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Precise Calibration of Electric Field Sensors for Radiated-Susceptibility Testing

Präzise Kalibrierung von elektrischen Feldsensoren für Störfestigkeitsprüfungen mit Feldern

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Abstract
Judgements upon the CE-compliance of products are of great economic importance. Therefore, the calibration of field sensors for electromagnetic compatibility (EMC) susceptibility testing in the frequency range of 80 – 1000 MHz calls for traceability, optimum accuracy and economy. In the Seibersdorf calibration laboratory, this has been achieved by application of a TEM-cell and a set of precision reference dipoles. A broadband reference sensor is calibrated on the basis of these high-precision primary standards with an expanded uncertainty (at two standard deviations) of 0.4 dB. Routine calibrations are performed by an economized, swept-frequency substitution method using the reference sensor. The expanded uncertainty is 0.5 dB, providing a reliable basis for industrial EMC measurements.

Übersicht
CE-Konformitätsbewertungen von Produkten haben große wirtschaftliche Bedeutung. Deshalb erfordert die Kalibrierung von Feldsensoren für Störfestigkeitsuntersuchungen bei der Prüfung der elektromagnetischen Verträglichkeit (EMV) im Frequenzbereich 80 - 1000 MHz Rückführbarkeit, höchste Genauigkeit und Wirtschaftlichkeit. Im Seibersdorfer Kalibrierlabor wurde das durch Einsatz einer TEM-Zelle und eines Sets von Präzisions-Referenzdipolen erreicht. Auf Basis dieser hochpräzisen Primärstandards wird ein breitbandiger Referenzsensor mit einer Gesamt-Unsicherheit (bei zwei Standardabweichungen) von 0,4 dB kalibriert. Routinekalibreierungen erfolgen nach einer wirtschaftlichen Substitutionsmethode mit Hilfe des Referenzsensors im kontinuierlichen Frequenzablauf. Die Gesamt-Unsicherheit ist 0,5 dB, was eine verläßliche Basis für industrielle EMV-Messungen schafft.

Für die Dokumentation
Echoarmer Raum, elektromagnetische Verträglichkeit, EMV, Feldsensoren, Kalibrierung, Meßunsicherheit, TEM-Zelle.

1. Introduction

Radiated-susceptibility or radiated-immunity testing is an integral part of electromagnetic compatibility (EMC) compliance tests of electronic equipment under Directive 89/336 [1]. The International Basic Standard is IEC 61000-4-3 [2]. It describes test methods in the frequency range of 80 MHz to 1 GHz. As computer clock rates and mobile radio services continue to enter increasingly higher frequencies, test specifications up to 2 GHz can be forseen. The current test severity levels are 3 V/m for domestic or light industrial environment and 10 V/m for industrial environment. Higher test levels are used in the automotive industry, aircraft industry, military and others.

The standard test procedure [2] specifies a precalibration of the test field in a fully anechoic chamber (area of uniform field). This is done with an appropriate field sensor in 16 defined positions. The equipment under test (EUT) is not present. The sensor is operated under clearly defined field conditions: 2 polarizations (horizontal, vertical), single frequencies without modulation, moderate dynamic range. Therefore, the calibration can account for these conditions and a very good accuracy can be achieved when certain rules are followed.

In this paper, we show how field sensors should be calibrated for application in radiated-susceptibility testing. A description of the optimized methods developed in the Seibersdorf EMC test and calibration laboratory is given and accompanied by an estimation of test and calibration uncertainties.

2. Standard specifications for the calibration of field sensors

IEEE Std. 1309-1996 [3] gives some key requirements regarding basic calibration methods and procedures. As the extent to which a field sensor must be calibrated and characterized depends on its intended use, the grade of calibration shall be specified with respect to

- method of calibration
- time constant
- time domain or frequency domain
- modulation response
- amplitude levels measured
- isotropy
- frequencies measured
- sensor orientation in the field
- response time
- uncertainty.

Three calibration methods are provided:

A Calibration using a transfer standard (a field sensor similar to the one being calibrated), that has traceability to a national standards laboratory. The transfer standard is used to measure and calibrate the field used for calibrating the field sensor under test.

