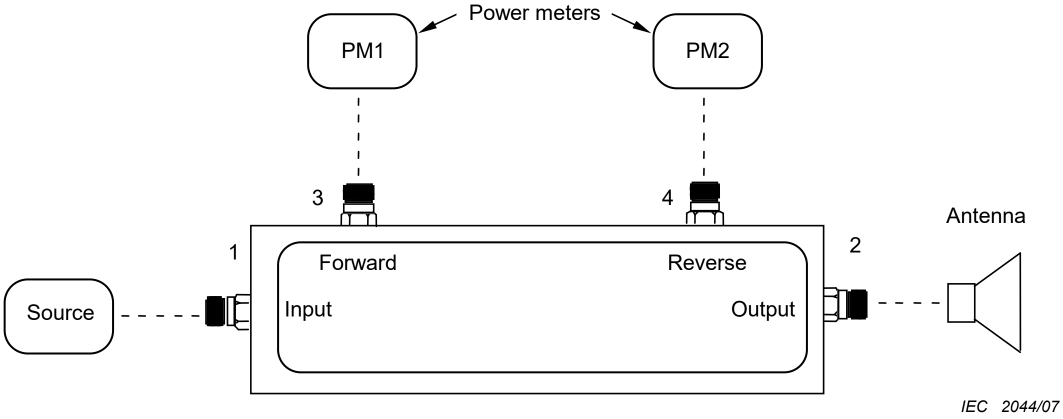

Figure I.2 – Setup for measuring net power to a transmitting device

The forward coupling, reverse coupling and transmission coupling are defined as the following equations in case where each port is connected with a matched load and a matched source:

$$C_{\mathrm{fwd}} = \frac{P_3}{P_1},$$

$$C_{\mathrm{rev}} = \frac{P_4}{P_2},$$

$$C_{\mathrm{trans}} = \frac{P_2}{P_1},$$

where P_1, P_2, P_3, P_4 are the respective powers at each port of the directional coupler.

The net power delivered to the transmitting device is then:

$$P_{\mathrm{net}} = \frac{C_{\mathrm{trans}}}{C_{\mathrm{fwd}}} PM_1 - \frac{PM_2}{C_{\mathrm{rev}}},$$

where PM_1 and PM_2 are the power meter readings in linear units.

Where the VSWR of the antenna is known, then a single three-port coupler can be used. For example, when the antenna has a VSWR of 1,5 this is equivalent to a voltage reflection coefficient (VRC) of 0,2.

The accuracy is affected by the directivity of the coupler. The directivity is a measure of the coupler's ability to isolate the forward and the reverse signals. For a well-matched transmitting device, the reverse power is much smaller than the forward power. The effect of the directivity is therefore less important than in a reflectivity application. For example, when the transmitting antenna has a VSWR of 1,5 and the coupler has a directivity of 20 dB, the absolute maximum uncertainty in the net power due to the finite directivity is 0,22 dB – 0,18 dB = 0,04 dB with a U-shaped distribution (where the 0,22 dB is the loss of the apparent incident power due to VSWR of 1,5).

The net power delivered to the transmitting device is then:

$$P_{\mathrm{net}} = C_{\mathrm{fwd}} PM_1 \left(1 - VRC^2\right)$$

I.4.2.2 Establishing a standard field using horn antennas

The gain of the horn antenna is determined by the methods described in I.3.3. The on-axis electric field (in V/m) is determined by

$$E = \sqrt{\frac{\eta_0 P_{\mathrm{net}} g}{4\pi}} \frac{1}{d},$$

where $\eta_0 = 377\ \Omega$ for free space, P_{net} (in W) is the net power determined by the method described in I.4.2.1, g is the numeric gain of the antenna determined by I.3.3 and d (in m) is the distance from the antenna aperture.

I.4.2.3 Chamber validation test frequency range and frequency steps

The chamber VSWR test shall cover the frequency range for which the calibration of the probe is intended, and use the same frequency steps as given in I.2.3.

VSWR tests shall be carried out in the chamber at the lowest and highest frequencies of operation of each antenna. Where narrow band absorbers are used, e.g. ferrites, more frequency points may need to be measured. The chamber should be used for probe calibration only in the frequency range where it meets the VSWR criteria.

I.4.2.4 Chamber validation procedure

The chamber used for the probe calibration shall be verified by the following procedure, except in cases where the physical conditions of the chamber do not allow it to be used. In such cases the alternative method of I.4.2.7 can be applied.

