Examination of the SVSWR methods using the Monte Carlo Method

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***Abstract*— Site Voltage Standing Wave Ratio (SVSWR) based EMC test site validation methods for the frequency range 1 to 18 GHz are analyzed with the Monte Carlo method. Simulations with a simple ray tracing simulation model are performed with certain assumptions for chamber size and absorber return loss. Since none of the methods define a measurand a proposal is given which can be applied to several measurement methods. This creates a possibility to compare the different methods but leads to negative systematic errors. The magnitude of the systematic error depends on the site validation method itself. The higher the number of measurement points of a method the lower is the systematic error. Another outcome of the Monte Carlo simulation is the repeatability for each method. It can be shown that the repeatability is improved by the application of a post processing filter as proposed by the Time Domain SVSWR method. A second approach to improve the repeatability is a large number of measurement points.**

Keywords—EMC, SVSWR, site validation, monte carlo method

I. Introduction

More than 15 years ago SVSWR was introduced in CISPR 16-1-4 [1] as a site validation method for EMC chambers in the frequency range 1 to 18 GHz. Those days the responsible working group decided to use only equipment that is already available in an EMC laboratory. A new omnidirectional transmit antenna, was developed for this purpose. So, the method was designed without the need of an automatic antenna positioning system and a vector network analyzer (VNA). Typically, both pieces of equipment are used for convenience and to reduce the required time to perform a site validation.

In the subsequent years several authors published detailed analysis of the method. Some [2][3] concluded that SVSWR is an effective method to validate anechoic chambers for the purpose of EMC measurements. Others [4][5] report that SVSWR underestimates the chamber performance and is not suitable for chamber validation.

A new method in [6] is called Time Domain SVSWR (TD VSWR), which is based on time domain gating of the frequency response instead of searching for a standing wave by movement of an antenna. The proposal was taken over by the American National Standard C63.25.1 [7].

Another method based on Spherical Wave Expansion [8] was published in 2019. A subsequent improvement [9] uses the term mode filtering, so the described method is called mode filtering SVSWR (MF SVSWR).

None of the methods has a definition of the measurand. As consequence the calculation of the systematic error of each measurement method is impossible [10]. For none of the methods an uncertainty calculation is presented. Attempts for correlation between SVSWR and TD SVSWR exists [7] but are based on real measurements and not on a theoretical basis.

An indispensable tool in analyzing complicated models is the Monte Carlo (MC) method [11]. In case of site validation, it can serve two purposes. It is useful to estimate the repeatability of measurement methods caused by positioning errors. This is done by small variation of the antenna positions and observing the impact on the measurement result. Additionally, it can be used to analyze the site validation result of different methods in a theoretical environment. In this paper such analyzes had been performed for the SVSWR method and its successors.

II. Simulation Model

A simple but very effective simulation model had been presented by [2]. It models an anechoic chamber by the direct ray E_D between transmit and receive antenna and the reflected rays coming from the ground E_G, the ceiling E_C, the right wall E_R, the left wall E_L and the back wall E_B. These six rays are added at the receive antenna and will lead to the receive field strength E, see (1) and Fig. 1. Due to the high front-to-back ratio of typical receive antennas, the reflection from the wall behind the receive antenna is neglected.

$$\underline{E} = \underline{E_D} + \underline{E_G} + \underline{E_C} + \underline{E_R} + \underline{E_L} + \underline{E_B} \tag{1}$$

The magnitude and phase of each path x is calculated by the wave propagation formula of an omnidirectional source using the path length r_x and the wave number k, see (2). The absorbers are modelled by a reflection coefficient R_x which is set to 1 for the direct ray. The normalization factor E_0 is set to 1 for simplification.

$$\underline{E_x} = R_x E_0 \left(\frac{e^{-jkr_x}}{r_x}\right) \tag{2}$$

In a more realistic scenario, the antenna pattern of the transmit and the receive antenna is taken into consideration. The reflection coefficient of the absorbers depends on the frequency, the polarization, and the incident angle. Additionally, a phase shift in the reflected ray is introduced by the absorber. In this publication those antenna and absorber specific properties had not been taken into consideration. It is not the goal to simulate a real anechoic chamber. A simple model is sufficient, because the major effect, the superposition of multiple rays with certain phase relationship is implemented. A calculation of the transmit antenna pattern influence on the SVSWR result can be found at [12].

