Calculation of Antenna Pattern Influence on Radiated Emission Measurement Uncertainty

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Abstract—**In radiated emission measurements an error is introduced by the directive receive antenna. The Monte Carlo Method was used to calculate this error where measured antenna pattern had been taken into account. Although there are large differences between the classical test set-up and the two improvements antenna tilting and antenna bore sighting the impact to the measurement uncertainty is low. For a test distance of 3 m the measurement uncertainty can be reduced from 5.62 dB to 5.43 dB with antenna tilting. With a bore sight antenna tower a reduction to 5.31 dB is feasible. The bias and uncertainty given by CISPR 16-4-2 are not adequate.**

Antenna radiation pattern, Electric field measurement, Error analysis, Monte Carlo methods

I. Introduction

The calculation of the measurement uncertainty is an important part of each EMC compliance test method. In the past years a CISPR ad-hoc group evaluated uncertainty estimations for the most important EMC emission measurement methods. Since 2002 a good basis for uncertainty budgets is available in CISPR 16-4-2 [1]. These budgets are intended as information for the user of the standard and should help to calculate their own estimation.

In CISPR 16-4-2 the method presented in the Guide to the Expression of Uncertainty in Measurement (GUM) [2] was used. All of the uncertainty contributions are so called Type B contributions which are based on experience, reference data, manufacturer specification, previous measurement data and data provided in calibration certificates. One of the uncertainty contributions for the radiated emission test is called directivity difference. The reason for this contribution can be explained by the definition of the measurand and the definition of the antenna factor.

The measurand for radiated emission testing is defined by the maximum electric field strength between 1 m and 4 m height at a certain distance d on an Open Area Test Site.

$$E = V \cdot AF \tag{1}$$

The electric field is converted to a voltage by the measuring antenna. This voltage is measured with a RF receiver.

The antenna factor of antennas is valid for the main beam direction if directive broadband antennas are used. If the antenna is scanned in height the incident angle of the electrical field is not always the main beam direction. So the field strength is modified by the radiation pattern

$$E = V \cdot AF \cdot P(\varphi) \tag{2}$$

Since the pattern or the angle of incidence is unknown a correction of the field strength is not feasible or at least impractical. So an uncertainty contribution is introduced if a directive receive antenna is used.

The sign of the directivity error, defined as difference between measured electric field and electric field, is always negative due to the relation

$$P(\varphi) \leq 1 \tag{3}$$

The only possibility to reduce the error caused by the directivity is to tilt the receive antenna toward the ground [3][4]. There are two methods possible to implement this: (1) antenna tiling where the tilting angle is the same for all antenna heights. (2) antenna bore sighting where the tilting angle is increased with the antenna height.

II. CISPR 16-4-2

In CISPR 16-4-2 the directivity error is called directivity difference. The reason for this name is a requirement for broadband measuring antennas, called complex antennas, in CISPR 16-1-4 [5]. It reads: "The main lobe of the radiation pattern of the antenna shall be such that the response in the direction of the direct ray and that in the direction of the ray reflected from the ground do not differ by more than 1 dB."

An antenna which meets this requirement is used to estimate the directivity error. This estimation is shown in Tab. I. In the frequency range from 30 MHz to 200 MHz the error is 0 dB for horizontal polarization. This is based on the assumption the H-plane pattern is perfect circular. For the upper frequency range and for vertical polarization the error is -1.0/0.0 dB. This means the error is between these two numbers with the same probability.

Advanced readers of CISPR 16-4-2 will recognize the different sign of the values of Tab. 1 and the standard. This is because the standard shows the required correction, which has the inverse sign of the error.

TABLE I. DIRECTIVITY DIFFERENCE ERROR OF CISPR 16-4-2 (30 M VALUES OMITTED)

Frequency	3 m		10 m	
	Hor.	***Ver.***	***Hor.***	***Ver.***
30 MHz – 200 MHz	0.0 dB	-1.0/0.0 dB	0.0 dB	-1.0/0.0 dB
200 MHz – 1 GHz	-1.0/0.0 dB	-1.0/0.0 dB	-1.0/0.0 dB	-1.0/0.0 dB

III. CALCULATION OF INFLUENCE

The propagation of electric waves on Open Area Test Sites is described well in the literature [6]. The electric field of an omni directional source is

$$\underline{E} = \sqrt{\frac{\eta_0 P}{4\pi d^2}} e^{-j\frac{2\pi}{\lambda}d} \tag{4}$$