The probe shall be located at the measurement position using a support material with a low permittivity (e.g. styrene foam) in accordance with Figure I.3 and Figure I.4.

A field probe is placed at the location where it will be used for calibration. Its polarization and position along the boresight of the transmitting horn antenna will be varied to determine the chamber VSWR. The transmit antenna shall be the same for both the chamber VSWR test and the probe calibration.

The arrangements of the standard gain horn antenna and the probe inside the chamber are shown in Figure I.3. The probe and the horn antenna shall be set on the same horizontal axis with a separation distance L measured from the front face of the antenna to the centre of the probe.

In every case the field probe shall be laterally positioned in the centre of the horn antenna face.

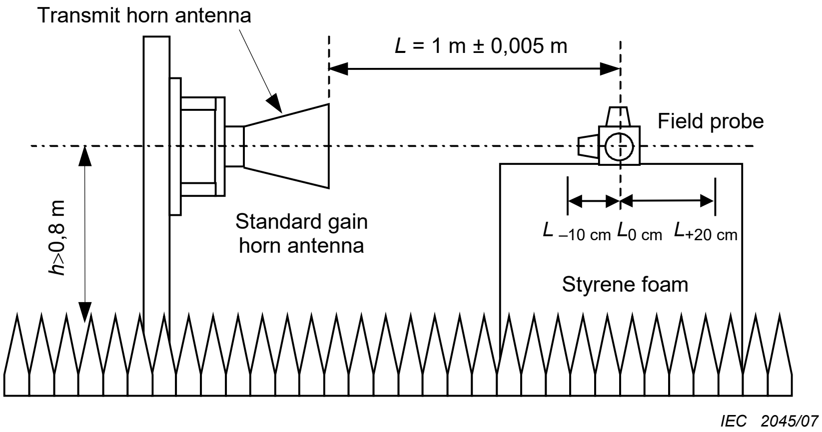

Figure I.3 – Test setup for chamber validation test

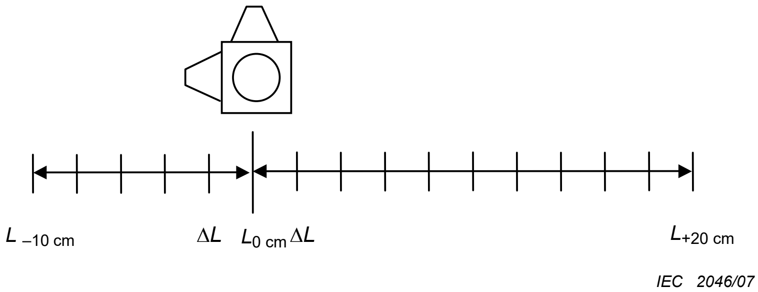

Figure I.4 – Detail for measurement position ΔL

The setup is illustrated in Figure I.3 and Figure I.4, where $L_{-10\ \mathrm{cm}}$ to $L_{+20\ \mathrm{cm}}$ is the probe calibration distance, measured from the face of the horn antenna to the centre of the field probe. $L_{0\ \mathrm{cm}}$ is defined as position 0.

The positions will be L-10 cm, L-8 cm, L-6 cm, …,L_0, L+2 cm, L+4 cm, …, L+20 cm, ΔL = 2 cm.

If the probe is placed in the near field of the transmitting horn antenna (distance < 2 D^2/λ, where D is the largest dimension of the antenna and λ is the free space wavelength), the gain of the transmitting antenna is not constant, and may need to be determined for each position.

A constant power creating certain field strength (e.g. 20 V/m) at 1 m distance is applied for all probe positions. With the transmit antenna and field probe both vertically polarized, the probe readings for all positions at all frequencies are recorded. The test is repeated with antenna and probe horizontally polarized.

All the readings shall satisfy the requirement shown in I.4.2.5.

I.4.2.5 VSWR acceptance criteria

VSWR measurement results shall be compared by using the following procedure. For the calculation of the field strength, refer to I.4.2.2.

a) Calculation of the field strength

The electrical field strength in the spatial area between the distances 90 cm and 120 cm is calculated in 2 cm steps for each frequency.

This calculation is based on the E-field strength of a 1 m distance used for verification.

b) Data adjustment

Data is adjusted with the following process because the probe used for the VSWR measurement may not deliver a reading equal to the calculated field strength.

