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**Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communication devices, 30 MHz to 6 GHz –
Part 4: General requirements for using the finite element method for SAR calculations**

**Détermination du débit d'absorption spécifique (DAS) maximal moyenné dans le corps humain, produit par les dispositifs de communications sans fil, 30 MHz à 6 GHz –
Partie 4: Exigences générales d'utilisation de la méthode des éléments finis pour les calculs du DAS**



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Partie 4: Exigences générales d'utilisation de la méthode des éléments finis pour les calculs du DAS**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 17.220.20

IEC ISBN 978-2-8322-8535-0
IEEE ISBN 978-1-5044-7044-5 STD24401

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

DETERMINING THE PEAK SPATIAL-AVERAGE SPECIFIC ABSORPTION RATE (SAR) IN THE HUMAN BODY FROM WIRELESS COMMUNICATION DEVICES, 30 MHZ TO 6 GHZ –

Part 4: General requirements for using the finite element method for SAR calculations

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The text of this standard is based on the following IEC documents:

FDIS	Report on voting
106/515/FDIS	106/521/RVD

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

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A list of all parts in the IEC/IEEE 62704 series, published under the general title *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz*, can be found on the IEC website.

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INTRODUCTION

Finite element methods have reached a level of maturity that allows their application in specific absorption rate (SAR) assessments of professional-use and consumer-use wireless communication devices. In the recent past, SAR compliance assessments for small transmitters were performed almost exclusively using measurements. Some wireless communication devices are used in situations where experimental SAR assessment is extremely complex or not possible at all. National regulatory bodies (e.g. US Federal Communications Commission) encourage the development of consensus standards and encouraged the establishment of the ICES Technical Committee 34 Subcommittee 2. The benefits to the users and the regulators include standardized and accepted protocols, verification and validation techniques, benchmark data, reporting format and means for estimating the overall assessment uncertainty in order to produce valid, repeatable, and reproducible data.

The purpose of this document is to specify numerical techniques and models to determine peak spatial-average specific absorption rates (SAR). SAR will be determined by applying finite element method simulations of the electromagnetic field conditions produced by wireless communication devices in models of the human anatomy. Intended users of this document are (but are not limited to) wireless communication device manufacturers, service providers for wireless communication that are required to certify that their products comply with the applicable SAR limits, and government agencies.

Several methods described in this document are based on techniques specified in IEC/IEEE 62704-1:2017.

DETERMINING THE PEAK SPATIAL-AVERAGE SPECIFIC ABSORPTION RATE (SAR) IN THE HUMAN BODY FROM WIRELESS COMMUNICATION DEVICES, 30 MHZ TO 6 GHZ –

Part 4: General requirements for using the finite element method for SAR calculations

1 Scope

This part of IEC/IEEE 62704 describes the concepts, techniques, and limitations of the finite element method (FEM) and specifies models and procedures for verification, validation and uncertainty assessment for the FEM when used for determining the peak spatial-average specific absorption rate (psSAR) in phantoms or anatomical models. It recommends and provides guidance on the modelling of wireless communication devices, and provides benchmark data for simulating the SAR in such phantoms or models.

This document does not recommend specific SAR limits because these are found elsewhere (e.g. in IEEE Std C95.1 [1]¹ or in the guidelines published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [2]).

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 62209-1, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Part 1: Devices used next to the ear (Frequency range of 300 MHz to 6 GHz)*

IEC/IEEE 62704-1:2017, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 1: General requirements for using the finite-difference time-domain (FDTD) method for SAR calculations*

IEEE Std 1528, *IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head From Wireless Communications Devices: Measurement Techniques*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO, IEC, and IEEE 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>
- IEEE Dictionary Online: available at <http://dictionary.ieee.org>

¹ Numbers in square brackets refer to the Bibliography.

3.1

mesh

<finite-difference time-domain method> discrete representation of the simulation model as a set of voxels in a regular three-dimensional Cartesian arrangement

Note 1 to entry: In the scientific literature, the mesh is often referred to as a "grid."

[SOURCE: IEC/IEEE 62704-1:2017, 3.21, modified – The specific context "<finite-difference time-domain method>" has been added.]

3.2

mesh

<finite element method> discrete representation of the simulation model as a set of tetrahedral elements in an irregularly three-dimensional arrangement

Note 1 to entry: In the scientific literature, the mesh is often referred to as a "grid."

3.3

element

smallest three-dimensional part of a mesh

EXAMPLE A voxel or a tetrahedron.

3.4

subregion

spatially limited three-dimensional region within a computational domain

3.5

accepted power

power delivered to a load by a source

4 Abbreviated terms

ASCII	American Standard Code for Information Interchange
BVP	Boundary Value Problem
DoF	Degrees of Freedom
DUT	Device Under Test
FDTD	Finite-Difference Time-Domain
FEM	Finite Element Method
PDE	Partial Differential Equation
PEC	Perfect Electric Conductor
PMC	Perfect Magnetic Conductor
psSAR	peak spatial-average Specific Absorption Rate
SAR	Specific Absorption Rate
SI	International System of Units
TVFE	Tangential Vector Finite Elements

5 Finite element method – basic description

This document describes applications of the finite element method (FEM) to calculate the specific absorption rate (SAR). Reasons for using FEM include its proven track record in a broad range of electromagnetic applications, and its ability to use an unstructured, usually tetrahedral, mesh that conforms to complicated geometries, employing arbitrarily small elements where needed and larger elements elsewhere.

Multiple ways exist to solve Maxwell's equations with FEM. Implementations can be based on field quantities or on potential quantities, and may be formulated using either the weighted residual method or the variational method [3], [4]. The weighted residual method starts directly from the partial differential equation (PDE) of the boundary value problem, whereas the variational method starts from the variational representation of the boundary value problem. All implementations have the following in common:

- a) They are based on PDEs, not on integral equations. The PDEs are derived from Maxwell's equations augmented by proper boundary conditions in order to frame a well-defined boundary value problem on a finite computational domain.
- b) The size of the computational domain is finite. Radiation towards infinity is implemented through an open boundary condition on its outer boundaries. Radiated fields outside the domain can be computed by integrating over a boundary that encloses the radiating structure.
- c) After applying excitations and boundary conditions and discretizing the computational domain into a mesh, the derived PDE is transformed into a matrix equation in which the matrix is large, sparse, and banded. "Large" is a consequence of having a large number of unknowns, several per element on a large mesh. "Sparse" and "banded" are consequences of the fact that all interactions are formulated as local interactions.
- d) In the limit of infinitesimally small elements, the solution approaches the exact solution of the PDE.

Annex A contains more information on FEM, along with references to literature and a discussion of its limitations. Clause 8 describes a set of tests is described that shall be used to determine whether a particular implementation of FEM is correct and sufficiently accurate to be used for SAR calculations.

This document refers to Nédélec elements of the first kind, which are polynomially exact up to order 0 ($H_0(\text{curl})$ or edge elements) as lowest order; up to order 1 ($H_1(\text{curl})$ elements) as second lowest order; and up to order 2 ($H_2(\text{curl})$ elements) as third lowest order [5]. If an implementation of the FEM is applied with one of these orders, the respective parts of the code verification shall be executed with this order.

6 SAR calculation and averaging

6.1 General

The local specific absorption rate (SAR) in a location in tissue is given in Equation (1):

$$SAR = \frac{\sigma E^2}{2\rho} \quad (1)$$

where ρ is the mass density of the tissue, E is the magnitude of the electric field vector, and σ is the electric conductivity. Since the local SAR can vary strongly with position, the quantity of interest is often the peak spatial-average SAR. Contemporary safety standards and guidelines specify time-averaged whole-body-averaged SAR limits and psSAR limits, neither of which should be exceeded. The spatial-average SAR is averaged over a specified mass with a specified volume, e.g. 1 g or 10 g of tissue in the shape of a cube [1], [2].

