

Electromagnetic compatibility (EMC) —

Part 4-20: Testing and measurement techniques — Emission and immunity testing in transverse electromagnetic (TEM) waveguides

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National foreword

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**Electromagnetic compatibility (EMC)
Part 4-20: Testing and measurement techniques –
Emission and immunity testing
in transverse electromagnetic (TEM) waveguides
(IEC 61000-4-20:2003)**

Compatibilité électromagnétique (CEM)
Partie 4-20: Techniques d'essai
et de mesure –
Essais d'émission et d'immunité
dans les guides d'onde TEM
(CEI 61000-4-20:2003)

Elektromagnetische Verträglichkeit (EMV)
Teil 4-20: Prüf- und Messverfahren -
Messung der Störaussendung
und Störfestigkeit in transversal-
elektromagnetischen (TEM-) Wellenleitern
(IEC 61000-4-20:2003)

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Foreword

The text of document CIS/A/419/FDIS, future edition 1 of IEC 61000-4-20, prepared by CISPR SC A, Radio-interference measurements and statistical methods, in cooperation with SC 77B, High frequency phenomena, of IEC TC 77, Electromagnetic compatibility, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61000-4-20 on 2003-04-01.

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Annexes designated "normative" are part of the body of the standard.

Annexes designated "informative" are given for information only.

In this standard, annexes A, B, C and ZA are normative and annexes D and E are informative.

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61000-4-20:2003 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

CISPR 14	NOTE	Harmonized in EN 55014 series (not modified).
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IEC 61000-2-9	NOTE	Harmonized as EN 61000-2-9:1996 (not modified).

Foreword to amendment A1

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Annex ZA has been added by CENELEC.

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IEC 61000-4-3	NOTE	Harmonized as EN 61000-4-3:2006 (not modified).
CISPR 16-4-2	NOTE	Harmonized as EN 55016-4-2:2004 (not modified).

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INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

- General considerations (introduction, fundamental principles)
- Definitions, terminology

Part 2: Environment

- Description of the environment
- Classification of the environment
- Compatibility levels

Part 3: Limits

- Emission limits
- Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

- Measurement techniques
- Testing techniques

Part 5: Installation and mitigation guidelines

- Installation guidelines
- Mitigation methods and devices

Part 6: Generic Standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as International Standards, Technical Specifications or Technical Reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and a second number identifying the subdivision (example: 61000-6-1).

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 4-20: Testing and measurement techniques – Emission and immunity testing in transverse electromagnetic (TEM) waveguides

1 Scope and object

This part of IEC 61000 relates to emission and immunity test methods for electrical and electronic equipment using various types of transverse electromagnetic (TEM) waveguides. This includes open (for example, striplines and EMP simulators) and closed (for example, TEM cells) structures, which can be further classified as one-, two-, or multi-port TEM waveguides. The frequency range depends on the specific testing requirements and the specific TEM waveguide type.

The object of this standard is to describe

- TEM waveguide characteristics, including typical frequency ranges and EUT-size limitations;
- TEM waveguide validation methods for EMC measurements;
- the EUT (i.e. EUT cabinet and cabling) definition;
- test set-ups, procedures, and requirements for radiated emission testing in TEM waveguides and
- test set-ups, procedures, and requirements for radiated immunity testing in TEM waveguides.

[A1] NOTE Test methods are defined in this standard for measuring the effects of electromagnetic radiation on equipment and the electromagnetic emissions from equipment concerned. The simulation and measurement of electromagnetic radiation is not adequately exact for quantitative determination of effects for all end-use installations. The test methods defined are structured for a primary objective of establishing adequate repeatability of results at various test facilities for qualitative analysis of effects.

This standard does not intend to specify the tests to be applied to any particular apparatus or system(s). The main intention of this standard is to provide a general basic reference for all interested product committees of the IEC. For radiated emissions testing, product committees should select emission limits and test methods in consultation with CISPR. For radiated immunity testing, product committees remain responsible for the appropriate choice of immunity tests and immunity test limits to be applied to equipment within their scope. This standard describes test methods that are separate from those of IEC 61000-4-3. These other distinct test methods may be used when so specified by product committees, in consultation with CISPR and TC 77. **[A1]**

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050(161), *International Electrotechnical Vocabulary (IEV) – Chapter 161: Electromagnetic compatibility*

IEC 60068-1, *Environmental testing – Part 1: General and guidance*.