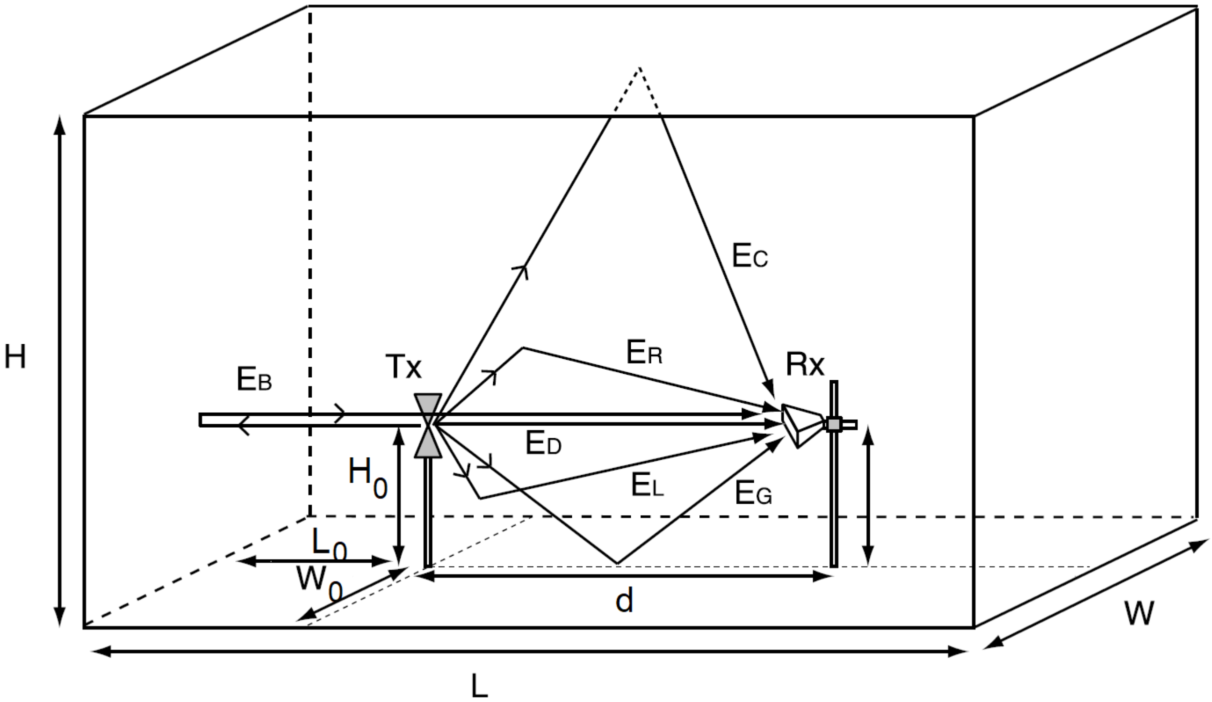


Fig. 1. Propagation path model according to [2], transmit antenna is located at the center point of the test volume

A. Vector representation

The vector sum given in (1), can be also plotted in the complex plane for each frequency, see Fig. 2. While the magnitude of each vector is almost constant, the phase can be altered by changing the term kr_x in (2). This is done either by changing the position of the transmit antenna which leads to a change in the path length r_x or by changing k by varying the frequency.

If the frequency is fixed and transmit antenna is moved away from the receive antenna, all vectors except E_B rotate counterclockwise. They rotate in the same direction but with different rotation speed because each path length is different. E_B rotates clockwise because the path length becomes smaller.

If the position of the antennas is fixed and the frequency is increased all vectors will rotate counterclockwise. The speed of rotation is different for each vector because each path length is different.

SVSWR and MF SVSWR are based on changing the position of the transmit antenna and evaluating the result for each frequency. TD SVSWR is based on a fixed position of the transmit antenna and evaluating the result for the whole frequency band.