NOTE Cubical averaging volumes are applied in all existing standards for the measurement of psSAR, and are also recommended by [1], [2] and [6]. Other averaging volumes have been proposed, e.g. in [2], and might be included in future revisions of this document.

6.2 SAR averaging

6.2.1 General

The objective of the methods to evaluate the psSAR described here is to yield results that correspond to the methods and definitions of Clause 6 of IEC/IEEE 62704-1:2017, which describes how to compute psSAR on a rectangular mesh. The same algorithm shall be applied to calculate psSAR for FEM simulations within this document. Since the algorithm of Clause 6 of IEC/IEEE 62704-1:2017 is specified on rectilinear meshes with varying mesh step, the vector components of the electric fields, the conductivity, and the mass density of the finite element mesh shall be resampled on a Cartesian mesh. The resampling is carried out with increasingly fine mesh steps until convergence of the dissipated power is reached in the subregions where local SAR maxima are located. In order to reduce the computation time for the iterative resampling and SAR averaging, subregions with local SAR maxima are identified in a pre-scan. In these subregions, the psSAR is then calculated according to Clause 6 of IEC/IEEE 62704-1:2017. The maximum psSAR of all subregions shall be reported as the psSAR maximum together with its interpolation uncertainty. The details of the steps of the algorithm are provided in 6.2.2.

6.2.2 Evaluation of psSAR with an FEM mesh

6.2.2.1 General

The following steps shall be carried out to resample the geometry and the power density in a set of subregions around local SAR maxima for the application of the SAR averaging algorithm of IEC/IEEE 62704-1:2017.

- a) Specify an orientation of a rectilinear mesh relative to the coordinate system of the FEM mesh considering the relevant features of the model; this orientation shall align with surface planes or conducting planes of the phantom or of the DUT.
- b) Iteratively resample the geometry and local SAR distribution in the rectilinear mesh and evaluate psSAR at each iteration until convergence is achieved (see 6.2.2.2).
- c) Report the highest psSAR of all subregions together with its interpolation uncertainty.

6.2.2.2 Calculation of the psSAR on an iteratively refined rectangular mesh

The psSAR shall be evaluated on a rectilinear mesh that encompasses a subregion around a local SAR maximum with individual equidistant mesh steps for each axis. Each mesh cell is assigned the local distribution of the dissipated power, the conductivity, and the mass density.

- a) The mass density for each mesh cell shall be assigned by nearest-neighbour interpolation of the mass density distribution of the tetrahedral mesh.
- b) The conductivity for each mesh cell shall be assigned by nearest-neighbour interpolation of the mass density distribution of the tetrahedral mesh.
- c) In the mesh cells that have a mass density different from zero, the dissipated power density is calculated by evaluating the electric field of the finite element mesh in the centre of the mesh cell of the rectilinear mesh.
- d) The initial mesh step length Δ_0 for each axis of the rectilinear mesh shall be calculated in accordance with Equation (2):

$$\Delta_0 \leq 3 \sqrt[3]{\frac{m}{\rho_{\max}}} \quad (2)$$

where

m is the averaging mass of the target volume;

$\rho_{\max}$ is the maximum mass density of the geometry in the computational domain.

- e) The psSAR for the subregion under evaluation shall be calculated on the initial mesh according to the procedure specified in IEC/IEEE 62704-1:2017. Then the subregion shall be resampled on a rectilinear mesh with a reduced mesh step size $\Delta_{i+1} = 0,5 \Delta_i$. This procedure shall be repeated until the difference in psSAR from the previous iteration to the present iteration is less than 1 %.

6.3 Power scaling

In FEM simulations, the accepted power is generally delivered to the device by means of a port with known characteristic impedance. Depending on the input impedance of the device, a specific power level is accepted by the antenna or load. The simulation results, including SAR, will be relative to this accepted power. To obtain the SAR for a different accepted power level, such as the target accepted power, the SAR results shall be adjusted by scaling using Equation (3):

$$SAR_{\text{scaled}} = SAR_{\text{scaled}} \frac{P_{\text{acc,target}}}{P_{\text{acc,computed}}} \quad (3)$$

where

$P_{\text{acc,target}}$ is the target accepted power;

$P_{\text{acc,computed}}$ is the accepted power computed by the FEM simulation.

For these calculations, $P_{\text{acc,computed}}$ is the power delivered to the load by the simulation, which is found from the complex voltage and current at the feed-point of the FEM mesh in accordance with Equation (4):

$$P_{\text{acc,computed}} = \frac{1}{2} \text{Re} \{ UI^* \} \quad (4)$$

where U and I are complex quantities, and the asterisk indicates complex conjugate.

If an incident plane wave source is applied, SAR can be scaled based on the incident power density. The incident power density can be computed using Equation (5):

$$P_{\text{inc}} = \frac{1}{2} \text{Re} \{ E_{\text{inc}} \times H_{\text{inc}}^* \} \quad (5)$$

where E_{inc} and H_{inc} represent the incident electric field and magnetic field from the plane wave. The computed incident power density can then be used to scale the SAR in the same manner as the accepted power.

Changes in SAR due to performance variations in radio frequency (RF) components that affect $P_{\text{acc,target}}$ (due to thermal, electrical, or other tolerances) shall be determined during experimental validation of the numerical model of the DUT (see 7.3). It shall be considered either by choosing the maximum possible value for $P_{\text{acc,target}}$ or by adding the performance variation in the uncertainty budget (see 7.4).

7 Considerations for the uncertainty evaluation

7.1 General

Assuming the FEM code has been implemented correctly, which shall be determined with the tests described in Clause 8, some uncertainties remain. This Clause 7 shows how they shall

be evaluated to obtain a measure of overall assessment uncertainty. It follows the computational uncertainty scheme of Clause 7 in IEC/IEEE 62704-1:2017, with modifications appropriate to FEM. As stated in the cited clause, the computational uncertainties are divided into the following three categories:

- a) discretization accuracy and uncertainty due to mesh density,
- b) numerical accuracy of the specific FEM implementation,
- c) accuracy of the numerical representation of the actual DUT.

Subclauses 7.2 through 7.4 specify general procedures for the evaluation of the uncertainty. When applied to device or application-specific FEM-based SAR simulation standards, there might be modifications appropriate to those applications. Further information can be found in Clause 7 of IEC/IEEE 62704-1:2017 and in [7], [8].

7.2 Uncertainty due to device positioning, mesh density, and simulation parameters

7.2.1 General

A representative model of the test configuration shall be used to determine the uncertainties due to mesh density, open boundary conditions, and other associated simulation parameters. For FEM, the contributions to the uncertainty due to device and phantom positioning are considered small because the mesh adapts to the surface of arbitrarily shaped objects. The remaining uncertainties are assumed to be covered in the evaluation of the uncertainty of the mesh density. Table 1 shows an example template for the quantification of the numerical uncertainty due to contributions described in 7.2.2 through 7.2.6.

Table 1 – Budget of the uncertainty contributions of the numerical algorithm and of the rendering of the test-setup or simulation-setup

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance (%)	Probability distribution	Divisor $f(d, h)$	c_i	Uncertainty (%)	v_i or v_{eff}
Mesh convergence	7.2.2		N	1	1		
Open boundary conditions	7.2.3		N	1	1		
Power budget	7.2.4		N	1	1		
Convergence of psSAR sampling	7.2.5		R	1,73	1		
Phantom dielectrics	7.2.6		R	1,73	1		
Combined std. uncertainty ($k = 1$)							
NOTE 1 Column headings a to h are given for reference.							
NOTE 2 Columns c, g, and h are filled in based on the results of the DUT simulations.							
NOTE 3 Abbreviations used in Table 1:							
N, R, U – normal, rectangular, U-shaped probability distributions							
Divisor – divisor used to get standard uncertainty							
NOTE 4 The divisor is a function of the probability distribution and degrees of freedom (v_i and v_{eff}).							
NOTE 5 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of psSAR.							