IEC 61000-2-11, *Electromagnetic compatibility (EMC) – Part 2-11: Environment – Classification of HEMP environments*. Basic EMC publication

[A1] Text deleted **[A1]**

IEC 61000-4-23, *Electromagnetic compatibility (EMC) – Part 4-23: Testing and measurement techniques – Test methods for protective devices for HEMP and other radiated disturbances*. Basic EMC publication

IEC/TR 61000-4-32, *Electromagnetic compatibility (EMC) – Part 4-32: Testing and measurement techniques – HEMP simulator compendium*

IEC/TR 61000-5-3, *Electromagnetic compatibility (EMC) – Part 5-3: Installation and mitigation guidelines – HEMP protection concepts*. Basic EMC publication

Ⓐ CISPR 16-1-1, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-1: Radio disturbance and immunity measuring apparatus – Measuring apparatus*

CISPR 16-1-4, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Ancillary equipment – Radiated disturbances*

CISPR 16-2-3, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 2-3: Methods of measurement of disturbances and immunity – Radiated disturbance measurements*

CISPR 16-2-4, *Specification for radio disturbance and immunity measuring apparatus and methods – Part 2-4: Methods of measurement of disturbances and immunity – Immunity measurements* Ⓐ

CISPR 22, *Information technology equipment – Radio disturbance characteristics – Limits and methods of measurement*

3 Definitions and abbreviations

3.1 Definitions

For the purposes of this part of IEC 61000, the definitions given in IEC 60050(161) (IEV), as well as the following, apply.

3.1.1

transverse electromagnetic (TEM) mode

waveguide mode in which the components of the electric and magnetic fields in the propagation direction are much less than the primary field components across any transverse cross-section

3.1.2

TEM waveguide

open or closed transmission line system, in which a wave is propagating in the transverse electromagnetic mode to produce a specified field for testing purposes

3.1.3

TEM cell

enclosed TEM waveguide, often a rectangular coaxial line, in which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes. The outer conductor completely encloses the inner conductor

3.1.4

two-port TEM waveguide

TEM waveguide with input/output measurement ports at both ends

3.1.5**one-port TEM waveguide**

TEM waveguide with a single input/output measurement port. Such TEM waveguides typically feature a broadband line termination at the non-measurement-port end

3.1.6**stripline**

terminated transmission line consisting of two or more parallel plates between which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes. Usually the sides are open for EUT access and monitoring

3.1.7**inner conductor or septum**

inner conductor of a coaxial transmission line system, often flat in the case of a rectangular cross-section. The inner conductor may be positioned symmetrically or asymmetrically with respect to the outer conductor

3.1.8**outer conductor or housing**

outer conductor of a coaxial transmission line system, often having a rectangular cross-section

3.1.9**characteristic impedance**

for any constant phase wave-front, the magnitude of the ratio of the voltage between the inner conductor and the outer conductor to the current on either conductor. The characteristic impedance is independent of the voltage/current magnitudes and depends only on the cross-sectional geometry of the transmission line. TEM waveguides are typically designed to have a 50 Ω characteristic impedance. TEM waveguides with a 100 Ω characteristic impedance are often used for transient testing

3.1.10**anechoic material**

material that exhibits the property of absorbing, or otherwise reducing, the level of electromagnetic energy reflected from that material

3.1.11**broadband line termination**

termination which combines a low-frequency discrete-component load, to match the characteristic impedance of the TEM waveguides (typically 50 Ω), and a high-frequency anechoic-material volume

3.1.12**correlation algorithm**

mathematical routine for converting TEM waveguide voltage measurements to open-area test sites (OATS), semi-anechoic chamber (SAC), or free space field strength levels

3.1.13**EUT type**

grouping of products with sufficient similarity in electromagnetic characteristics to allow testing with the same test installation and the same test protocol

3.1.14**exit cable**

cable that connects the EUT to equipment external to the TEM waveguide or exiting the usable test volume defined in 5.1.2.

3.1.15

interconnecting cable

cable that connects subcomponents of the EUT within the test volume but does not exit the test volume

3.1.16

test set-up support

non-reflecting, non-conducting, low-permittivity support and positioning reference that allows for precise rotations of the EUT as required by a correlation algorithm or test protocol

NOTE 1 A typical material is foamed polystyrene. Wooden supports are not recommended (see [7]¹).