B Calibration using calculated field strengths. The field sensor under test is placed in a calculated reference field based on the geometry of the field source and the field source measured input parameters.

C Calibration using a primary standard (reference) sensor, that contains no active or passive electronic devices and has its calibration traceable to a national standards laboratory based on international standards. It is used to determine the field strength used to calibrate the sensor under test.

Under methods A and B, **Table 1** lists the devices and setups that shall be used to generate standard fields for calibrations.

IEEE Std C95.3-1991 [4] describes TEM-cell, anechoic chamber with open-ended waveguide and waveguide chamber in greater technical detail. **IEEE Std 291-1991** [5] describes the calibration of aperture antennas, e. g. pyramidal horns.

3. Calibration facilities

3.1 Primary standards

TEM-cell

A TEM-cell is a shielded, asymmetric transmission line. Due to the defined geometry, the electric field-strength E in the center of the cell can be calculated [6] using (1).

Table 1: Methods of generating electromagnetic fields for frequency domain calibration in the range of 80 MHz to 1 GHz

Method/facility	Frequency range	Calculable field	Characteristic/limitation
TEM-cell	Up to 200 MHz (500 MHz)	Y	Upper frequency limit determined by cell dimension
Anechoic chamber with open-ended waveguide (OEG) or pyramidal horn antenna	200 – 450 MHz (OEG) 450 MHz – 1 GHz (horn)	Y Y	Accuracy depending on absorber quality and chamber dimensions
Waveguide chamber	300 MHz – 1 GHz	Y	Wave impedance different from free-space
GTEM-cell	Up to 1 GHz	N	Field-generating device

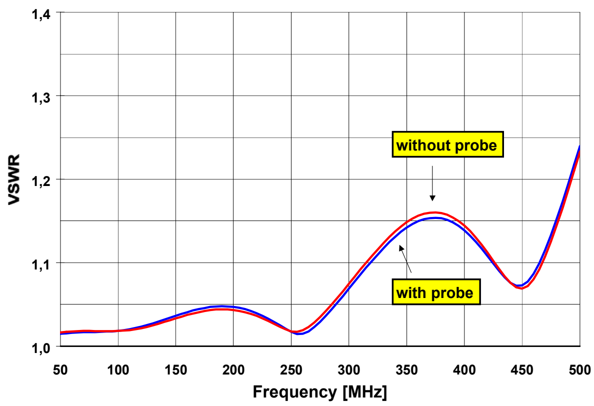

Fig. 1: Standing wave ratio measured at the input of the TEM3 cell of the Seibersdorf Calibration Laboratory

$$E = \frac{\sqrt{P_P . Z_l}}{d} \quad (1)$$

where

P_P power of the TEM-wave propagating through the cell

d = H/2 = vertical distance between septum and outer conductor in the central section

Z_l line impedance.

The upper limit of the frequency range of operation is given by the cutoff-frequency for higher-order modes $f_c = c_0/2b$, where c_0 is the speed of light and b is the width of the cell.

We use a cell with a vertical distance d between septum and outer conductor of 9 cm. The cutoff frequency is 500 MHz. The cell has a standard Crawford-design [6]. **Fig 1** shows the *SWR* of this cell as a function of frequency. These data are used to derive the measurement uncertainties. The method of power measurement in a TEM-cell has been described in [7].

Precision reference dipoles

We have developed the precision reference dipoles PRD [8, 9]. The phase imbalance of the PRD-baluns is less than 1°. Amplitude unbalance is less than 0.12 dB for frequencies up to 1 GHz. **Table 2** lists the PRD antenna factors at the resonant frequencies of the standard set defined by CISPR and ANSI. Antenna factors at any intermediate frequency can be readily calculated by our NEC-based program ANTENNA. Though the PRDs can also be used to generate a calculable, standard field in a fully anechoic chamber, they are used as receive antennas in this application.

