

IEEE Recommended Practice for Validation of Computational Electromagnetics Computer Modeling and Simulations

IEEE Electromagnetic Compatibility Society

Sponsored by the
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IEEE Recommended Practice for Validation of Computational Electromagnetics Computer Modeling and Simulations

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Abstract: This recommended practice is a companion document for IEEE Std 1597.1™-2008. Examples and problem sets to be used in the validation of computational electromagnetics (CEM) computer modeling and simulation techniques, codes, and models are provided. It is applicable to a wide variety of electromagnetic (EM) applications including but not limited to the fields of antennas, signal integrity (SI), radar cross section (RCS), and electromagnetic compatibility (EMC). This document shows how to validate a particular solution data set by comparing it to the data set obtained by measurements, alternate codes, canonical, or analytic methods.

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Introduction

This introduction is not part of IEEE Std 1597.2-2010, IEEE Recommended Practice for Validation of Computational Electromagnetics Computer Modeling and Simulations.

The development of standards and recommended practices for computational electromagnetics (CEM) computer modeling and simulation and code validation has been a topic of much interest within the electromagnetics (EM) community primarily since the mid 1980s. This has been due to advancements in computer hardware and software technologies as well as the arrival of new CEM codes and applications as we know them today. The areas of concern include, but are not limited to, analyzing printed circuit board (PCB) radiated and conducted emissions/immunity, system-level electromagnetic compatibility (EMC), radar cross section (RCS) of complex structures, and the simulation of various EM environment effects (E^3) problems. In particular, there are concerns regarding the lack of well-defined methodologies to achieve code-to-code or even simulation-to-measurement validations within a consistent level of accuracy.

IEEE Std 1597.2-2010 is a companion document to the IEEE Std 1597.1TM-2008.^a The scope of IEEE Std 1597.1 is to develop a standard for the validation of CEM computer modeling and simulation techniques and codes in differing EMC applications. The standard provides a basis for analytical and empirical validation of CEM codes and configurations focusing on several key areas.

The scope of this recommended practice is to develop a recommended practice for use in CEM computer modeling and simulation applications to guide the EMC design of PCBs to large, complex systems. Areas to be addressed include the following:

- General guidelines for creating CEM models
- Development of modeling methodologies for small-to-large scale canonical, standard validation, and benchmark problems
- Reducing uncertainty and errors in modeling applications
- Developing fundamental modeling techniques that are consistent with collaborative, multi-disciplinary engineering applications

The recommended practice will aid modelers and analysts in the selection and application of appropriate modeling and simulations methodologies, physics, and solution techniques to achieve accurate results and to complement measurements and EMC design tasks for a range of progressively complex problems.

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Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	1
1.3 Background.....	2
2. Normative references.....	3
3. Acronyms and abbreviations	3
4. CEM modeling and simulation validation process	4
4.1 General	4
4.2 Levels of model validation	5
5. Problem sets	6
5.1 Problem categories and validation problems	6
5.2 Canonical validation problems	7
5.3 Benchmark validation problems	27
5.4 Standard validation problems	37
5.5 Publication of reference problems and results on the Web.....	45
6. Self-references for model validation	50
6.1 General	50
6.2 Computational-based self-referenced models.....	50
6.3 Geometry-based self-referenced models.....	51
7. Numerical calculation of the validation rating using the feature selective validation technique.....	53
7.1 Implementing the feature selective validation technique.....	53
7.2 Procedure.....	53
7.3 Grade and Spread.....	66
Annex A (informative) Bibliography	70
Annex B (informative) Basic descriptions of common CEM techniques.....	78
Annex C (informative) Guidelines on the selection of CEM techniques and codes.....	85
Annex D (normative) Validation problems: special cases.....	92
Annex E (informative) Identifying sources of error in CEM modeling and simulation	103
Annex F (informative) Guidelines for reporting solver performance.....	106
Annex G (informative) Combinatorial modeling rules.....	110
Annex H (informative) Data used for FSV comparison	111
Annex I (informative) Glossary.....	113

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1. Overview

1.1 Scope

This recommended practice is a companion document for IEEE Std 1597.1-2008.¹ It provides examples and problem sets to be used in the validation of computational electromagnetics (CEM) computer modeling and simulation 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), analysis of radar cross section (RCS), signal integrity (SI), and the analysis of antennas. This document shows how to validate a particular solution data set by comparing it to the data set obtained by measurements, alternate codes, canonical, or analytic methods.

1.2 Purpose

This recommended practice serves as an aid to CEM modelers and analysts in the selection and application of appropriate computer modeling and simulation methodologies, physics, and solution techniques to achieve accurate results. It also serves to complement measurements and EM design tasks for a range of

¹ Information on references can be found in Clause 2.

progressively complex problems through the use of modeling problem examples for small-to-large scale canonical, benchmark, and standard validation problems. Finally, this recommended practice provides a detailed description of a validation process, i.e., the Feature Selective Validation (FSV) method, which compares a particular solution data set to a reference data set.