With the help of Fig. 1 the path length and incident angles are calculated by

$$d_1 = \sqrt{R^2 + (h_1 - h_2)^2} \tag{5}$$

$$d_2 = \sqrt{R^2 + (h_1 + h_2)^2} \tag{6}$$

$$\varphi_1 = \arctan\left(\frac{h_2 - h_1}{R}\right) \tag{7}$$

$$\varphi_2 = \arctan\left(\frac{h_2 + h_1}{R}\right) \tag{8}$$

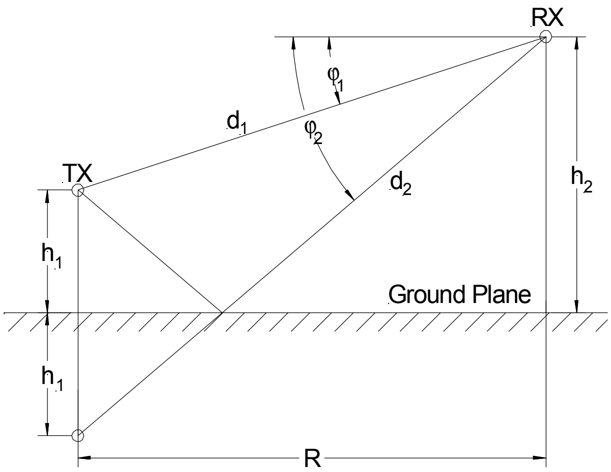

Figure 1. Geometry for wave propagation on Open Area Test Site

Then the electric field is calculated by

$$\underline{E} = \sqrt{\frac{\eta_0 P}{4\pi d_1^2}} e^{-j\frac{2\pi}{\lambda}d_1} + \sqrt{\frac{\eta_0 P}{4\pi d_2^2}} e^{-j\frac{2\pi}{\lambda}d_2} e^{j\varphi_R} \tag{9}$$

Where $\varphi_R=0$ for vertical polarization and $\varphi_R=\pi$ for horizontal polarization.

If a directive antenna is used Formula 9 is modified in the following way

$$\underline{E}_{Dir} = P(\varphi_1)\sqrt{\frac{\eta_0 P}{4\pi d_1^2}} e^{-j\frac{2\pi}{\lambda}d_1} + P(\varphi_2)\sqrt{\frac{\eta_0 P}{4\pi d_2^2}} e^{-j\frac{2\pi}{\lambda}d_2} e^{j\varphi_R} \tag{10}$$

The error due to the directive receive antenna, in dB, is

$$\Delta E = 20\log\left(\frac{\max\left|\underline{E}_{Dir}\right|\Big|_{1m\le h_2\le 4m}}{\max\left|\underline{E}\right|\Big|_{1m\le h_2\le 4m}}\right) \tag{11}$$

For an EUT the source of radiation is generally not known. It must be somewhere within the EUT. To account for this a random variable with an uniform distribution is introduced

$$h_{RX}(h_1)\ldots\{0.1m \le h_1 \le 2m\} \tag{12}$$

This means the source of radiation is somewhere between the palette (0.1 m) and the maximum EUT height (2 m) with equal probability.

If Formula 11 is applied to h_{RX} a nonlinear transformation is performed

$$h_{RX} \xrightarrow{\Delta E} E_{Pattern} \tag{13}$$

that leads to a random variable $E_{Pattern}$. $E_{Pattern}$ is the probability density function (PDF) of the error. An example for this nonlinear transformation is shown in Fig. 2.

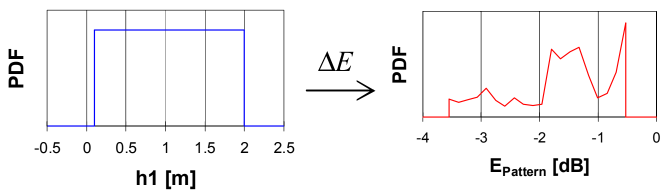

Figure 2. Example nonlinear transformation

As measures for the random variable $E_{Pattern}$ the mean and the standard deviation are used. The mean is the bias which has to be corrected. The standard deviation is used in the uncertainty calculation.