– E-field strength indication value of the probe at a 1 m distance shall be adjusted to the 1 m position of the calculation. The obtained difference between probe indications and calculated strength is used as the correction value *k* for all the data at 90 cm and 120 cm.

  For example: comparison between probe measurement value V_{mv} (e.g. 21 V/m) and calculated value V_{cv} (e.g. 20 V/m) at 1 m distance. In this case the correction value *k* is $V_{cv} - V_{mv} = -1$ V/m.

– The correction value *k* shall be added to the data that is observed at 90 cm to 120 cm measurement positions.

– The same calculation shall be applied to all measurement values of all measured frequencies. In the case of the above example, *k* = –1 V/m. Therefore *k* = –1 is added to all probe measurement value data.

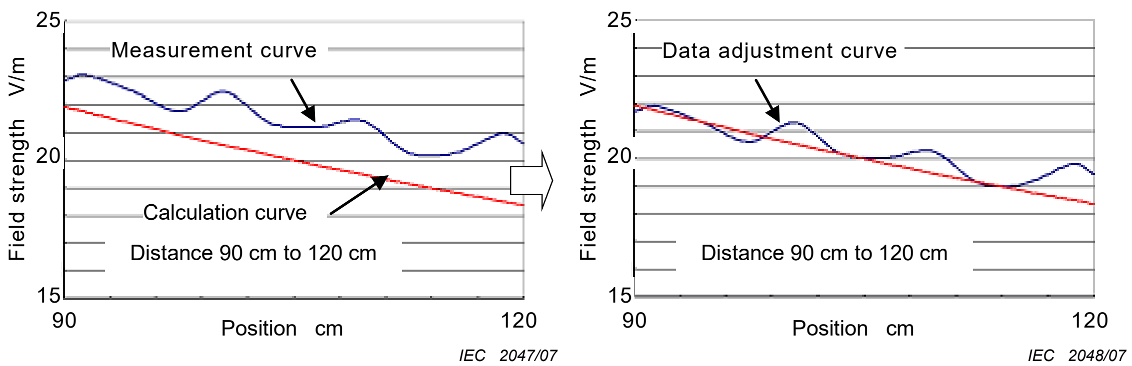

Figure I.5 – Example of data adjustment

c) Comparison of measurement data and calculation data

When the data difference in calculation curve and measurement curve exceeds ± 0,5 dB in any measurement position, the chamber shall not be used for probe calibration.

NOTE The 0,5 dB criterion is established according to the measurement uncertainty budget and has been verified in several existing chambers that are suitable for calibration of field probes (including at least one national measurement institute calibration facility). It is anyhow only one contributor to the overall uncertainty.

Some field probes have a metal box or a pole such as the battery or a circuit. These units may cause reflection errors at certain distances and frequencies. When these probes are used, the influence of the reflection shall be minimized e.g. by rotating the probe or changing its orientation.

I.4.2.6 Probe fixture validation

The probe fixture may cause reflections of electromagnetic fields during the probe calibration. Therefore, the influence of the fixture on the calibration results shall be checked in advance.

The procedure defined in this clause shall be performed for any new probe fixtures to be used.

Procedure:

a) Place the probe on a reference support made of a material with a relative permittivity of less than 1,2 and a dielectric loss tangent less than 0,005. The location of the probe shall be the same as for the calibration setup. The reference fixture should be as small as possible. Any other supporting structures shall be as non-intrusive as possible, and at least 50 cm away from the probe. Support structures in front (between the antenna and the probe) or behind the probe should be avoided.

b) Generate a standard field that is within the dynamic range of the probe at the calibration position.

c) Record the probe reading for all calibration frequency points. Rotate or re-position the probe as necessary for all calibration geometries (for three-axis isotropic field probes, each axis may need to be aligned separately), and repeat steps 1 and 2. Record probe readings for all orientations.

d) Remove the reference fixture and replace it with the calibration fixture to be qualified. Repeat steps 2, and 3.

e) Compare results from steps 3 and 4. The difference between the readings with the two fixtures for the same probe orientation shall be less than ± 0,5 dB.

I.4.2.7 Alternative chamber validation procedure

This alternative chamber validation procedure is applicable when the validation procedure of I.4.2.4 cannot be applied.

A field probe is placed at the location where it will be used for calibration. Its polarization and position along the boresight of the transmitting horn antenna will be varied to determine the chamber VSWR. The transmit antenna shall be the same for both the chamber VSWR test and the probe calibration.