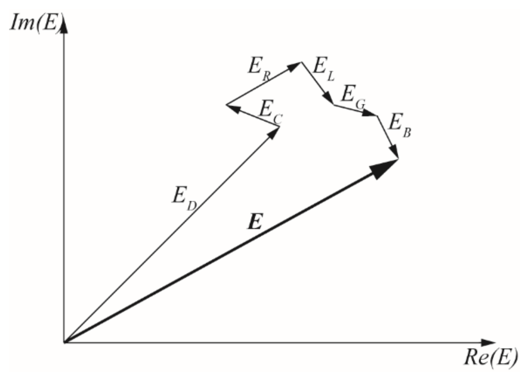


Fig. 2. Vector representation

B. Definition of measurand

None of the standardized SVSWR methods have a definition of the measurand. If the concept of searching for minima and maxima along a line is followed, the maximum SVSWR is given by (3).

$$S_{VSWR,max} = \frac{|\underline{E_D}| + \left(|\underline{E_G}| + |\underline{E_C}| + |\underline{E_R}| + |\underline{E_L}| + |\underline{E_B}|\right)}{|\underline{E_D}| - \left(|\underline{E_G}| + |\underline{E_C}| + |\underline{E_R}| + |\underline{E_L}| + |\underline{E_B}|\right)} \quad (3)$$

This occurs if all vectors in the numerator are in phase, see (4) and all reflections are in anti-phase to the direct ray in the denominator, see (5)

$$e^{-jkD} = e^{-jkr_g} = e^{-jkr_c} = e^{-jkr_r} = e^{-jkr_l} = e^{-jkr_b} \quad (4)$$

$$e^{-jkD} = e^{-jkr_g+\pi} = e^{-jkr_c+\pi} = e^{-jkr_r+\pi} = e^{-jkr_l+\pi} = e^{-jkr_b+\pi} \quad (5)$$

Since it is improbable that these conditions are fulfilled, the requisite for a statistical treatment of the problem is met.

The maximum SVSWR is defined as measurand. Reference [6] also uses this definition, but without calling it measurand. It implies that all SVSWR methods will lead to negative systematic errors.

C. Assumptions

The simulations are done for a test distance of d=3 m and a test volume diameter of 1.5 m. The size of the chamber is assumed with L=9 m, W=6.1 m and H=5 m. The center of the test volume is placed L_0=3 m in front of the back wall and W_0=3 m from the left side wall. The asymmetry is selected intentionally to avoid identical path length for the reflection from the left side and right side wall. The antenna height is H_0=1 m above floor. The reflection factor is assumed with R_X=0.1, which represents an absorber return loss of 20 dB. It is not intended to perform a simulation of a realistic chamber. The goal is to investigate the different site validation methods in a controlled environment. The simulated SVSWR values are only meaningful in comparison to each other.

III. SVSWR

The SVSWR method is described by CISPR 16-1-4 to validate anechoic chambers in the frequency range 1 to 18 GHz. The transmit antenna is placed on four 40 cm lines in the front (F), center (C), right (R) and left (L) side of the test volume, see Fig. 3. An additional line is located above the front point at the top of the test volume. Each line consists of six unequal distributed measurement points placed at 0 cm, 2 cm, 10 cm, 18 cm, 30 cm and 40 cm. The receive antenna is placed at a fixed distance *d* from the front extent of the test volume to the receive antenna reference point.

A correction of the path loss is required. The field strength *E* is multiplied by the ratio of the distance of the point d_x to the distance of the reference position d_{ref}., see (6). The reference position is the nearest point to the receive antenna.

$$\underline{E_c} = \underline{E}\frac{d_x}{d_{ref}} \tag{6}$$

The SVSWR for each line is calculated by ratio of maximum and minimum electric field of the six points, expressed in decibel, see (7)

$$S_{VSWR} = 20log\left(\frac{max\left(\left|\underline{E_{c,1}}\right|,\left|\underline{E_{c,2}}\right|,\left|\underline{E_{c,3}}\right|,\left|\underline{E_{c,4}}\right|,\left|\underline{E_{c,5}}\right|,\left|\underline{E_{c,6}}\right|\right)}{min\left(\left|\underline{E_{c,1}}\right|,\left|\underline{E_{c,2}}\right|,\left|\underline{E_{c,3}}\right|,\left|\underline{E_{c,4}}\right|,\left|\underline{E_{c,5}}\right|,\left|\underline{E_{c,6}}\right|\right)}\right) \tag{7}$$

A maximum frequency step size of 50 MHz, which is defined by the working group to compensate for the small number of measurement points, because they were aware that maxima and minima are not found at each frequency. The effect of not finding maxima and minima at each frequency is called undersampling by several authors [4][6]. Knowing this effect CISPR 16-1-4 adverts the reader not to interpret a single frequency and to look to adjacent octaves in chapter 7.10.