1.3 Background

In general, CEM techniques and codes, and the manner in which they are used to analyze a given problem, can produce quite different results. These results are affected by the way in which the underlying physics formalisms have been implemented within the codes including the mathematical basis functions, numerical solution methods, numerical precision, and the use of building blocks (primitives) to generate computational models.

Despite all CEM codes having their basis in Maxwell's equations of one form or another, 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, non-matrix), 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 combine to affect accuracy, solution convergence, and overall validity of the computer model.

The critical areas that must be addressed include model accuracy, convergence, and techniques or code validity for a given set of canonical, benchmark, and standard validation models. For instance, uncertainties may arise when the predicted results using one type of CEM technique do not agree favorably or consistently with the results of other techniques or codes of comparable type or even against measured data on benchmark models. Furthermore, it can be difficult to compare the results between certain techniques or codes despite their common basis in Maxwell's equations. Exceptions can be cited, in particular, when comparing the results of "similar" codes grouped according to their physics, solution methods, and modeling element domains. Nevertheless, disparities even among codes in a certain "class" have been observed. Many examples can be cited where fairly significant deviations have been observed between analytical or computational techniques and empirical based methods. Differences are not unexpected, but the degree of disparity in certain cases cannot be readily explained nor easily discounted, which has led to the often asked question: "Which result is accurate?"

The annexes at the end of this document supplement the main body by providing more detailed information, data sets, and guidelines. Annex A is the bibliography for the overall document and allows the interested reader to pursue more detailed information on a given topic. Annex B provides a brief summary of over twenty-five CEM techniques, allowing the reader to gain insight into some of the possible methods that can be selected for validation. Annex C describes some of the more common CEM techniques and provides guidelines on how to match the appropriate CEM techniques or codes to the CEM modeling and simulation problems being faced. Annex D gives some special case validation problems involving complex systems. Annex E identifies many common sources of errors that can be introduced into the CEM modeling and simulation process. By understanding how and why these errors may occur, it is sometimes possible to prevent these errors. If the errors cannot be corrected, this knowledge provides valuable insight into why a specific simulation does not match expected validation results. Annex F provides guidelines for reporting solver performance, an aspect of CEM modeling and simulation that is closely related to accuracy validations. Because accuracy and performance are related and are frequently reported together, this annex provides information necessary to uniformly report performance. Annex G outlines several combinatorial modeling rules to follow when performing piecewise simulations in order to ensure the highest level of accuracy in the ultimate result. Annex H provides the data used to perform the FSV validation process in Clause 7. Annex I is the glossary and includes the definitions of many terms that are specific to this document.

2. Normative references

The following referenced documents and URLs are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

AFRL-DE-TR-2003-1092, "Vlasov Antenna Data for Electromagnetic Code Validation," Air Force Research Laboratory (AFRL) Directed Energy Directorate Final Report, Greenwood, A., and Hendricks, K., June 2003. (See 5.5.4.)

Archambeault, B., and Ruehli, A., "Introduction to 2001 special challenging EMC modeling problems," *IEEE International Symposium on Electromagnetic Compatibility*, vol. 2, pp. 799–804, Aug. 2001. (See 5.4.3.)

Archambeault, B., et al., "A proposed set of specific standard EMC problems to help engineers evaluate EMC modeling tools," *IEEE International Symposium on Electromagnetic Compatibility*, vol. 2, pp. 1335–1340, Aug. 2001. (See 5.4.1.1, 5.4.1.2, and 5.4.2.1.)

Balanis, Constantine A., *Antenna Theory: Analysis and Design, Second Edition*, John Wiley & Sons, Inc., 1996. (See 5.2.1.1, 5.2.1.2, and 5.2.1.4.)

IEEE EMC-S TC-9, Standard Modeling Problems.²

IEEE German EMC Chapter, AG Numerische Modellierung.³

IEEE Std 1597.1™-2008, IEEE Standard for Validation of Computational Electromagnetics Computer Modeling and Simulation.^{4, 5}

Rajamani, V., et al., "Validation of Modal/MoM in shielding effectiveness studies of rectangular enclosures with apertures," *IEEE Transactions on Electromagnetic Compatibility*, vol. 48, pp. 348–353, May 2006. (See 5.4.2.2.)

Woo, A. C., et al., "Benchmark Plate Radar Targets for the Validation of Computational Electromagnetics Programs," *IEEE Antennas and Propagation Magazine*, vol. 34, no. 6, pp. 52–56, Dec. 1992, and vol. 35, no. 1, pp. 84–89, Feb. 1993. (See 5.5.4.)

3. Acronyms and abbreviations

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions*, Annex I, and ANSI C63.14-1998 [B2] should be consulted for terms not defined in this clause.^{6, 7}

ABC	absorbing boundary condition
ADM	Amplitude Difference Measure

² Available at <http://www.ewh.ieee.org/cmte/tc9/Problems/index.html>.

³ Available at http://www.ewh.ieee.org/r8/germany/emc/ag_num/index.html.