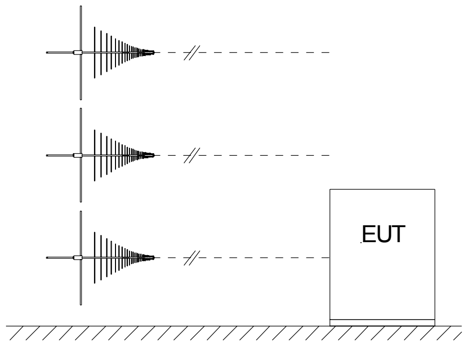

Figure 3. Emission test set-up, antenna parallel to ground plane

Another nonlinear transformation can be performed which gives the PDF of the receive height. This can be useful when analyzing the incident angles towards the receive antenna.

A. Standard mounting

In the classical test set-up used by the majority of the test houses for emission measurements according to CISPR 16-2-3 [7] and ANSI C63.4 [8] the main beam direction of the receive antenna is parallel to the ground plane, see Fig. 3.

B. Antenna tilting

One possible way for reduction of the directivity error is to tilt the receive antenna towards the ground plane, see Fig. 4. The tilting angle φ is constant over the receive antenna height and is calculated by

$$\varphi = \frac{\arctan\left(\frac{h_2 + h_1}{R}\right) + \arctan\left(\frac{h_2 - h_1}{R}\right)}{2} \quad (14)$$

This means the main beam direction of the receive antenna is placed in the middle between the direct and the reflected ray. CISPR 16-1-4 suggests this approach to meet its 1 dB pattern requirement. The transmit height h_1 as well as the receive height h_2 are required. Since both heights are random variables an optimum tilting angle can not be found. To solve this issue average values are assumed

$$\begin{aligned} h_1 &= 1m \\ h_2 &= 2.5m \end{aligned} \quad (15)$$

which lead to

$$\begin{aligned} \varphi_{3m} &= 38° \\ \varphi_{10m} &= 13.9° \end{aligned} \quad (16)$$

These angles are used for both polarizations and in the whole frequency range from 30 MHz to 1 GHz. Using different tilting angles is not practical, since the EMC test has to be stopped several times for changing the angle.

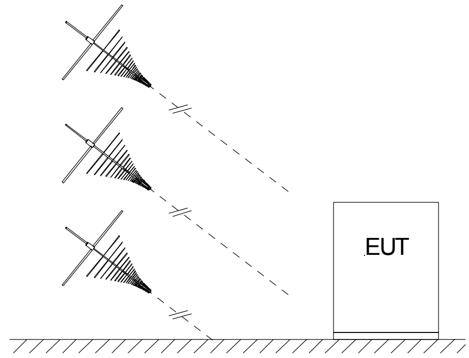

Figure 4. Emission test set-up, antenna tilting

The modification of a commercial available antenna mast can be done which a special designed bracket. Care has to be taken that the automatic polarization changer of the mast is deactivated. When changing the polarization the antenna has to be turned inside the mounting bracket.

C. Antenna bore sighting

Another method for the reduction of the directivity error is antenna bore sighting. The tilting angle of the receive antenna is increased with the antenna height, see Fig. 5. A special antenna mast is required to implement this technique, see ETS [9] and Sunol [10].

The mast controller tilts the antenna during height scanning to

$$\varphi = \arctan\left(\frac{h_2 - h_1}{R}\right) \quad (17)$$

If we keep the assumption of an average transmit height of

$$h_1 = 1m \quad (18)$$

the range of the angles are

$$\begin{aligned} 0° \le \varphi_{3m} \le 45° \\ 0° \le \varphi_{10m} \le 16.7° \end{aligned} \quad (19)$$