Reference [2] found that the 40 cm scan line is too short to find the minimum and maximum from the ground reflection at a height of 1 m. Reference [4] compares the situation in the chamber with the situation on a cable, by assuming a single reflection and concludes that only six points are not sufficient to find the peaks for each frequency. Reference [6] finds this analogy misleading since there is more than one reflection present, which leads to a much more complicated and irregular pattern.

The word undersampling implies that an error can be avoided if sufficient points are sampled. This is not the case, because the phase condition given in (4) and (5) may not be met even if a very fine position pattern is used. The situation can be compared with reverberation chambers. The maximum field strength in two probe locations is different even if very many tuner steps are used.

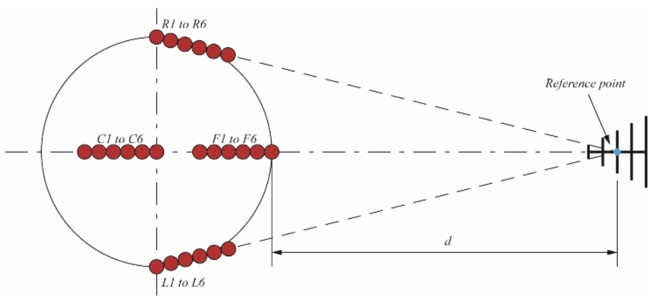


Fig. 3. SVWR test setup from CISPR 16-1-4 [1]

To estimate the systematic error and the positioning-based repeatability, the MC method with 10000 trials per frequency is applied. The position of the transmit antenna located at point F6 as well as the position of the receive antenna is varied in all three orthogonal directions. A normal distribution with a standard deviation of 1 cm is assumed for each axis. The subsequent points F5 to F1 found by application of the standardized position pattern to F6. For each frequency the probability distribution function (PDF) is calculated, while only the 2.5 %, 50 % and 97.5 % points of the resulting cumulative distribution function (CDF) are plotted together with the measurand calculated by (3), see Fig. 4a.

The median (50 %) SVSWR is more than 2.3 dB below the measurand, which shows that a systematic error occurs. 95 % of the MC samples are between the 2.5 % and 97.5 % point. Therefore, the repeatability is defined as this interval. With a value of approximately 2 dB the repeatability is large compared to the median of 2 dB. Below 4 GHz the SVSWR drops, due to the insufficient path length, as described by [2].

An approach to reduce the systematic error is to increase the points on each line. To test the effect of this idea, the number of points is increased to 41 in 1 cm steps. The result is a decreased systematic error of 1.2 dB, shown in Fig. 4b. For the repeatability only a small improvement from 2 dB to 1.8 dB can be observed.

The effect of the equal distributed points can be seen in the result. At the frequencies 11.5 GHz, 14 GHz and 16 GHz negative peaks can be seen at the 2.5 % line. These peaks will shift if the point setup is changed to another equal distributed scheme. So, an enhanced point setup is only effective if it consists of unequal distributed measurement points.