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⁶ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

⁷ The numbers in brackets correspond to those of the bibliography in Annex A.

CEM	computational electromagnetics
E	electric field
EM	electromagnetic
EMC	electromagnetic compatibility
EMCC	Electromagnetic Code Consortium
EMC-S	Electromagnetic Compatibility Society (of the IEEE)
EMI	electromagnetic interference
FDM	Feature Difference Measure
FDTD	finite-difference time-domain
FSV	Feature Selective Validation
GDM	Global Difference Measure
MoM	method of moments
NASA	National Aeronautics and Space Administration
NEC	Numerical Electromagnetics Code
PCB	printed circuit board
PEC	perfectly electrically conducting
PEEC	partial element equivalent circuit
RCS	radar cross section
SE	shielding effectiveness
TC-9	Technical Committee 9 (on CEM, of the IEEE EMC-S)
TEM	transverse electromagnetic
TLM	transmission line method
TSAM	Transformable Scale Aircraft-like Model

4. CEM modeling and simulation validation process

4.1 General

The validation process for modeling and simulation results is dependent on exactly what is being validated and what data is available to support the validation. The preferred process is to validate the unknown case against a known reference. To this end, standard problems and other means of obtaining a reference are described in IEEE Std 1597.1TM-2008 together with a procedure to compare the resulting data sets. Where no suitable reference case can be obtained, validation is possible by using self-referencing schemes. While less encompassing, these schemes still permit a high level of confidence to be achieved. The flow chart shown in Figure 1 provides the route that is taken.

NOTE—The terms *modeling* and *simulation* can, in most places, be used interchangeably.⁸

⁸ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

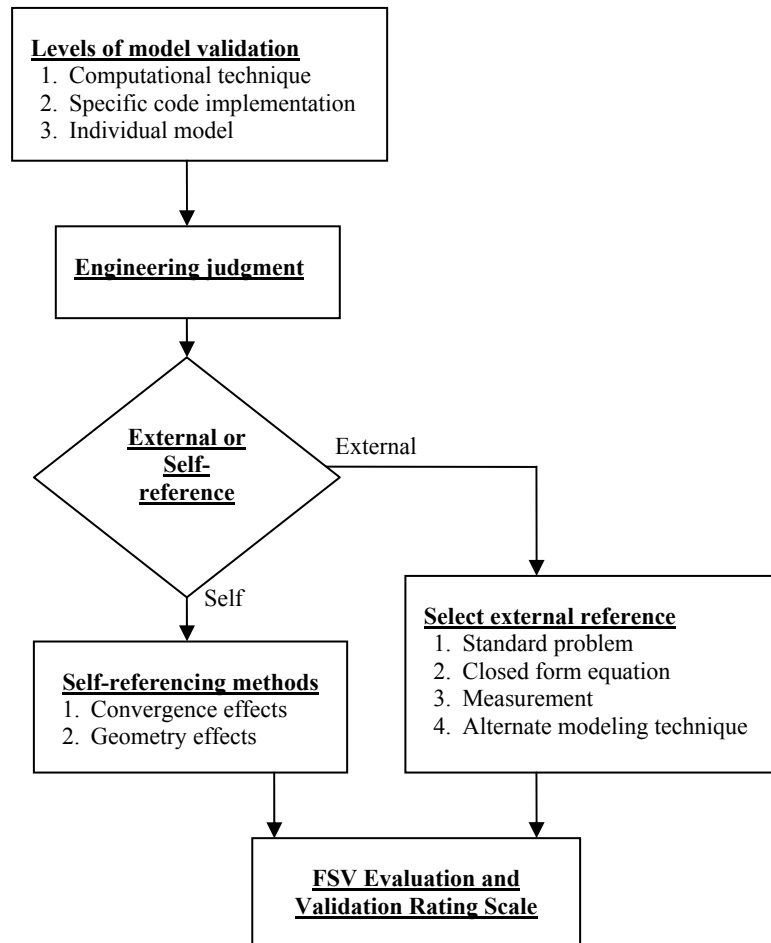


Figure 1—Validation flow chart

This recommended practice provides a wide variety of reference problems that are similar to the types of problems encountered at the work place, and the results of these given problems can be used to compare to the user's problem and hence validate a modeling or simulation tool. The FSV method is a means to consistently compare the model being validated to the reference data, and Clause 7 contains additional information to support the implementation of the FSV method and to provide assistance in the interpretation of the results produced by the method.

4.2 Levels of model validation

There are three different levels to a complete model validation. When deciding how to validate a model, it is important to consider which levels of validation are needed. The levels are as follows:

- a) Mathematical level: Computational technique validation
- b) Implementation level: Individual software code implementation validation
- c) Model level: Specific model validation

The first level determines if the underlying computational technique is correct. The second expands this to include a particular code implementation, and the third includes the specific details of a model. For a complete model validation, all three of these levels are required to be correct. See IEEE Std 1597.1™-2008 for more details on these three levels of validation and how they are analyzed and compared using external and self-references, and the FSV procedure.

