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Electric field probe calibration method by using a TEM cell for reference field generation

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Abstract. The article presents a method to calibrate electric field probes using a transverse electromagnetic (TEM) cell as a reference. The TEM cell generates uniform and repeatable fields for accurate calibration. The process and setup are carefully detailed to ensure precise generation and measurement. We perform a full uncertainty analysis, considering factors like power delivery, septum-to-wall distance, impedance mismatch, and field inhomogeneity. The total uncertainty of the calibration is 10 % of the electric field amplitude, ensuring good accuracy. To validate the method, measurements are compared with data from an accredited laboratory over a frequency range of 9 kHz to 300 MHz. The results show excellent agreement, with errors within acceptable limits. This confirms the reliability and robustness of the method. The proposed approach provides a reliable solution for accurate electric field probe calibration.

1 Introduction

The accurate measurement of electric fields is critical in various domains, including electromagnetic compatibility (EMC) testing, environmental monitoring, and health and safety evaluations. The electric field probes are indispensable tools for these applications, but their performance heavily relies on proper calibration. Inaccurate probe calibration can lead to erroneous measurements, affecting the reliability of test results and assessments.

Several methods have been developed for the calibration of electric field probes, with on widely accepted approach involving the use of a transverse electromagnetic (TEM) cell. [1] first introduced the TEM cell as a reliable means of generating standard electromagnetic fields, later formalized in calibration methods described by [2, 3, 4]. These methods ensure a controlled electromagnetic environment, providing consistency in measurements and making the TEM cell an ideal tool for calibration purposes.

This article presents a comprehensive calibration method using a TEM cell as a reference source for electric fields. The method provides a controlled environment that enables precise calibration across a wide range of field strengths and frequencies, ensuring reliable probe performance.

The paper is structured as follows: Section 2 describes the calibration method, including the measurement setup, conditions, and uncertainty considerations. Section 3 focuses on the validation of the method through comparison with results from an accredited external laboratory. Finally, Section 4 concludes this work.

2 Calibration method

2.1 Measurement setup

The core of the calibration method involves using a TEM cell to generate the reference electric field. In this study, a Schwarzbeck TEMZ-type TEM cell is employed. The TEM cell consists of two parallel conductive ground planes separated by a central conductor, known as the septum. The septum is terminated at both ends with connectors, through which the RF signal is injected at one end generate the electromagnetic field inside the cell. Due to the design of the TEM cell, the electric field generated is vertical with respect to the septum plane.

Figure 1 presents the calibration setup for the electric field measurement. To measure the generated electric field, the setup includes an attenuator connected to the second connector of the TEM cell. The attenuated signal is then measured using a calibrated power probe of type R&S URV5-Z2 equipped with a millwattmeter. A 50-ohm matching load is connected to the probe to ensure proper impedance matching, which is critical for accurate measurements.

As noted by [5, 8], the TEM cell is effective in minimizing reflections and maintaining a uniform field distribution during calibration. The electric field strength inside the cell is adjusted by controlling the input power from the RF source, allowing for precise control over the field intensity.

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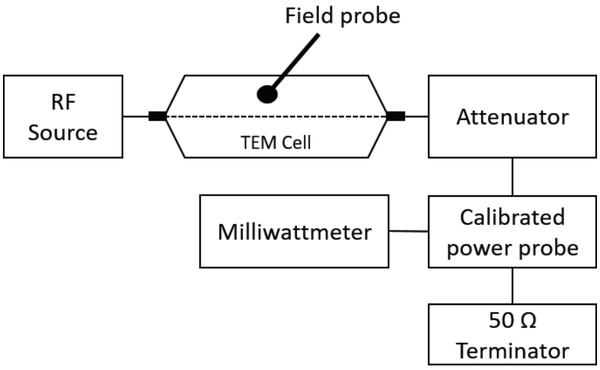

Fig. 1. Calibration setup of the reference electric field generation by using a TEM cell.

As shown in Figure 2, the probe to be calibrated is positioned at the 3D center of the cell, midway between the septum and the cell wall. The coordinates $P_c(x_0 = 0, y_0 = 0, z_0 = -100)$ designate this central position. In this study, we used a triaxial broadband isotropic electric field probe for measurements and validation. This setup ensures that the probe is exposed to a uniform and well-defined reference electric field.