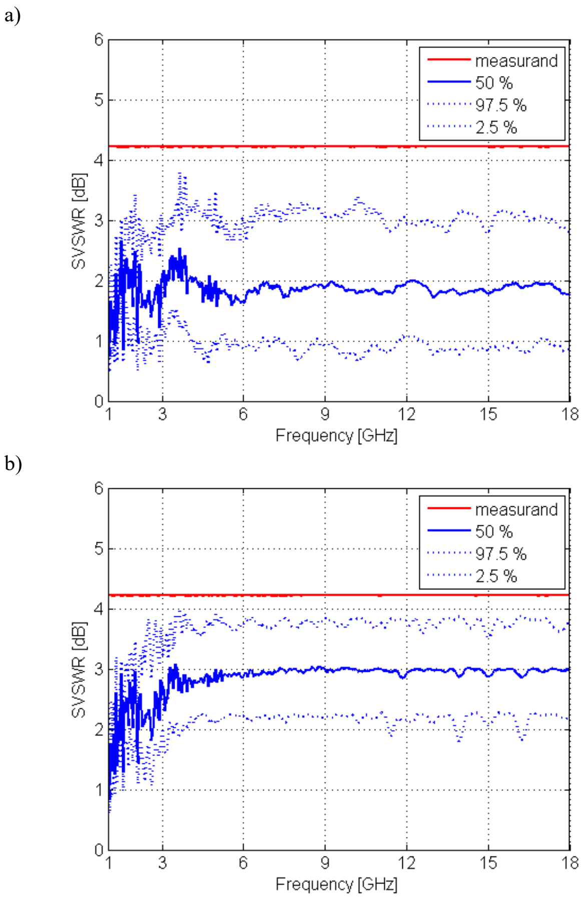


Fig. 4. SVSWR simulation result a) standard steps b) 41 steps

IV. TD SVSWR

The TD SVSWR method is described by ANSI C63.25.1 [7]. On the contrary to SVSWR the complex transfer function is determined at four points instead of four lines, see Fig. 5. A VNA with time domain capability is required. At each point a frequency sweep with a maximum frequency step size of 1.5 MHz is taken, which is transformed into time domain. In the time domain G_{in} (Gate in) is found by applying a pass filter around the direct ray. In the next step the pass filter is switched to a stop filter to cancel the direct ray. The remaining response is called G_{out} (Gate out) and corresponds to the reflections. Both responses are transformed back to the frequency domain. After this the TD SVSWR, expressed in decibel, is calculated by (8) and (9)

$$\underline{\Gamma} = \frac{\underline{G_{out}}}{\underline{G_{in}}} \tag{8}$$

$$S_{VSWR,TD} = 20log\left(\frac{1+|\underline{\Gamma}|}{1-|\underline{\Gamma}|}\right) \tag{9}$$

To be able to directly compare SVSWR to TD SVSWR results, a data post processing is applied to $S_{VSWR,TD}$. Therefore the mean value $S_{VSWR,TD,mavg}$ and the standard deviation $S_{VSWR,TD,std}$ of a moving window filter with a bandwidth of 120 MHz is used to calculate the final result $S_{VSWR,TD,PP}$, see (10).

$$S_{VSWR,TD,PP} = S_{VSWR,TD,mavg} + 0.676\ x\ S_{VSWR,TD,std} \tag{10}$$

Reference [12] found that the selection of the gating window has a significant effect on the result. Due to edge effects of the gating algorithm a wider bandwidth than 1 to 18 GHz is required for TD SVSWR [7].

To estimate the systematic error and the repeatability, the MC method is used. On the contrary to the standardized method G_{in} and G_{out} are directly calculated without applying time domain transformation or gating, see (11) and (12).

$$\underline{G_{in}} = \underline{E_D} \tag{11}$$

$$\underline{G_{out}} = \underline{E_G} + \underline{E_C} + \underline{E_R} + \underline{E_L} + \underline{E_B} \tag{12}$$

Due to the larger number of frequency points the number of MC samples has to be reduced due to computer memory shortage. With a number of 1000 trials per frequency the position of the transmit antenna (front point F) and the receive antenna is varied in all three orthogonal directions. A normal distribution with a standard deviation of 1 cm is assumed for each axis.

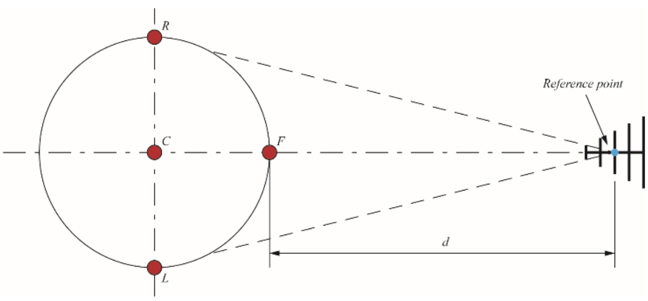


Fig. 5. TD SVWR test setup from ANSI C63.25.1 [7]

For each frequency the PDF is calculated, while only the 2.5 %, 50 % and 97.5 % points of the resulting CDF are plotted with the measurand calculated by (3), see Fig. 6.

