



BSI Standards Publication

Electromagnetic compatibility (EMC)

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

National foreword

This British Standard is the UK implementation of EN IEC 61000-4-20:2022. It is identical to IEC 61000-4-20:2022. It supersedes BS EN 61000-4-20:2010, which will be withdrawn on 25 March 2025.

The UK participation in its preparation was entrusted to Technical Committee GEL/210, EMC - Policy committee.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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(IEC 61000-4-20:2022)

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Techniques d'essai et de mesure - Essais d'émission et
d'immunité dans les guides d'onde TEM
(IEC 61000-4-20:2022)

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und Messverfahren - Messung der Störaussendung und
Prüfung der Störfestigkeit in transversal-
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European foreword

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- latest date by which the document has to be implemented at national (dop) 2022-12-25 level by publication of an identical national standard or by endorsement
- latest date by which the national standards conflicting with the (dow) 2025-03-25 document have to be withdrawn

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

IEC 60068-1	NOTE Harmonized as EN 60068-1
IEC 60118-13	NOTE Harmonized as EN IEC 60118-13
IEC 61967-2	NOTE Harmonized as EN 61967-2
IEC 62132-2	NOTE Harmonized as EN 62132-2
CISPR 25	NOTE Harmonized as EN IEC 55025
CISPR 14 (series)	NOTE Harmonized as EN IEC 55014-2 (series)
CISPR 16-4-2	NOTE Harmonized as EN 55016-4-2
IEC 61000-2-9	NOTE Harmonized as EN 61000-2-9
IEC 61000-4-3	NOTE Harmonized as EN IEC 61000-4-3
CISPR 16-2-3:2016	NOTE Harmonized as EN 55016-2-3:2017 (not modified)
CISPR 32	NOTE Harmonized as EN 55032
CISPR 20:2006	NOTE Harmonized as EN 55020:2007 (not modified) +A11:2011

Annex ZA (normative)

Normative references to international publications with their corresponding European publications

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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.

NOTE 1 Where an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60050-161	-	International Electrotechnical Vocabulary (IEV) - Part 161: Electromagnetic compatibility	-	-
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	EN IEC 55016-1-1	-
CISPR 16-1-4	-	Specification for radio disturbance and immunity measuring apparatus and methods - Part 1-4: Radio disturbance and immunity measuring apparatus - Antennas and test sites for radiated disturbance measurements	EN IEC 55016-1-4	-

CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references	11
3 Terms, definitions and abbreviated terms	11
3.1 Terms and definitions.....	11
3.2 Abbreviated terms.....	14
4 General	15
5 TEM waveguide requirements.....	15
5.1 General.....	15
5.2 General requirements for the use of TEM waveguides	16
5.2.1 Test volume and maximum EUT size	16
5.2.2 Validation of usable test volume	16
5.3 Special requirements and recommendations for certain types of TEM waveguides.....	23
5.3.1 Set-up of open TEM waveguides	23
5.3.2 Alternative TEM mode verification for a two-port TEM waveguide	23
5.3.3 TEM mode generation for a four-port TEM waveguide	23
5.4 Figures for Clause 5	24
6 Overview of EUT types	26
6.1 General.....	26
6.2 Small EUT	26
6.3 Large EUT	26
7 Laboratory test conditions.....	26
7.1 General.....	26
7.2 Climatic conditions.....	26
7.3 Electromagnetic conditions	26
8 Evaluation and reporting of test results.....	27
Annex A (normative) Emission measurements in TEM waveguides	28
A.1 Overview.....	28
A.2 Test equipment	28
A.3 Correlating TEM waveguide voltages to electric field strength data	28
A.3.1 General	28
A.3.2 Correlation algorithms	29
A.4 Emission measurement correction factors	33
A.4.1 Reference emission sources	33
A.4.2 Arrangement of small EUTs	34
A.4.3 Calculation of the small EUT correction factor	34
A.5 Emission measurement procedures in TEM waveguides	37
A.5.1 EUT types.....	37
A.5.2 EUT arrangement	37
A.6 Test report.....	38
A.7 Figures for Annex A	39
Annex B (normative) Immunity testing in TEM waveguides.....	44
B.1 Overview.....	44
B.2 Test equipment	

B.2.1	General	44
B.2.2	Description of the test facility	44
B.3	Field uniformity area calibration	45
B.4	Test levels	45
B.5	Test set-up	45
B.5.1	Arrangement of table-top equipment	45
B.5.2	Arrangement of floor-standing equipment	46
B.5.3	Arrangement of wiring	46
B.6	Test procedures	46
B.7	Test results and test report	46
B.8	Figures for Annex B	47
Annex C (normative)	HEMP transient testing in TEM waveguides	49
C.1	Overview	49
C.2	Immunity tests	49
C.2.1	General	49
C.2.2	Radiated test facilities	50
C.2.3	Frequency domain spectrum requirements	51
C.3	Test equipment	51
C.4	Test set-up	52
C.5	Test procedure	52
C.5.1	General	52
C.5.2	Severity level and test exposures	53
C.5.3	Test procedure	53
C.5.4	Test execution	54
C.5.5	Execution of the radiated immunity test	54
C.6	Figure for Annex C	55
Annex D (informative)	TEM waveguide characterization	56
D.1	Overview	56
D.2	Distinction between wave impedance and characteristic impedance	56
D.3	TEM wave	57
D.3.1	General	57
D.3.2	Free-space TEM mode	57
D.3.3	Waveguides	57
D.4	Wave propagation	58
D.4.1	General	58
D.4.2	Spherical propagation	58
D.4.3	Plane wave propagation in free space	58
D.4.4	Velocity of propagation	58
D.5	Polarization	58
D.6	Types of TEM waveguides	59
D.6.1	General	59
D.6.2	Open TEM waveguides (striplines, etc.)	60
D.6.3	Closed TEM waveguides (TEM cells)	60
D.7	Frequency limitations	60
D.8	Figures for Annex D	61
Annex E (informative)	Calibration method for E-field probes in TEM waveguides	69
E.1	Overview	69
E.2	Probe calibration requirements	69
E.2.1	General	69

E.2.2	Calibration frequency range	69
E.2.3	Calibration volume	70
E.2.4	Probe dimensions	70
E.2.5	Perturbations of TEM waveguide fields due to the probe	70
E.2.6	Frequency steps	71
E.2.7	Field strength	71
E.3	Requirements for calibration instrumentation	71
E.3.1	Specifications of TEM waveguide	71
E.3.2	Harmonics and spurious signals	72
E.3.3	Probe fixture	72
E.3.4	Measuring net power to a transmitting device using directional couplers	72
E.4	E-field probe calibration	73
E.4.1	Calibration methods	73
E.4.2	Calibration procedure using a two-port TEM waveguide	73
E.4.3	Calibration procedure using one-port TEM waveguide	74
E.5	Figures for Annex E	77
Annex F (informative)	Instrumentation uncertainty of emission measurement results	79
F.1	Radiated disturbance measurements using a TEM waveguide	79
F.1.1	Measurand for radiated disturbance measurements using a TEM waveguide	79
F.1.2	Symbols of input quantities common to all disturbance measurements	79
F.1.3	Symbols of input quantities specific to TEM waveguide measurements	79
F.2	Input quantities to be considered for radiated disturbance measurements using a TEM waveguide	79
F.3	Uncertainty budget and rationale for the input quantities for radiated disturbance measurements using a TEM waveguide	80
F.3.1	Uncertainty budget for radiated disturbance measurements using a TEM waveguide	80
F.3.2	Rationale for the estimates of input quantities for radiated disturbance measurements using a TEM waveguide	81
F.4	Figures for Annex F	87
Annex G (informative)	Measurement uncertainty of immunity testing due to test instrumentation	89
G.1	General symbols	89
G.2	Symbol and definition of the measurand	89
G.3	Symbols for input quantities	89
G.4	Example: Uncertainty budget for immunity test	89
G.5	Rationale for the estimates of input quantities	90
Annex H (informative)	Correlation of emission and immunity limits between EMC test facilities	93
H.1	Overview	93
H.2	Dipole in free space (representing FAR set-up)	93
H.3	Dipole in half space (representing OATS or SAC set-up)	95
H.4	Dipole in a TEM-mode transmission line	96
H.5	Dipole in a reverberation chamber	97
H.6	Correlation	98
H.7	Example of emission limits	99
H.8	Figures for Annex H	100
Annex I (informative)	TEM waveguide transient characterization	103
I.1	Overview	103