3.2 Field generating devices

For routine calibrations, swept-frequency techniques are a must. The setup must permit operation over the whole frequency range. This is possible with an ultra-broadband antenna in a fully anechoic chamber or a GTEM-cell. In both cases, a field is set up and measured by the reference sensor. Then the reference sensor is replaced by the sensor to be calibrated and exposed to the same field. This procedure is called substitution method. It is very accurate, provided that

(1) the setup does not change

Table 2: PRD free-space antenna factors, reference impedance 100 Ω

Frequency [MHz]	Element length [mm]	Element diameter [mm]	AF (NEC) free-space [dB(1/m)]
30	2358.0	25	-5.21
35	2021.0	25	-3.89
40	1765.0	25	-2.74
45	1561.0	25	-1.71
50	1405.0	25	-0.80
60	1167.0	25	0.77
70	996.0	25	2.11
80	870.0	25	3.27
80	890.5	6	3.27
90	791.0	6	4.29
100	710.5	6	5.20
120	591.0	6	6.78
140	505.5	6	8.12
160	441.5	6	9.28
180	391.0	6	10.30
200	351.0	6	11.22
250	280.0	6	13.15
300	232.0	6	14.74
300	235.5	3	14.74
350	201.4	3	16.07
400	175.8	3	17.23
450	155.9	3	18.26
500	140.0	3	19.18
550	127.0	3	20.00
600	116.2	3	20.76
650	107.1	3	21.45
700	99.3	3	22.10
750	92.6	3	22.70
800	86.6	3	23.26
850	81.4	3	23.78
900	76.8	3	24.28
950	72.7	3	24.75
1000	68.9	3	25.20

(2) the position of measurement is reproduced exactly
(3) the transmitted power remains exactly the same
(4) the two sensors have approximately the same volume
(5) the cables connecting sensor head and readout do not disturb the field
(6) the field generating device is largely anechoic.

The criterions (1) to (3) can be fulfilled by careful, automatic operation. Condition (4) restricts the kinds of sensors that can be calibrated by substitution with a particular reference sensor. Condition (5) also limits the applicability of the method to certain constructions of sensors, but can be fulfilled by all types with fiber optic or high-impedance transmission lines. Condition (5) must be carefully checked. According to our experiments [7, 8, 9], fully anechoic chambers are applicable, if the site attenuation is within about ± 4 dB of theoretical free-space reference values. State-of-the-art GTEM-cells have shown acceptable results, if the spacing between septum and outer conductor is at least 10 times the vertical dimension of the sensor.

4. Optimized calibration methods

4.1 Primary standard

We selected a combination of methods B (calculable field source) and C (reference sensor) for greater flexibility in practical applications. We built a set of three TEM-cells of different size and, correspondingly, different cutoff-frequencies (50 MHz, 150 MHz, 500 MHz). A TEM-cell for frequencies up to 1 GHz we found to be very susceptible to measurement errors associated with the positioning of the sensor and its cable. Therefore, method B is applied for frequencies up to 500 MHz only.

For frequencies of 200 MHz and above, the following options exist:

* Fully anechoic chamber with open-ended waveguide/horn antenna as transmit antenna. The field-strength is calculated on the basis of the antenna gain and the assumption of ideal free-space wave propagation in the chamber. The antenna gain can either be calculated from the antenna dimensions or measured using a two-antenna method or three-antenna method (method B).
* Fully anechoic chamber with calculable reference sensor (method C).
* Waveguide chamber (method B).

We selected the fully anechoic chamber together with our precision reference dipoles PRD [9] as receive antennas. Though the PRD has been designed for use with frequency-selective detection, it can also be connected directly to a high-precision, broadband power meter. Thus, the principle is method C, still. We apply this method regularly at frequencies above 480 MHz. In the range of 200 – 480 MHz there is an overlap with the TEM-cell which has been successfully used for experimental verifications of the calibration results [7].