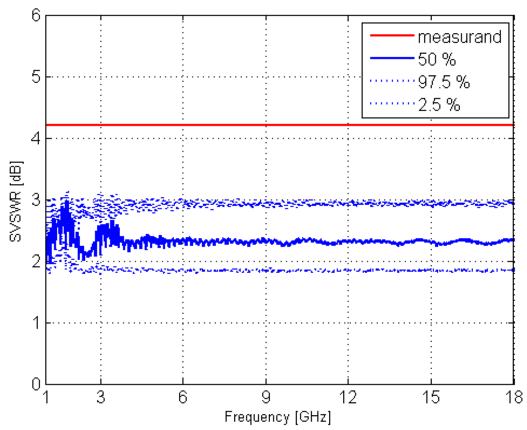
Below 6 GHz a different result can be observed, but here the insufficient path length as found for SVSWR cannot be the reason. The cause is the standard deviation of the position variation. If it is increased, e.g., to 10 cm, the effect disappears, because the change in phase between each MC sample increases. So, the phase of each path becomes statically independent and the simulation more accurate.

The median TD VSWR, see Fig. 6a, result is approximately 0.5 dB higher than the SVSWR result. This can be explained with the result before applying the post processing filter as shown in Fig. 6b. It is nearly equal to SVSWR result. So, the increase in the post processing TD SVSWR result is based on (8) where 0.676 times the standard deviation is added.

The repeatability is smaller compared to SVSWR and has a value of approximately 1.2 dB. When comparing Fig. 6a and 6b, it is obvious that the better repeatability is based on the applied moving average and not on the method itself.

It is claimed that the undersampling issue of SVSWR is solved by TD SVSWR [6]. Fig. 7a shows a TD SVSWR simulation where only one reflection is present in the system. In this case no frequency dependency is observed. In case of multiple reflections, see Fig. 7b, a frequency dependency is seen, because the result is based on the vector sum of all reflections. The phase criterion given in chapter IIb is valid in an updated manner and can be interpreted as a different kind of undersampling.

a)



b)

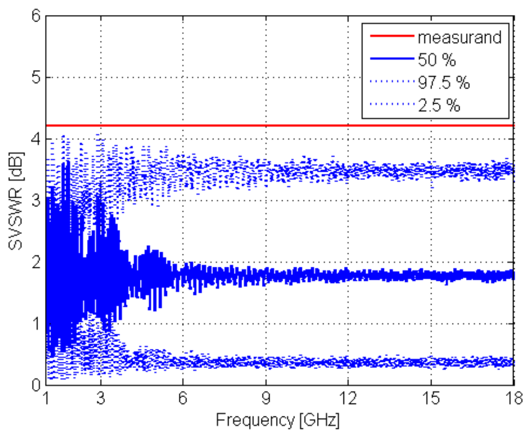
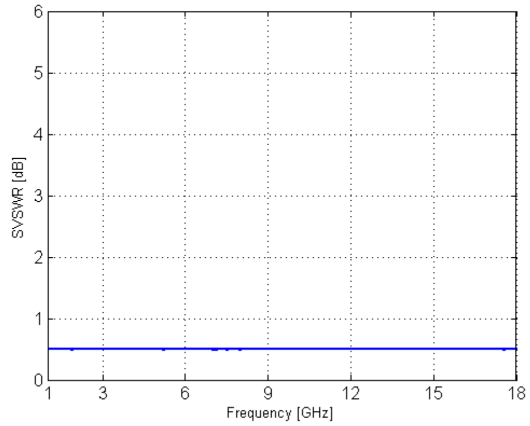


Fig. 6. TD SVWR simulation result a) after b) before post-processing

a)



b)