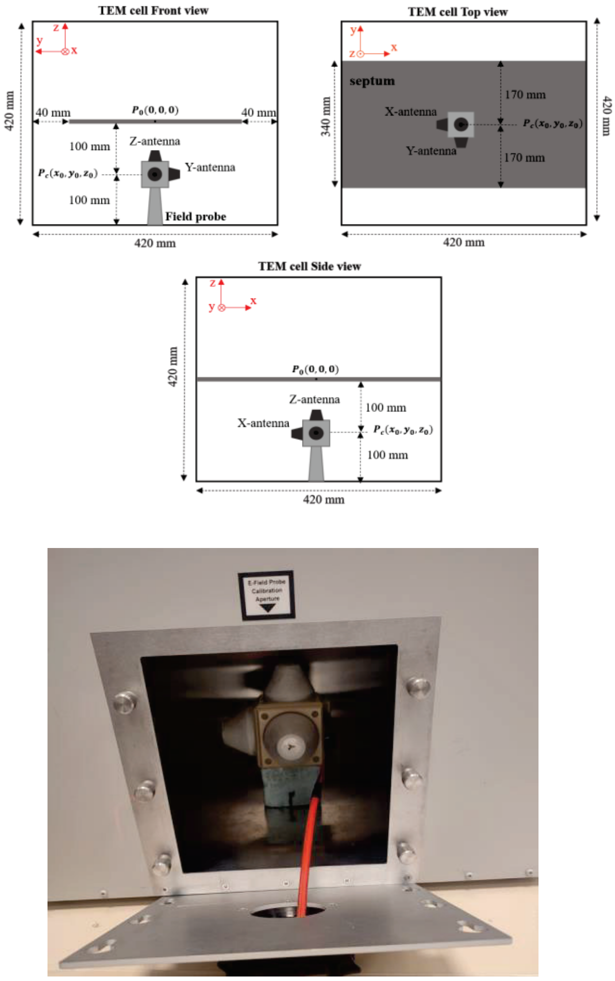

Fig. 2. Positioning of the field probe in the TEM cell.

2.2 Measurement conditions

The measurements are conducted within a controlled laboratory environment to ensure the accuracy and reliability of the calibration results. The laboratory is maintained at a stable temperature of 23±1.5 °C, which minimizes temperature-related fluctuations that could affect the performance of the electric field probes. In addition, the relative humidity in the laboratory is kept below 60 % to avoid moisture-related issues that could affect the measurements or the equipment. All ambient conditions, including temperature and humidity, are continuously monitored and recorded throughout the calibration process. This data is retained for reference and quality assurance, ensuring the any variations in environmental conditions are documented and can be taken into account during data analysis.

2.3 Uncertainty analysis for the measurement model

The electric field E_{TEM} generated within the TEM cell is modeled mathematically as follows:

$$E_{TEM} = \frac{\sqrt{P_{net}\mathrm{Re}(Z_0)}}{d} f(x,y,z) \qquad (1)$$

with:

- P_{net} is the net power delivered to the TEM cell.
- Z_0 is the characteristic impedance of the TEM cell.
- d is the distance between the septum and the lower wall of the cell.
- $f(x,y,z)$ is the inhomogeneity factor of the electric field along the x, y and z axes with reference to the central position $P_c(x_0, y_0, z_0)$. It is defined as:

$$f(x,y,z) = \frac{E_{TEM}(x,y,z)}{E_{TEM}(x_0,y_0,z_0)} = 1 + \varepsilon(x,y,z) \qquad (2)$$

where $\varepsilon(x,y,z)$ represents the uncertainty associated to the inhomogeneity factor along the x, y and z axes.
The uncertainty associated with the electric field is expressed as:

$$\frac{u^2(E_{TEM})}{E_{TEM}^2} = \frac{1}{4}\frac{u^2(P_{net})}{P_{net}^2} + \frac{1}{4}\frac{u^2(Z_0)}{\mathrm{Re}(Z_0)^2} + \frac{u^2(d)}{d^2} + \varepsilon(x,y,z) \qquad (3)$$

2.3.1 Input power measurement

The accurate measurement of the net power P_{net} delivered within the TEM cell is crucial for the uncertainty budget of the electric field calibration process. The mathematical model for P_{net} is expressed as:

$$P_{net} = \frac{C_p}{\left|S_{21}^{cell}\right|^2 \left|S_{21}^{att}\right|^2} \langle P_{mes} \rangle_n \qquad (4)$$

with:

- $\langle P_{mes} \rangle_n$ is the average of results from n measurements by the calibrated power probe.
- C_p is the calibration correction factor of the calibrated power probe.
- S_{21}^{cell} and S_{21}^{att} are the transmission coefficients of the TEM cell and attenuator, respectively.

