±0.1	normal; k=1
Attenuation: antenna – receiver	a_c	±0.2	normal; k=2
Hybrid antenna: antenna factor	F_a	±2.0	normal; k=2
Receiver correction: sine wave voltage	δV_{sw}	±1.0	normal; k=2
Receiver correction: pulse amplitude response	δV_{pa}	±1.5	rectangular
Receiver correction: pulse repetition rate response	δV_{pr}	±1.5	rectangular
Receiver correction: noise floor proximity	δV_{nf}	+0.5/0.0	rectangular
Mismatch: antenna – receiver	δM	+1.4/-1.8	U-shaped
Hybrid antenna correction: antenna factor frequency interpolation	δF_{af}	±0.3	rectangular
Hybrid antenna correction: antenna factor height deviation	δF_{ah}	+0.6/-0.8	rectangular
Hybrid antenna correction: directivity difference	δF_{adir}	+3.0/-6.2	rectangular
Hybrid antenna correction: phase centre location	δF_{aph}	±0.3	rectangular
Hybrid antenna correction: cross-polarisation	δF_{acp}	±0.4	rectangular
Hybrid antenna correction: balance	δF_{abal}	±1.0	rectangular
Site correction: site imperfections	δA_N	±2.4	triangular
Site correction: separation distance	δd	±0.2	rectangular
Site correction: table material and setup	δA_{NT}	±1.0	rectangular
Site correction: table height	δh	±0.1	normal; k=2
Expanded uncertainty		*±7.2*	

C. Choosing the antenna factor

The standard recommendation in the EMC community is to use a free-space antenna factor for electromagnetic interference measurements. The free-space antenna factor represents single values at each frequency, independent of antenna height, polarization and distance to the EUT. In practice, all measured antenna factors are affected by some adjacent objects, especially when the standard site method [25] is used for antenna calibration.

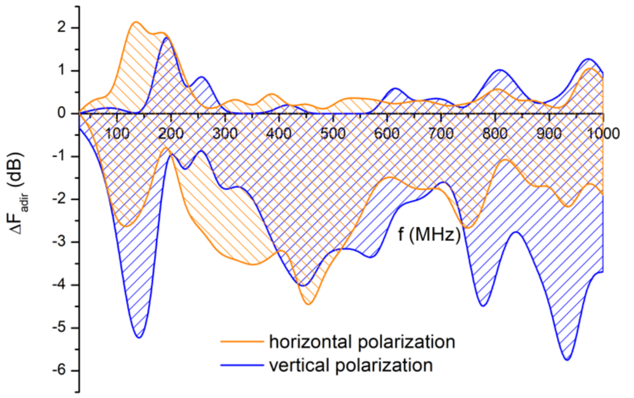


Fig. 7. Frequency dependence of antenna factor variation versus height over ground plane for a hybrid Bilog antenna.

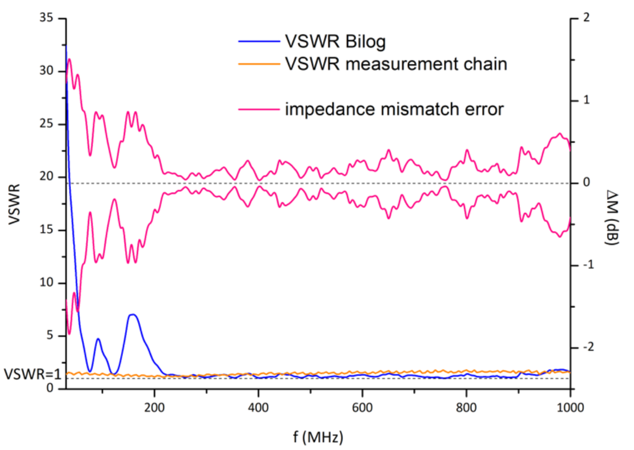


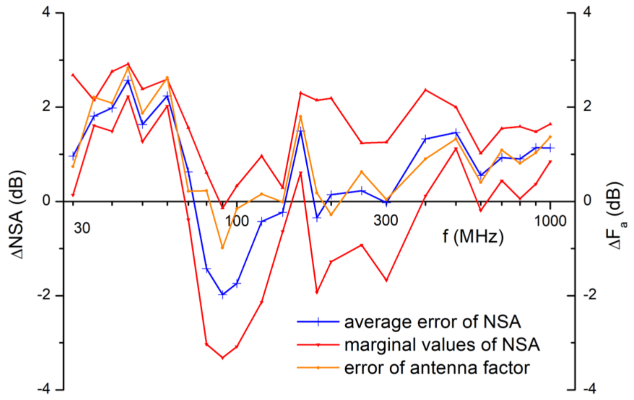
Fig. 8. Frequency dependence of the maximum error of the impedance mismatch between a hybrid Bilog antenna and a receiver.

In [18] it was shown that the measurement of the antenna factor F_{asite} performed at the same test site as the EMI measurement with the standard site method is evidently affected by the environment and thus also by the imperfections of the test site, as evidenced by the high correlation value between the measured values of NSA and consequently the antenna factor, see Fig. 9. At the same time, this measurement shows the imperfect properties of hybrid antennas. All these sources of potential uncertainties are then already included in the uncertainty of the antenna factor measurement.