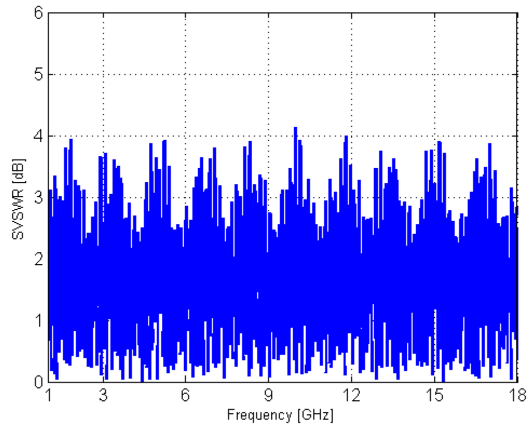


Fig. 7. TD SVSWR simulation a) only one reflection b) all reflections

V. MF SVSWR

The MF SVSWR method was proposed by [8] and extended by [9] to overcome the fact that broadband antennas with a small ringdown time are required by TD SVSWR. For this method the transmit antenna is moved along the circumference of the test volume by the anechoic chamber turntable, see Fig. 8. The complex electric field strength $E(\varphi)$ is determined at n points with certain angular step size of φ_{step}. It is translated to the center of the turntable, by applying a complex path length correction, see (13) and (14).

$$R_1 = \sqrt{\left(R_0 - r_0 cos(\varphi)\right)^2 + \left(r_0 sin(\varphi)\right)^2} \qquad (13)$$

$$\underline{E_t}(\varphi) = \underline{E}(\varphi)\frac{R_1}{R_0}e^{jk(R_1-R_0)} \qquad (14)$$

To prove the effect of this translation in the simulation model, it is performed on the direct ray.

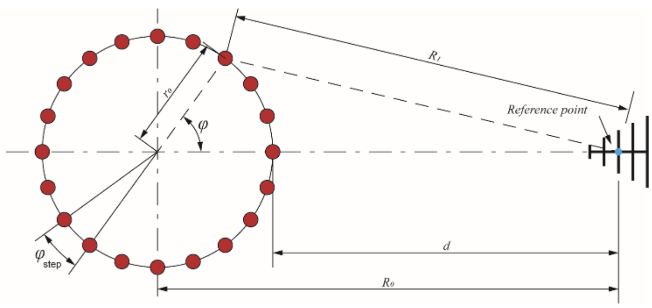


Fig. 8. MF SVWR test setup

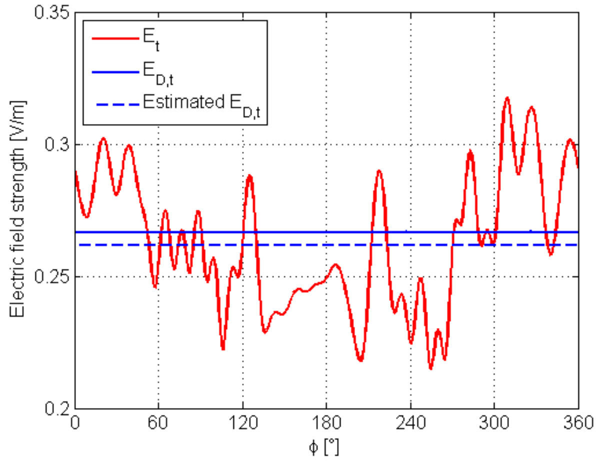


Fig. 9. Electric field strength at 1 GHz

Equation (2) can be written as (15) since the path length is specified with R_1 in Fig. 8.

$$\underline{E_D} = E_0\left(\frac{e^{-jkR_1}}{R_1}\right) \qquad (15)$$

Applying the translation (14) leads to (16)

$$\underline{E_{D,t}} = E_0\left(\frac{e^{-jkR_1}}{R_1}\right)\frac{R_1}{R_0}e^{jk(R_1-R_0)} = E_0\left(\frac{e^{-jkR_0}}{R_0}\right) \qquad (16)$$

So, the translated field strength $E_{D,t}$ at any angle φ will be identical to the field strength at the center of the test volume, which is independent from φ.

This property is used to estimate the field strength of the direct ray by averaging the field strength along the circumference, see (16)

$$\underline{E_{D,t}} \approx \frac{1}{n}\sum_{\varphi=1}^{n} E_t(\varphi) \qquad (16)$$

This approximation works well as long there are sufficient samples, and the magnitudes and phase angles of the reflections are statistically independent at each angle.

With an approximation of the direct ray, it is possible to calculate the reflection coefficient Γ like it is done for TD SVSWR. For each frequency n results are calculated, where the maximum is taken.

Fig. 9 shows the absolute value of electric fields at 1 GHz as exemplification. The requirement on statistical properties is not met, because the phase change between each point is small. So, a deviation between the direct ray and the estimator is observed. An analysis of the error is not given so far and is also not scope of this paper.