The relative uncertainty associated with P_{net} is quantified by considering multiple sources of uncertainty. These components include the repeatability of power measurements, assessed through statistical analysis to evaluate measurement consistency. Additionally, the correction factor for the power probe is given from its calibration certificate. The potential drift of the probe over time is also taken into account. Furthermore, the uncertainties associated with the transmission coefficients of the TEM cell and the attenuator are included. These uncertainties are determined from measurements of the S-parameters using a calibrated vector network analyzer (VNA) in laboratory. Specifically, the uncertainty of the transmission coefficient of the TEM cell is estimated by considering the impact of the presence of a probe within the cell. The overall relative uncertainty can then be represented as:

$$\frac{u^2(P_{\mathrm{net}})}{P_{\mathrm{net}}^2}=\frac{u^2(\langle P_{\mathrm{mes}}\rangle_{\mathrm{n}})}{\langle P_{\mathrm{mes}}\rangle_{\mathrm{n}}^2}+\frac{u^2(C_{\mathrm{p}})}{C_{\mathrm{p}}^2}+4\frac{u^2\left(S_{21}^{\mathrm{cell}}\right)}{\left\|S_{21}^{\mathrm{cell}}\right\|^2}+4\frac{u^2\left(S_{21}^{\mathrm{att}}\right)}{\left\|S_{21}^{\mathrm{att}}\right\|^2} \tag{5}$$

2.3.2 Error of cell septum distance

The uncertainty associated with the measurement of the distance d between the septum and the lower wall of the TEM cell influences the accuracy of electric field assessments. The distance is measured using either a laser rangefinder or a caliper. The measured distance can be expressed mathematically as follows:

$$d=\langle d_{\mathrm{mes}}\rangle_{\mathrm{n}}+C_{\mathrm{q}}+C_{\mathrm{j}}+d_{\mathrm{nom}}\alpha\Delta T \tag{6}$$

with:

- $\langle d_{\mathrm{mes}}\rangle_{\mathrm{n}}$ is the average of n measurements taken with the laser rangefinder or caliper.
- C_{q} is the correction for quantization error during the measurement reading.
- C_{j} is the correction for measurement accuracy corresponding to the distance.
- d_{nom} is the nominal distance between the septum and the wall.
- α is the thermal expansion coefficient relevant to the TEM cell.
- ΔT is the temperature variation.

The correction for measurement accuracy C_{j} is neglected, along with the term involving the product of the nominal distance and the temperature variation ($d_{\mathrm{nom}}\alpha\Delta T$). The relative uncertainty associated with the distance d is then expressed as:

$$\frac{u^2(d)}{d^2}=\frac{u^2(\langle d_{\mathrm{mes}}\rangle_{\mathrm{n}})}{d^2}+\frac{u^2(C_{\mathrm{q}})}{d^2}+\frac{(d_{\mathrm{norm}}\alpha)^2}{d^2}u^2(\Delta T) \tag{7}$$

2.3.3 Inhomogeneity field factor

The evaluation of the inhomogeneity of the electric field is important for the calibration of the probe inside the TEM cell. This uncertainty component is assessed through CST simulations by evaluating the field within a distance of 20 mm from the central position $P_c(x_0, y_0, z_0)$, by varying the location along the longitudinal axis x, transverse axis y, and vertical axis z.

Figure 3 presents the variations of the electric field along the three axis for a frequency of 300 MHz. We observe that the field variations along the longitudinal axis x (the direction of propagation) are negligible. Therefore, the inhomogeneity depends primarily on the y and z components.