I.2	Test equipment	103
I.3	Test set-up	103
I.4	TEM waveguide characterization by correlation	104
I.5	Quantification of the Pcc	105
I.6	Performable transient test signals	105
I.7	Figures for Annex I	106
	Bibliography	108

Figure 1 – Flowchart of TEM mode and field uniformity verification procedure with the “constant forward power” method (see 5.2.2.4.1)	24
Figure 2 – Flowchart of TEM mode and field uniformity verification procedure with the “constant field strength” method (see 5.2.2.4.2)	25
Figure A.1 – Routing the exit cable to the corner at the ortho-angle and the lower edge of the test volume in a TEM waveguide (see A.5.2)	39
Figure A.2 – Basic ortho-axis EUT positioner or manipulator (see 3.1.13, A.4.2, A.5.1.2, A.5.2)	40
Figure A.3 – Die pattern and axis alignment for an EUT [26] (see A.3.2.3.2)	41
Figure A.4 – Non-redundant twelve-face and axis orientations for a typical EUT [26] (see A.3.2.3.2)	42
Figure A.5 – Open-area test site (OATS) emission measurements geometry (see A.3.2.4)	43
Figure B.1 – Example of test set-up for single-polarization TEM waveguide (see Clause B.5)	47
Figure B.2 – Uniform area calibration points in a TEM waveguide (see Clause B.3)	48
Figure C.1 – Pulse waveform frequency domain spectral magnitude between 100 kHz and 300 MHz (see C.2.1)	55
Figure D.1 – Simple waveguide (no TEM mode) (see D.3.3)	61
Figure D.2 – Example of waveguides supporting TEM-mode propagation (see D.3.3)	61
Figure D.3 – E-field polarization vector (see Clause D.5)	61
Figure D.4 – Simple transmission line model for TEM mode propagation (see D.6.1)	62
Figure D.5 – One- and two-port TEM waveguide concepts (see D.6.1)	62
Figure D.6 – Operation of four-port TEM waveguides (see D.6.1)	62
Figure D.7 – Two-port TEM cell (symmetric septum) (see D.6.1 and D.6.3)	63
Figure D.8 – One-port TEM cell (asymmetric septum) (see D.6.1 and D.6.3)	64
Figure D.9 – Stripline (two plates) (see D.6.1 and D.6.2)	66
Figure D.10 – Stripline (four plates, balanced feed) (see D.6.1)	67
Figure D.11 – Four-port TEM waveguide (symmetric parallel septa) (see D.6.1 and D.6.3)	68
Figure E.1 – Example of test points for calibration volume validation (see E.2.3)	77
Figure E.2 – Set-up for validation of probe perturbation (see E.2.5)	77
Figure E.3 – Set-up for measuring net power to a transmitting device (not to scale) (see E.3.4)	77
Figure E.4 – Example set-up for E-field probe calibration with two-port TEM waveguide (see E.4.2)	78
Figure E.5 – Example set-up for E-field probe calibration with one-port TEM waveguide and alternative method (see E.4.3.2)	78
Figure E.6 – Equivalent circuit of monopole antenna and measuring apparatus (see E.4.3.3)	78

Figure F.1 – Deviation of the QP detector level indication from the signal level at receiver input for two cases, a sine-wave signal and an impulsive signal with a pulse repetition frequency of 100 Hz	87
Figure F.2 – Deviation of the peak detector level indication from the signal level at receiver input for two cases, a sine-wave signal and an impulsive signal with a pulse repetition frequency of 100 Hz	88
Figure H.1 – Representation of a short centre-fed dipole and a more general source representing an EUT (see Clause H.2)	100
Figure H.2 – Vertical source and receiving dipoles located over a perfectly-conducting ground plane of infinite extent (see Clause H.3)	100
Figure H.3 – Two types of TEM cells with a vertically polarized dipole source and the source to receive port geometry defined (see Clause H.4)	101
Figure H.4 – Reverberation chamber with a source dipole, a stirrer to randomize the fields, and a general receive antenna (see Clause H.5)	101
Figure H.5 – TEM waveguide Class A and Class B emission limits correlated from CISPR 32 [68] (see Clause H.7)	102
Figure I.1 – Test set-up	106
Figure I.2 – Signal windowing	107
Figure I.3 – Example of a heatmap – Pcc for a test point in the uniform area	107
Table 1 – Values k for expanded uncertainty with normal distribution	18
Table B.1 – Uniform area calibration points	45
Table B.2 – Test levels	45
Table C.1 – Radiated immunity test levels defined for this document	50
Table E.1 – Calibration frequencies	71
Table E.2 – Calibration field strength level	71
Table F.1 – Uncertainty budget for radiated disturbance measurement results using a TEM waveguide from 30 MHz to 1 000 MHz (example)	80
Table F.2 – Uncertainty budget for radiated disturbance measurement results using a TEM waveguide from 1 GHz to 6 GHz (example)	81
Table F.3 – Values of S_{lim} for 30 MHz to 1 000 MHz	83
Table F.4 – Values of S_{lim} for 1 GHz to 6 GHz	84
Table G.1 – Example uncertainty budget of the immunity test level	90
Table H.1 – Summary of the emission correlation parameters	99

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61000-4-20 has been prepared by subcommittee 77B: High frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility, in cooperation with CISPR (International Special Committee on Radio Interference) subcommittee A: Radio-interference measurements and statistical methods.

It forms Part 4-20 of IEC 61000. It has the status of a basic EMC publication in accordance with IEC Guide 107.

This third edition cancels and replaces the second edition published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) provide information on the testing of large EUTs (including cables);

- b) apply the work on measurement uncertainties by adapting the work completed in CISPR and TC 77 (for emissions and immunity);
- c) update the validation procedure for the test volume regarding field uniformity and TEM mode verification;
- d) provide information concerning two-port and four-port TEM waveguides;
- e) add a new informative annex (Annex I) dealing with transient TEM waveguide characterization; and
- f) add information dealing with dielectric test stands for EUTs.

The text of this International Standard is based on the following documents:

Draft	Report on voting
77B/853/FDIS	77B/855/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts of the IEC 61000 series, published under the general title *Electromagnetic compatibility (EMC)*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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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 are and will be published with the part number followed by a dash and a second number identifying the subdivision (example: IEC 61000-6-1).

This part is an International Standard which gives emission, immunity and HEMP and IEMI transient testing requirements.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

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

1 Scope

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

The object of this document is to describe

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

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

This document does not intend to specify the tests to be applied to any particular apparatus or system(s). The main intention of this document is to provide a general basic reference for all interested product committees of the IEC. For radiated emission measurements, product committees select emission limits and measurement methods in consultation with CISPR standards. 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 document describes test methods that are separate from those of IEC 61000-4-3 [34].¹

¹ Numbers in square brackets refer to the Bibliography.