4.2 Method for the calibration of customer's sensors

We calibrate a reference sensor by the methods described under 4.1 above. Then we set up a field in the anechoic chamber and calibrate the sensor under test by substitution with the reference sensor. This corresponds to method A of [3]. The reasons for the choice of methods as described above are the following:

Selection of the primary standards

* At frequencies below about 200 MHz, there is no alternative to TEM-cells. They are very reliable and accurate.
* Our TEM3-cell performs very well at frequencies up to 480 MHz and our reference sensor is sufficiently small to fit into it without violating the criterion regarding the maximum permissible test volume. Therefore, we extend the method up to 480 MHz.
* We made measurements and calculations of the gains of dipole antennas, open-ended waveguides and horn antennas. For our dipoles, we achieved a coincidence between theoretical calculations and practical measurements of 0.15 dB at two standard deviations [9]. For the aperture antennas, results were worse than that. Therefore, we prefer our PRDs. We use it as receive antennas (method C), because this allows to eliminate the influence of chamber imperfections in a more reliable way than method B.

Routine calibration service

* Method A is the only economic solution for a routine calibration service. It minimizes handling time and personal cost due to the use of broadband field-generating facilities.

5 Calibration uncertainties

We apply the methods for the evaluation of uncertainties that are described in [10].

5.1 Uncertainty in the calibration of a reference sensor in a TEM-cell

The field-strength E in a TEM-cell is calculated from (1). For this example, we assume that the quantities P_P, Z_l and d can be determined with the following uncertainties:

Power

We use a power meter that consists of the power head and the D.C. microamperemeter. The power head is a thermal bolometer. The accuracy of the calibration of the power meter was specified by the German Calibration Service DKD (Deutscher Kalibrierdienst) in the Certificates of Calibration No. 1289/98-08 and 1290/98-08 in accordance with [10].

The contributions to the total uncertainty in the power measurement are

- the uncertainty in the absolute calibration of the bolometer DKD specification:
  $U_1' = 0.098$ dB (k = 2) in the worst-case frequency range (80 – 100 MHz);
  $U_1' = 0.095$ dB (k = 2) above (100 – 1000 MHz);
  therefore, $u_1' = 11.41 \cdot 10^{-3}$ (f < 100 MHz) / $11.06 \cdot 10^{-3}$ (f ≥ 100 MHz)
- the linearity error of the instrument; the maximum deviation that was measured in the calibration at DKD was 0.33 % in power. Therefore, using a rectangular distribution, $u_2' = 1.92 \cdot 10^{-3}$

Therefore, the total uncertainty in the power measurement is

$$u_P' = \sqrt{u_1'^2 + u_2'^2}$$
$$= 11.57 \cdot 10^{-3} \text{ (f < 100 MHz)} / 11.23 \cdot 10^{-3} \text{ (f} \geq 100 \text{ MHz)}$$

Line impedance

In Figure 1, a characterization of our TEM-cells has been given. In the worst case, the line impedance can vary between Z_l*SWR and Z_l/SWR. For the TEM3-cell at, e. g., 110 MHz, SWR = 1.02. Thus, $Z_{max} = 51.0\ \Omega$ and $Z_{min} = 49.0\ \Omega$. The uncertainty in Z, based on a rectangular distribution, is shown in **Fig 2**.

Dimension d

Optical inspection of our TEM3-cell showed a variation in d of less than 1 mm over the test volume. Using a rectangular distribution we obtain $u_d' = 6.42 \cdot 10^{-3}$.

Mismatch between power meter and TEM-cell

For the calibration of the reference sensor at field strengths up to 100 V/m, the power head can be connected directly to the cell output. The VSWRs are
VSWR (power head) = 1.03:1,
VSWR (TEM3-cell): See Figure 1.

With a U-shaped distribution [10] , the corresponding uncertainty in the measured power is

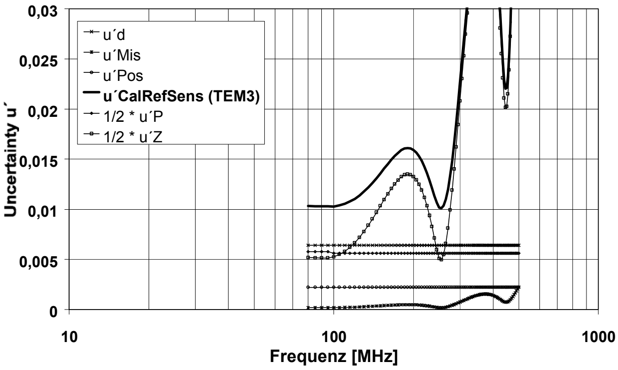

Fig. 2: Uncertainties in the calibration of the reference sensor in the TEM-cell

$$u'_{Mis} = \frac{\left(\left(1 \pm |\Gamma_{P.H.}| \cdot |\Gamma_{TEM3}|\right)^2 - 1\right)}{\sqrt{2}}$$, see Fig. 2.