NOTE—The term *numerical* could be used equally in place of *computational*—the authors of this document have chosen to use the term *computational*.

5. Problem sets

5.1 Problem categories and validation problems

There are many different types of EM modeling and simulation problems, and the use of well-defined cases with known solutions are an excellent means of validating a modeling tool or procedure. However, it is impossible to define every possible case and create a suitable reference problem. Therefore a variety of validation cases were created to span the range of problems that may be encountered. Users are encouraged to select validation cases that most closely match their types of problems, recognizing that more than one validation case may be needed to cover the range of problems they are interested in. It should be noted that the library of standard cases is dynamic and additional materials will be added over time.

This recommended practice defines three types of validation cases: canonical, benchmark, and standard. In the following subclauses, multiple problems of each of the three types are provided, along with a final subclause, 5.5, that points to an alternate “living” source (continuously updated) of validation problems from which users may choose.

The simplest problems are straightforward *canonical* problems, which often provide significant challenges for full-wave EM techniques and codes due to the need to “break” the physical geometry into small parts. The input impedances (real and imaginary) and far-field radiation patterns are detailed for each problem. These canonical validation problems have a closed form solution that will allow comparison of the user’s simulation results to the theoretical results.

The next level in complexity is *benchmark* validation problems. These problems tend to have a simple geometry with only a few objects, so they represent specific types of problems often encountered in the field of EMC. Although these problems do not have closed form solutions, many of them have been previously solved by a number of different codes and techniques. Thus, the user’s simulation results should be compared against these previously obtained results.

The highest level of complexity is *standard* validation problems. These problems have a complex geometry and are intended to represent real-world scenarios. As with the benchmark validation problems, no closed form solution is available but many of these problems have been solved by a number of different codes and techniques. Once again, the user’s simulation results should be compared against these previously obtained results.

NOTE 1—In order to keep each validation problem self-contained, and for ease of reading, every validation problem includes a mini reference clause at its end.

NOTE 2—Unless otherwise specified, all equations in this document are MKS rationalized.

5.2 Canonical validation problems

5.2.1 Antenna canonical validation problems

5.2.1.1 Finite length dipole antenna input impedance

The dipole antenna is one of the simplest structures in EMC problems, as shown in Figure 2. The values of the real and imaginary input impedance are well known for a dipole antenna; the impedance varies versus frequency (wavelength compared to the antenna physical length).

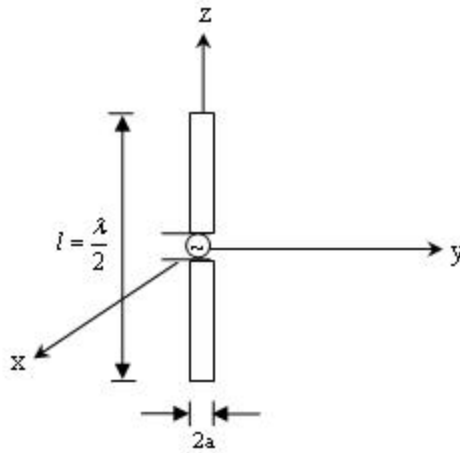


Figure 2—Dipole antenna geometry (where $a \ll l$)

Assuming the antenna is located in free space, the real and imaginary parts of the input impedance at the input terminals are given by Equation (1) from Figure 2.

$$\begin{aligned} R_{in} &= \frac{R_r}{\sin^2(kl/2)} \\ X_{in} &= \frac{X_m}{\sin^2(kl/2)} \end{aligned} \quad (1)$$

where

- R_{in} is the input resistance at the input (feed) terminals
- X_{in} is the input reactance at the input (feed) terminals
- R_r is the radiation resistance at the current maximum
- X_m is the radiation reactance at the current maximum
- k is the wave number
- l is the length of the antenna

NOTE—The radiation resistance and reactance for an assumed current distribution result in sine and cosine integral expressions that are readily available in any graduate level antenna text. The radiation resistance is also the antenna input impedance because the current maximum for a half-wavelength dipole occurs at the input terminals.

The input impedance of a dipole for varying lengths (in wavelengths) has been computed and provided in an Excel[®] file *5-2-1-1-Dipole_Input_Impedance.xls* (see IEEE EMC-S Web site).⁹ The radius of the dipole is assumed to be very small compared to the length.

While many different simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the Method of Moments (MoM), is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem, versus a volume-based technique where the surrounding air would be required to be part of the model.

Reference

Balanis, Constantine A., *Antenna Theory: Analysis and Design, Second Edition*, John Wiley & Sons, Inc., 1996.¹⁰

5.2.1.2 Finite length dipole antenna far-field radiation pattern

Many software packages have, as an option, the capability to display antenna patterns. In order to explore the capability of a code to predict far-field radiation patterns, it is useful to validate against a well-known solution. The far-field pattern for a dipole in free space, as shown in Figure 3, can be useful to validate the ability of a simulation code to correctly find far fields.