These other distinct test methods may be used when so specified by product committees, in consultation with CISPR and TC 77.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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) – Part 161: Electromagnetic compatibility*

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: Radio disturbance and immunity measuring apparatus – Antennas and test sites for radiated disturbance measurements*

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-161 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1.1

anechoic material

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

3.1.2

broadband transmission-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 volume of high-frequency anechoic material

3.1.3

characteristic impedance

for any constant phase wave-front, magnitude of the ratio of the voltage between the inner conductor and the outer conductor to the current on either conductor and which is independent of the voltage/current magnitudes and depends only on the cross-sectional geometry of the transmission line

Note 1 to entry: TEM waveguides are typically designed to have a characteristic impedance of 50 Ω . TEM waveguides with a characteristic impedance of 100 Ω are often used for transient testing.

3.1.4

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

3.1.5

EUT type

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

3.1.6

exit cable

cable that connects the EUT to equipment external to the TEM waveguide or cable exiting the usable test volume

Note 1 to entry: The usable test volume is specified in 5.2.1.

3.1.7

forward power

P_{fwd}

power that is applied to the port of the waveguide

3.1.8

forward power for immunity testing

P_{test}

forward power required to establish the test field strength E_{test} during immunity testing

Note 1 to entry: See Equation (16) and Equation (17) for the constant forward power (5.2.2.4.1) and constant field strength (5.2.2.4.2) methods, respectively.

3.1.9

four-port TEM waveguide

TEM waveguide with two input/output ports at each end

3.1.10

hyper-rotated TEM waveguide

TEM waveguide that has been reoriented such that its ortho-axis is normal to the surface of the Earth

Note 1 to entry: Additional details are given in [6].

3.1.11

inner conductor

septum

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

3.1.12

interconnecting cable

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

3.1.13

manipulator

any type of manual or automatic non-metallic test set-up support similar to a turntable, and capable of supporting an affixed EUT throughout numerous positions as required by a correlation algorithm or test protocol

Note 1 to entry: An example of a manipulator design is shown in Figure A.2 in Clause A.7.

3.1.14**one-port TEM waveguide**

TEM waveguide with a single input/output port

Note 1 to entry: Such TEM waveguides typically feature a broadband transmission-line termination at the non-port end.

3.1.15**ortho-angle**

angle that the diagonal of a cube makes to each side face at the trihedral corners of the cube

Note 1 to entry: 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°.

Note 2 to entry: Figure A.2 a) in Clause A.7 shows a diagram of the ortho-angle.

Note 3 to entry: When associated with the EUT, this angle is usually referred to as the ortho-axis.

3.1.16**outer conductor**

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

3.1.17**primary field component****primary component**

electric field component aligned with the intended test polarization

Note 1 to entry: 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.

3.1.18**resultant field****amplitude**

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

3.1.19**secondary field component****secondary 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**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

Note 1 to entry: Striplines usually have open sides for EUT access and monitoring.

3.1.21**TEM cell**

closed TEM waveguide, often a rectangular coaxial transmission line, in which a wave is propagated in the transverse electromagnetic mode to produce a specific field for testing purposes and with an outer conductor completely enclosing an inner conductor

3.1.22**TEM waveguide**

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

3.1.23 test field strength

E_{test}

field strength of the primary field component in V/m that is used for immunity testing

Note 1 to entry: Different levels of E_{test} are given in Annex B.

3.1.24 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 to entry: A typical material is foamed polystyrene. Wooden supports are not recommended (see [4]).

3.1.25 transverse electromagnetic mode 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

3.1.26 two-port TEM waveguide

TEM waveguide with an input/output port at each end

3.1.27 verification field strength

$E_{\text{verification}}$

field strength used for verification of the uniform area

Note 1 to entry: This field strength should be the field strength at which the field probe has been calibrated, to reduce uncertainties due to the nonlinearity of the field probe.

3.2 Abbreviated terms

BALUN	balanced-to-unbalanced
DFT	discrete Fourier transform
E-field	electric field strength
EUT	equipment under test
FAR	fully anechoic room
FFT	fast Fourier transform
FS	free space
FSOATS	free space open-area test site
GTEM	gigahertz transverse electromagnetic
HEMP	high-altitude electromagnetic pulse
HS	half space
IEMI	intentional electromagnetic interference
OATS	open-area test site
Pcc	Pearson correlation coefficient
PDF	probability density function
RC	reverberation chamber
RF	radio frequency
SAC	semi-anechoic chamber
S/N	signal-to-noise

SPD	surge protective device
TDR	time-domain reflectometer
TE	transverse electric (mode), (H-mode)
TEM	transverse electromagnetic
TL	transmission line
TM	transverse magnetic (mode), (E-mode)
UFA	uniform field area
VSWR	voltage standing wave ratio

4 General

This document describes the basic characteristics and limitations of TEM waveguides, namely test volume, field uniformity, purity of the TEM mode, and frequency ranges. Various general properties of TEM waveguides are described 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.

TEM waveguides can also be used as field generators for testing the immunity of equipment to electromagnetic fields. Details are given in Annex B and Annex C. Immunity testing in TEM waveguides is cited in several other documents listed in the Bibliography. Field generation properties can also be used for measuring field strength; see other publications listed in the Bibliography.

Additional information for TEM waveguide characterization, electric field strength (E-field) probe calibration, measurement uncertainty, and the time domain characterization of TEM waveguides is given in Annex D, Annex E, Annex F, Annex G, Annex H, and Annex I respectively.

TEM waveguide tests 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. For further information see other publications listed in the Bibliography.

In this document, CW measurements of electric field strength are expressed in terms of RMS values, while transient measurements are expressed in peak values.

5 TEM waveguide requirements

5.1 General

TEM waveguides can be used for emission measurements and immunity tests when certain requirements are met. For the validation of a TEM waveguide the methods described in Clause 5 shall be applied.

Clause 5 focuses on general validation aspects such as the dominant TEM mode and field homogeneity. Specific validation requirements for emission measurements, immunity testing, and transient testing are given in Annex A, Annex B, and Annex C, respectively.

5.2 General requirements for the use of TEM waveguides

5.2.1 Test volume and maximum EUT size

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

The usable test volume of a TEM waveguide (see Figure D.6 to Figure D.11 in Clause D.8) is established by the “uniform area” as defined in 5.2.2. The propagation direction of the waveguide TEM mode (typically the z -axis) is perpendicular to a uniform area (in a transverse plane, typically the xy -plane). In the xy -plane the entire cross-section of the usable test volume shall fulfil the requirements of the uniform area specified in 5.2.2. The minimum value for the distance h_{EUT} between the EUT and each conductor or absorber of the waveguide (see Figure D.7 to Figure D.11) is given by the distance between the boundary of the uniform area (see 5.2.2) and the conductor. However, h_{EUT} should not be zero, to avoid possible changes in the EUT operational condition due to close coupling between the EUT and the conducting structures of the TEM waveguide (h_{EUT} should be larger than $0,05 h$, h being the spacing between conducting structures). Along the z -axis (propagation direction) the usable test volume is limited by $z_{\text{min}} \leq z \leq z_{\text{max}}$, where z_{min} and z_{max} are established using the methods of Clause 5. The length of the test volume is $L = z_{\text{max}} - z_{\text{min}}$. The TEM mode requirements of a uniform area shall be validated for cross-sections at each EUT test point z used with $z_{\text{min}} \leq z \leq z_{\text{max}}$. Alternately, it can be assumed that the TEM mode requirements are fulfilled for any z in the range $z_{\text{min}} \leq z \leq z_{\text{max}}$ under the following conditions:

- if the 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 Figure D.6 to Figure D.11 with a constant aspect ratio of h to w (inherent shape) for $0 \leq z \leq z_{\text{max}}$, or,
- if the TEM mode requirements are fulfilled at the positions z_{min} and z_{max} , and the waveguide cross-section is constant or uniformly tapered for $z_{\text{min}} \leq z \leq z_{\text{max}}$, and the derivatives dh/dz and dw/dz are a smooth function for $z_{\text{min}} \leq z \leq z_{\text{max}}$ (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 be verified to be not larger than $0,6 w \times 0,6 L$ (see Figure D.7 to Figure D.11).

