



IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations

STANDARDS

IEEE Electromagnetic Compatibility Society

Developed by the
Standards Development Committee

IEEE Std 1597.1™-2022
(Revision of IEEE Std 1597.1-2008)

IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations

Developed by the

Standards Development Committee
of the
IEEE Electromagnetic Compatibility Society

Approved 13 May 2022

IEEE SA Standards Board

Abstract: A method to validate computational electromagnetics computer modeling and simulation techniques, codes, and models is defined in this standard. It is applicable to a wide variety of electromagnetic applications including, but not limited to, the fields of electromagnetic compatibility, radar cross section, signal integrity, and antennas. Validation of a particular solution data set can be achieved by comparison to the data set obtained by measurements, alternative codes, canonical methods, or analytic methods.

Keywords: antennas, computational electromagnetics, convergence, electromagnetic compatibility, electromagnetic interference, IEEE 1597.1™, modeling and simulation, numerical techniques, radar cross section, rating scale, signal integrity, validation

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2023 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 8 September 2023. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-8779-5 STD25471
Print: ISBN 978-1-5044-8780-1 STDPD25471

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers are not necessarily members of IEEE or IEEE SA and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning this standard, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon their own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus balloting process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE is the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, nor be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter's views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s).

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and subcommittees of the IEEE SA Board of Governors are not able to provide an instant response to comments, or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or in revisions to an IEEE standard is welcome to join the relevant IEEE working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

¹Available at: <https://development.standards.ieee.org/myproject-web/public/view.html>.

²Available at: <http://standards.ieee.org/about/contact/>.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has

³Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴Available at: <https://standards.ieee.org/standard/>.

⁵Available at: <https://standards.ieee.org/about/sasb/patcom/materials/>.

filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents/>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. IEEE standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, and interference protection practices and all applicable laws and regulations.

Participants

At the time this IEEE standard was completed, the Computational Electromagnetic Working Group had the following membership:

Alistair Duffy, *Chair*

Joshua Ashley	Paul Edwards	Alastair Ruddle
Luca Bastianelli	Mike Johnson	Andy Sayers
Christine Blair	Chris Jones	Christian Schuster
Keith Bramley	Brian-YS Lee	Morteza Shahpari
Colin Brench	Renier Marchand	Morten Soerensen
James Brown	Anthony Martin	Geoff South
Zhizhang Chen	Anton Menshov	Sasidhar Tadanki
Sam Connor	Akhil Paul	Jim West
John Dawson	Shiva Shastha Rai	Gideon Wiid
Simeon Earl	Vignesh Rajamani	Gang Zhang
	Julio Rojas	

The following members of the individual Standards Association balloting group voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

Pin Chang	Hyeong Ho Lee	Moises Ramos
Samuel Connor	David Lewis	R.K. Rannow
Alistair Duffy	Ting Li	Balaji Sankarshanan
Timothy Harrington	Valter Mariani Primiani	Walter Struppler
Marco Hernandez	Jon Martens	Kin Sze
Werner Hoelzl	Jose Moreira	Sasidhar Tadanki
Martin Hudlicka	P. Sivaraman	Richard Tell
SangKwon Jeong	Bansi Patel	Raul Velazquez
Laszlo Kadar	Davy Pisssoort	John Vergis
Stuart Kerry	Alexander Prokop	Oren Yuen
Yongbum Kim		Nicholas Zagrodnik

When the IEEE SA Standards Board approved this standard on 13 May 2022, it had the following membership:

David J. Law, *Chair* **Ted Burse, *Vice Chair*** **Gary Hoffman, *Past Chair*** **Konstantinos Karachalios, *Secretary***

Edward A. Addy	Johnny Daozhuang Lin	Mark Siira
Ramy Ahmed Fathy	Kevin Lu	Dorothy V. Stanley
J. Travis Griffith	Daleep C. Mohla	Lei Wang
Guido R. Hiertz	Andrew Myles	F. Keith Waters
Yousef Kimiagar	Damir Novosel	Karl Weber
Joseph L. Koepfinger*	Annette D. Reilly	Sha Wei
Thomas Koshy	Robby Robson	Philip B. Winston
John D. Kulick	Jon Walter Rosdahl	Daidi Zhong

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 1597.1-2022, IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations.