7.2.2 Mesh convergence

The mesh convergence has a major impact on the accuracy of the results; therefore, psSAR results produced with a specific initial mesh M need to be compared with psSAR results produced with a denser mesh M' . Either of the following two strategies shall be applied depending on whether the FEM code used for the psSAR evaluation employs adaptive mesh refinement or not.

- a) If the applied FEM code does not employ adaptive mesh refinement, the number of elements per wavelength used for the initial mesh M shall be increased by at least 50 % considering the respective wavelengths in the dielectrics.
- b) If the applied FEM code uses adaptive mesh refinement, additional adaptive passes shall be performed until the total number of elements has increased by at least 20 % for second or third lowest order and 50 % for lowest order.

In both cases, the electric field vector components shall be recorded in the region where the psSAR maximum is expected (psSAR region). It shall be ensured that both the minimum and the maximum edge lengths in the psSAR region and the region around the antenna of the denser mesh M' are not greater than 50 % of the respective edge lengths of M . The location of the electric field maximum in the psSAR region of mesh M' shall not deviate by more than the minimum mesh edge length from the location of the electric field maximum within the psSAR region of mesh M . The maximum psSAR deviation shall be reported as an uncertainty with rectangular probability distribution.

The coordinates of the psSAR region and antenna region shall be reported.

7.2.3 Open boundary conditions

The impact of open boundary conditions shall be determined by moving the boundaries outward by one quarter-wavelength for several test cases, e.g. at the locations of the maximum electric field energy and magnetic field energy at the boundary. The maximum deviation of the target quantity (e.g. maximum deviation of psSAR) from all investigated cases with shifted open boundary conditions shall be reported.

NOTE The location of the maximum electric energy or maximum magnetic energy at the boundary might correspond to the main beam of a radiating structure, or to its reactive field.

7.2.4 Power budget

The accepted power fed into the computational domain shall be recorded and summed up at the sources. The sum of the power absorbed in all lossy regions and elements in the computational domain and radiated into the open boundary condition shall be recorded and compared to the accepted power. Depending on numerical uncertainties, such as poor convergence or roundoff errors, the sum of the absorbed and the radiated power will not be precisely equal to the accepted power. As a linear relationship exists between SAR and power, the error of the power budget is directly proportional to the SAR uncertainty. The deviation shall be reported as an uncertainty.

When simulating devices with multiple sources operating simultaneously, the correct loading of all ports shall be implemented. It is recommended to excite each port separately while loading the inactive ports with the reference impedance in order to compute the full S -parameter matrix of the multiport system. As such, the SAR and the total power budget for a given excitation vector may be calculated by superimposing the fields for any excitation vector and load. For details refer, for example, to [9], [10], [11], [12], or [13].

7.2.5 Convergence of psSAR sampling

The calculation of the peak spatial-average SAR as described in 6.2.2.2 requires iterative sampling of the tetrahedral mesh on a rectilinear mesh. The relative difference of the psSAR from the last iteration step and the previous one shall be reported as an uncertainty with rectangular probability distribution.

7.2.6 Dielectric parameters of the phantom or body model

The dielectric parameters of the tissues or tissue-equivalent medium of the phantom or body model are usually affected by uncertainties according to their specification. The impact of these uncertainties on the psSAR shall be evaluated by applying the minimum and maximum conductivity and permittivity (four different combinations). The minimum and maximum shall be chosen according to the uncertainty that is reported by the reference of the dielectric parameters. Dielectric parameters for particular reference phantoms or models can be specified with an uncertainty of zero. In this case, no additional evaluations are required, and the corresponding entry in Table 1 shall be set to zero. The maximum deviation from the psSAR obtained using the nominal value of the permittivity and conductivity shall be reported.

7.3 Uncertainty and validation of the developed numerical model of the DUT

7.3.1 General

The purpose of 7.3 is to assess simulation uncertainty contribution related to the accuracy of the DUT modelling, with respect to the SAR induced in the exposed phantom. Among other parameters, the evaluated SAR depends on the RF current distribution in the DUT and therefore has an uncertainty associated with the limited accuracy due to simplifications introduced to a CAD-based DUT model. The level of details necessary to develop an accurate numerical model of a real device and the evaluation of its uncertainty depend on the testing or exposure assessment configurations. Many exposure conditions include the DUT in close proximity to the exposed object with some degree of interaction between them. This interaction can be accounted for by the FEM. In general, to properly account for this interaction, it is important not to define a fixed distribution of the RF currents on the DUT model, for example, by using a set of distributed current sources or by forcing the magnetic fields to a particular value in the solver software. The antenna feed-point(s) of the DUT model shall be fed by one or more sources which ensure that the contributions of all parts of the DUT which contribute to the RF current distribution be appropriately reproduced. The accuracy of this model shall be evaluated by comparing the measurements and the simulations of the electromagnetic fields generated by the DUT at specific reference locations.

In order to isolate the uncertainty of the DUT model from other uncertainty contributions as much as possible and to reduce the potential differences between the measurement setup and simulation model for the purpose of uncertainty evaluation, the reference test configuration should be limited to those details which are essential for the characterization of the RF transmission and of the exposure characteristics during normal operation of the DUT. If the output power cannot be determined, for example, by measurements of the conducted power, the test conditions, such as RF channels or duty factors, shall be chosen with respect to the maximum output power following product specifications, applied wireless technology, etc. The number of tests required for the following cases is minimized and the test configurations are simplified according to the closest distance d between the DUT and the phantom.

- $d \geq \lambda/2$ or $d \geq 200$ mm: Under such exposure conditions, electromagnetic field measurement techniques developed for exposure assessment are applicable and practical, for example, [14].
- $d < \lambda/2$ and $d < 200$ mm: Under such exposure conditions, developed SAR measurement techniques are applicable and practical (IEC 62209-1 and IEEE Std 1528).

The uncertainty for these cases shall be determined with the methods described in 7.3.2 and 7.3.3.

7.3.2 Uncertainty of the DUT model ($d \geq \lambda/2$ or $d \geq 200$ mm)

Where no accurate reference field distribution is available, such as an analytical solution, it is sufficient to experimentally validate the field generated by the DUT at a distance no further than the distance at which the exposure is evaluated. The electric field and magnetic field shall be scanned along a line parallel to the axis of the body of the device or subsystem that contains the antenna and radiating structures, whichever is more representative and conservative for the exposure condition under evaluation, in steps no greater than $\lambda/4$ or 100 mm (whichever is less) and compared to the numerical values. At least three points overlapping the device dimension and one point extending beyond the device dimension shall be scanned. If scattering, for example, from conducting ground cannot be excluded due to limitations of the testing environment, the scatterers shall be modelled in the numerical simulations of the DUT. If such scatterers are included in the test setup, at least two different distances in steps of $\lambda/4$ between them shall be measured and simulated, where at least one of these measurement distances shall be less than the exposure distance. The SAR uncertainty, based on a rectangular probability distribution, shall be assessed as the maximum deviation of the square of the field components normalized to the maximum experimental value, using Equation (6)

$$U_{\text{SAR}} [\%] = 100 \times \text{MAX} \left(\frac{|E_{\text{ref}}^2(n) - E_{\text{num}}^2(n)|}{E_{\text{ref,max}}^2}, \frac{|H_{\text{ref}}^2(n) - H_{\text{num}}^2(n)|}{H_{\text{ref,max}}^2} \right) \quad (6)$$

where

U_{SAR}	is the uncertainty as a percentage;
E_{ref}	is the experimentally determined incident electric field strength at location n or its accurate reference solution;
H_{ref}	is the experimentally determined incident magnetic field strength at location n or its accurate reference solution;
E_{num}	is the numerically determined incident electric field strength at location n ;
H_{num}	is the numerically determined incident magnetic field strength at location n ;
$E_{\text{ref,max}}$	is the maximum of the experimentally determined incident electric field strength of all measured locations or its accurate reference solution;
$H_{\text{ref,max}}$	is the maximum of the experimentally determined incident magnetic field strength of all measured locations or its accurate reference solution.