NOTE ISO 11452-3 [37] defines an EUT size of $0,33 w \times 0,6 L$, and MIL-STD-461G [47] recommends $0,5 w \times 0,5 L$.

The maximum usable EUT height should 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 the septum and the floor in a typical TEM cell). For all TEM waveguides, the EUT shall fit within the usable test volume for all of its rotation positions.

Most documents restrict the EUT size to $0,33 h$. The maximum usable EUT height may be larger than $0,33 h$ if the manufacturer or the user documents information about the measurement uncertainty for larger EUTs. More information about loaded waveguide effects is given in [39] and [40].

5.2.2 Validation of usable test volume

5.2.2.1 General

Subclause 5.2.2 uses the concept of a “uniform area,” which is a hypothetical area in which variations of the field magnitude are acceptably small (see [18]). The physical dimensions of a TEM waveguide determine the size of this uniform (plane) area. Unless the EUT can be fully illuminated in a smaller surface, the maximum size of an EUT is also related to the size of the usable test volume (see 5.2.1).

If no other definition is given in a product standard or by the manufacturer of the TEM waveguide, the uniform area should be a vertical plane orthogonal to the propagation direction of the field. The uniform area should be a single plane coincident with the front face of the EUT. Use of a vertical plane in this description assumes that the direction of the TEM mode propagation is near horizontal (oriented along the z -axis) and the plane wave propagation is given. If the TEM mode propagation direction is in some other direction, the uniform area plane may be re-orientated accordingly.

NOTE 1 In general, the exact shape and the location of the uniform area are not specified but are determined using the procedures of this document.

Use of the transmission line configuration of the TEM waveguide avoids perturbation due to ground-reflected fields as in a semi-anechoic chamber test set-up; thus, uniform fields may be established in the proximity of the inner and outer conductors (in the normal direction only).

In principle, the uniform area may be located at any distance from the input port of a TEM waveguide; the location will depend on the specific geometry. The uniform area is valid only for that distance from the input port at which it is validated. To allow EUT rotation, the uniform area shall be spaced at a distance at least greater than the largest EUT-enclosure dimension away from the end of the usable test volume $z_{\max}$ defined in 5.2.1.

The uniform area shall be validated in the empty enclosure. The frequency range is from the lowest to the highest frequency of intended use of the TEM waveguide. When the frequencies are swept, the first frequency step shall not exceed 1 % of the fundamental frequency, and thereafter 1 % of the preceding frequency in the entire frequency range. One constraint on the sweep speed is the response time of the field probe. The validation of the usable test volume shall be performed with a non-modulated signal.

NOTE 2 The TEM field is the dominant mode and the cavities are low Q values, therefore resonances are not expected to be narrow. For this reason the use of logarithmic frequencies is acceptable for the validation of the usable test volume.

Depending on the size of the uniform area, it shall be validated at least at five test points (four at the corners and one at the centre). The spacing between two test points shall be less than or equal to 50 cm.

NOTE 3 Choosing a larger number of test points results in a better outcome of the testing of the field homogeneity. Using more test points also results in a more accurate estimation of the overall field homogeneity.

5.2.2.2 Field uniformity verification

5.2.2.2.1 General

The field uniformity may be verified by the constant forward power method (5.2.2.2.2) or the constant field strength method (5.2.2.2.3). With the constant forward power method the forward power is kept constant for all grid points and all test frequencies. With the constant field strength method, the primary component of the electric field strength is kept constant for all grid points and all test frequencies. While the constant field strength method is more laborious it is also more accurate, since the linearity of the power meter is usually better than the linearity of the field probe and the field probe is always operated at the field strength that it has been calibrated for.

5.2.2.2.2 Constant forward power method

The field is considered to be sufficiently homogeneous, if statistically at least 75 % of the measured primary electric field components E_i are within a 6 dB range. A primary electric field component tolerance greater than 6 dB but less than 10 dB is allowed for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual tolerance and frequencies are stated in the test report. The statistical approach is based on the mean value and standard deviation of the primary field component as defined in Equation (1) and Equation (2) to assess the variation of the primary field component over the uniform area.

At test point i the measured primary field component is given as E_i . The mean value $\bar{E}$ and the standard deviation σ_E are calculated for N test points in logarithmic values.

$$\bar{E} = \frac{1}{N} \sum_{(N)} E_i \quad (1)$$

$$\sigma_E = \sqrt{\frac{1}{N-1} \sum_{(N)} (E_i - \bar{E})^2} \quad (2)$$

The assumption of a normal distribution for the samples of the primary field component leads to Equation (3) for the probability that 75 % of the measurement results will fall in the range $2 \cdot k \cdot \sigma_E$.

$$\bar{E} - k \cdot \sigma_E \leq E_i \leq \bar{E} + k \cdot \sigma_E \quad (3)$$

where the factor k is chosen to be 1,15 (see Table 1).

In case of immunity testing, besides proving that the field is homogeneous, it is also required that a given percentage of the test points result in a field strength that is greater than or equal to the test-level field strength E_{test} . The combination of these conditions leads to Equation (4).

$$E_{\text{test}} \leq E_i \leq E_{\text{test}} + E_{\text{margin}} \quad (4)$$

Comparing the range in Equation (4) with Equation (3) gives Equation (5) and Equation (6) with the requirement for field homogeneity.

$$E_{\text{test}} \leq E_i \leq E_{\text{test}} + 2 \cdot k \cdot \sigma_E \quad (5)$$

$$\sigma_E = \frac{\text{margin}}{2 \cdot k} \quad (6)$$

For 75 % probability, ($k = 1,15$) and a margin of 6 dB, the standard deviation shall be

$$\sigma_E \leq \frac{6 \text{ dB}}{2 \cdot 1,15} \approx 2,61 \text{ dB}.$$

For 75 % probability, ($k = 1,15$) and a margin of 10 dB, the standard deviation shall be

$$\sigma_E \leq \frac{10 \text{ dB}}{2 \cdot 1,15} \approx 4,35 \text{ dB}.$$

Table 1 – Values k for expanded uncertainty with normal distribution

Factor k	1	1,15	1,3	1,5	2	3
Probability %	68,3	75,0	80,6	86,6	95,5	99,7

5.2.2.2.3 Constant field strength method

At test point i the measured forward power is given as $P_{\text{fwd},i}$. The mean value $\bar{P}_{\text{fwd}}$ and the standard deviation σ_P are calculated for N test points in logarithmic values using Equation (7) and Equation (8).

$$\bar{P}_{\text{fwd}} = \frac{1}{N} \sum_{(N)} P_{\text{fwd},i} \quad (7)$$

$$\sigma_P = \sqrt{\frac{1}{N-1} \sum_{(N)} (P_{\text{fwd},i} - \bar{P}_{\text{fwd}})^2} \quad (8)$$

The assumption of a normal distribution for the samples of the primary field component leads to Equation (9) for the probability that 75 % of the test results $P_{\text{fwd},i}$ will fall in the range of $2 \cdot k \cdot \sigma_P$

$$\bar{P}_{\text{fwd}} - k \cdot \sigma_P \leq P_{\text{fwd},i} \leq \bar{P}_{\text{fwd}} + k \cdot \sigma_P \quad (9)$$

where the factor k is chosen to be 1,15 (see Table 1).