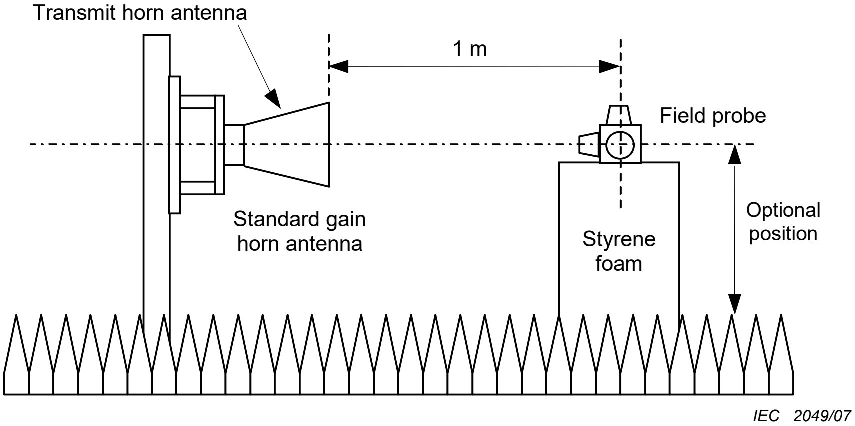

Figure I.6 – Example of the test layout for antenna and probe

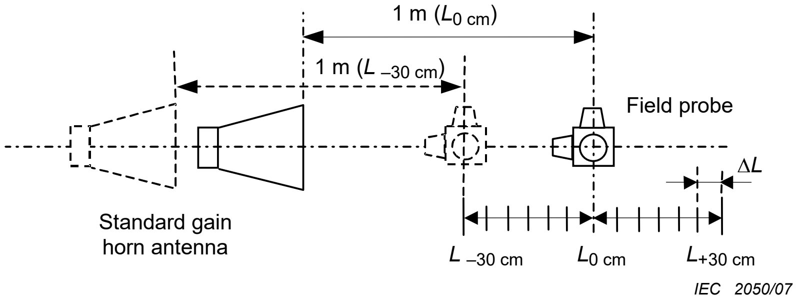

Figure I.7 – Test setup for chamber validation test

The setup is illustrated in Figures I.6 and I.7, where the probe calibration distance, measured from the face of the horn antenna to the centre of the field probe is maintained at a fixed distance, i.e. 1 m.

It is desirable to use material with low permittivity for the probe fixture to avoid influences on the measurement. The fixture used for probe calibration shall be evaluated separately (see I.4.2.6).

The positions will be L - 30 cm, L - 25 cm, L - 20 cm, ..., L_0, L + 5 cm, L + 10 cm, ..., L + 30 cm, ΔL is 5 cm.

A constant field, e.g. 20 V/m, is generated for all positions. The generated field strength needs to be within the dynamic range of the field probe. With the transmit antenna and field probe both vertically polarized: record the probe reading for all positions at all frequencies. Repeat the test with the antenna and probe horizontally polarized.

At each frequency, there will be 26 independent probe readings (13 positions, and two polarizations). The maximum spread of the readings at each frequency shall be less than ±0,5 dB.

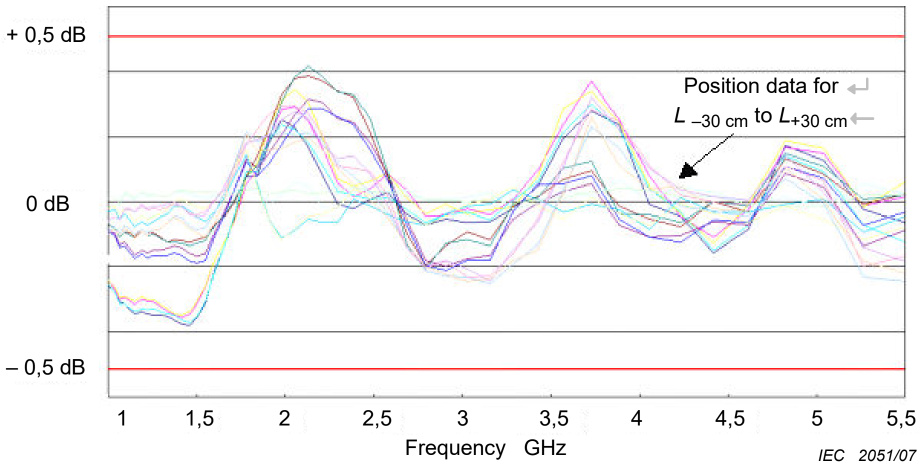

Figure I.8 – Example alternative chamber validation data

I.4.3 Probe calibration procedure

Many modern probes have internal correction factors to provide a linear response. Calibration laboratories may adjust the factors during calibration to give a probe response of ±0,5 dB from the ideal. If adjustments are made, the calibration laboratory should report the response both before and after adjustment.