For a DUT which is mounted on a ground plane, the reference ground plane shall be used to represent the intended operating conditions. In cases where regions below the ground plane are inaccessible and there is no exposure concern, the reference points for the electromagnetic field measurements and simulations shall be located above the ground plane.

The measurements required for these evaluations shall be performed with instrumentation that minimizes the perturbation of the measured fields for more reliable comparison with the simulation results. Depending on the physical dimensions of the field sensors used, there may be inherent spatial averaging over the region occupied by the field sensors. This can lead to larger discrepancies between the measured and simulated field results. It is recommended that miniature electric field and magnetic field probes/sensors be used to keep the uncertainty of the comparison to the minimum. The reference documentation of the applied instrumentation and/or appropriate measurement standards, describing the specific application of this general approach, should provide sufficient details to help ensure high quality of the reference configuration setup. Their uncertainties shall be determined appropriately. The uncertainty of the developed model of the DUT shall be evaluated according to Table 2.

Table 2 – Budget of the uncertainty of the developed model of the DUT

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance %	Probability distribution	Divisor $f(d, h)$	c_i	Uncertainty %	v_i or v_{eff}
Uncertainty of the DUT model (incident near- or far-field distribution with or without dependence on the load)	7.3.2 or 7.3.3		N	1	1		
Uncertainty of the phantom model, i.e. of the absorption and of the backscattering (if applicable)	7.3.4		N	1	1		
Uncertainty of the measurement equipment and procedure	According to manufacturer specification and/or applied methodology		N	1	1		
Combined standard uncertainty ($k = 1$)							
Columns c, g and h shall be filled in based on the results of the DUT simulations.							
NOTE 1 Column headings a to h are given for reference.							
NOTE 2 Abbreviations used in Table 2:							
N – normal probability distribution							
NOTE 3 The divisor is a function of the probability distribution and degrees of freedom (v_i and v_{eff}).							
NOTE 4 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of SAR.							

7.3.3 Uncertainty of the DUT model ($d < \lambda/2$ and $d < 200$ mm)

In the reactive near-field of the source, the coupling of the fields directly with the body may have a strong effect on the transmitter. In this case, the only way to determine the uncertainty of the DUT model is by SAR measurements. In such a case, the uncertainty of the phantom model contributes to the uncertainty of the model of the DUT. However, simplified measurements can be used. It is recommended to use a flat phantom for the measurements because the uncertainty of the numerical model of such a phantom is expected to be negligible, such that a particular evaluation of the phantom uncertainty is not necessary. Otherwise, the phantom uncertainty shall be assessed separately by applying the procedure specified in 7.3.4.

In order to determine the effect of backscattering, different distances between the DUT and the phantom shall be evaluated in order to take into account different loading conditions. The uncertainty shall be determined by assessing the deviation of the SAR amplitude and distribution for three different distances. The default distance d_0 between DUT and phantom shall be the same as the one required by the SAR simulation. In most cases this will be the distance of the intended use as specified by the manufacturer or by the relevant measurement standards, for example, IEC 62209-1 and IEEE Std 1528. This distance shall lie within the $d < \lambda/2$ and $d < 200$ mm range. The other two distances to be evaluated are $0,5 d_0$ and $1,5 d_0$. If the default distance d_0 is zero, the DUT shall be evaluated at zero, at the maximum of the $d < \lambda/2$ and $d < 200$ mm range (whichever is less) and at 10 % of this maximum. If the distance of $1,5 d_0$ exceeds the maximum of the $d < \lambda/2$ and $d < 200$ mm range (whichever is

less) by more than 30 %, a distance of $0,75 d_0$ shall be evaluated instead. If the SAR levels at the larger distances are too low to be measured with sufficient accuracy (e.g. due to noise), two alternative distances shall be evaluated at which the SAR level shall be sufficiently high above the noise level and at which different characteristics of the incident field (near- and far-field range) should be covered. A rationale for these distances shall be given.

The uncertainties shall be determined by the experimental and numerical assessment of the SAR distribution for the three different separation distances between the DUT and the phantom, as described above, on a mesh with steps no larger than 15 mm or $\lambda_D/2$ (whichever is less considering the reduced wavelength λ_D in the dielectric) at no less than 100 points in a volume as close as possible to the volume containing the SAR maximum. The cross section of the volume shall entirely cover the surface of the device that faces the phantom. At least two parallel planes shall be measured. The mesh step refers to the measurement mesh. For the numerical evaluation, a finer mesh is generally required. At each distance d , the SAR uncertainty is evaluated according to Equation (7).

$$U_{\text{SAR},d} [\%] = 100 \times \text{MAX} \frac{|SAR_{\text{ref}}(n) - SAR_{\text{num}}(n)|}{SAR_{\text{ref,max}}} \quad (7)$$

where

SAR_{ref}	is the experimentally determined local (unaveraged) SAR value at position n or its accurate reference solution;
SAR_{num}	is the numerically determined local SAR value at position n ;
$SAR_{\text{ref,max}}$	is the experimentally determined maximum SAR value of all measured positions or its accurate reference solution.

Only the maximum SAR uncertainty of the three distances shall be reported. The reference documentation of the applied instrumentation and/or appropriate measurement standards, describing the specific application of this general approach, should provide sufficient details to help ensure high quality of the reference configuration setup. Their uncertainties shall be determined appropriately following the procedures described in IEC 62209-1 and IEEE Std 1528. The uncertainty of the developed model of the DUT shall be evaluated according to Table 2.

7.3.4 Phantom uncertainty ($d < \lambda/2$ and $d < 200$ mm)

For phantoms other than the flat phantom at an evaluation distance $d < \lambda/2$ and $d < 200$ mm, the phantom uncertainty shall be assessed separately. The objective of this evaluation is the assessment of the numerical representation of more complex phantom shapes or inhomogeneous dielectrics. The phantom model shall be exposed to incident plane waves from all orthogonal directions of the coordinate system (e.g. front, back, left, right, top, bottom) and two orthogonal polarizations of the incident electric field vector for each direction (twelve evaluations). The following uncertainty components shall be evaluated as specified in 7.2:

- mesh convergence (7.2.2);
- open boundary conditions (7.2.3);
- convergence of psSAR sampling (7.2.5).

The uncertainty contribution of the phantom dielectrics is evaluated as part of 7.2 and shall not be repeated here.

The phantom uncertainty shall be evaluated according to Table 1 for each of the twelve polarizations. The maximum uncertainty shall be used as the phantom uncertainty.

7.3.5 Model validation

The following steps shall be followed for the validation of the model:

- Determine the uncertainty budget of the numerical model U_{sim} by evaluating the SAR uncertainty of the numerical model of the setup of 7.3.2 or 7.3.3 according to Equation (7) or Equation (8).
- Determine the uncertainty budget of the measurement evaluation U_{ref} .
- Verify whether the deviation between the measured SAR value at point n , $v_{\text{ref},n}$ (or its accurate reference), and the simulated SAR value $v_{\text{sim},n}$ is within the combined uncertainty of U_{ref} and U_{sim} by evaluating Equation (8).

$$E_n = \sqrt{\frac{(v_{\text{sim},n} - v_{\text{ref},n})^2}{\left(v_{\text{sim},n} U_{\text{sim}(k=2)}\right)^2 + \left(v_{\text{ref},n} U_{\text{ref}(k=2)}\right)^2}} \leq 1 \quad (8)$$

If the electric field strength or the magnetic field strength is determined in the DUT model uncertainty simulations and measurements instead of SAR, these values shall be squared to calculate the respective $v_{\text{ref},n}$ and $v_{\text{sim},n}$.