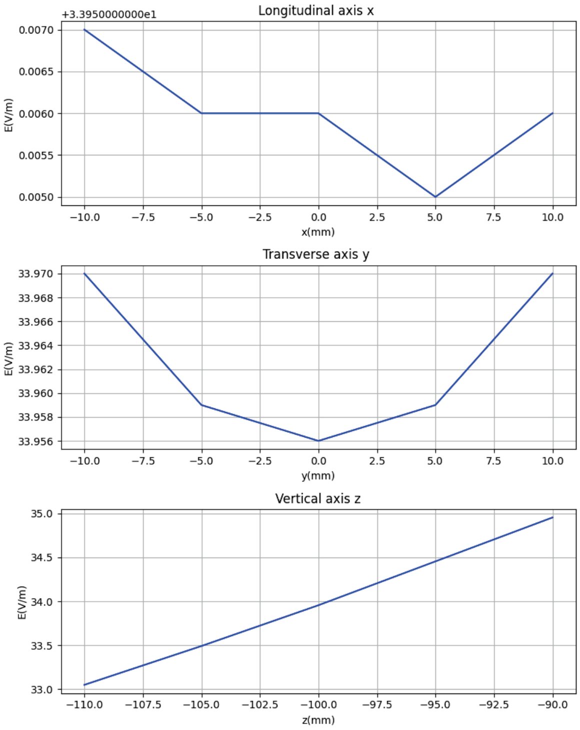

Fig. 3. Electric field distribution along the x, y, and z axes (CST simulation, f = 300 MHz), with respect to the central position $P_c(x_0, y_0, z_0)$.

The uncertainty component associated with the total inhomogeneity of the field is then given by:

$$\varepsilon^2(x,y,z)=u^2(y)+u^2(z) \tag{8}$$

The uncertainties associated with the field inhomogeneity along the transverse axis y and the vertical axis z, $u(y)$ and $u(z)$, are determined using a rectangular distribution, based on the maximum and minimum simulated values of the field.

2.3.4 Impedance mismatch error

The impedance mismatch of the TEM cell can lead to errors in the accurate determination of electric field values, impacting the reliability of the measurements. The estimation of the uncertainty related to the characteristic impedance Z_0 of the TEM cell is determined through measurements of its S-parameters. As shown in Figure 4, the TEM cell is modeled as a transmission line characterized by an impedance Z_0, with the load defined by an impedance Z_{L} and the source characterized by an impedance Z_{s} (typically set a 50 Ω) [6, 7].

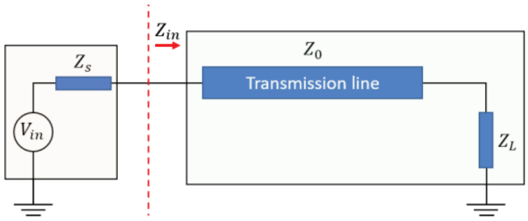

Fig. 4. Impedance modeling of the TEM cell.

The reflection coefficient of the cell S_{11} is defined based on the input impedance of the transmission line Z_{in} and the source impedance Z_{s}:

$$S_{11} = \frac{Z_{in} - Z_S}{Z_{in} + Z_S} \tag{9}$$

The input impedance Z_{in} is expressed as:

$$Z_{\mathrm{in}} = Z_0 \frac{Z_{\mathrm{L}} + Z_0 \tan \beta l}{Z_0 + Z_{\mathrm{L}} \tan \beta l} \tag{10}$$

where β represents the phase constant of the transmission line, and *l* indicates the length of the transmission line segment. The input impedances for short-circuit and open-circuit conditions are expressed as follows:

$$Z_{\mathrm{in}}^{\mathrm{cc}} = \mathrm{j}\, Z_0 \tan \beta l = Z_{\mathrm{s}} \frac{1 + S_{11}^{\mathrm{cc}}}{1 - S_{11}^{\mathrm{cc}}} \tag{11}$$

$$Z_{\mathrm{in}}^{\mathrm{co}} = Z_0 \frac{1}{\mathrm{j} \tan \beta l} = Z_{\mathrm{s}} \frac{1 + S_{11}^{\mathrm{co}}}{1 - S_{11}^{\mathrm{co}}} \tag{12}$$

Here, S_{11}^{cc} and S_{11}^{co} are the reflection coefficients of the cell in short-circuit and open-circuit configurations, respectively. The characteristic impedance Z_0 of the TEM cell is derived from the measurements of its S_{11} parameter in both short-circuit and open-circuit conditions. It is defined by:

$$Z_0 = \sqrt{Z_{\mathrm{in}}^{\mathrm{cc}}\, Z_{\mathrm{in}}^{\mathrm{co}}} \tag{13}$$

The uncertainty associated with the mathematical model of the characteristic impedance Z_0 is expressed as:

$$\frac{u^2(Z_0)}{Z_0^2} = \frac{1}{4}\, u^2(S_{11}^{\mathrm{cc}}) + \frac{1}{4}\, u^2(S_{11}^{\mathrm{co}}) \tag{14}$$

The uncertainties $u(S_{11}^{cc})$ and $u(S_{11}^{co})$ are determined from S-parameter measurements using a calibrated VNA on the TEM cell in both short-circuit and open-circuit configurations.