The field is considered to be sufficiently homogeneous in the constant field strength method, if statistically at least 75 % of the measured forward powers $P_{\text{fwd},i}$ are within the tolerance of 0 dB to 6 dB above the minimum value P_{test} . This results in Equation (10).

$$P_{\text{test}} \leq P_{\text{fwd},i} \leq P_{\text{test}} + 6 \text{ dB} \quad (10)$$

Comparing the range in Equation (10) with Equation (9) gives Equation (11) and Equation (12) with the requirement for field homogeneity.

$$2 \cdot k \cdot \sigma_P \leq 6 \text{ dB} \quad (11)$$

$$\sigma_P \leq \frac{6 \text{ dB}}{2 \cdot k} \quad (12)$$

A forward power tolerance greater than 6 dB but less than 10 dB is allowed for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual tolerance and frequencies are stated in the test report.

The statistical approach is based on the assumption of normal distribution and the calculation of the mean value and the standard deviation of the forward power.

For 75 % probability, ($k = 1,15$) and a margin of 6 dB, the standard deviation shall be

$$\sigma_P \leq \frac{6 \text{ dB}}{2 \cdot 1,15} \approx 2,61 \text{ dB}.$$

For 75 % probability, ($k = 1,15$) and a margin of 10 dB, the standard deviation shall be

$$\sigma_P \leq \frac{10 \text{ dB}}{2 \cdot 1,15} \approx 4,35 \text{ dB}.$$

5.2.2.3 TEM mode verification

TEM waveguides can exhibit resonances above a certain cut-off frequency that is 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. This verification of the TEM mode applies to waveguides used either for immunity testing or emission measurements. The TEM mode behaviour shall be confirmed at regular intervals (see 5.2.2.4).

NOTE 1 Generally, a TEM waveguide manufacturer provides documentation on the TEM mode behaviour.

The TEM mode is considered to be dominant if statistically at least 75 % of the measured secondary (unintended) electric field components are at least 6 dB less than the primary component of the electric field. Secondary electric field components at levels up to –2 dB of the primary field component are allowed for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual tolerance and frequencies are stated in the test report.

NOTE 2 The 6 dB criterion of 5.2.2.3 describes the dominant TEM mode rather than the field uniformity, and is separate from and will not be confused with the field uniformity requirements of 5.2.2.2.

The statistical description of the ratio of the secondary and primary electric field component is based on the assumption of a Rayleigh distribution. For a Rayleigh-distributed measurand, the 75 % quantile $Q_{75\%}$ can be calculated analytically. It can be assumed that 75 % of the test points have a ratio lower than the quantile $Q_{75\%}$.

At test point i the measured primary field component is given as $E_{\text{prim},i}$ and the secondary field component as $E_{\text{sec},i}$. $E_{\text{sec},i}$ is the larger one of the two secondary field components. Both values are to be expressed for N test points in linear values. As given in Equation (13), the parameter s_R of the Rayleigh distribution can be estimated from the measured field components.

$$s_R \approx \sqrt{\frac{1}{2 \cdot N} \sum_{(N)} \left(\frac{E_{\text{sec},i}}{E_{\text{prim},i}} \right)^2} \quad (13)$$

The P -quantile of the Rayleigh distribution can be calculated by Equation (14).

$$Q_P = \sqrt{-2 \cdot s_R^2 \cdot \ln(1-P)} \quad (14)$$

For $P = 0,75$ the 75 % quantile $Q_{75\%}$ is determined according to Equation (15):

$$Q_{75\%} = \sqrt{-2 \cdot s_R^2 \cdot \ln(1-0,75)} = s_R \cdot 1,6651 \quad (15)$$

For $Q_{75\%} < 0,5$ it can be assumed that statistically 75 % of the test points have a secondary field component that is at least 6 dB less than the primary field component. For $Q_{75\%} < 0,794$ it can be assumed that statistically 75 % of the test points have a secondary field component that is at least 2 dB less than the primary field component.

5.2.2.4 Field uniformity and TEM mode measurement procedure

5.2.2.4.1 Constant forward power method

The procedure for carrying out the validation is known as the "constant forward power" method and is as follows.

- a) Position the three-axis probe at one of the points in the grid.
- b) Apply a forward power P_{fwd} to the TEM waveguide input port so that the primary component of electric field strength is to be $E_{\text{verification}}$ through the frequency range with the frequency steps specified in 5.2.2.1, and record the readings of all the forward powers and primary and secondary component field strengths.
- c) With the same forward power, measure and record the primary and secondary field strengths at the other test points.
- d) Calculate the standard deviation σ_E according to Equation (2) of 5.2.2.2. All measurement results are expressed in dB(V/m).
- e) Calculate the 75 % quantile $Q_{75\%}$ of the ratio of the secondary to the primary field component according to Equation (15) of 5.2.2.3. The calculation shall be performed using linear values.
- f) The standard deviation σ_E shall be less than 2,61 dB. It may be in the range of $2,61 \text{ dB} \leq \sigma_E \leq 4,35 \text{ dB}$ for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual values and frequencies are stated in the test report.
- g) The 75 % quantile $Q_{75\%}$ shall be less than 0,5. It may be in the range of $0,5 \leq Q_{75\%} \leq 0,794$ for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual values and frequencies are stated in the test report.
- h) Knowing the forward power P_{fwd} , the mean value of the primary field component and the standard deviation of the primary field component, the required forward power P_{test} for immunity testing (see Annex B) with the test field strength E_{test} can be calculated using Equation (16). The calculation shall be performed using linear values. The coverage factor k shall be chosen according to Table 1. In general, k shall be 1,15. The forward power shall be recorded.

$$P_{\text{test}} = \frac{E_{\text{test}}^2}{(\bar{E} - k \cdot \sigma_E)^2} \cdot P_{\text{fwd}} \quad (16)$$

- i) Confirm that the test system (e.g. the power amplifier) is not in saturation. Assuming that E_{test} has been chosen as 1,8 times a required test level of electric field strength, perform the following procedure over the frequency range:
 - 1) decrease the output from the signal generator by 5,1 dB from the level needed to establish a forward power of P_{test} , as determined in the preceding step;
 - 2) record the new forward power delivered to the TEM waveguide;
 - 3) subtract the forward power measured in step 2) from P_{test} . If the difference in power is between 3,1 dB and 5,1 dB, then the amplifier is not saturated and is adequate for use. If the difference is less than 3,1 dB, then the amplifier is saturated and is not suitable for use.

A flowchart of the procedure is shown in Figure 1 (see 5.4).

EXAMPLE If at a given test point 81 W gives a denominator in Equation (16) of 9 V/m, then 9 W is used for a test field strength of 3 V/m.

5.2.2.4.2 Constant field strength method

The procedure for carrying out the validation is known as the "constant field strength" method and is as follows.