The linearity check process should be applicable to the probe to be calibrated. For the influences of linearity on the calibration system, refer to I.3.2.

NOTE When it is not possible to adjust the probe, any non-linearity should be compensated for by the user when carrying out the field uniformity calibration.

The probe calibration shall use the measurement system/environment, which satisfies the requirement of I.4.

I.4.3.1 Test setup

A fixture that is not fully qualified according to I.4.2.6 can result in large measurement uncertainties. Therefore, the probe fixture validated per I.4.2.6 shall be used.

The calibration of the field probe should be done according preferably to the user specification or manufacturer's specification regarding the probe orientation. This orientation shall also be used in the test laboratory to limit the effect of isotropy. If the manufacturer does not specify any field probe orientation in the data sheet, the calibration should be performed in the probe orientation which can be considered as the "normal use" orientation of the probe or according to a preferred orientation defined by the test lab (which will use the probe). In any case the calibration report shall include the field probe orientation for which the calibration was undertaken.

The example of the measurement setup is shown in the Figures I.9 and I.10.

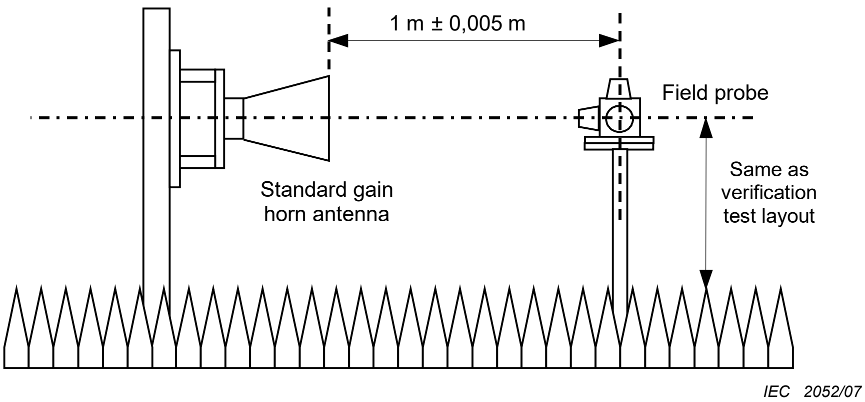

Figure I.9 – Field probe calibration layout

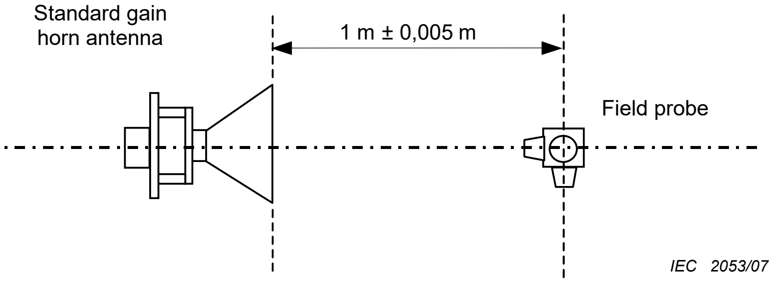

Figure I.10 – Field probe calibration layout (Top view)

I.4.3.2 Calibration report

The measurement results obtained in consideration of I.4.3.1 shall be reported as a calibration report.

This calibration report shall contain at least the following:

a) calibration environment;
b) probe manufacturer;
c) type designation;
d) serial number;
e) calibration date;
f) temperature and humidity;
g) details of the calibration data:
   – frequency;
   – applied field strength (V/m);
   – probe reading (V/m);
   – probe orientation;
h) measurement uncertainty.

NOTE IEEE Std 1309 [2] includes some guidance for probe-calibration measurement uncertainty.

I.5 Alternative probe calibration environments and methods

This clause describes the environment requirement for alternative calibration sites, e.g. necessary for the calibration in the low frequency range.

The calibration can be done in environments defined as independent from the test environment described in IEC 61000-4-3. In contrast to the equipment, which is tested for immunity, field probes are typically small and usually not equipped with conducting cables.