Since the mid-1960s, a number of computational electromagnetics (CEM) techniques have been developed and numerical codes have been generated to analyze various electromagnetic compatibility (EMC) and related electromagnetics problems. Whereas each is based on classical electromagnetic theory and implements Maxwell's equations in one form or another, these techniques and, primarily, the manner in which they are used to analyze a given problem can produce different results. Lacking is the availability of a well-defined, mature, and robust methodology for validating computational electromagnetic techniques within a consistent level of accuracy. Indeed, this has eluded the EMC community for many years and methods have been sought to address this deficiency. Concerns persist regarding the validity, accuracy, and applicability of existing numerical techniques to the general class of EMC problems of interest. Relevant problems include, but are not limited to, the following: printed circuit board radiated and conducted emissions/immunity, system-level EMC, radar cross section of complex structures, antenna radiation, large platform electromagnetic environment effects, and human body specific absorption rate.

Although these techniques and codes have been applied to myriad electromagnetic problems, there can still exist a lack of confidence, and current validation practices have not always proven reliable. Computer predictions have been compared to measurements to provide a first-order validation, but there is also much interest in how the techniques, when applied to a given problem or a class of problems, compare to each other and the fundamental theory upon which they are based. Hence, additional efforts are needed to establish a standardized method for validating these techniques and to instill confidence in them.

Therefore, the purpose of this standard is to define the specific process and steps that shall be used to validate CEM techniques and to significantly increase understanding as it pertains to their implementation and application to practical EMC problem-solving tasks. The standardized process is used to validate various techniques against each other as well as against measurement baselines, in order to determine the degree of agreement or convergence and to identify the potential error sources that would lead to divergent trends.

This standard is an update of its original version to reflect the evolution of the subject of validation of computational electromagnetics, including topics such as more discussion of validation and verification, broadening the discussion on validation tests and clarifying the content of a test report. In developing the standard, the working group see this a very much part of the transition of validation of computational electromagnetics from something that is undertaken in an *ad hoc*, or locally consistent, way to a more formal discipline.

Contents

1. Overview	10
1.1 Scope	10
1.2 Purpose	10
1.3 Word usage	10
1.4 Background	11
1.5 Accuracy, uncertainty, and related issues	11
2. Normative references	15
3. Acronyms and abbreviations	15
4. Computational electromagnetics modeling and simulation validation process	16
4.1 General	16
4.2 Levels of model validation	16
4.3 Preparation for validation using engineering judgment	17
4.4 External references or self-references	18
5. External references for model validation	18
5.1 General	18
5.2 Closed-form equation references	18
5.3 Standard problem references	19
5.4 Measurement references	19
5.5 Alternative modeling technique-derived reference	20
6. Self-references for model validation	21
6.1 General	21
6.2 Convergence-based self-referenced models	21
6.3 Geometry-based self-referenced models	22
7. Selection of an appropriate validation method	22
8. Numerical calculation of the validation rating using the feature selective validation procedure	23
8.1 General	23
8.2 Feature selective validation	23
8.3 Validation rating scale	24
8.4 FSV Procedure	24
8.5 Additional steps	31
8.6 Application specific context	33
9. Validation Report	33
Annex A (informative) Bibliography	35
Annex B (informative) Guidelines on the selection of CEM techniques and codes	42
Annex C (informative) Examples of CEM and related computational techniques	45

IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulations

1. Overview

1.1 Scope

This standard specifies methods to validate computational electromagnetics (CEM) computer modeling and simulation (M&S) techniques, codes, and models. It is applicable to a wide variety of electromagnetic (EM) applications including but not limited to the fields of electromagnetic compatibility (EMC), radar cross section (RCS), signal integrity (SI), and antennas. Validation of a particular solution data set can be achieved by comparison to the data set obtained by measurements, alternative codes, canonical methods, or analytic methods.