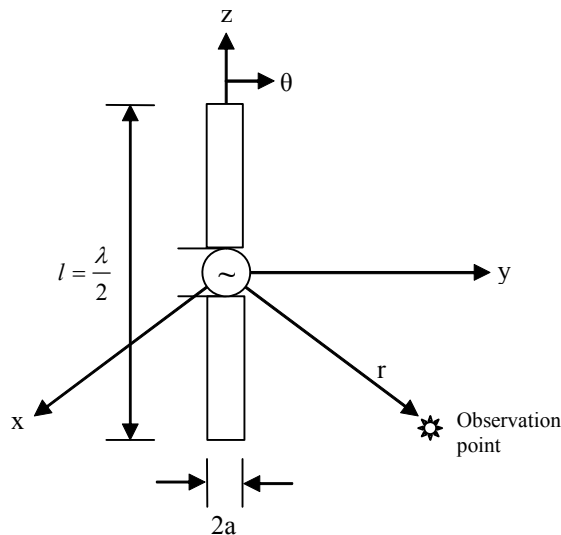


Figure 3—Dipole antenna geometry (where $a \ll l$)

The far field of an antenna is defined as the field for observation points sufficiently distant from an antenna so that the field is considered to be completely transverse electromagnetic (no component of the electric and magnetic field in the direction of propagation). This distance is commonly taken to be as shown in Equation (2):

$$R_{\min} = \frac{2D^2}{\lambda} \quad (2)$$

⁹ Excel is a registered trademark of Microsoft Corporation.

¹⁰ Information on references can be found in Clause 2.

where

$R_{\min}$ is the minimum distance considered to be the far-field distance
 D is the maximum dimension of the antenna
 λ is the wavelength

From Balanis, the far fields for a dipole antenna are given in Equation (3) and Equation (4).

$$\begin{aligned} E_r &\approx E_\phi = 0 \\ E_\theta &= j\eta \frac{I_0 e^{-jkr}}{2\pi r} \left[\frac{\cos\left(\frac{kl}{2}\right) \cos\theta - \cos\left(\frac{kl}{2}\right)}{\sin\theta} \right] \\ H_r &= H_\theta = 0 \\ H_\phi &\approx j \frac{I_0 e^{-jkr}}{2\pi r} \left[\frac{\cos\left(\frac{kl}{2}\right) \cos\theta - \cos\left(\frac{kl}{2}\right)}{\sin\theta} \right] \end{aligned} \quad (3)$$

So,

$$\begin{aligned} |E| &= \frac{I_0 \eta}{2\pi r} \left[\frac{\cos\left(\frac{kl}{2}\right) \cos\theta - \cos\left(\frac{kl}{2}\right)}{\sin\theta} \right] \\ |H| &= \frac{I_0}{2\pi r} \left[\frac{\cos\left(\frac{kl}{2}\right) \cos\theta - \cos\left(\frac{kl}{2}\right)}{\sin\theta} \right] \end{aligned} \quad (4)$$

where

E is the electric field
 H is the magnetic field
 I_0 is the maximum current through the antenna
 η is the intrinsic wave impedance
 l is the length of the wire
 r is the distance to the observer
 k is the wave number
 θ is the angle from the z axis

The far-field pattern (E and H) for a half-wave dipole is calculated and a sample graph is provided in Figure 4. The computed result can be found in the Excel file *Dipole antenna far field.xls* (see IEEE EMC-S Web site). The field is plotted for $\theta = 0^\circ$ to 360° . The field values are in decibels.

While many different simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface

currents) would be needed for this problem versus a volume-based technique where the surrounding air, as well as the air to the distant observation point in the far field would be required to be part of the model.