3.1.17

ortho-angle

angle that the diagonal of a cube makes to each side face at the trihedral corners of the cube. Assuming that the cube is aligned with the TEM waveguide Cartesian coordinate system, the azimuth and elevation angles of the projection of the cube diagonal are 45°, and the angles to the face edges are 54,7° (see Figure A.2a)

NOTE 2 When associated with the EUT, this angle is usually referred to as the ortho-axis.

3.1.18

primary (field) component

electric field component aligned with the intended test polarization

NOTE 3 For example, in conventional two-port TEM cells, the septum is parallel to the horizontal floor, and the primary mode electric field vector is vertical at the transverse centre of the TEM cell.

3.1.19

secondary (field) component

in a Cartesian coordinate system, either of the two electric field components orthogonal to the primary field component and orthogonal to each other

3.1.20

resultant field (amplitude)

root-sum-squared values in V/m of the primary and the two secondary field components

3.1.21

manipulator

any type of manual or automatic non-metallic fixtures similar to a turntable, and capable of supporting an affixed EUT throughout numerous positions as required by a correlation algorithm or test protocol. The material has to meet the requirements defined for the test set-up support (see 3.1.16). For example, see Figure A.2

3.1.22

hyper-rotated TEM waveguide

TEM waveguide that has been reorientated such that its ortho-axis is normal to the Earth's surface (see [6])

¹ Figures in square brackets refer to the bibliography.

3.1.23**gravity-dependent / -independent**

the gravitation force of the earth has a fixed direction. The EUT can be rotated around all three axes. Due to different rotation positions the EUT is affected by the gravitation force in different directions. The EUT is gravity-independent if it is working properly in all positions, which means working properly regardless of the direction of the gravity vector relative to the EUT. The EUT is gravity-dependent if it does not work properly in one or more test positions

3.2 Abbreviations

BALUN	Balanced-to-unbalanced transformer
DFT	Discrete Fourier Transform
EUT	Equipment under test
FFT	Fast Fourier Transform
GTEM	Gigahertz transverse electromagnetic mode
HEMP	High-altitude electromagnetic pulse
OATS	Open-area test site
PoE	Points of entry
RF	Radiofrequency
SAC	Semi-anechoic chamber
SPD	Surge protective device
TDR	Time-domain reflectometer
TE	Transverse electric (mode), (H-mode)
TEM	Transverse electromagnetic mode
TM	Transverse magnetic (mode), (E-mode)
VSWR	Voltage-standing-wave-ratio

4 General

This standard describes basic characteristics and limitations of TEM waveguides, namely test volume, field uniformity, purity of the TEM mode, and frequency ranges. An introduction and some fundamental characteristics of TEM waveguides are given in Annex D.

Radiated emission measurements in a TEM waveguide are usually correlated with the open-area test site (OATS) and semi-anechoic chamber (SAC) methods, which provide valid and repeatable measurement results of disturbance field strength from equipment. In this case so-called correlation algorithms are used to convert TEM waveguide measurement results to OATS-equivalent data, as described in Annex A. Product committees should demonstrate that good correlation exists between measurement results using typical product types.

TEM waveguides can also be used as field generators for testing the immunity of equipment to electromagnetic fields. Details are given in Annex B. Immunity testing in TEM waveguides is cited in several other standards listed in Annex E.

TEM waveguide measurements are not restricted to radiated measurements on fully assembled equipment; they may also be applied to the testing of components, integrated circuits, and the shielding effectiveness of gasket materials and cables.

5 TEM waveguide requirements

TEM waveguides can be used for emission and immunity measurements when certain requirements are met. For the validation of a TEM waveguide the following methods shall be applied.

NOTE This clause focuses on general validation aspects such as the dominant TEM mode and field homogeneity. Specific validation requirements for emission, immunity, and transient testing are given in the annexes.

5.1 General requirements for the use of TEM waveguides

5.1.1 TEM mode verification

TEM waveguides may exhibit resonances above a certain cut-off frequency determined by the cross-sectional dimensions and/or the waveguide length. For practical use, the field in a TEM waveguide is considered to propagate in a TEM mode when the following requirements are met. Generally, a TEM waveguide manufacturer has to verify and document the TEM mode behaviour over the desired frequency range and include verification data with the system documentation.