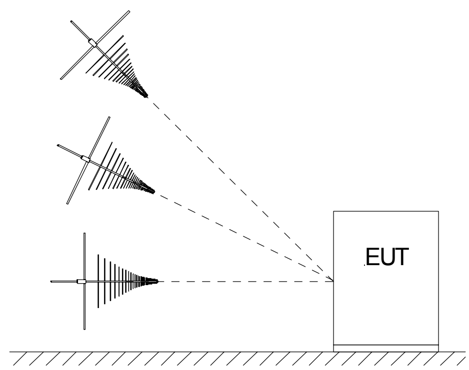

Figure 5. Emission test set-up, antenna tilting

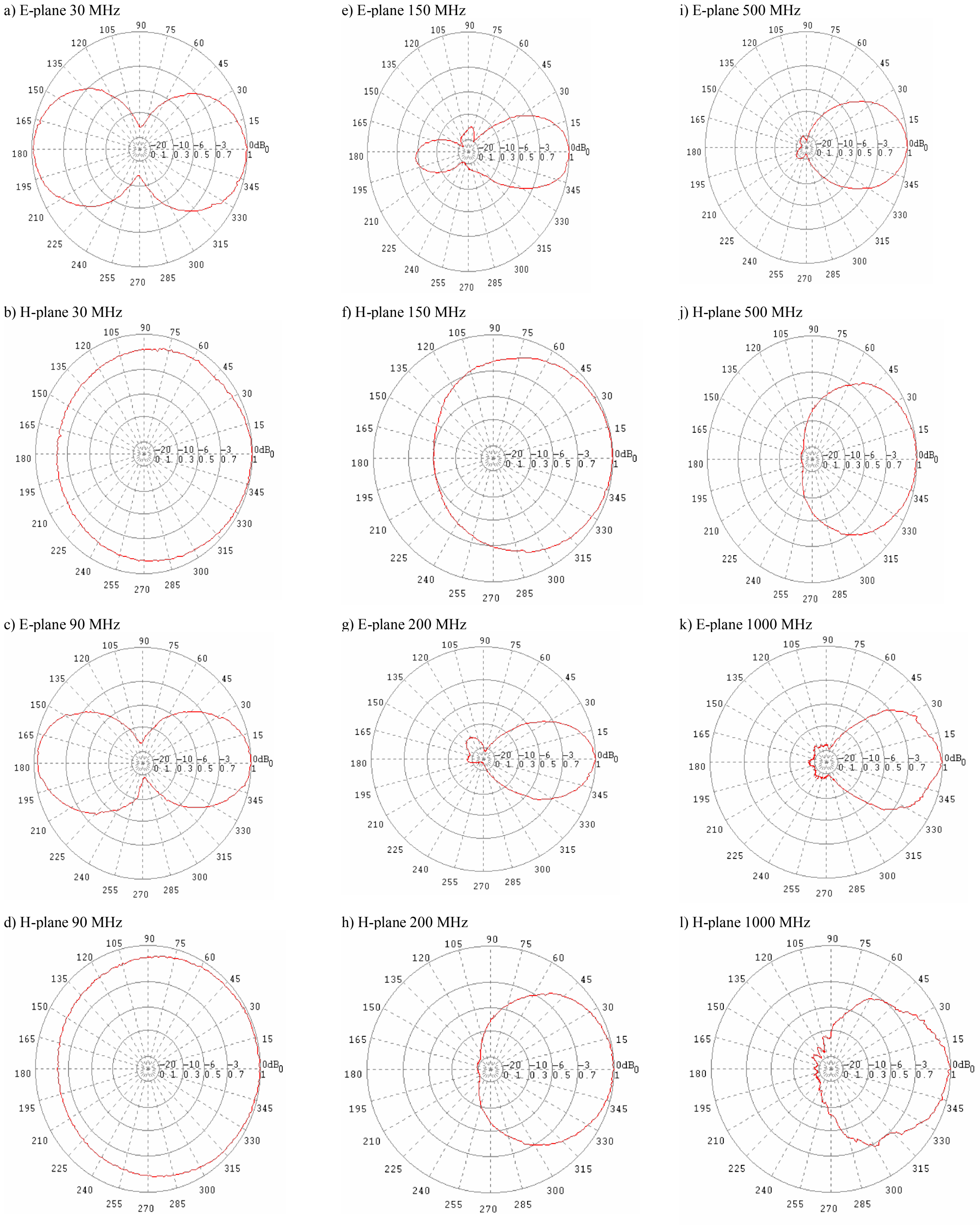

Figure 6. Radiation Pattern of Schwarzbeck VULB 9160

IV. ANTENNA PATTERN

All the simulations in this paper are performed with a VULB 9160 from Schwarzbeck [11]. The radiation pattern from 30 MHz to 1 GHz can be seen in Fig. 6. Below 150 MHz the E-plane pattern is nearly ideal. Above this frequency the antenna becomes directive and exceeds a gain of 7 dBi above 200 MHz. It can be seen clearly that the H-plane pattern below 150 MHz is not perfect circular.

This broadband receive antenna is typical for EMC emission measurements. The construction is similar to other popular antennas like ETS Lindgren 3142C, Schaffner BiLog CBL 6111C or Sunol JB Series.

V. RESULTS

The PDF of the error $E_{Pattern}$ is calculated using the Monte Carlo Method. This numerical method can be used in uncertainty calculation and is described in a supplement of the GUM [12].