- a) Position the three-axis probe at one of the points in the grid.
- b) Apply a forward power P_{fwd} to the TEM waveguide input port so that the primary component of electric field strength is to be $E_{\text{verification}}$ through the frequency range with the frequency steps specified in 5.2.2.1, and record the readings of all the forward powers and primary and secondary components of the field strengths.
- c) With the same field strength $E_{\text{verification}}$, measure and record the readings of all the forward powers and the primary and secondary field components of the field strengths at the other grid points.
- d) For field uniformity verification, calculate the standard deviation σ_P for all the forward powers measured at the points according to Equation (8) of 5.2.2.2.3. All measurement results are expressed in dBm.
- e) The standard deviation σ_P shall be smaller than 2,61 dB.

A maximum of 5 % of the test frequencies (at least one frequency) may be in the range of $2,61\text{ dB} \leq \sigma_E \leq 4,35\text{ dB}$. The actual values and frequencies shall be stated in the test reports.

- f) For TEM mode verification, calculate the 75 % quantile $Q_{75\%}$ of the ratio of the secondary to the primary field component according to Equation (15) of 5.2.2.3. The calculation shall be performed in linear values.
- g) The 75 % quantile $Q_{75\%}$ shall be smaller than 0,5. It may be in the range of $0,5 \leq Q_{75\%} \leq 0,794$ for a maximum of 5 % of the test frequencies (minimum of one frequency), provided that the actual values and frequencies are stated in the test reports.
- h) For immunity tests (see Annex B), knowing the forward power and the field strength $E_{\text{verification}}$, the necessary forward power P_{test} for the required test-field strength E_{test} can be calculated using Equation (17). The forward power shall be recorded.

$$P_{\text{test}} = \left(\frac{E_{\text{test}}}{E_{\text{verification}}} \right)^2 \cdot (\bar{P}_{\text{fwd}} + k \cdot \sigma_P) \quad (17)$$

- i) Confirm that the test system (e.g. the power amplifier) is not in saturation. Assuming that E_{test} has been chosen as 1,8 times a required test level of electric field strength, perform the following procedure in the frequency range:
 - 1) decrease the output from the signal generator by 5,1 dB from the level needed to establish a forward power of P_{test} , as determined in the above steps;
 - 2) record the new forward power delivered to the TEM waveguide;
 - 3) subtract the forward power measured in step b) from P_{test} . If the difference in power is between 3,1 dB and 5,1 dB, then the amplifier is not saturated and is adequate for use. If the difference is less than 3,1 dB, then the amplifier is saturated and is not suitable for use.

A flowchart of the procedure is shown in Figure 2 (see 5.4).

The uniformity validation is applicable for all EUTs whose individual faces (including any cabling) can be fully enclosed by the "uniform area". It is intended that the full uniform area validation is carried out annually or when changes have been made to the enclosure configuration (e.g. TEM cell or stripline within a shielded enclosure).

5.3 Special requirements and recommendations for certain types of TEM waveguides

5.3.1 Set-up of open TEM waveguides

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

NOTE 1 Ambient signal levels are defined in Annex A, Annex B, and Annex C and strongly depend 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 recommended. Additional anechoic material can be placed appropriately in the shielded room to minimize reflections. These distances are given for guidance only. 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-461G [47] requires open TEM waveguides to be positioned in a shielded room. MIL-STD-461G [47] sets a minimum required distance to the walls in relation to the size of the waveguide. CISPR 20 [69] requires a minimum distance of 800 mm from walls, floor, and ceiling, corresponding to $1 h$.

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

As an alternative to the provisions in 5.2.2, the usable frequency range of a two-port TEM waveguide can be established using the following verification 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 usable frequency range shall fulfil Equation (18):

$$A_{\text{tloss}} = \left| 10 \lg \left(\frac{P_{\text{output}}}{P_{\text{fwd}} - P_{\text{refl}}} \right) \right| \leq 1 \text{ dB} \quad (18)$$

where

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

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

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

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

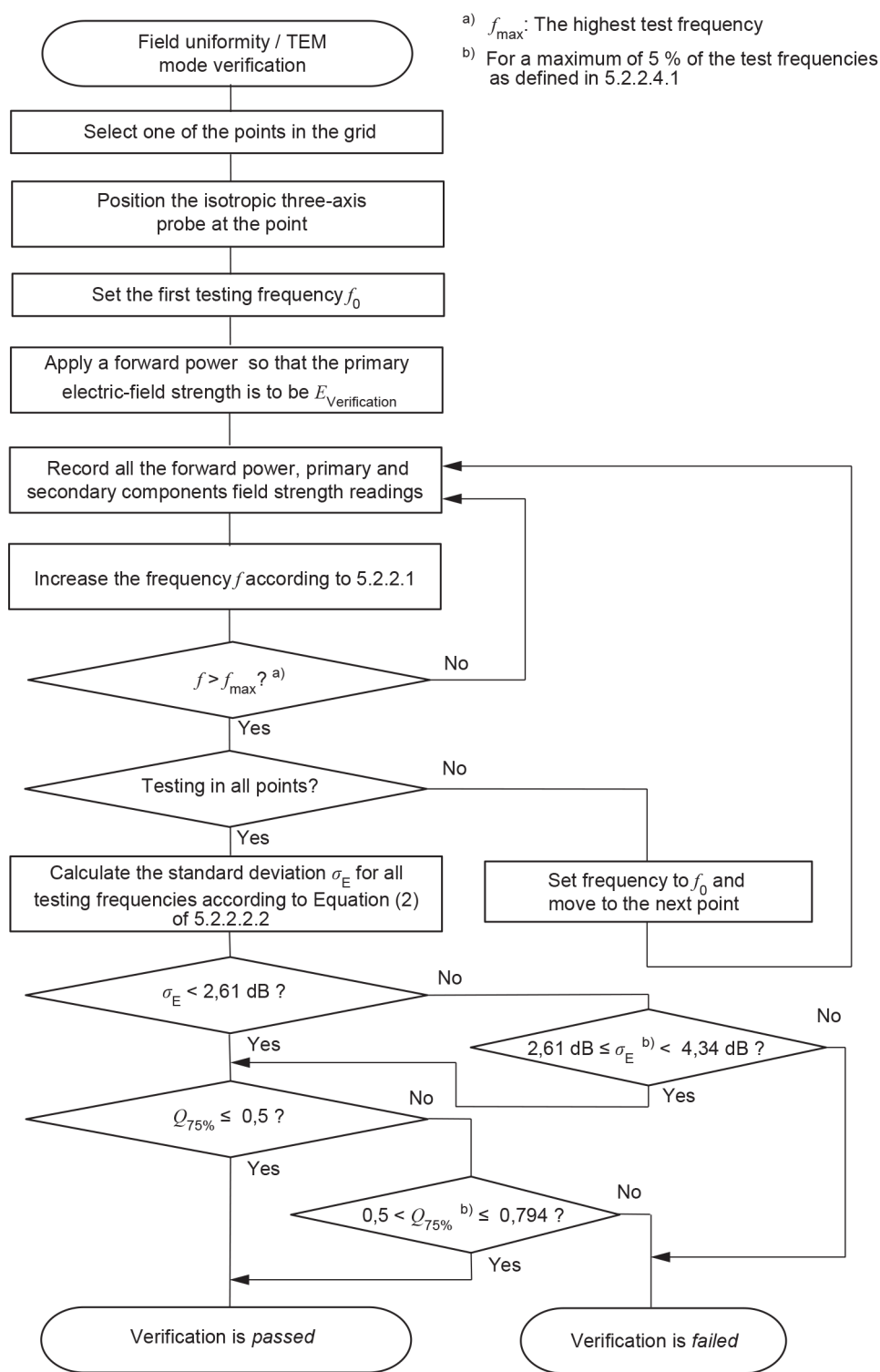
NOTE 1 The reflected, forward and backward (output) powers are measured with respect to the characteristic impedance of the TEM waveguide. An impedance transformer is not used. Equation (18) is valid for a characteristic impedance of 50 Ω .