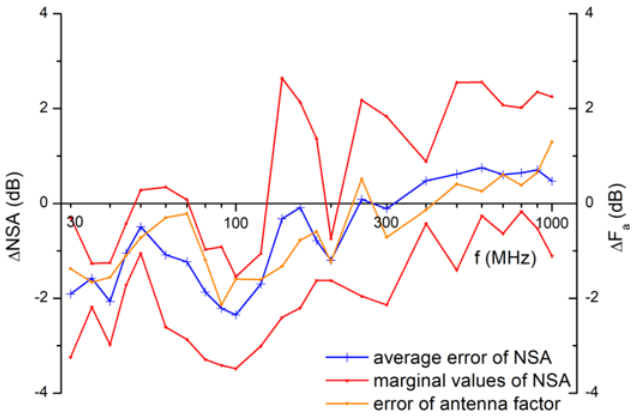
On the other hand, the uncertainty of the measurement of the antenna factor can be minimised [16]. By using a pair of dipole antennas with known parameters in combination with the measured antenna and additionally taking into account possible covariances; since it is a trio of almost identical measurements; we can reduce the measurement model:

$$E = V_r + a_c + F_{asite} + \delta V_{sw} + \delta V_{pa} + \delta V_{pr} + \delta V_{nf} + \delta M + \delta F_{af} + \delta F_{acp} + \delta F_{abal} + \delta d + \delta A_{NT} + \delta h, \quad (10)$$

and subsequently also an estimate of the uncertainty of the EMI measurement. In this way, we achieve further reduction of the MIU EMI measurement, see Fig. 10. The MIU can be reduced to the value of 3.8 dB for measurements of both polarizations.



(a)



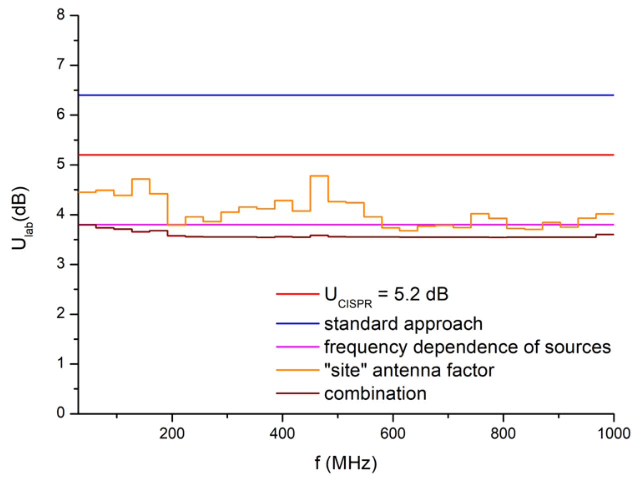
(b)

Fig. 9. Similarity in the deviation values of the NSA and the deviation values of the Bilog antenna factor measured in the EMC laboratory for (a) horizontal and (b) vertical polarization.

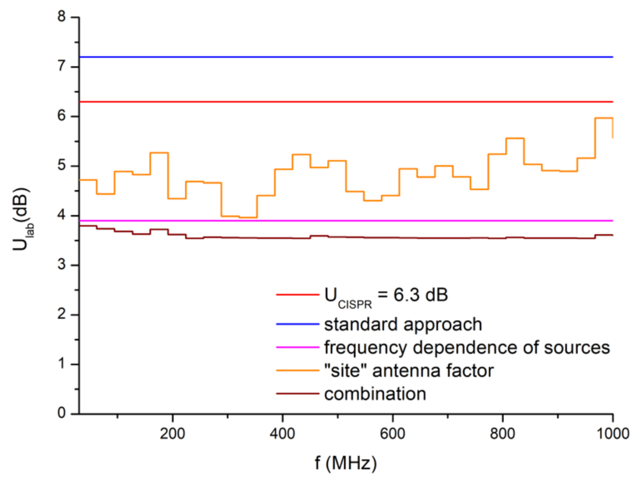
4. CONCLUSION

In this paper, an alternative method for estimating the MIU or the extended uncertainty of the EMI measurement is described, following the procedures of the standardised guides. Common MIU determination procedures do not usually lead to a reduction in uncertainty. A reduction of the measurement uncertainty can be achieved by replacing the broadband hybrid antenna with a simpler dipole antenna, which is, however, narrowband and therefore extends the measurement. Or it is necessary to use a test site with a measurement distance of 10 m instead of 3 m, which in turn makes the investment in the measurement more expensive.

The two main approaches proposed achieved MIU reduction while being completely independent and can be used separately. First, the frequency dependence of the individual uncertainty contributions was taken into account, and then the uncertainty calculation for specific subranges was applied. The second option is internal calibration, determining the antenna factor and measuring antenna at the test site. The antenna factors obtained in this way contain information about the imperfections of the site, the influence of the reference ground plane and the auxiliary equipment used, especially the measuring antenna. Thanks to these two steps, the entire uncertainty was reduced from 7.2 dB to max. 3.8 dB (violet/pink line). However, such a reduction requires detailed knowledge of the measurement and its equipment and also prolongs the time of the uncertainty estimation.



(a)



(b)

Fig. 10. Estimated uncertainty of the EMI measurement for (a) horizontal and (b) vertical polarisation of antennas.

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