A. *Statistical measure of $E_{Pattern}$*

Fig. 7 shows the mean and the standard deviation that are calculated from the PDF of $E_{Pattern}$. As expected the error is smaller for a test distance of 10 m. The reason for this is the smaller angles of incidence at this distance. Further a reduction of the error is seen when tilting or bore sighting is used.

For a test distance of 3 m the bias can be up to -2.7 dB. This is much larger than the bias suggested by CISPR 16-1-4 of -0.5 dB. Also the standard deviation of 1.1 dB exceeds the value 0.29 dB given by the standard. It is important to mention that the given uncertainty is valid after the correction of the bias.

Interesting is that the largest error does not occur at the frequency with the narrowest beam width. This fact can be explained with the probability distribution of the receive height. At a frequency of 1 GHz the receive antenna is placed between 1 m and 1.5 m where the angles φ_1 and φ_2 are small with a probability of 88%. At 200 MHz the maximum field strength is found above 1.5 m with a probability of 57%. Large errors can only occur if the two angles are large.

B. *Impact on measurement uncertainty*

When comparing the results of chapter V.A. it is very important to keep the combined standard uncertainty in mind. In the combined standard uncertainty all uncertainty contributions of the measurement are united. Fig. 8 shows the dependency on the antenna pattern error. Reduction of the antenna error, by using tilting or bore sighting, will have a strong impact if the gradient of the curve is high. Since the calculated standard deviations are below 1.2 dB the pattern error has a low impact. It is not a contribution which dominates the measurement uncertainty.