2.3.5 Overall uncertainty budget

The evaluation of the overall uncertainty related to the calibration of the electric field E_{TEM} is based on the quadratic summation of individual uncertainty components, as detailed in the previous sections. Table 1 provides a summary of the uncertainty components and their respective contributions to the overall uncertainty budget, evaluated at the highest operational frequency of 300 MHz. The expanded overall uncertainty, with a coverage factor of 2, is standardized in this study to 10 % of the electric field amplitude.

Table 1. Uncertainty budget for TEM cell calibration at 300 MHz.

Component	**Sensitivity coefficient**	**Uncertainty contribution (%)**
Net power delivered to the TEM cell	0.50	0.10
Characteristic impedance of the TEM cell	0.50	1.13
Septum-to-wall distance measurement	1	0.46
Inhomogeneity factor (transverse axis)	1	0.04
Inhomogeneity factor (vertical axis)	1	4.85
Overall uncertainty (coverage factor = 1)	**4.90 %**	
Overall uncertainty (coverage factor = 2)	**9.80 %**	

3 Method validation

The validation of the method have been conducted by using a broadband isotropic electric field probe calibrated at the NPL (National Physical Laboratory), identified by the serial number s/n 101752. The measurements were carried out by comparing the correction factors for fields values from 1 V/m to 120 V/m across frequency points ranging from 9 kHz to 300 MHz, as shown in Table 2. The comparison have been performed separately along each antenna axis (X, Y, and Z).

Table 2. Parameters of the comparative study with NPL measurements.

Frequency MHz	**Actual field strength V/m**	**Range V/m**
0.009	10	30
0.01	10	30
0.015	10	30
0.02	10	30
0.03	10	30
0.05	10	30
0.07	10	30
0.09	10	30
0.1	10	30
0.2	10	30
0.5	10	30
1	10	30
10	10	30
30	10	30
100	1	10
100	3	10
100	8	10
100	10	10

100	10	10
100	20	30
100	30	30
100	30	100
100	50	100
100	100	100
100	100	300
100	150	300
100	200	300
180	10	30
300	10	30

The key indicator for this validation is the normalized error between the measurements from the laboratories. The external laboratory reports a maximum absolute uncertainty of 8 % for the correction factor within the measurement range applied in this comparative study.

Figure 8 presents the results of the normalized error between the two measurements on the three antenna axes.

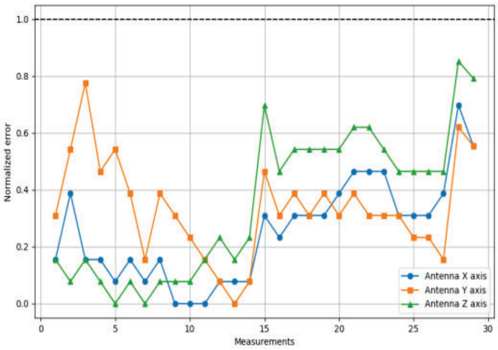

Fig. 5. Normalized error between measurements for the probe antenna along the X, Y, and Z.

We can observe that the error does not exceed 1 across the entire measurement range, which confirms the laboratory ability to meet the stated uncertainties in the 9 kHz to 300 MHz frequency range.

4 Conclusion

In this article, a comprehensive calibration method for electric field probes using a TEM cell as a controlled and reliable reference source has been presented. The calibration process is explained step by step, starting with the measurement setup. A Schwarzbeck TEM cell was used to generate uniform and reproducible reference electric fields. A detailed uncertainty analysis was performed, addressing all relevant sources of uncertainty, including the net power delivered to the cell, the septum-to-wall distance, field inhomogeneity, and impedance mismatch. The overall expanded uncertainty of the calibration was set at 10% of the electric field amplitude, which shows a high level of precision and control over the calibration process. To validate the method, measurements were compared with those from an accredited external laboratory across a wide frequency range (9 kHz to 300 MHz) for a triaxial isotropic probe. The evaluated correction factors showed excellent agreement between the two laboratories. The normalized errors remained within acceptable limits, confirming the robustness of the method and its ability to meet the required uncertainty specifications.

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