I.5.1 Field probe calibration using TEM cells

A rectangular TEM cell can be used to establish standard fields for field probe calibrations. The upper usable frequency of a TEM cell can be determined by methods described in 5.1 of IEC 61000-4-20.The upper frequency of a TEM cell is typically a few hundreds MHz. The field at the centre of a TEM cell between the septum and the top or bottom plate is calculated from:

$$E = \frac{\sqrt{Z_0 P_{\text{net}}}}{h} \text{ (V/m)},$$

where Z_0 is the characteristic impedance of the TEM cell (typically 50 Ω), P_{net} is the net power in Watt, which is determined according to I.4.2.1, h is the separation distance between the septum and the top or bottom plate (in m).

The VSWR of the TEM cell should be kept small, e.g. less than 1,3 to minimize the measurement uncertainties.

An alternative method of measuring P_{net} is to use a calibrated, low VSWR attenuator and power sensor connected to the output port of the TEM cell.

I.5.2 Field probe calibration using waveguide chambers

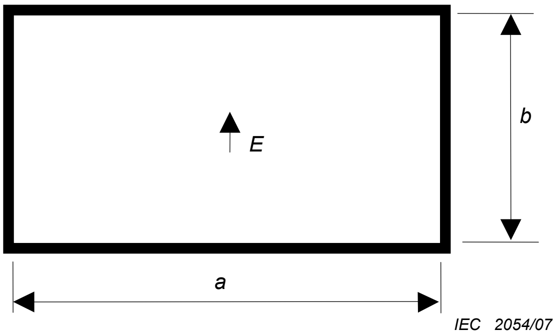

Figure I.11 – Cross-sectional view of a waveguide chamber

Calibration labs shall ensure that waveguide chambers operate in their dominant TE_{10} mode. Frequencies that can excite higher order modes shall be avoided. Waveguide manufacturers typically specify the frequency ranges for which only a dominant mode can exist. This can also be determined from the dimensions of the waveguide. The use of waveguide chambers is limited to approximately 300 MHz to 1 000 MHz with typical sized probes.

For a waveguide chamber with inner dimensions of *a* (m) x *b* (m) (*a*>*b*), the cut-off frequency of the dominant TE_{10} mode is:

$$(f_c)_{10} = \frac{1}{2a\sqrt{\mu\varepsilon}},$$

where μ and ε are the permeability and permittivity of the waveguide media. For air-filled waveguides, $\mu = \mu_0 = 400\pi$ nHm^{-1} and $\varepsilon = \varepsilon_0 = 8{,}854$ pFm^{-1}. The cut-off frequency for an air-filled waveguide chamber is:

$$(f_c)_{10} = \frac{150}{a}\ \text{MHz.}$$

The root-mean-square electric field at the centre of the waveguide is:

$$E = \sqrt{\frac{2\eta_0 P_{net}}{ab\sqrt{1-\left((f_c)_{10}/f\right)^2}}}\ \text{(V/m),}$$

where *f* (in MHz) is the frequency of operation, $\eta_0 = 377\ \Omega$ for air-filled waveguide, P_{net} (in W) is the net power delivered to the waveguide, and is determined by the method described in I.4.2.1. Note that the field inside a waveguide chamber is not a TEM wave, and the field is the largest at the centre of the waveguide (with a sinusoidal distribution, tapering to zero on the sidewalls). It is recommended that field probe calibrations be performed at the centre of the waveguide, where the field distribution has less variation (is more uniform) than at other locations. For more information on waveguide including how to calculate cut-off frequencies for other modes, refer to [5].

I.5.3 Field probe calibration using open-ended waveguides

An analytical solution and an empirical solution for the near-field gain of open-ended waveguides are provided in [6]. Since a simple theoretical solution for the near-field gain of open-ended waveguides is not available, one should determine the near-field gain of an open-ended waveguide by either full-wave numerical techniques or by measurement techniques as described in [4].

Once the near-field gain of the open-ended waveguides is determined, the calibration shall follow the procedure listed in I.4.3.