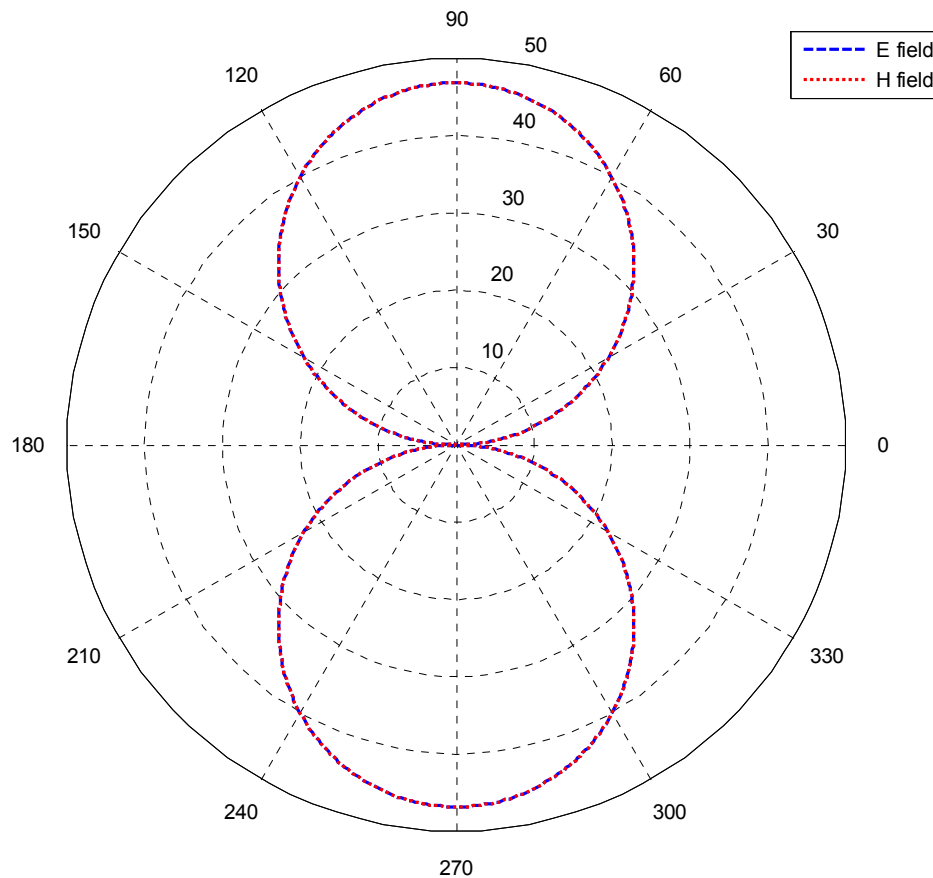


Figure 4—Far-field pattern of a half-wave dipole

References

Balanis, Constantine A., *Antenna Theory: Analysis and Design, Second Edition*, John Wiley & Sons, Inc., 1996.¹¹

[B76] Kraus, John D., and Marhefka, Ronald J., *Antennas for All Applications*, Third edition.

5.2.1.3 Loop antenna radiation resistance

Consider the geometry of Figure 5 for a wire loop antenna in free space.

¹¹ Information on references can be found in Clause 2.

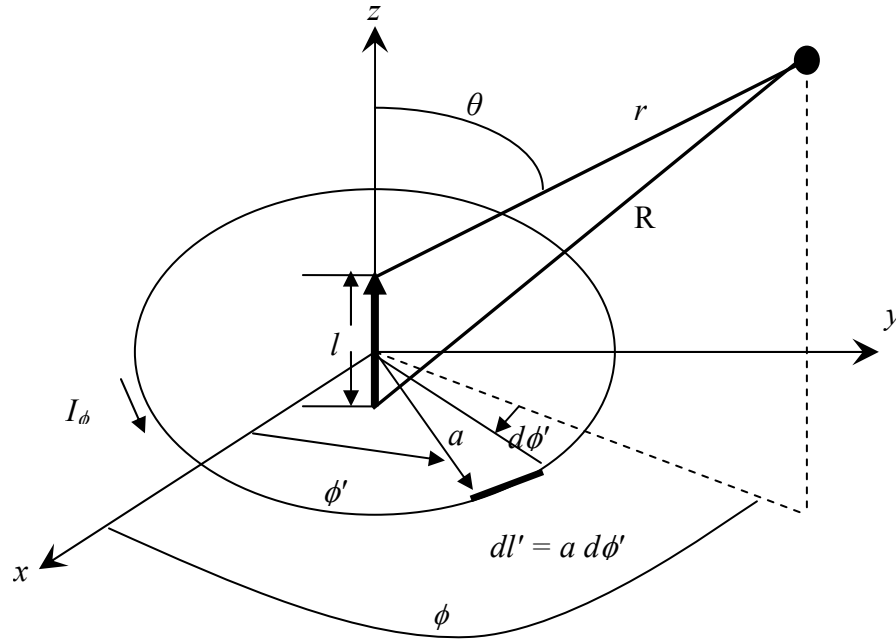


Figure 5—Geometry for circular loop

A loop antenna can be considered equivalent to an infinitesimal magnetic dipole where the axis is perpendicular to the plane of the loop. Invoking duality, the fields radiated by a small loop are given by Equation (5):

$$\begin{aligned} H_r &= j \frac{ka^2 I_0 \cos \theta}{2r^2} \left[1 + \frac{1}{jkr} \right] e^{-jkr} \\ H_\theta &= -\frac{(ka)^2 I_0 \cos \theta}{4r} \left[1 + \frac{1}{jkr} - \frac{1}{(kr)^2} \right] e^{-jkr} \\ E_\phi &= \eta \frac{(ka)^2 I_0 \sin \theta}{4r} \left[1 + \frac{1}{jkr} \right] e^{-jkr} \end{aligned} \quad (5)$$

where

- H is the magnetic field
- E is the electric field
- I_0 is the maximum current through the antenna
- η is the intrinsic wave impedance
- r is the distance to the observer
- k is the wave number
- a is the radius of the loop
- θ is the angle from the normal to the loop (from z axis)

These expressions are valid everywhere except the origin.