1.2 Purpose

This standard provides a defined framework for comparing the results of various CEM techniques, codes, and models in a repeatable way against a set of references, which may include “golden” benchmarks, standard validation, and canonical problem sets as well as self-validation. These data are based on theoretical formulations or obtained as a result of performing high-quality measurements and, in certain cases, based on accurate analyses that have undergone and withstood peer validation. The importance of this standard is that it provides an agreed and repeatable framework for undertaking the validation process. The outcome of such validation is the quantification of any resultant comparisons and the logical explanation by which that quantification has taken place. In all cases, the outcome from this standard is the support for logical and informed engineering decision making. The standard itself is not a replacement for good engineering practice but an approach to provide supporting evidence for logical decision making.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6, 7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may equals is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can equals is able to*).

1.4 Background

Despite all CEM codes having their basis in one form or another of Maxwell's equations, their accuracy and convergence rate depends on how the physics equations are cast (e.g., integral or differential form, frequency or time domain), what numerical solver approach is used (full or partial wave, banded or partitioned matrix, nonmatrix), inherent modeling limitations, approximations, and so forth. The physics formalism, available modeling primitives (canonical surface or volumetric objects, wires, patches, facets), analysis frequency, and time or mesh discretization further conspire to affect accuracy, solution convergence, and overall validity of the computer model. The quality of results is also, and primarily, dependent on the knowledge and experience of the person implementing the model. Tools to support validation are also tools to support education and the development of good modeling practice.

The critical areas that must be addressed in the development of the modeler's knowledge and experience include understanding of the factors that influence model fidelity and convergence, along with the validity of techniques or codes for a given set of canonical, standard validation, and benchmark models.

1.5 Accuracy, uncertainty, and related issues

1.5.1 Measurement accuracy

In measurements the *accuracy* of a test method comprises two elements (ISO 5725-1 [B46]⁸): *precision*, which reflects random errors, and *bias*, which reflects systematic errors. The *trueness* of a test result relates to the bias element. This distinction is illustrated in Figure 1, which compares the (hypothetical) results of measurements by two test methods, which have associated biases due to systematic errors as well as probability distributions due to random error sources, with a reference value (assumed to be derived from an analytical model) and a simulated result. The two theoretical results are not subject to random errors and are therefore single values.

In Figure 1 the biases of the two test methods are of the same magnitude, but in opposite directions, while their associated precisions are different (Test 2, with the broader distribution, is less precise than Test 1). In this case the simulation bias is smaller than either of the two test biases. However, in the absence of a known reference the model would be judged as a poor match to Test 1, but a good match to Test 2. Nonetheless, the temptation would be to conclude that Test 1 is more reliable, since it is more precise, but precision does not in itself imply greater trueness. It should be noted that bias and precision are completely independent, and that bias cannot be reliably quantified without knowing the true value.

1.5.2 Simulation accuracy

Unlike measurements, errors in simulation results are purely systematic and arise from limitations in three main areas (Christie et al. [B21]):

- a) Incomplete and/or inaccurate system data (e.g., geometry, electrical properties, boundary conditions, initial conditions, outputs)
- b) Incomplete and/or inaccurate EM physics models (e.g., inappropriate CEM methods, software implementation errors)

⁸The numbers in brackets correspond to those of the bibliography in Annex A.