In a more realistic scenario, the antenna pattern of the transmit and the receive antenna need to be taken into consideration. The simple estimation with the mean value is not possible anymore, because the magnitude of the direct ray changes with the angle φ. It must be assumed that slow changes of the field strength are caused by the antenna pattern and rapid changes are caused by reflections. A kind of low pass filtering along φ is required to distinguish between slow and rapid changes. Reference [9] implemented this with a Fourier transformation, low pass filtering and back transformation.

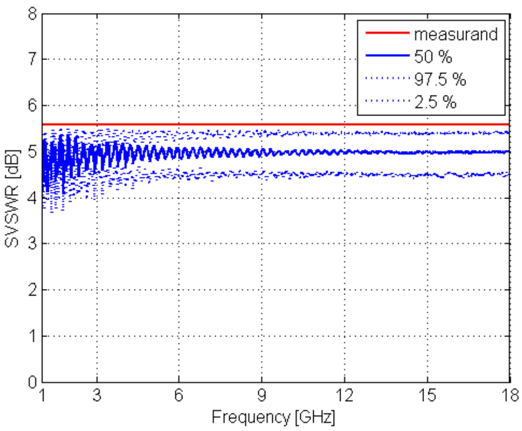
To estimate the systematic error and the repeatability, the MC method is used. On the contrary to the proposed method [9] the result is directly derived without applying Fourier transformation and filtering, since the direct ray is known.

With a number of 1000 trials per frequency the position of the test volume center and receive antenna is varied in all three directions. A normal distribution with a standard deviation of 1 cm is assumed for each axis. For each frequency the probability distribution function (PDF) is calculated, while only the 2.5 %, 50 % and 97.5 % of the resulting CDF are plotted with the measurand calculated by (3), see Fig. 10a.

Below 6 GHz a different result can be observed, with the same reason as explained for TD SVSWR. The measurand is different for two reasons. The first one is that the measurement is performed at the back of the test volume. There the influence is dominated by the reflection of the back wall, because the path length of reflection is getting smaller compared to the path length of the direct ray when coming closer to the back wall. Second, the magnitude of the reflection is magnified during the translation, due to the multiplication with R_1/R_0, which is larger than 1. So, the measurand is with 5.7 dB significantly higher than for the other SVSWR methods with 4.2 dB.

The median MF VSWR result is at 5 dB, considerably closer to the measurand as other SVSWR methods. Also, the repeatability is with 1 dB smaller compared to other methods. The reason is the large number of measurement point. If the number is decreased, e.g., if the angular step size is increased to 36 °, the result changes, see Fig. 10b. The median MF VSWR is reduced to 3.7 dB and the repeatability is increased to 2.5 dB.

a)



b)

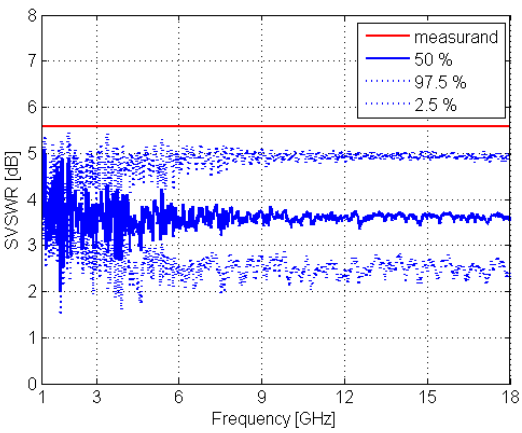


Fig. 10. MF SVWR simulation result a) 1 ° stepsize b) 36 ° stepsize

VI. Conlcusion

In this paper all three SVSWR methods are investigated with the Monte Carlo Method and compared to a defined measurand. The systematic error mainly depends on the number of points within the test volume and not on the method itself. This is caused by the probability to find an in-phase condition of the reflection vectors, which increases with the number of points.

A kind of undersampling occurs with all validation methods and cannot be avoided principally. In fact, undersampling is not an issue if the validation method is sensitive to chamber imperfections.

The goal for new methods or improvements is to find a good compromise between time effort due to number of measurement points and measurement uncertainty. In particular, the measurement uncertainty had been not taken into account in recent years.

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