NOTE 1 The TEM mode behaviour must be confirmed at regular intervals (see B.2.2).

Using an immunity-type uniform-area calibration procedure (according to B.2.2) the magnitudes of the secondary (unintended) electric field components shall be at least 6 dB less than the primary component of the electric field, over at least 75 % of the measured points in a defined cross-section of the TEM waveguide (perpendicular to the propagation direction). For this 75 % of measurement points, a primary electric field component tolerance greater than ${}_{+6}^{-0}$ dB up to ${}_{+10}^{-0}$ dB, or a secondary electric field component level up to -2 dB of the primary field component, is allowed for a maximum of 3 % of the test frequencies (at least one frequency), provided that the actual tolerance and frequencies are stated in the test reports. For large TEM waveguides a maximum of 3 % of the test frequencies is recommended; up to 5 % is allowed if stated in the test reports. The frequency range is 30 MHz up to the highest frequency of intended use of the TEM waveguide. The first frequency step shall not exceed 1 % of the fundamental frequency and thereafter 1 % of the preceding frequency in 80 MHz to 1 000 MHz, 5 % below 80 MHz and above 1 000 MHz. One constraint on the sweep speed is the response time of the field probe. This verification of the TEM mode applies to waveguides used either for immunity or emissions testing.

NOTE 2 For transient measurements the start frequency should be 100 kHz.

NOTE 3 The 6 dB criterion from 5.1.1 specifies the dominant TEM mode and not the field uniformity. A field is considered uniform if the requirements of B.2.2 are fulfilled. Further information about field uniformity is given in [17].

5.1.2 Test volume and maximum EUT size

The maximum size of an EUT is related to the size of the “usable test volume” in the TEM waveguide. The “usable test volume” of the TEM waveguide depends on the size, geometry, and the spatial distribution of the electromagnetic fields.

The “usable test volume” of a TEM waveguide (see Figures A.6 to A.9) depends on the “uniform area” as defined in B.2.2. The propagation direction of the waveguide TEM mode (typically z-axis) is perpendicular to a uniform area (transverse plane, typically xy-plane). In

the xy -plane the whole cross-section of the usable test volume has to fulfil the requirements of the uniform area defined in B.2.2. The minimum value for the distance h_{EUT} between EUT and each conductor or absorber of the waveguide (see Figures A.6 to A.9) is given by the distance between the boundary of the uniform area (see B.2.2) and the conductor. However, h_{EUT} should not be zero, in order to avoid the possible change of the EUT operational condition by the close coupling between EUT and conductors of the waveguide (recommended: h_{EUT} should be larger than $0,05 h$). Along the z -axis (propagation direction) the usable test volume is limited by $z_{\text{min}} \leq z \leq z_{\text{max}}$. The length of the test volume is $L = z_{\text{max}} - z_{\text{min}}$. The requirements of a uniform area have to be fulfilled for cross-sections at each z with $z_{\text{min}} \leq z \leq z_{\text{max}}$. It can be assumed that the TEM mode requirements are fulfilled for $z_{\text{min}} \leq z \leq z_{\text{max}}$ under the following conditions:

- if TEM mode requirements are fulfilled at the position z_{max} , and the geometry of the waveguide is similar to one of the types shown in Figures A.6 to A.9 with a constant aspect ratio of h to w (inherent shape) for $0 < z < z_{\text{max}}$, or,
- if TEM mode requirements are fulfilled at the positions z_{min} and z_{max} , and the waveguide cross-section is constant or uniformly tapered for $z_{\text{min}} < z < z_{\text{max}}$ and the derivatives dh/dz and dw/dz are a smooth function for $z_{\text{min}} < z < z_{\text{max}}$ (no kinks or steps in the conductor geometries).

The maximum size of an EUT is related to the size of the “usable test volume”. The EUT shall not be larger than $0,6 w$ times $0,6 L$ (see Figures A.6 to A.9).

NOTE 1 The ISO 11452 series recommends an EUT size of $0,33 w \times 0,6 L$, and MIL-STD 462D recommends $0,5 w \times 0,5 L$.