Loop antennas with electrically small circumferences or perimeters have small radiation resistances that are usually less than their loss resistances. The radiation resistance of the loop can be increased and made comparable to the characteristic impedance of practical transmission lines by increasing (electrically) its perimeter and/or the number of turns.

Please note that the input impedance (of an antenna) is the impedance presented by an antenna at its terminals. The radiation resistance of an antenna is the ratio of the power radiated by an antenna to the square of the RMS antenna current referred to a specified point. The total power radiated is equal to the power accepted by the antenna minus the power dissipated in the antenna.

For the geometry depicted in Figure 5, the radiation resistance depends on the electrical size of the loop. When the internal radius, a , of the loop is large with respect to the wavelength, λ , the radiation resistance will vary considerably from that of, for example, a small loop. Different approximations of radiation resistance for varying loop sizes are compared as follows:

When the radius of the loop is large ($a \geq \lambda/2$)

$$R_r \approx 60\pi^2 \left(\frac{C}{\lambda} \right)$$

When the radius of the loop is intermediate ($\lambda/6\pi \leq a \leq \lambda/2$)

$$R_r \approx \frac{1}{ka} \left[-2J_1(2ka) + \int_0^{2ka} J_0(y) dy \right]$$

When the radius of the loop is small ($a < \lambda/6\pi$)

$$R_r \approx 20\pi^2 \left(\frac{C}{\lambda} \right)^4$$

where

- R_r is the radiation resistance
- C is the circumference of the loop
- k is the wave number, $2\pi/\lambda$
- a is the radius of the loop
- $J_p(y)$ is a Bessel function of the first kind of order p

Each of the representative plots of the radiation resistance are shown in Figure 6, Figure 7, and Figure 8.

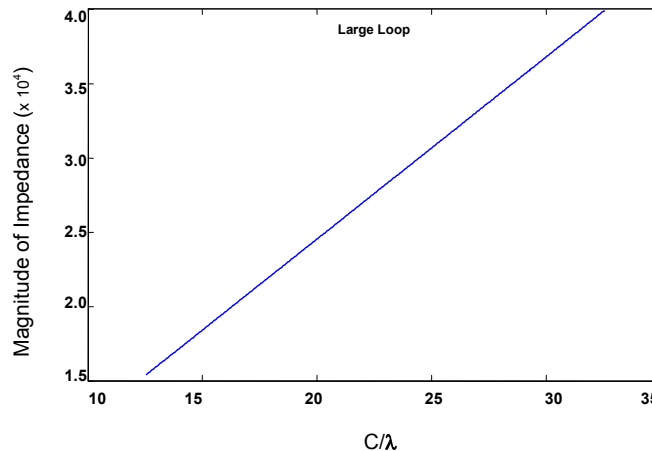


Figure 6—Radiation resistance of a large loop antenna

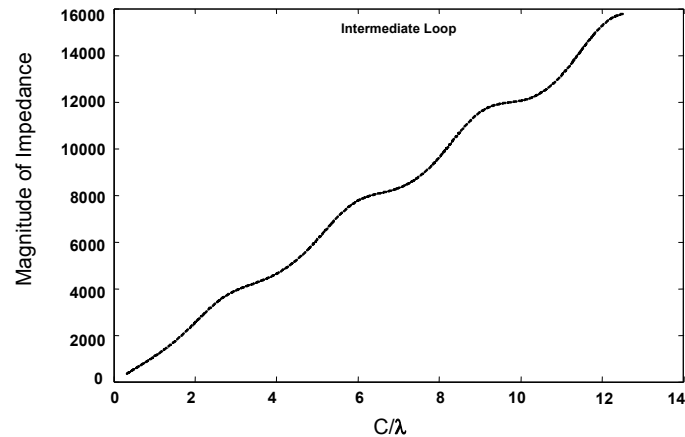


Figure 7—Radiation resistance of a intermediate size loop antenna

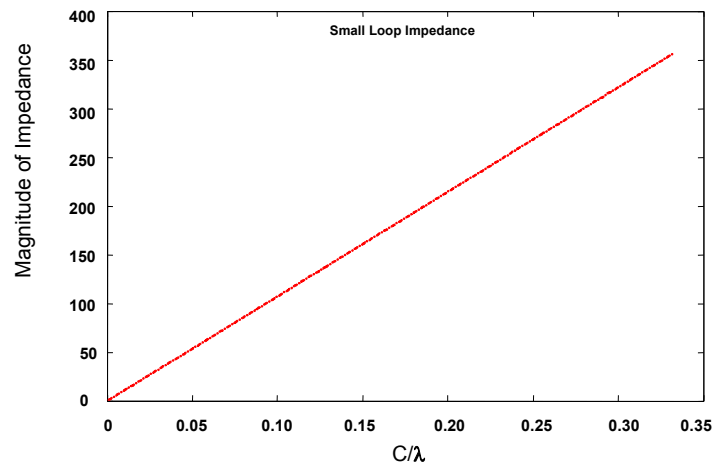


Figure 8—Radiation resistance of a small loop antenna

The magnitude of the radiation resistance of a loop antenna where the radius varies from small to large (compared to wavelength) is computed. The results are presented in an Excel file, *loop antenna radiation resistance.xls* (see IEEE EMC-S Web site).