Field distortion

Our transfer standard probe occupies only less than 1/10 of the height between septum and outer conductor of the TEM3-cell. The loading causes a change in the line impedance and, consequently, a change in the field-strength. The VSWR of the TEM3-cell was measured both with and without the probe inside, see Figure 1. The differences were insignificant and the VSWR did not exceed the maximum values specified above. Therefore, uncertainties due to the presence of the sensor in the cell are contained in $u_Z´$.

Positioning error

The positioning error can be easily controlled within ± 1 mm. The spacing between inner and outer conductor is 90 mm. The field-strength varies with height, where the correct value is found exactly in the center. At a distance of 1 cm from septum / outer conductor, the field is about 1.5 dB higher / lower than in the center. From field-mappings we find a field variation of less than 0.1 dB within 3 mm. Assuming a rectangular distribution, $u´_{Pos} = 2.22 \cdot 10^{-3}$.

Combined uncertainty

From the above contributions we find the combined uncertainty in field-strength

$$u'_{CalRefSens(TEM3)} = \sqrt{\left(\tfrac{1}{2}u'_P\right)^2 + \left(\tfrac{1}{2}u'_Z\right)^2 + {u'_d}^2 + {u'_{Mis}}^2 + {u'_{Pos}}^2}$$,

see Fig 2.

5.2 Uncertainty in the field-strength measured with a precision reference dipole PRD

The uncertainty in the antenna factor of a PRD has been shown to be $u´_{AF,PRD} = 8.46 \cdot 10^{-3}$ [8, 9]. Further contributions to the total uncertainty are the power measurement and the mismatch between PRD and power meter.

From 5.1, the uncertainty in the power measurement is

$u´_P = 11.57 \cdot 10^{-3}$ (f < 100 MHz) / $11.23 \cdot 10^{-3}$ (f ≥ 100 MHz)

Mismatch between PRD (with matching attenuator, return loss > 30 dB) and power meter:
VSWR (power head) = 1.030:1 ; $|\Gamma_{P.H.}| = 0.0148$
VSWR (PRD) = 1.065:1; $|\Gamma_{PRD}| = 0.0316$
With a U-shaped distribution [10] , the mismatch uncertainty is

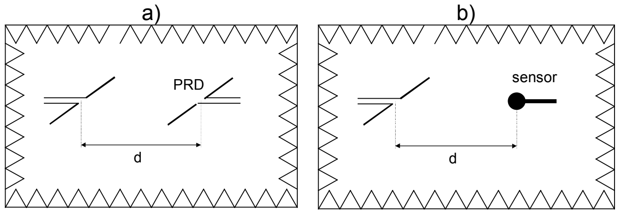

Fig. 3: Calibration of a field sensor in the anechoic chamber by substitution with precision reference dipoles
a) Field-strength measurement with the precision reference dipole
b) Field-strength measurement with the sensor

$$u'_{Mis} = \frac{\left(\left(1 \pm |\Gamma_{P.H.}| \cdot |\Gamma_{PRD}|\right)^2 - 1\right)}{\sqrt{2}} = 0.66 \cdot 10^{-3}$$

Thus, the combined uncertainty is

$$u'_{E,PRD} = \sqrt{\left(\tfrac{1}{2}u'_P\right)^2 + {u'_{AF,PRD}}^2 + {u'_{Mis}}^2} = 10.27 \cdot 10^{-3}$$

5.3 Uncertainty in the calibration of the reference sensor by substitution with the precision reference dipoles in the anechoic chamber

This is done in two steps, see **Fig. 3**:
(1) A field is set up in the chamber and measured by the dipole
(2) The dipole is replaced by the reference sensor and the field is measured again.

The contributions to the uncertainty in the calibration result are the following.