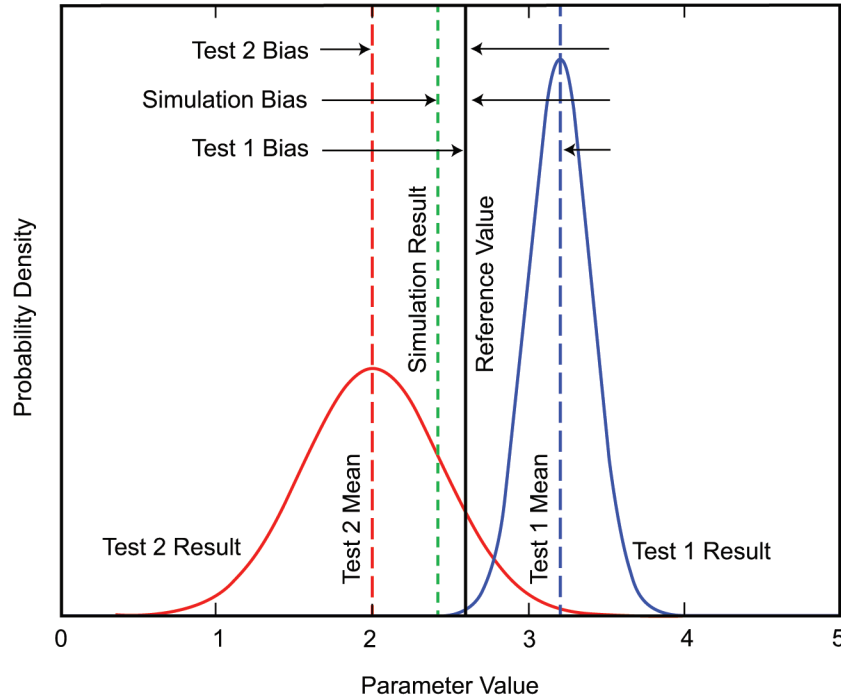


Figure 1—Hypothetical test, reference, and simulation results (Ruddle [B72])

- c) Limitations in the accuracy of the numerical approximations used to solve the underlying equations (e.g., poor methods, implementation errors, inadequate discretization), including truncation and rounding errors

Consequently, there is no equivalent of measurement precision in relation to simulations, and the accuracy of simulation results is solely reflected in terms of bias.

The use of standard CEM problems, which are fully and unambiguously defined, and for which accepted and reliable reference results are available, helps ensure that error sources relating to item a) are eliminated in the process of CEM solver verification. This should allow items b) and c) to be identified if present, provided that the CEM solver that is applied is fully appropriate to the physics of the standard CEM problem under investigation. It is essential to correctly match the CEM solver capability to the CEM problem under investigation, as not all CEM solvers are universally applicable to all CEM problems. Thus, an unwary analyst could attempt to model behavior that strays beyond the capabilities of the selected CEM method.

It is possible for different analysts using the same software tools and the same basic geometrical and materials information to produce CEM models that differ because of the choices made in relation to geometrical simplification, mesh generation and assignment of material properties. It is possible for further deviations to occur when CEM models are constructed for different CEM methods. For example, those methods that use a structured hexahedral mesh have the potential to introduce so-called “stair-casing” approximations of curved geometry, whereas methods that use an unstructured tetrahedral mesh can achieve a more conformal piecewise linear approximation to curves. For standard CEM problems used for verification purposes, all reasonable efforts should be taken so that there are no appreciable differences in geometry or material properties, with the result that any residual differences shall be attributable to solver and discretization/mesh issues.

1.5.3 Repeatability, reproducibility, and replicability

In assessing the *repeatability* of a test method, measurements are repeated on the same test object by the same operator using the same methodology and equipment within short intervals of time (ISO 5725-1 [B46]) to

help quantify the maximum precision of the test result in terms of the distribution of random errors affecting that measurement. The aim of *reproducibility* tests, “obtained with the same method on identical test items in different laboratories with different operators using different equipment” (ISO 5725-1 [B46]), is to help quantify the minimum precision of the measurement. However, as random error is not a phenomenon that afflicts simulations the notions of repeatability and reproducibility as defined in IEEE Std 1597.1-2008 [B44] are not relevant to simulations. There is potential for numerical round-off error and other inherent numerical differences to become magnified as large-scale computational simulations are scaled up to run on highly parallel systems, one only needs to think of the “butterfly effect” to consider possible outcomes from small perturbations when transformed and magnified in complex systems, but these effects are not the same as the random errors of measurements. Nonetheless, running the same model with the same solver on the same hardware configuration should produce the same result.