NOTE 2 This is an alternative verification method for a two-port TEM waveguide of the type described in ISO 11452-3 [37], and is based on the assumption that resonating higher order modes will extract energy from the TEM mode.

5.3.3 TEM mode generation for a four-port TEM waveguide

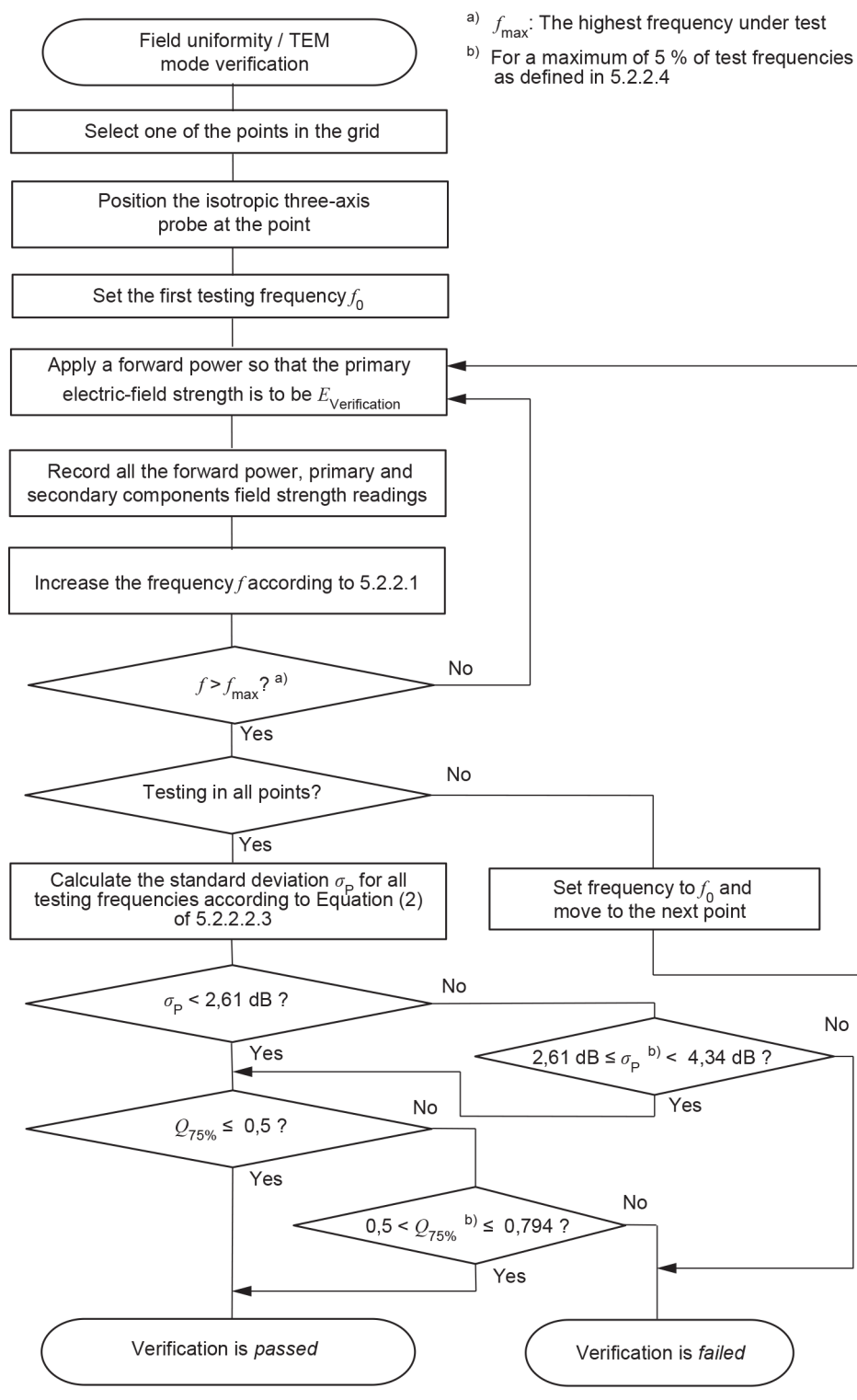
In order to generate a TEM mode, input signals shall be applied into ports 1 and 2 with the same amplitude and reversed phase as is shown in Figure D.6 (see Clause D.8). Ports 3 and 4 shall be terminated with 50 Ω lumped loads (see [38] and [63]).

5.4 Figures for Clause 5



IEC

Figure 1 – Flowchart of TEM mode and field uniformity verification procedure with the “constant forward power” method (see 5.2.2.4.1)



IEC

Figure 2 – Flowchart of TEM mode and field uniformity verification procedure with the “constant field strength” method (see 5.2.2.4.2)

6 Overview of EUT types

6.1 General

An EUT type is a group of products with sufficient similarity in electromagnetic characteristics or mechanical dimensions such 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 measurements, to allow a uniform arrangement in the test volume.

6.2 Small EUT

An EUT is defined as a small EUT if the largest dimension of the enclosure is smaller than one wavelength at the highest test frequency (for example at 1 GHz, $\lambda = 300$ mm), and without any cables connected to the EUT.

6.3 Large EUT

An EUT is defined as a large EUT if it is

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

However, a single EUT with interconnecting cables being part of that EUT, and with a cable routing that is not changed during the test, is considered to be a small EUT if the overall EUT dimensions meet the requirement specified in 6.2.

7 Laboratory test conditions

7.1 General

In order to minimize the effect of environmental parameters on test results, the test shall be carried out in climatic and electromagnetic reference conditions as specified in 7.2 and 7.3.

7.2 Climatic conditions

Unless otherwise specified by the committee responsible for the generic or product standard, the climatic conditions at the test site shall be within any limits specified for the operation of the EUT and the test equipment by their respective manufacturers.

Tests shall not be performed if the relative humidity is so high as to cause condensation on the EUT or the test equipment.

Where there is evidence that the measurements covered by this document are influenced by climatic conditions, this shall be noted in the test report.

7.3 Electromagnetic conditions

The electromagnetic conditions at the test site shall be such as to guarantee the correct operation of the EUT in order not to influence the test results.

8 Evaluation and reporting of test results

Testing shall be performed according to a test plan which shall be included in the test report. Test results and reporting requirements are dependent upon the type of test being performed.

The test report shall contain all the information necessary to reproduce the test. In particular, the following shall be recorded:

- a) the items specified in the test plan;
- b) identification of the EUT and any associated equipment, for example, brand name, product type, serial number;
- c) identification of the test equipment, for example, brand name, product type, serial number;
- d) any special environmental conditions in which the test was performed;
- e) any specific conditions necessary to enable the test to be performed;
- f) performance level defined by the manufacturer, requestor or purchaser;
- g) for immunity, performance criterion specified in the generic, product or product-family standard;
- h) for immunity, any effects on the EUT observed during or after the application of the test disturbance, and the duration for which these effects persist;
- i) for immunity, the rationale for the pass/fail decision (based on the performance criterion specified in the generic, product or product-family standard, or agreed between the manufacturer and the purchaser);
- j) any specific conditions of use, for example cable length or type, shielding or grounding, or EUT operating conditions, which are required to achieve compliance;
- k) drawing and/or pictures of the test set-up and EUT arrangement.