The maximum usable EUT height is recommended to be $0,33 h$, with h equal to the distance between the inner and outer conductors (conductor spacing) at the centre of the EUT in the test volume (for example, between septum and floor in a TEM cell). For all TEM waveguides, the EUT shall fit within the usable test volume for all rotation positions.

NOTE 2 Most standards restrict EUT size to $0,33 h$. Most data sheets from TEM cell suppliers limit the EUT height to a maximum of $0,5 h$. Except for highly accurate calibration, such as for field probes and sensors, the EUT height can exceed $0,33 h$, but it must not exceed the manufacturer's recommendations. The maximum usable EUT height can be higher than $0,33 h$ if the manufacturer provides information about the measurement uncertainty for larger EUTs. The measurement uncertainty must be stated in the test report. More information about loaded waveguide effects is given in [25].

5.1.3 Loaded waveguide effects

Under consideration.

NOTE 1 To measure the effects of a loaded waveguide, the following procedures have been proposed:

- surface current measurements on the EUT placed in free space (OATS is also an option) or in a TEM waveguide;
- field measurements with an isotropic sensor;
- input-port time-domain reflectometer (TDR) or voltage-standing-wave-ratio (VSWR) measurements;
- insertion loss for two-port TEM waveguides;
- monopole inserted through the outer conductor of the TEM waveguide.

NOTE 2 For radiated emissions, correlations with large EUTs have shown an average 1 dB enhancement in correlated field strength (see [20]).

NOTE 3 Influence of the test set-up support or manipulator should also be checked (see [4]).

5.2 Special requirements for certain types of TEM waveguides

5.2.1 Set-up of open TEM waveguides

To minimize ambient effects, open TEM waveguides should be installed inside a shielded room.

NOTE 1 The permitted ambient signal is defined in Annexes A, B, and C and strongly depends on the test objectives.

A minimum distance of one plate spacing h from the open TEM waveguide to the shielded-room floor, walls, and ceiling is required. Additional anechoic material can be placed appropriately in the shielded room to minimize reflections.

The distances above are given for guidance only. The reflection (and transmission in two-port cells) is the final measure for sufficient decoupling of the TEM waveguide from the shielded room. Note that it is possible to construct an open TEM waveguide where one plate consists of the floor of the shielded room and the other is an installed septum.

NOTE 2 MIL-STD 462 requires open TEM waveguides to be positioned in a shielded room. The required minimum distance to walls should be set in relation to the size of the waveguide. MIL-STD 462D RS105 requires a distance of two times h from the closest metallic ground including ceiling, shielded room walls, and so forth, where h is the maximum vertical separation of the plates. CISPR 20 requires a minimum distance of 800 mm from walls, floor, and ceiling, corresponding to one h .

5.2.2 Alternative TEM mode verification for a two-port TEM waveguide

As an alternative to 5.1.1 the useful frequency range of a two-port TEM waveguide can be established using the following measurement method.

Before testing the EUT, the TEM waveguide resonances shall be determined for two-port TEM devices with the test set-up and EUT installed, with EUT power off. In this case, the transmission loss of the TEM waveguide in the useful frequency range shall be

$$A_{tloss} = \left| 10 \cdot \lg \left(\frac{P_{refl}}{P_{fwd}} + \frac{P_{output}}{P_{fwd}} \right) \right| \leq 1 \text{ dB} \quad (1)$$

where

A_{tloss} is the transmission loss of the loaded waveguide, in dB;

P_{refl} is the reflected power measured at the input port, in W;

P_{fwd} is the forward power measured at the input port, in W;

P_{output} is the output power measured at the second (output) port, in W.

NOTE 1 The reflected, forward and backward (output) power is measured with respect to the characteristic impedance of the TEM waveguide. An impedance transformer is not used. It is measured "in line" only. Equation (1) is valid for a 50 Ω characteristic impedance.

NOTE 2 This is an alternative verification method for a two-port TEM waveguide of the type listed in ISO 11452-3. It is based on the assumption that resonating higher order modes will extract energy from the TEM mode.

5.3 Measurement uncertainty considerations

General procedures to evaluate measurement uncertainties are under consideration. Procedures following A.4.2.1 are recommended to estimate uncertainties.

NOTE Uncertainty estimation methods for TEM waveguides are discussed, for example, in [3], [22] and [30].