The verification according to Equation (8) shall be carried out at every point n that is larger than 5 % of the maximum measured or simulated value $\text{MAX}(v_{\text{sim},n}; v_{\text{ref},n})$.

If the deviation is within the combined uncertainty, i.e. if $E_n \leq 1$ for any considered point, the combined standard uncertainty in Table 2 is the uncertainty for the DUT model. If the deviation is not within the expected uncertainty, the DUT model is not valid and shall be revised.

7.4 Uncertainty budget

The overall assessment uncertainty budget for the numerical simulation results shall be calculated from the contributions of 7.2 and 7.3 and shall be summed up as shown in Table 3. The minimum achievable uncertainty depends on the level of detail to which a particular exposure situation can be modelled. Subclause 7.4 of IEC/IEEE 62704-1:2017 discusses the acceptable level of uncertainty that can be expected from simulations using the FDTD method. Particular tolerances may be specified in the respective application oriented guidelines based on IEC/IEEE 62704-1:2017.

NOTE At present, appropriate levels of uncertainty for simulation results of the FEM cannot be given due to the lack of application examples. Expected levels of uncertainties are similar to those obtained with the FDTD method according to IEC/IEEE 62704-1:2017.

Table 3 – Overall assessment uncertainty budget for the numerical simulation results

a	b	c	d	e	f	g	h
Uncertainty component	Subclause	Tolerance (%)	Probability distribution	Divisor $f(d, h)$	c_i	Uncertainty (%)	v_i or v_{eff}
Uncertainty of the DUT model with respect to simulation parameters	7.2		N	1	1		
Uncertainty of the developed numerical model of the DUT	7.3		N	1	1		
Combined std. uncertainty ($k = 1$)							
Expanded std. uncertainty ($k = 2$)							
NOTE 1 Column headings a to h are given for reference. NOTE 2 Columns c, g, and h are filled in based on the results of Table 1 and Table 2. NOTE 3 Abbreviation used in Table 3: N – normal probability distribution Divisor – divisor used to get standard uncertainty NOTE 4 The divisor is a function of the probability distribution and degrees of freedom (v_i and v_{eff}). NOTE 5 c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of psSAR.							

8 Code verification

8.1 General

8.1.1 Rationale

This Clause 8 provides procedures for the following two levels of code verification:

- code performance verification (8.2, 8.3 and 8.4);
- canonical benchmarks (8.5).

An implementation of the FEM can be verified by the manufacturer according to the benchmarks specified in this Clause 8. A code that has passed the quality criteria can be deemed to be "compliant with IEC/IEEE 62704-4". This Clause 8 follows the code verification scheme of Clause 8 in IEC/IEEE 62704-1:2017, with modifications according to the requirements of the FEM. The objectives of the different levels of verification are described in 8.2 through 8.5.

The objective of the code verification within the framework of the IEC/IEEE 62704 series is to demonstrate the technically correct implementation of a numerical algorithm for the quantification of the electromagnetic fields induced in the human body. In case of the FDTD method, the correctness of the implementation can be verified by evaluating the particular numerical error of the Yee-algorithm. These errors depend on the ratio of the mesh resolution with respect to the wavelength. They are well known and are described in the peer-reviewed literature. A numerical code that exactly reproduces these errors is therefore assumed to be a correct implementation of the Yee-algorithm. Because of its unique definition, such verification can be performed with the simple means specified in IEC/IEEE 62704-1:2017, regardless of the quantification of its accuracy with respect to the physically correct solution.

For FEM, a large number of different implementations exist. This document is not restricted to any particular formulations or implementations of FEM. Numerical errors depend on the particular implementation (basis functions, etc.). To the best knowledge of the working group that developed this document, there is no comprehensive methodology to quantify these errors, and the numerical solutions for generic examples converge against their physical solutions when the step sizes of the computational meshes approach zero. The verification of an FEM code according to this document is carried out by demonstrating the convergence of the numerical solution to the physically correct one for a number of relevant benchmarks, where an exact analytical solution of the physical problem is available.

For the more complex benchmarks, code verification for both FDTD and FEM relies on typical generic configurations used in SAR measurements. Exact numerical or analytical solutions are generally not available for such configurations. Reference solutions have been obtained, e.g. with alternative methods, interlaboratory comparisons, or validation against experimental results. Providing that the parameters (dielectrics, exact dimensions, etc.) of a model to be simulated are known with sufficient accuracy, the deviations of the simulation results from reference results generally depend on details of the meshed representation of the model geometry in the computational domain. The meshing parameters are usually under the control of the code or its operator. Hence, a comparison of the results of complex geometries would rather show differences between individual simulations and not between the numerical methods as such.

8.1.2 Code performance verification

The code performance verification described in 8.2 and 8.3 provides methods to determine whether the FEM has been implemented correctly and works accurately within the constraints of its finite numerical accuracy. It further determines the quality of the open boundary conditions and specific parts of the post processing algorithms. All numerical results are compared to the analytical solutions of the respective physical problems. Subclause 8.4 specifies the test of the implementation of the psSAR averaging algorithm according to 6.2.

The results for the code verification shall be assessed as a function of the applied degrees of freedom (DoF).

NOTE 1 The number of DoF, i.e. the total number of unknowns, depends on the number of elements and the number of unknowns associated with each element (see Clause 5).

NOTE 2 In general, the number of DoF can be chosen individually for each benchmark to reach the required accuracy. The benchmarks do not specify the number of DoF to apply, but may give guidance on how to choose or modify it.

8.1.3 Canonical benchmarks

The canonical benchmarks described in 8.5 assess the accuracy of a code and its applicability considering the interaction of its different modules, such as mesh generation, computational kernel, representation of sources, data extraction algorithms of the post processor, etc.

8.2 Code performance verification

8.2.1 Propagation in a rectangular waveguide

The assessment of the propagation characteristics of a code provides the means to verify the basic implementation of the FEM, such as accuracy and convergence for free space and for dielectric interfaces. Rectangular waveguides are characterized in terms of wave number and reflection coefficient for the different configurations. Convergence to the physically correct value within a specified tolerance shall be demonstrated for an increasing number (at least three) of DoF. Minimum or maximum values are not specified for the number of DoF.

- a) Specification of the waveguide – The rectangular waveguide model is specified with perfectly conducting walls (Figure 1). Its widths in the x - and y -directions are 120 mm and 60 mm, respectively. All directions and dimensions correspond to the coordinate system as shown in Figure 1. The excitation is placed perpendicular to the orientation of the waveguide. The distance from the source to the fields to be recorded shall be 60 mm. The length of the waveguide should be chosen such that reactive fields that can be caused by the truncation of the computational domain do not reach the region where the fields are recorded.
- b) TE (transverse electric) polarization – For the TE_{10} mode, the waveguide shall be terminated with perfect electrical conductors (PEC) as boundary conditions in the x - and y -directions. The E_y components at the source location (Figure 2) shall be excited with the analytical solution of the TE_{10} mode. This mode can be excited by setting the E_y components at the location of the source or the waveguide port (Figure 2) to the values calculated from Equation (9).

$$E_y = E_0 \sin \frac{x\pi}{w} \quad (9)$$

where

E_0 is an arbitrary electric field strength amplitude;

x is the location of the E_y component;

w is the width of the waveguide.

Alternative methods for the field excitation may be used, such as particular solvers to determine the propagating modes in the waveguide, or preconfigured sources if the code provides them. In any case, it shall be asserted that only the fundamental propagating mode exists at the location where the fields are recorded (Figure 2).