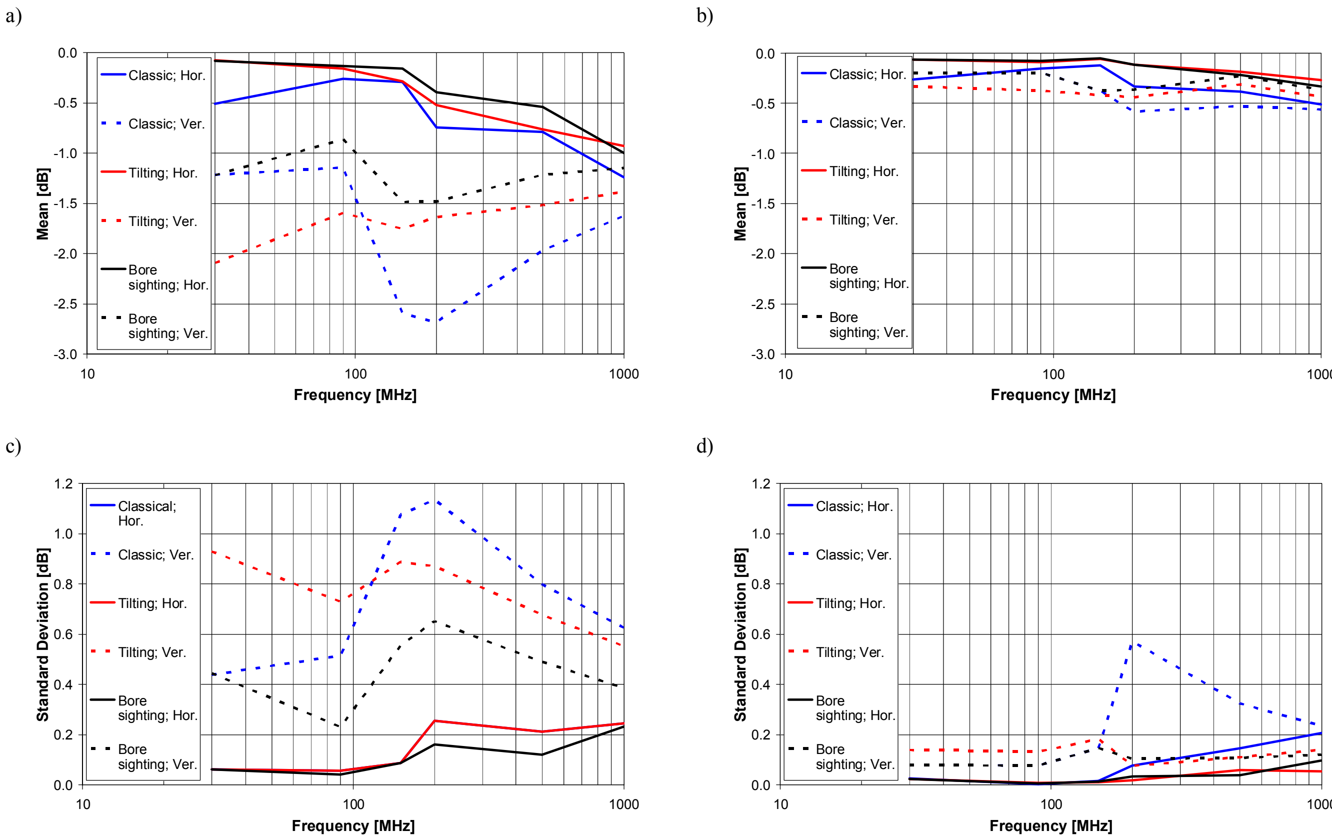

Figure 7. Statistical measure of $E_{Pattern}$ a) Mean 3 m b) Mean 10 m c) Standard Deviation 3 m d) Standard Deviation 10 m

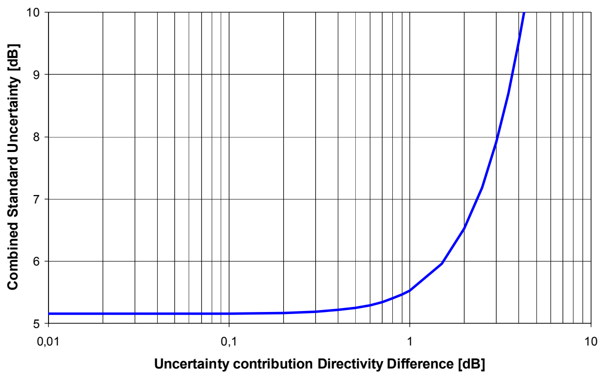

Figure 8. Impact of the antenna directivity contribution to the combined standard uncertainty.

The calculated combined standard uncertainty is shown in Tab. II. For a test distance of 10 m the error is in the same range for all three methods. The improvement from 5.14 dB to 5.02 dB is not significant. The differences are larger for a test distance of 3 m. The measurement uncertainty of 5.62 dB can be reduced to 5.43 dB with tilting and to 5.31 dB with bore sighting.

TABLE II. DIRECTIVITY ERROR FOR ANTENNA BORE SIGHTING

Method	**Pol.**	**R [m]**	**Probability 1 dB criterion [%]**	**Combined standard uncertainty [dB]**	
				30 MHz – 200 MHz	***200 MHz – 1 GHz***
Classic	Hor.	3	15	4.95	5.18
		10	100	4.94	5.04
	Ver.	3	2	5.46	5.62
		10	81	5.02	5.14
Tilting	Hor.	3	100	4.97	5.23
		10	100	4.94	5.02
	Ver.	3	78	5.36	5.43
		10	83	5.02	5.02
Bore sight	Hor.	3	24	4.95	5.17
		10	100	4.94	5.03
	Ver.	3	12	5.14	5.31
		10	86	5.02	5.02

C. Probability of compliance with 1 dB criterion

With the formulas given in chapter 3 it is possible to calculate the probability distribution function of the receive height as well. This information can be used to calculate the incident angles φ1 and φ2. Using

$$C_{1dB} = \left| 20\log\left(\frac{P(\varphi_1)}{P(\varphi_2)}\right)\right| \qquad (20)$$

the PDF for the 1 dB criterion is calculated. Tab. II. shows also the lowest probability that the 1 dB requirement is met. Especially in the classical test set-up in vertical polarization the probability that the requirement is met is only 2%. With none of the presented methods it is possibly to comply with the limit in vertical polarization. Since the measurement uncertainty is acceptable and the antenna pattern is typical the criterion is questionable.

VI. CONCLUSION

With antenna tilting and antenna bore sighting the directivity error can be reduced. It was shown that improvement of the measurement uncertainty is minimal. Only 0.31 dB can be gained at a test distance of 3 m using a bore sight antenna tower. It must be analyzed if the improvement by a fraction of a decibel in the combined standard uncertainty justifies the investment of such a mast. These masts consist of more dielectric material so the coupling with the measuring antenna may be higher and must be taken into consideration.

The Monte Carlo Method is very effective to solve this problem. It is the only technique to take measured data into consideration.

Further work will be the calculation of the uncertainty contribution for different EUT sizes. With the size of the EUT the incident angles to the receive antenna will change significantly. So the results will be different for floor standing and table top EUTs.

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