6 Overview of EUT types

An EUT type is a group of products with sufficient similarity in electromagnetic characteristics or mechanical dimensions that testing with the same test installation and the same test protocol is allowable. The EUT type and its configuration are valid for immunity testing and emission measurement to allow a uniform arrangement in the test volume.

6.1 Small EUT

An EUT is defined as a small EUT if the largest dimension of the case is smaller than one wavelength at the highest test frequency (for example, at 1 GHz $\lambda = 300$ mm), and if no cables are connected to the EUT. All other EUTs are defined as large EUTs.

6.2 Large EUT

An EUT is defined as a large EUT if it is

- a small EUT with one or more exit cables,
- a small EUT with one or more connected non-exit cables,
- an EUT with or without cable(s) which has a dimension larger than one wavelength at the highest test frequency,
- a group of small EUTs arranged in a test set-up with interconnecting non-exit cables, and with or without exit cables.

Annex A (normative)

Emission testing in TEM waveguides

A.1 Introduction

This annex describes emission testing in TEM waveguides. TEM waveguide validation and correlation data should usually be supplied by the manufacturer of the TEM waveguide (Clauses A.3 and A.4). This allows the user to focus on Clauses A.5 and A.6.

Two methods are possible for determining the compliance of TEM waveguide emissions test results with a limit.

- Without correlation to the OATS method

This approach has been applied to specific product families (for example, procedures for integrated circuits, military devices, vehicle components and modules, etc., as described in the references of Annex E. In this case, TEM waveguide readings are used and compared directly to an independent disturbance limit or guideline, usually developed specifically for one type of TEM waveguide. In some cases, the TEM waveguide limits may be derived from limit values used in other test facilities (see [36]).

- With correlation to the OATS method

This approach is applicable for EUTs which have to comply with disturbance limits given in terms of an OATS field strength at a specific distance.

Only the second test method is described in detail in this annex. Emission testing using TEM waveguides requires a TEM waveguide validation for EUTs in order to demonstrate the suitability of the TEM waveguide being used. For each EUT type a validation procedure shall be carried out as described in Clause A.4. In cases where only relative comparison will be made within the same EUT product family, correlation to OATS or other test sites is not required. In that case, product committees shall supply specific limits to determine the compliance of the measurement data.

Correlation or conversion algorithms are described in Clause A.3. Correlation algorithms use TEM waveguide voltage measurements to estimate equivalent OATS field strengths. Free space field strengths may also be estimated. These field strengths, along with test results from the EUT type validation procedure, may then be compared to the requirements in normative standards. The test procedures typically require that the EUT be rotated about all three axes. Thus, the EUT needs to be mechanically stable and gravity-independent (see 3.1.23).

NOTE If a hyper-rotated TEM waveguide is used (see [6]), the TEM waveguide is reorientated so that its ortho-axis is normal to the earth's surface. The EUT is rotated by $\pm 120^\circ$ about its vertical axis (which is its ortho-axis). The EUT need not be rotated around its horizontal axis. The EUT can be gravity-dependent.

All requirements in this annex given for small EUTs are normative. Large EUTs and specific considerations regarding EUT arrangements and cabling are deferred for elaboration in the next edition of this standard.

A.2 Test equipment

The test equipment shall comply with the relevant requirements of CISPR 16-1.

NOTE An isotropic field sensor can be seen as an antenna (see CISPR 16-1 for antenna requirements). The calibration procedures of isotropic field probes and their specifications are described in [24].

A.3 Correlating TEM waveguide voltages to *E*-field data

A.3.1 General remarks

This procedure is intended to establish an alternative to OATS emissions test methods. The TEM waveguide results are converted to equivalent OATS *E*-field data. This clause describes an algorithm based on the assumption that the radiated power as measured by a TEM waveguide will be radiated by a dipole positioned above a perfectly conducting ground plane. In case of dispute the method originally used, either OATS or TEM waveguide, takes precedence.

Correlation routines include the distance between EUT and each conductor, h_{EUT} , and the conductor spacing h (or plate separation) at the centre of the EUT (see Figures A.6b and A.7b) in the calculation. These parameters are analogous to the EUT height over ground h_g and the antenna separation s (Figure A.5) in an OATS measurement. The voltages measured with the EUT placed in the TEM waveguide are generated by the EUT emissions. After rotation (repositioning) of the EUT according to the requirements of the correlation routine, further voltage measurements are taken until all required positions have been measured. The correlation routine then uses this data to simulate an OATS measurement.