- c) TM (transverse magnetic) polarization – For the fundamental TM mode, the waveguide shall be terminated with perfect electrical conductors as boundaries in the x -direction and with perfect magnetic conductors in the y -direction. The fundamental mode for a waveguide consisting of perfect electric-conductor and perfect magnetic-conductor boundaries is the TM_{10} mode. The mode can be excited by setting the E_x components at the source location (Figure 2) to the values calculated from Equation (10).

$$E_x = E_0 \cos \frac{x\pi}{w} \quad (10)$$

where

E_0 is an arbitrary electric field strength amplitude;

x is the location of the E_x component;

w is the width of the waveguide.

Alternative methods for the field excitation may be used, such as particular solvers to determine the propagating modes in the waveguide, or preconfigured sources if the code provides them. In any case, it shall be asserted that only the fundamental propagating mode exists at the location where the fields are recorded (Figure 2).

- d) Excitation – The TE_{10} and TM_{10} modes shall be used as excitations for the waveguide model. The frequencies to be evaluated range from 500 MHz to 2 GHz, with a step size of 25 MHz. Separate simulations shall be carried out for each frequency (61 simulations in total). The frequency range covers both the reactive and the propagating range of the TE_{10} and TM_{10} modes in the waveguide.

- e) Dielectric parameters – The waveguide shall be simulated with three homogeneous isotropic media (see Figure 1):

$$\varepsilon_r = 1,0; \sigma = 0,0 \text{ S/m};$$

$$\varepsilon_r = 2,0; \sigma = 0,0 \text{ S/m};$$

$$\varepsilon_r = 2,0; \sigma = 0,2 \text{ S/m}.$$

- f) Field components to be recorded – The E_x components shall be recorded at the locations specified in Figure 2 for the calculation of the dispersion relation as described in the next step.
- g) Calculation of the dispersion relation – The numerical wave numbers $k_{x,\text{num}}$ and $k_{z,\text{num}}$ shall be calculated from the E_x components recorded at the locations in Figure 2 using the identities of Equation (11) and Equation (12).

$$k_{x,\text{num}} = -\frac{j}{\Delta_s} \ln \left(\frac{E_{01} + E_{21} - \sqrt{-4E_{11}^2 + (E_{01} + E_{21})^2}}{2E_{11}} \right) \quad (11)$$

$$k_{z,\text{num}} = -\frac{j}{\Delta_s} \ln \left(\frac{E_{10} + E_{12} - \sqrt{-4E_{11}^2 + (E_{10} + E_{12})^2}}{2E_{11}} \right) \quad (12)$$

where Δ_s is the distance between the locations of the recorded components (30 mm). The numerical wave number can be calculated using Equation (13).

$$k^2 = k_x^2 + k_z^2 \quad (13)$$

The reference solutions of the numerical wave vector for comparison with Equation (8) and Equation (12) can be obtained by solving the physically correct dispersion relation of the waveguide, in accordance with Equation (14), Equation (15), and Equation (16).

$$k = \sqrt{\omega\mu_0(\omega\varepsilon_r\varepsilon_0 + j\sigma)} \quad (14)$$

$$k_x = \frac{\pi}{w} \quad (15)$$

$$k_z = \sqrt{k^2 - k_x^2} \quad (16)$$

- h) Data reporting – The numerical wave numbers for each frequency shall be evaluated as a function of the number of DoF for each frequency. For each waveguide model configuration in Table 4, the maximum deviation from the physical wave number shall be evaluated as a function of frequency. These deviations shall be less than or equal to the tolerances given in Table 4. In addition, the number of DoF at which the tolerance is reached shall be reported for each simulation. To demonstrate convergence, it shall be shown in suitable graphs that the deviation of the numerical wave number from the physical result decreases when the number of DoF increases.

The maximum deviations reported in Table 4 are relevant for the compliance of the code to the requirements of this document.

Dimensions in millimetres

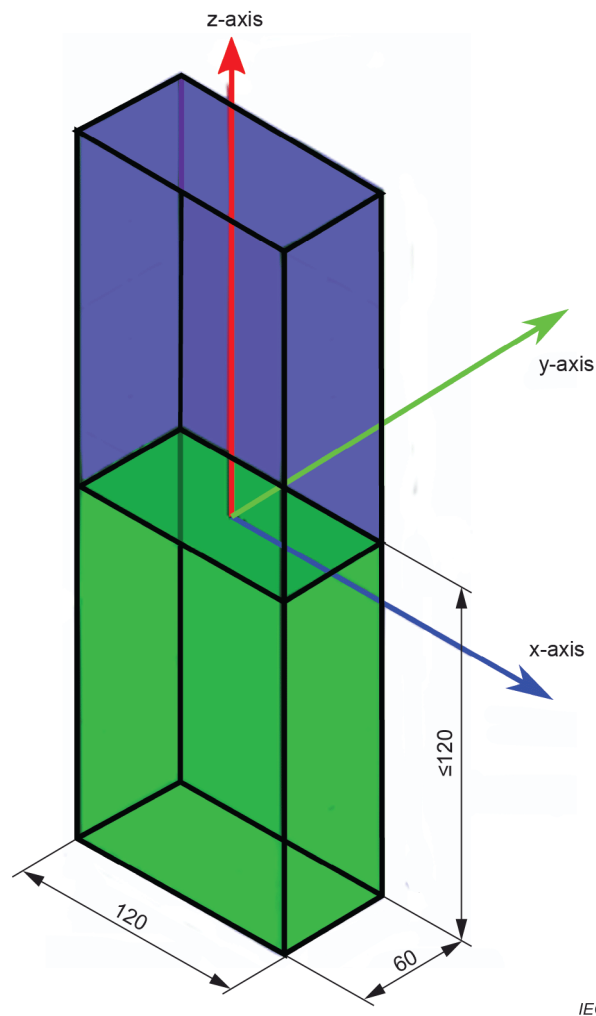
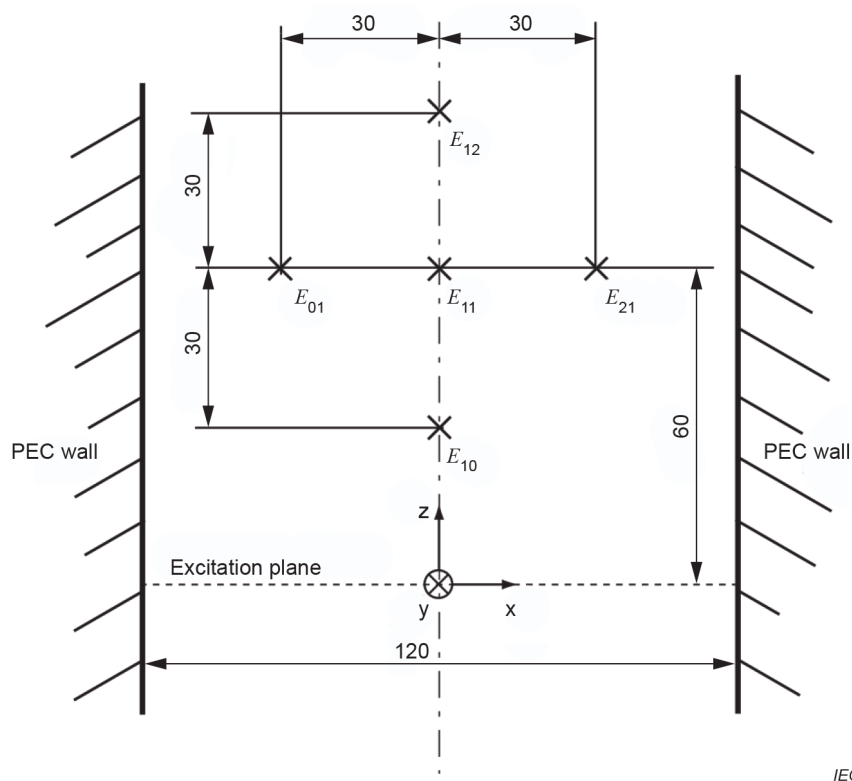