I.5.4 Calibration of field probes by gain transfer method

A transfer probe can be used to establish standard fields in a field-generating device (working standard device). The transfer probe response can be either determined by theoretical computations (for probes such as dipoles), or by calibrations performed according to the methods described in I.5.1 or I.5.2. The transfer function of the working standard, such as a GHz TEM cell, can be determined from the transfer probe. The field distribution in the working standard device should be mapped by the transfer probe; i.e. it has to be measured at as many locations as necessary to assess the field homogeneity in the test volume. Once the transfer function of the working standard device is known, probe calibration can be performed at other power levels provided that the working standard device is linear. A probe to be calibrated shall be placed at the same location where the transfer probe has been.

The transfer method is accurate if the following conditions are met:

- the setup does not change between the transfer and calibration procedures;
- the probe position during measurements is reproduced;
- the transmitted power remains the same;
- the probe under test is similar in construction (size and element design) to the transfer probe;
- the cables connecting the sensor head and readout do not disturb or pick up the field;
- the working standard device is largely anechoic.

References [7] and [8] have more information on this method.

I.6 Reference documents

[1] STUBENRAUCH, C., NEWELL, C. A. C., REPJAR, A. C. A., MacREYNOLDS, K., TAMURA D. T., LARSON, F. H., LEMANCZYK, J., BEHE, R., PORTIER, G., ZEHREN, J. C., HOLLMANN, H., HUNTER, J. D., GENTLE, D. G., and De VREEDE, J. P. M. International Intercomparison of Horn Gain at X-Band. *IEEE Trans. On Antennas and Propagation*, October 1996, Vol. 44, No. 10.

[2] IEEE 1309, *Calibration of Electromagnetic Field Sensors and Probes, Excluding Antennas, from 9 kHz to 40 GHz*.

[3] KANDA, M. and KAWALKO, S. Near-zone gain of 500 MHz to 2.6 GHz rectangular standard pyramidal horns. *IEEE Trans. On EMC*, 1999, Vol. 41, No. 2.

[4] NEWELL, Allen C., BAIRD, Ramon C. and Wacker, Paul F. Accurate measurement of antenna gain and polarization at reduced distances by extrapolation technique. *IEEE Trans. On Antennas and Propagation*, July 1973, Vol. AP-21, No. 4.

[5] BALANIS, C. A.. *Advanced Engineering Electromagnetics*. John Wiley & Sons, Inc., 1989, pp 363-375.

[6] WU, Doris I. and KANDA, Motohisa. Comparison of theoretical and experimental data for the near field of an open-ended rectangular waveguide. *IEEE Trans. On Electromagnetic Compatibility*, November 1989, Vol. 31, No. 4.

[7] GLIMM, J., MÜNTER, K., PAPE, R., SCHRADER, T. and SPITZER, M. *The New National Standard of EM Field Strength; Realisation and Dissemination*. 12th Int. Symposium on EMC, Zurich, Switzerland, February 18-20, 1997, ISBN 3-9521199-1-1, pp. 611-613.

[8] GARN, H., BUCHMAYR, M., and MULLNER, W. Precise calibration of electric field sensors for radiated-susceptibility testing. *Frequenz* 53 (1999) 9-10, Page 190-194.

Annex J
(informative)

Measurement uncertainty due to test instrumentation

J.1 General

This annex gives information related to measurement uncertainty (MU) of the test level setting according to the particular needs of the test method contained in the main body of the standard. Further information can be found in [1, 2][2].

This annex shows an example of how an uncertainty budget can be prepared based upon level setting. Other parameters of the disturbance quantity such as modulation frequency and modulation depth, harmonics produced by the amplifier may also need to be considered in an appropriate way by the test laboratory. The methodology shown in this annex is considered to be applicable to all parameters of the disturbance quantity.

The uncertainty contribution for field homogeneity including test site effects is under consideration.

J.2 Uncertainty budgets for level setting

J.2.1 Definition of the measurand

The measurand is the hypothetical test electric field strength (without an EUT) at the point of the UFA selected according to the process of 6.2.1 step a) and 6.2.2 step a) of this standard.

J.2.2 MU contributors of the measurand

The following influence diagram (see Figure J.1) gives an **example** of influences upon level setting. It applies to both calibration and test processes and it should be understood that the diagram is not exhaustive. The most important contributors from the influence diagram have been selected for the uncertainty budget Tables J.1 and J.2. As a minimum, the contributions listed in Tables J.1 and J.2 shall be used for the calculation of the uncertainty budgets in order to get comparable budgets for different test sites or laboratories. It is noted that a laboratory may include additional contributors in the calculation of the MU, on the basis of its particular circumstances.

[2] Figures in square brackets refer to the reference documents in Clause J.4.