NOTE Information about correlation and correlation data for emission measurements can be found in [5], [8] [17] [22], [34] [36], [40] and [41].

The following subclause describes only an algorithm based on a three-position measurement. Other algorithms have been proposed and may be useful for some EUTs (see [31] and [41]).

A.3.2 Correlation algorithms

The two subclauses A.3.2.1 and A.3.2.2 show different and independent correlation approaches. Subclause A.3.2.1 describes the basic approach of correlation routines for the "multipole model". It uses a set of waveguide measurements in order to determine the equivalent multipole moments. Subclause A.3.2.2 describes another correlation routine which uses three voltage measurements. This procedure is often referred to as the "total radiated power method".

A.3.2.1 Multipole model

Any radiation source of finite size may be replaced by an equivalent multipole expansion which gives the same radiation pattern outside a volume encompassing the source. If the source is electrically small (characteristic dimensions less than 0,1 times the wavelength), then the initial multipole expansion terms, effectively electric and magnetic dipoles, will yield an accurate simulation of the source. The above statement holds for an arbitrary source. If the source itself consists of electric and magnetic dipole-like elements only, then the size restriction with respect to the wavelength may be relaxed.

The basic approach of correlation routines between TEM waveguides and open-area test site or free space data is to use a set of TEM waveguide measurements in order to determine the multipole moments. Usually three complex-valued orthogonal dipole moments are used, requiring six or more measurements. With the basic three-measurement method, radiated power is available, but not multipole moments. Once the multipole moments are known, radiation either in free space or over an infinite ground plane may be simulated numerically. In this way, it is possible to simulate the various source-to-receiver antenna configurations required by OATS emission standards.

For two-port TEM waveguides, measurements at both ports yield both amplitude and relative phase information (see [14], [29], [30], [35] and [38]). In this manner both the magnitude and the phase of the multipole moments may be determined and the radiation pattern accurately simulated, including possible nulls due to phase cancellation. For one-port TEM waveguides no relative phase information is available; thus, it is only possible to determine the magnitudes of the multipole moments (see [36], [40] and [41]). Because relative phase information is not known, one-port TEM waveguide correlation routines assume that all of the multipole moments radiate in phase. This yields an upper bound estimate only (see [10], [28] and [39]). Detailed radiation patterns cannot be simulated. The upper bound estimate is valid for comparison to standards limits. In [31] and [32] it was shown that cross-polar coupling does occur in TEM waveguides. The influences on emissions measurements have been shown there.

A.3.2.2 One-port TEM waveguide correlation routine

The one-port correlation routine is based on three voltage measurements made in a TEM waveguide from which the total radiated power of the EUT may be calculated. The individual dipole moments are not separately determined. The total radiated power is then used to simulate the maximum EUT fields over a ground plane based on a model of parallel dipoles (source and receive dipole) transmitting the same total power, either both dipoles are horizontal or vertical.

A.3.2.2.1 TEM cell voltage measurements: three positions

The EUT emissions are measured in three positions that are determined as follows. An (x,y,z) axis system is assigned to the TEM cell. A standard choice is to align the z -axis in the direction of propagation, the y -axis parallel to the E -field (vertical) and the x -axis parallel to the H -field. The centre of the EUT is placed at $(x = 0, y, z)$ with $x = 0$ in the middle of the septum. A local "primed" coordinate system (x', y', z') is assigned to the EUT. Position a aligns x' with x , y' with y , and z' with z , as indicated in Figure A.3. Position b is obtained by simply permuting the primed EUT axes: x' to y , y' to z , and z' to x . This is equivalent to two 90° rotations of the EUT. Position c is obtained by a further permutation: x' to z , y' to x , z' to y . Designating the three radiated voltage measurements by V_{p1} , V_{p2} , V_{p3} , it can be shown (see [31] and [41]) that the total radiated power P_0 due to the EUT is given by

$$P_0 = \frac{\eta_0}{3\pi} \cdot \frac{k_0^2}{e_{0y}^2 Z_C} \cdot S^2, \quad \text{in W} \quad (\text{A.1})$$

where

$$S = \sqrt{V_{p1}^2 + V_{p2}^2 + V_{p3}^2}, \quad \text{with } V_p \text{ in V} \quad (\text{A.2a})$$

$$S = \sqrt{10^{\frac{V_{p1}|_{dB} - 120}{10}} + 10^{\frac{V_{p2}|_{dB} - 120}{10}} + 10^{\frac{V_{p3}|_{dB} - 120}{10}}}, \quad \text{with } V_p|_{dB} \text{ in dB}\mu\text{V} \quad (\text{A.2b})$$

and

V_{p1}, V_{p2}, V_{p3} are the voltage measurements from three EUT positions;