Figure 1 – Waveguide filled half with free-space (green) and half with dielectric (blue)



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Figure 2 – Aligned rectangular waveguide and locations of the sample points E_{01} , E_{10} , E_{11} , E_{12} and E_{21} at which the E_x components are recorded

Table 4 – Results of the evaluation of the numerical dispersion characteristics to be reported for each mesh axis and each orientation of the waveguide for at least three increasing numbers of DoF

Quantity	Limit	TE-pol.			TM-pol.		
ε_r		1	2	2	1	2	2
σ [S/m]		0	0	0,2	0	0	0,2
max. dev. of simulated $\text{Re}\{k_z\}$ from numerical reference 5 % above cut-off	± 2 %						
max. dev. of simulated $\text{Im}\{k_z\}$ from numerical reference 5 % below cut-off	± 2 %						
max. dev. of simulated $\text{Im}\{k_z\}$ from numerical reference 5 % above cut-off	± 2 %	n.a.	n.a.		n.a.	n.a.	
max. dev. of simulated $\text{Re}\{k_z\}$ from numerical reference 5 % below cut-off	± 2 %	n.a.	n.a.		n.a.	n.a.	
NOTE pol. = polarization; n.a. = not applicable							

8.2.2 Planar dielectric boundaries

The implementation of planar dielectric interfaces shall be tested using the waveguide configurations described in 8.2.1 (waveguide, excitation, frequencies) as a function of the number of DoF. The dielectric interface shall be perpendicular to the z -axis. A dielectric boundary shall be introduced at a distance of 120 mm or larger from the excitation. The dielectric boundary is oriented perpendicularly to the PEC walls and divides the waveguide into two regions. A permittivity $\varepsilon_r = \varepsilon_1 = 1$ shall be used for the region that contains the excitation. The permittivity of the other region shall be $\varepsilon_r = \varepsilon_1 = 4$. A lossless (TE- and TM-polarization) and a lossy dielectric (TE-polarization only) shall be simulated ($\sigma = 0$ and $\sigma = 0,2$ S/m). The dielectric region extends to the end of the computational domain, and the length of the waveguide shall be chosen such that reflections from the mesh truncation of the computational domain do not reach the location at which the fields are recorded during the simulation.

The numerical reflection coefficient as a function of the frequency shall be extracted from the complex electric field strength amplitudes at the positions in Figure 2 (see 8.2.1). Closed-form expressions for the reflection coefficients for TE- and TM-polarization are in accordance with Equation (17) through Equation (20).

$$\rho_{TE} = \frac{k_{2z}}{k_{1z}} \quad (17)$$

$$r_{TE} = \frac{1 - \rho_{TE}}{1 + \rho_{TE}} \quad (18)$$

$$\rho_{TM} = \frac{\varepsilon_1 k_{2z}}{\varepsilon_2 k_{1z}} \quad (19)$$

$$r_{TM} = \frac{1 - \rho_{TM}}{1 + \rho_{TM}} \quad (20)$$

k_{1z} and k_{2z} are the wave numbers in the two dielectrics according to Equation (16) (see 8.2.1). $\varepsilon_1 = \varepsilon_2$ and are required for the evaluation of $r_{TE} = r_{TM}$.

For the evaluation of the numerical reflection coefficient, the steps for the extraction of the numerical wave number in free space as described in 8.2.1 shall be repeated. The numerical reflection coefficient shall then be evaluated in accordance with the following steps:

- a) Extraction of the reflection coefficient – The amplitudes of the propagating and the reflected waves E_p and E_r are given by Equation (21) through Equation (23).

$$E_p = \frac{1}{\Psi} \left[E_{10} e^{-jk_z(2z_r - z_0 - z_{11})} - E_{11} e^{-jk_z(2z_r - z_0 - z_{10})} \right] \quad (21)$$

$$E_r = \frac{1}{\Psi} \left[E_{11} e^{-jk_z(z_{10} - z_0)} - E_{10} e^{-jk_z(z_{11} - z_0)} \right] \quad (22)$$

where

$$\Psi = e^{-jk_z[2(z_r - z_0) + z_{10} - z_{11}]} - e^{-jk_z[2(z_r - z_0) + z_{11} - z_{10}]} \quad (23)$$

Here, z_r , and z_0 are the locations of the boundary and the source, respectively. z_{10} and z_{11} are the positions of the electric field sample points as shown in Figure 2 (see 8.2.1). k_x , k_{1z} , and k_{2z} are the components of the numerical wave vector evaluated using Equation (11) and Equation (12) (see 8.2.1). The amplitude reflection coefficient r is then calculated in accordance with Equation (24).

$$r = \frac{E_r}{E_p} \quad (24)$$

For the evaluation of k_{2z} the arrangement of the sample points shown in Figure 2 shall be repeated in the region filled with the dielectric ε_2 .

- b) Data reporting – The numerical reflection coefficient r shall be evaluated as a function of the frequency for reactive modes in a frequency range from 0,5 GHz to 0,6 GHz (below the cut-off frequency of the waveguides) and for propagating modes in a frequency range from 1,4 GHz to 2 GHz. Frequency steps of 25 MHz shall be applied. These deviations shall be in compliance with the tolerance given in Table 5. In addition, the number of DoF at which the tolerance is reached shall be reported for each simulation. For the demonstration of convergence, the final result shall be compared to the result of a coarser mesh with one-tenth the number of the DoF of the mesh of the final result. The deviation of the result of the coarser mesh from the physical result shall be larger than the deviation of the final result from the physical result.

The deviation of the simulated results from the numerical reference is relevant for the compliance of the code.

Table 5 – Results of the evaluation of the numerical reflection coefficient to be reported; frequency range is indicated for each value to be reported

Quantity	Limit for code compliance	TE-pol.		TM-pol.
ε_r		4	4	4
σ [S/m]		0	0,2	0
max. dev. of simulated $\text{Re}\{k_{2z}\}$ from numerical reference 1,4 GHz < f < 2 GHz	±5,0 %			
max. dev. of simulated $\text{Im}\{k_{2z}\}$ from numerical reference 0,5 GHz < f < 0,6 GHz	±5,0 %	n.a.		n.a.
max. dev. of simulated $\text{Re}\{r\}$ from numerical reference 1,4 GHz < f < 2 GHz	±5,0 %			
max. dev. of simulated $\text{Im}\{r\}$ from numerical reference 1,4 GHz < f < 2 GHz	±5,0 %	n.a.		n.a.
max. dev. of simulated $\text{Re}\{r\}$ from numerical reference 0,5 GHz < f < 0,6 GHz	±10,0 %			
max. dev. of simulated $\text{Im}\{r\}$ from numerical reference 0,5 GHz < f < 0,6 GHz	±10,0 %	n.a.		n.a.
NOTE 1 Larger tolerances apply for the deviation of the simulation from the reference for frequencies below cut-off.				
NOTE 2 pol. = polarization; n.a. = not applicable				

8.2.3 Open boundary conditions

Decay of the magnitude of the electric field vector in radial directions shall be compared to a reference solution that is obtained using the method of moments, available as a supplemental file from

https://www.iec.ch/dyn/www/f?p=103:227:12350535389069:::FSP_ORG_ID,FSP_LANG_ID:1303,25 and <https://standards.ieee.org/downloads.html>. The electric field shall be generated by a dipole of 300 mm length and element radius of 0,5 mm, operated at a frequency of 1 GHz. The dipole shall be simulated in a computational domain with a size of 500 mm along the dipole axis, and a distance of 500 mm in the other directions. The centre of the computational domain and the feed-point of the dipole shall be at the origin of the coordinate system. The number of degrees of freedom of the finite element mesh including the open boundary shall not exceed 4×10^6 for lowest, second lowest and third lowest order.