Repeatability and reproducibility only relate to the precision of a given test method, providing no information concerning any potential bias in the results. Consequently, simply recreating the same result by the same method does not indicate that it is correct. In the absence of a known and reliable reference result the only way to investigate bias effects (i.e., systematic errors) is to compare results obtained from approaches that are sufficiently different to help ensure that the systematic errors are different. The results from disparate origins that are sufficiently close can then be considered plausible since they provide mutual confirmation. In the absence of such mutual confirmation, it is not in fact possible to determine which, if any, of the results might be truer. This is equally true even if one of the data sources is a measurement and the other is a simulation.

The term *replicability* has been used to describe “the chance that an independent experiment targeting the same scientific question will produce a consistent result” (Kunz and Luebbers [B58]). This therefore seems an appropriate term to describe comparisons between the results of measurements using different test methods, between the results of CEM simulations using different CEM methods, and between CEM results, analytical models, and measurement data. Thus, for EM measurement and CEM simulation validation applications, *replicability* has been defined (Ruddle [B72]) as: the closeness of agreement, taking account of known uncertainties, between results obtained using different methods, which can include at least two of the following:

- a) Results obtained from a reliable analytical model
- b) Results obtained from a numerical simulation using a given CEM method
- c) Results obtained from a numerical simulation using a different CEM method
- d) The average obtained from a large series of EM test results obtained with a given EM test method
- e) The average obtained from a large series of EM test results obtained with a different EM test method

1.5.4 Measurement uncertainty

In many EM measurement standards the accuracy of the measurement method is represented by a *measurement uncertainty* (JCGM [B51]) that is estimated based on the evaluation of errors resulting from a number of identified contributors. The various contributions are combined to give an overall *standard uncertainty* (reflecting a 68% confidence interval), from which the *expanded uncertainty* (representing a 95% confidence interval) is derived. Hence for a measured value M with expanded uncertainty U , it is considered that there is 95% confidence that the true value lies within the interval $M \pm U$.

The identified contributors to the measurement uncertainty typically relate to the measurement instrumentation, including calibration processes, the measurement procedure (such as positioning errors), and the influence of the measurement environment. However, measurement uncertainty does not include consideration of potential variability in characteristics of the subject of the measurement. Nonetheless, lack of certainty regarding the details of the system under test (including geometry, materials, electrical properties etc.) shall also be a consideration when measurements on a limited sample (perhaps only one) is used to certify an entire class of items.

1.5.5 Error and uncertainty in simulations

The term *uncertainty quantification* is often used in relation to numerical simulations to describe methods for assessing the impact of model simplifications, lack of firm knowledge regarding the input data, and computational approximations on the predicted results. Such considerations include known issues such as numerical rounding effects, mathematical approximations in the solution algorithms, and assumptions and approximations in the model that do not reflect the real-world but are considered to be insignificant or tolerable. Examples of the latter include de-featuring complex geometry to remove electrically small holes, brackets, and fixings that are not expected to be significant at the frequencies of interest. These measures are typically introduced in order to make a simulation faster, more efficient, and/or cost-effective (or just plain feasible), and it is the role of validation to confirm the acceptability of these kinds of assumptions.

In addition, there can be unknown errors in the algorithms or programming mistakes, although verification activities are intended to identify these. Verification helps to quantify the impact of numerical rounding and other mathematical approximations to help ensure that the CEM solver provides results within the required tolerance. Some classes of simulation input are such that they can, at best, only be described in terms of a probability distribution. Typical examples in CEM applications include electrical properties of materials and the locations of individual cables within a larger cable bundle. Providing probability distributions for such inputs can enable simulation results to be similarly expressed in terms of probability distributions rather than single values (e.g., Fei et al. [B33]), but these should not be confused with the probability distributions that represent the precision or uncertainty (combining precision and estimated bias) of measurements.