S is the root-sum-square of measured voltages, in V;

$k_0 = \frac{2\pi}{\lambda}$ is the wave number, k_0 in $\frac{1}{\text{m}}$;

$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120 \pi \Omega = 377 \Omega$ is the free space wave impedance, η_0 , in Ω ;

Z_C is the characteristic impedance of the TEM waveguide (typically 50Ω) in Ω ;

e_{0y} is the field factor: the normalized y -component of the electric field of the TEM mode at the EUT location (for Equation (A.1): $(x = 0, y, z)$), e_{0y} in $\frac{\sqrt{\Omega}}{\text{m}}$.

NOTE For some EUTs, it may be necessary to test three orthogonal positions at each of four start positions (start positions a1, a2, a3 and a4 in Figure A.4) for a total of 12 canonical positions. The maximum voltage reading and the readings from the two corresponding orthogonal positions are then used in the usual three-position method. This is known as the "enhanced 3-position," or "12 measurement/input" method (see [21]).

A.3.2.2.2 Determining the field factor

The algorithm described here requires the primary y -component of the TEM mode electric field. Higher order field modes are not directly coupled to the voltage at the port. The field factor e_{0y} is the normalized y -component of the electric field of the TEM mode at a given test location of the EUT. Two possible procedures to derive the field factor e_{0y} are as follows.

A.3.2.2.2.1 Experimental procedure

The field factor can be determined experimentally via a measurement of the y -component of the electric field E_y in V/m (for an empty cell) at the location (x,y,z) of the EUT centre with a known input power P_i in watts

$$e_{0_y} = \frac{E_y(x,y)}{\sqrt{P_i}} \quad \text{in } \frac{\sqrt{\Omega}}{\text{m}} \quad (\text{A.3})$$

The e_{0_y} field factor for each specific type and size of TEM waveguide shall be provided by the manufacturer.

A.3.2.2.2.2 Analytical procedure

For a one-port TEM cell with asymmetric cross-section (for example, GTEM type), as shown in [41] the normalized TEM mode component can be analytically approximated with the equation

$$e_{0_y} = \frac{4}{a} \sqrt{Z_c} \cdot \sum_{m=1,3,5,\dots}^{\infty} \left(\frac{\cosh(My)}{\sinh(Mh)} \cdot \cos(Mx) \cdot \sin\left(M \frac{a}{2}\right) \cdot J_0(Mg) \right), \quad \text{in } \frac{\sqrt{\Omega}}{\text{m}} \quad (\text{A.4})$$

where

$M = m \frac{\pi}{a}$, $m = 1, 3, 5, \dots, \infty$, in 1/m;

a is the cell width (see Figures A.6 – A.9), in m;

h is the septum height, in m;

g is the gap width, in m;

x,y,z is the location of the EUT centre, in m;

J_0 is the zero-order Bessel function, J_0 without unit.

Only a few terms of this series need to be retained for a good approximation of e_{0_y} . General calculation results are given in [28].

A.3.2.3 Correlation to OATS

OATS method EUT emissions over a ground plane under far-field conditions are simulated by assuming that the same total radiated power, as measured in the TEM waveguide, is emitted by a short dipole (replacing the EUT). The equations for the fields from a dipole are well known and the ground plane may be accounted for by introducing an image dipole. The fields may be calculated over the equivalent height scan of the receiving antenna as required by the OATS method. The maximum signal from the two polarizations would then give the maximum possible field strength. Using the geometry factor $g_{\max}$ determined by the height-scan of the receiving antenna, an estimate for the maximum field $E_{\max}$ on an OATS is given by

$$E_{\max} = g_{\max} \cdot \sqrt{\frac{3\eta_0}{4\pi} P_0}, \quad \text{in } \frac{\text{V}}{\text{m}} \quad (\text{A.5})$$