Uncertainty in the field-strength measurement with the precision reference dipole

From Chapter 5.2: $u´_{E,PRD} = 10.27 \cdot 10^{-3}$

Positioning error

The positioning of a small receiving antenna or sensor can be repeated within ± 1 mm. At 1 m distance this corresponds to an uncertainty in field-strength of $u´_{Pos} = 0.577 \cdot 10^{-3}$ (rectangular distribution)

Quantization in the reference power measurement

The output power of the transmitter must remain constant during the calibration procedure. Therefore, it is monitored via a directional coupler and a power meter. The measurement ranges can be chosen such that the quantization error is always less than 0.1 % in power. Applying a rectangular distribution, $u´_{Quant} = 0.144 \cdot 10^{-3}$.

Field distortion

Supports and receive cable have some unwanted, secondary influence on the field distribution. The change in the field distribution due to the substitution (sensor for dipole) causes an error. This error depends largely on the support material and the construction of the sensor.

We use styrofoam supports. Our reference sensor has an overall dipole length of only 8 mm. It is very small and has a high-impedance transmission line. The following results are valid for this special setup, but should be approximately the same for all sensors with high-impedance or fiber-optic transmission lines.

We have made repeated measurements in which we changed probe support and cable layout. The standard deviation in field-strength was $u´_{FieldDistort} = 12.32 \cdot 10^{-3}$ (0.11 dB).

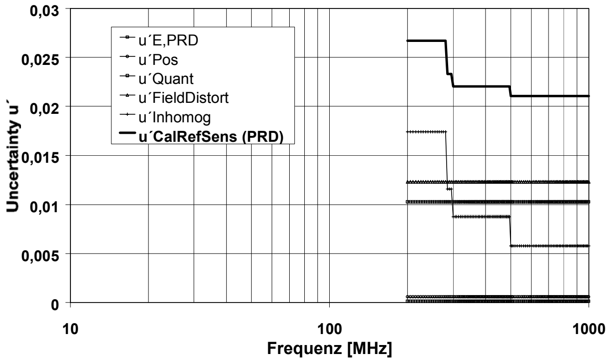

Fig. 4: Uncertainties in the calibration of the reference sensor by substitution with the precision reference dipole

Inhomogeneity of the test field

The dipole has an element length of 351 mm at 200 MHz, 140 mm at 500 MHz and 69 mm at 1 GHz. We have mapped the field over the volume that is occupied by one dipole element. The variation in field-strength was 0.3 dB at 250 MHz (maximum value), 0.2 dB at 280 MHz, 0.15 dB at 300 MHz and less than 0.1 dB above 500 MHz. The current distribution on the half-wave dipole weights the field such that the intensity around the center has most influence on the induced voltage and the intensity at the tip has much less. The resulting uncertainties from the inhomogeneity of the test field can be seen from **Fig. 4**.

Linearity errors of the meters

All measurements are made at all field levels that are finally desired for routine calibrations of sensors, i. e. 3 V/m, 10 V/m, 30 V/m and 100 V/m. Therefore, linearity errors need not be considered.

Combined uncertainty

From the above contributions we find the combined uncertainty in field-strength (Fig. 4)

$$u'_{CalRefSens(PRD)}$$
$$= \sqrt{u'_{E,PRD}{}^2 + u'_{Pos}{}^2 + 2 * u'_{Quant}{}^2 + 2 * u'_{FieldDistort}{}^2 + u'_{Inhomog}{}^2}$$

5.4 Uncertainty in routine field sensor calibrations using the substitution method

The method involves two steps:
(1) The reference sensor is set up in the chamber and the field is measured.
(2) The sensor to be calibrated (SUC) is exposed to the field.

The contributions to the uncertainty in the calibration result are the following.

Uncertainty in the calibration of the reference sensor

For miniumum uncertainty, we chose the TEM-cell based calibration for frequencies up to 300 MHz and the PRD based calibration above.

Positioning error

The position of the reference sensor can be reproduced with the customer´s sensor within typically ± 5 mm. At 1 m distance this corresponds to an uncertainty in field-strength of $u'_{Pos} = 2.885*10^{-3}$ (rectangular distribution).