The magnitude of the electric field vector shall be evaluated along radial lines at angles of 0° , $22,5^\circ$, 45° , 90° , 135° , and 270° , where 0° corresponds to the x -axis. The minimum radius for the evaluation shall be 100 mm, and the maximum radius shall be 490 mm.

The magnitude of the electric field vector shall be scaled to the reference solution using a least-squares fit. The deviation of the scaled magnitude of the electric field vector from the reference solution shall not be greater than 5 % for lowest order and 3 % for second and third lowest order anywhere on the radial lines. The maximum deviation shall be reported.

8.3 Weak patch test

8.3.1 General

The classic patch test was originally developed by mechanical engineers for assessing the convergence of a specific finite element formulation in elastic or thermal simulation codes [15]. Here convergence means that any admissible solution can exactly be reproduced if the mesh is refined enough. The underlying idea is that elements that can reproduce a constant function should be able to reproduce any admissible function if the mesh is refined enough. The rationale for this idea is that if one inspects a static field distribution on a small scale, it is locally constant. As an example, consider a low-frequency electric field finite element solver: if a few finite elements reproduce the homogeneous electric field in a parallel plate capacitor exactly, then the solver passes the classic patch test and reproduces any admissible electric field.

The properties of the classic patch test can be summarized as follows [15]:

- It is a necessary condition for assessing the convergence of any finite element approximation.
- Further to that, if properly extended and interpreted, it can provide
 - a sufficient requirement for convergence;
 - an assessment of the (asymptotic) convergence rate of the finite element tested;
 - a check on the robustness of the algorithm, and
 - a check that correct programming was achieved.

The concept of the classic patch test can be generalized to the concept of the so-called weak patch test. In the weak patch test the number of elements does not need to be limited to a few, but instead it can be required that for increasing mesh refinement the computational error with respect to an analytical solution converge to zero.

In full-wave FEM electromagnetics, only the weak patch test concept can be utilized, because many tangential vector finite elements do not satisfy the classic patch test. Furthermore, the full-wave electromagnetic field is locally not constant but behaves like a plane wave [16]. In order to specify a weak patch test, a boundary value problem for Maxwell's equations in a small region can be specified – say in a cube – where the field solution is a plane wave. If for increasing mesh refinement the computational error with respect to the exact plane wave decreases, the finite element solver satisfies the weak patch test.

8.3.2 Free-space weak patch test

8.3.2.1 General

The computational domain of the weak patch test is a cube having its centre at the origin of the coordinate system as shown in Figure 3. The cube is a part of the free space region, and is illuminated by an incident plane wave with complex amplitude E_0 . k_0 and η_0 are the free-space wave number and characteristic impedance, respectively, and $\hat{x}$, $\hat{y}$, $\hat{z}$ are unit vectors in the x , y , z coordinate directions. The tetrahedral mesh shall be generated by the default mesh generator utilized for the FEM code under verification; thus, the nodes of the tetrahedra are not required to be located on rectilinear lines. The tetrahedral finite elements shall have a maximum edge length of $d_{\max}$.

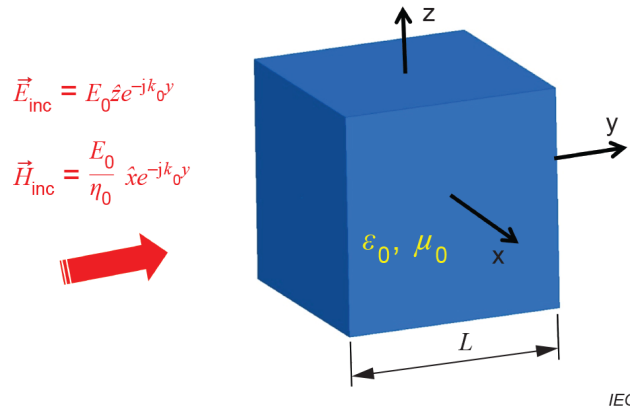


Figure 3 – Weak patch test arrangement: a free-space cube with edge length L illuminated by a plane wave

8.3.2.2 Excitation

The frequency of the incident plane wave is $f = 3$ GHz and the amplitude $E_0 = 1$ V/m. To generate the plane wave in the cube, an incident boundary condition on the $y = -L/2$ face of the cube [17] shall be specified. The lowest order incident boundary condition on the $y = -L/2$ face of the cube expressed by the total electric field strength $\vec{E}$ can be written as Equation (25) [17].

$$\hat{n} \times (\nabla \times \vec{E}) - jk_0 \vec{E}_\tau = jk_0 \eta_0 \vec{H}_{\text{inc}} \times \hat{n} - jk_0 \vec{E}_{\text{inc},\tau} \quad (25)$$

where $\hat{n} = -\hat{y}$ and subscript τ denotes tangential components of $\vec{E}$ on the $y = -L/2$ face of the cube comprising the surface triangles of the tetrahedral mesh. The incident boundary condition Equation (25) in this form is suitable for E-formulations where the primary unknown is the electric field strength $\vec{E}$. If the primary variable in the formulation is the magnetic field strength $\vec{H}$ (H-formulation), then the dual of Equation (25) can be derived in which the magnetic field strength $\vec{H}$ appears instead of $\vec{E}$. If the primary variables are potentials (i.e. a potential formulation is implemented), an equivalent form of Equation (25) can be obtained in terms of the potentials.

8.3.2.3 Specification of the boundary value problem

In order to assess whether the code can accurately model a plane wave, the size of the cube is specified as $L = \lambda_0/2$, where λ_0 is the wavelength in free-space. Furthermore, the following boundary conditions on the cube surfaces shall be specified:

- PEC on the planes $z = -L/2$ and $z = L/2$;
- PMC on the planes $x = -L/2$ and $x = L/2$;
- Open boundary conditions on the plane $y = L/2$.

8.3.2.4 Meshes

In order to assess the convergence behaviour of the FEM code, two meshes are specified: a coarse mesh and a fine mesh. To generate each mesh, two guiding parameters are provided for each mesh: the maximum tetrahedral edge length $d_{\max}$, and the maximum number of elements $N_{\max}$. In a mesh complying with the guiding parameters, the total number of elements shall be less than or equal to $N_{\max}$. Note that the guiding parameters $d_{\max}$ and $N_{\max}$ assure that there is only a reasonable size difference between the largest and smallest tetrahedra while limiting the number of elements. The coarse mesh consists of a substantially smaller number of tetrahedra than the fine mesh, and it is established such that the solution accuracy is still acceptable. This means that if the requirements for the coarse-mesh guiding parameters are satisfied, reasonable accuracy in the field quantities can be achieved. Furthermore, a correct implementation of FEM assures that whenever the mesh is refined adequately, the accuracy of the computation improves. A finite element code based on a solid formulation and implemented correctly shall demonstrate this property. Therefore, the fine-mesh guiding parameters are designed such that the accuracy of the computation based on the fine mesh should improve consistently compared to the coarse-mesh accuracy.

Finite element codes can utilize a wide range of vector finite elements. Therefore, depending on the approximation order, the finite element code should use three different sets of guiding parameters for generating coarse and fine meshes for finite elements of different orders. The three sets of guiding parameters are summarized in Table 6. The approximation orders that are not utilized in the finite element code under verification for SAR computation should be omitted from the reporting requirements.

Table 6 – Guiding parameters for coarse and fine mesh generation for the weak patch test

Mesh	lowest order		second lowest order		third lowest order	
	$d_{\max}$ (mm)	$N_{\max}$	$d_{\max}$ (mm)	$N_{\max}$	$d_{\max}$ (mm)	$N_{\max}$
Coarse	6,0	40 000	13,5	6 750	15,0	1 800
Fine	4,0	160 000	9,0	20 000	10,0	9 000