Annex A (normative)

Emission measurements in TEM waveguides

A.1 Overview

Annex A describes emission measurements in TEM waveguides.

The results of emission measurements made in TEM waveguides may be compared with limits derived in one of two ways:

a) TEM waveguide-based limits

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 listed in the Bibliography. In this case, TEM waveguide emission measurement results 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 [54]).

b) OATS-based limits

This approach is applicable for EUTs that are subject to disturbance limits given in terms of field strength at an OATS. A correlation algorithm is used to derive the open-area test site (OATS) field strength levels from TEM waveguide measurement results.

Only case b) is described in detail in Annex A. Emission measurements using TEM waveguides requires a validation 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 5. In cases where only relative comparison is made within the same EUT product family, then 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 algorithms are described in Clause A.3. Correlation algorithms use TEM waveguide voltage measurements to estimate equivalent OATS field strengths. Free-space field strength levels may also be estimated. These field strength levels, along with measurement results from the EUT type validation procedure, may then be compared to the requirements in documents.

A.2 Test equipment

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

NOTE An isotropic field sensor can be seen as an antenna (see CISPR 16-1-4 for antenna requirements). The calibration procedures of isotropic field probes and their specifications are described in Annex E and [35].

A.3 Correlating TEM waveguide voltages to electric field strength data

A.3.1 General

This procedure is intended to establish an alternative to OATS emission measurement methods. The TEM waveguide results are converted to equivalent OATS electric field strength (E-field) data. Clause A.3 describes an algorithm based on the assumption that the radiated power, as derived from a TEM waveguide measurement, is radiated by a dipole positioned above a perfectly conducting ground plane.

Correlation algorithms include in the calculation the distance between the EUT and each TEM waveguide conductor, h_{EUT} , and the conductor spacing h (or plate separation) at the centre of the EUT (see Figure D.7 to Figure D.11, in Clause D.8). 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 algorithm, further voltage measurements are taken until all required positions have been tested. The correlation algorithm then uses these data to simulate an OATS test.

NOTE Information about correlation methods and example correlation data for emission measurements can be found in [5], [9], [22], [30], [52], [54], [59], and [60].

Subclause A.3.2 describes an algorithm based on a three-position test. Other algorithms have been proposed that can be useful for some EUTs (see [47] and [60]).

A.3.2 Correlation algorithms

A.3.2.1 General

Subclauses A.3.2.2 and A.3.2.3 show independent correlation approaches. Subclause A.3.2.2 describes the basic approach of correlation algorithms using the "multipole model", which uses a set of TEM waveguide tests to determine the equivalent multipole moments. Subclause A.3.2.3 describes another correlation algorithm that uses only the three voltage measurements; this latter procedure is often referred to as the "total radiated power method."

A.3.2.2 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 preceding 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 algorithms between TEM waveguides and OATS or free space data is to use a set of TEM waveguide tests to determine the multipole moments. Usually three complex-valued orthogonal dipole moments are used, requiring six or more measurements. With the basic three-orientation method, radiated power is estimated, but not the individual multipole moments. Once the radiated power is estimated, radiated fields either in free space or over an infinite ground plane may be derived 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 [17], [44], [46], [53], and [56]). 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 [54], [59], and [60]). 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 [13], [43], and [57]). Detailed radiation patterns cannot be simulated. The upper bound estimate is valid for comparison to standard limits. In [47] and [49] it was shown that cross-polar coupling does occur in TEM waveguides. The influences on emission measurements data have also been shown in those references.

A.3.2.3 One-port TEM waveguide correlation algorithm

A.3.2.3.1 General

The one-port correlation algorithm 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 dipole and receive dipole) transmitting the same total power.

A.3.2.3.2 TEM waveguide voltage measurements

The voltages are measured at the TEM waveguide coaxial connector for three orientations of the EUT that are specified as follows. An (x,y,z) axis system is assigned to the TEM waveguide according to Figure D.7 to Figure D.11 (see Clause D.8). A standard choice is to align the z -axis in the direction of propagation, the y -axis parallel to the electric field vector (vertical) and the x -axis parallel to the magnetic field vector. 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. For example, position 65 aligns x' with x , y' with y , and z' with z , as indicated in Figure A.4. The triplets (65, 41, 24), (45, 21, 14), (15, 31, 54), and (35, 51, 64) form a set of three orthogonal orientations that can be used for the three-orientation correlation algorithm. Designating the three voltage measurements by V_{p1} , V_{p2} , V_{p3} , it can be shown (see [47] and [60]) that the total radiated power P_0 due to the EUT is given by Equation (A.1)

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

where the S factor is given by Equation (A.2) or Equation (A.3)

$$S = \sqrt{V_{p1}^2 + V_{p2}^2 + V_{p3}^2} \quad (\text{A.2})$$

$$S = \sqrt{10^{\frac{V_{p1|_{dB}} - 120}{10}} + 10^{\frac{V_{p2|_{dB}} - 120}{10}} + 10^{\frac{V_{p3|_{dB}} - 120}{10}}} \quad (\text{A.3})$$

and where

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

S is the root-sum-square of measured voltages;

$k_0 = \frac{2\pi}{\lambda}$ is the wave number;

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

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

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

For some EUTs, it can be necessary to test three orthogonal orientations at each of four start orientations (start orientations 65, 45, 15, and 35 in Figure A.4) for a total of 12 canonical orientations. The maximum voltage measurement and the voltage measurements from the two corresponding orthogonal orientations are then used in the usual three-orientation method [29].

A.3.2.3.3 Determining the field factor

- a) The algorithm described here requires the primary y -component 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.

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

- b) 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 according to Equation (A.4)

$$e_{0y} = \frac{E_y(x, y)}{\sqrt{P_i}} \quad (\text{A.4})$$

- c) Analytical procedure

For a TEM cell with a rectangular cross-section as shown in [60] the normalized TEM mode component can be analytically approximated with Equation (A.5)

$$e_{0y} = \frac{4}{a} \sqrt{Z_c} \cdot \sum_{m=1,3,5,\dots}^{\infty} \left(\frac{\cosh(M \cdot y)}{\sinh(M \cdot h)} \cdot \cos(M \cdot x) \cdot \sin\left(M \cdot \frac{a}{2}\right) \cdot J_0(M \cdot g) \right) \quad (\text{A.5})$$

where

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

a is the cell width (see Figure D.7 to Figure D.11 in Clause D.8) at z ;

h is the septum height at z ;

g is the gap width at z ;

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

J_0 is the zero-order Bessel function.

Only a few terms of this series need to be retained for a good approximation of e_{0y} . Field factor results for a variety of geometries are given in [43].

A.3.2.4 Correlation to OATS

EUT emissions over an OATS are simulated by assuming that the EUT's total radiated power, as estimated by the TEM waveguide tests, is the same as that emitted by a dipole (replacing the EUT) over an ideal perfectly conducting half-space.

The equations for the fields from a dipole are well known and the ideal ground plane is accounted for by introducing an image dipole. The fields are calculated over the equivalent height scan of the receive antenna as required by the OATS method. The simulated maximum received signal for two polarizations (horizontal, vertical) then gives the estimated maximum field strength $E_{\max}$. Using the geometry factor $g_{\max}$ determined by the height-scan of the receiving dipole, $E_{\max}$ is given by Equation (A.6) and Equation (A.7)

$$E_{\max} = g_{\max} \cdot \sqrt{\frac{3\eta_0}{4\pi} P_0} \quad (\text{A.6})$$