Quantization in the reference power measurement, field distortion, linearity errors of the meters

See Section 5.3.

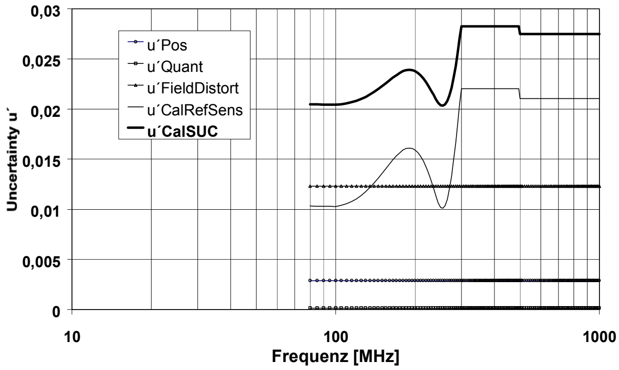

Fig. 5: Uncertainties in the routine sensor calibration by substitution with the reference sensor

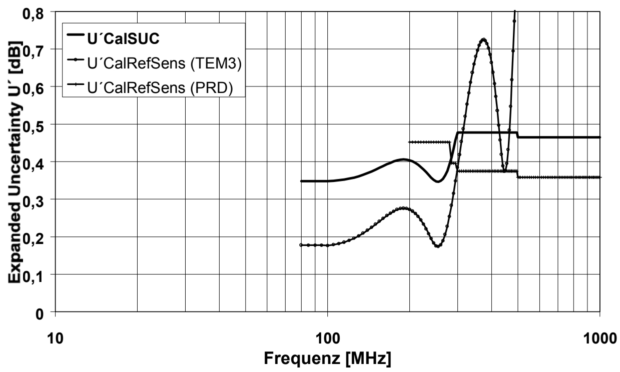

Fig. 6: Expanded uncertainties in the calibration of field sensors

Combined uncertainty

From the above contributions we find the combined uncertainty in the linear calibration factor of a sensor calibrated by the substitution method (Fig. 5) as

$$u'_{CalSUC} = \sqrt{u'^2_{CalRefSens} + u'^2_{Pos} + 2 * u'^2_{Quant} + 2 * u'^2_{FieldDistort}}$$

The term $u'_{FieldDistort}$ has been taken two times: One time for the influence of the reference sensor (for our sensor, the standard deviation was determined experimentally), and one time for the influence of the customer´s sensor under calibration (for this example we assume that it has the same characteristics as our reference sensor).

Expanded uncertainties

Fig. 6 summarizes the expanded uncertainties (at two standard deviations, 95.5 % confidence level). They are below 0.4 dB for the reference sensor and below 0.5 dB for the routine calibrations of customer´s sensors.

6. Summary and conclusions

In this paper, we describe the selection that was made in the Seibersdorf calibration laboratory to achieve maximum accuracy in reference standards, full traceability and best economy in procedures for routine calibrations. This is achieved by a two-fold approach:
(1) A reference sensor is calibrated in a TEM cell (80 – 300 MHz) and by substitution with calculable, precision dipoles (300 – 1000 MHz) in a fully anechoic chamber.
(2) Customer´s sensors are then calibrated by substitution with the reference sensor using swept-frequency techniques.

A very high level of accuracy has been reached by this method: The expanded uncertainty in the calibration of the reference standard sensor is less than 0.4 dB at two standard deviations at all frequencies. The expanded uncertainty in the calibration of customer´s sensors is less than 0.5 dB at two standard deviations at all frequencies, provided that the sensors have high-impedance or fiber-optic transmission lines beteween probe and readout. All measurements are fully traceable to national standards. Also, our results are compatible to results published by PTB Braunschweig [11]. On the basis of standard-gain horn antennas, we have successfully extended the method to frequencies up to 18 GHz.

The uncertainties have been derived from calculations and experiments using statistical methods. For verification, a comparison between the two standards, the TEM-cell and the dipoles, has been made. In the frequency range where both standards are applicable, the difference in the results was less than 0.15 dB [7]. This verifies the performance of the calibration facility and the estimations of uncertainty.

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