Moreover, uncertainty is also sometimes used to express the extrapolation of results from a limited number of simulation scenarios (and often only one) to account for a much wider range of geometries and materials properties. An example of the latter relates to the numerical assessment of basic restrictions on induced in-body quantities (ICNIRP [B48]) that are used for the quantification of human exposure to electromagnetic fields (IEC/IEEE 62704-1:2017 [B41]). In such applications there is significant variability in the size, shape, and electrical properties of the human population, but the computational resources required for such simulations are such that there is little appetite for simulating a range of material and geometrical parameters. Consequently, uncertainty is invoked as a mechanism for attributing a range of values to simulated results to account for the potential variabilities.

However, these aspects are very different from those considered in measurement uncertainty, which takes no account of the potential variability in characteristics of the system under test (such as the geometry and material properties). In the measurement context, uncertainty relates specifically to the random and systematic errors that are considered to have an impact on the precision and bias characteristics of the particular test method. Use of the term “uncertainty” in relation to simulation data is therefore undesirable due to the potential for confusion with the very different meaning of uncertainty in relation to measurements.

As an alternative, the term *CEM result tolerance* has been proposed for simulations (Ruddle [B72]), defined as: the interval or probability distribution around a nominal CEM result that reflects the degree of variability in the CEM model input parameters (geometrical detail, material properties, excitation conditions, field output locations, etc.) as well as the impact of mathematical approximations and numerical rounding.

Only a few elements of the CEM result tolerance (e.g., variability in field output locations) would also be represented in a measurement uncertainty analysis. However, if variability in characteristics of the subject of the measurement is to be considered in relation to simulations, then it would seem more reasonable that these aspects will also be included in the measurement uncertainty, to obtain results that are more directly comparable.

1.5.6 Comparing measurements and simulations

One fundamental difference between a test and a simulation is that while absolutely everything is known about the content of the CEM model, because it is deliberately introduced and specified, a physical system can be

constructed and tested without the same level of detailed knowledge of its constituent parts. For example, the electrical properties of materials and the exact routes of cables in real-world systems are often not known in detail.

A further difference between tests and simulations is that while parameters of interest such as current, voltage, electric, and magnetic field, etc., can usually be directly obtained from a simulation for specific locations without restraint, a measurement can only approximate some of these results, and then only as interpreted via a transducer with finite volume, the positioning of which may also be restricted by physical access limitations. Thus, the raw data provided by simulations and tests may not be directly comparable.

Furthermore, in a numerical model it is very easy to represent, for example, two parallel wires with specified conductivities that have a constant separation and are located in the same plane, or two conductors that are in perfect electrical contact, or a truly semi-anechoic environment. In a real-world test scenario, however, these arrangements are practically impossible to achieve. Hence the measured system almost certainly does not comply with the design intent of the experiment, and in this sense the measurement could well prove to be a poorer approximation to the system of interest than a CEM model.

In practice, therefore, simulations provide extensive information on systems that are invariably known in great detail, whereas measurements provide limited information on systems that are generally poorly understood. Achieving a sufficiently high level of fidelity between the measured and simulated systems is key to successful experimental validation of CEM simulations. This requires the analyst developing the model to have detailed knowledge of both the system under investigation and the equipment and procedures that are used in the measurements.

2. Normative references

There are no normative references in this standard.

3. Acronyms and abbreviations

For the purposes of this document, the following acronyms and abbreviations apply.

ADM	amplitude difference measure
CEM	computational electromagnetics
EM	electromagnetic
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMI/EMC	electromagnetic interference/electromagnetic compatibility
FDM	feature difference measure
FDTD	finite-difference time domain
FEM	finite element method
FSV	feature selective validation
GDM	global difference measure
MIL-STD	military standard
M&S	modeling and simulation
MoM	method of moments
OATS	open-area test site