While many different simulation techniques can be used for this loop antenna problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem as opposed to a volume-based technique where the surrounding air would be required to be part of the model.

Reference

Balanis, Constantine A., *Antenna Theory: Analysis and Design, Second Edition*, John Wiley & Sons, Inc., 1996.¹²

¹²Information on references can be found in Clause 2.

5.2.1.4 Loop antenna far-field radiation pattern

The field pattern of electrically small antennas of any shape (circular, elliptical, square, rectangular, etc.) is similar to that of an infinitesimal dipole with a null perpendicular to the plane of the loop and with its maximum along the plane of the loop. The far-field pattern for a loop antenna can be useful to validate the ability of a simulation code to correctly find far fields assuming a constant current distribution. The fields for a loop antenna in free space are given in Equation (6).

$$\begin{aligned} E_r &\cong E_\theta = 0 \\ E_\phi &\cong \frac{ak\eta_0 I_0 e^{-jkr}}{2r} J_1(ka \sin \theta) \\ H_r &\cong H_\phi = 0 \\ H_\theta &\cong -\frac{akI_0 e^{-jkr}}{2r} J_1(ka \sin \theta) \end{aligned} \tag{6}$$

where

- E is the electric field at the center
- H is the magnetic field
- a is the internal radius of the loop
- k is the wave number
- η_0 is the intrinsic impedance of free space
- r is the distance between the observer and the center of the loop antenna
- J_1 is a Bessel function of the first kind order 1
- I_0 is the maximum current through the loop
- θ is the angle from the normal to the loop (from z axis)

An example plot is shown in Figure 9.

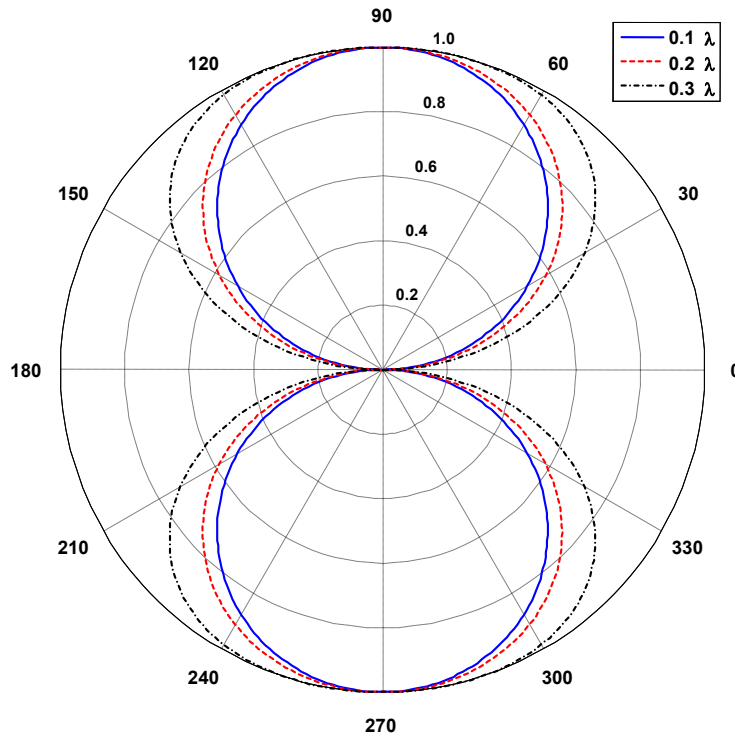


Figure 9—Normalized radiated field pattern

The results are grouped in an Excel file *Loop Antenna_Farfield.xls*, consisting of five worksheets (see IEEE EMC-S Web site). The first worksheet includes some notes about the problem; for more detail, see Balanis. The next three worksheets have the calculated data for loop antennas whose radii are 0.1λ , 0.2λ , and 0.3λ respectively. The final worksheet contains the comparison of the three mentioned cases and plots for radiated field pattern and radiated field intensity. All the data presented are normalized to the maximum value.

While many different full-wave simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem as opposed to a volume-based technique where the surrounding air, as well as the air to the distant observation point in the far field, would be required to be part of the model.

Reference

Balanis, Constantine A., *Antenna Theory: Analysis and Design, Second Edition*, John Wiley & Sons, Inc., 1996.¹³

¹³ Information on references can be found in Clause 2.

5.2.2 Signal integrity canonical validation problems

5.2.2.1 Coaxial problem

The (centered, round) coaxial line is a very simple structure with well-known closed form expressions for the fundamental transverse electromagnetic (TEM) mode. TEM mode propagation is, strictly speaking, only possible for purely lossless, linear, and isotropic media. Therefore, in this problem, conductors are perfectly electrically conducting (PEC) and the dielectric is free space, as shown in Figure 10.

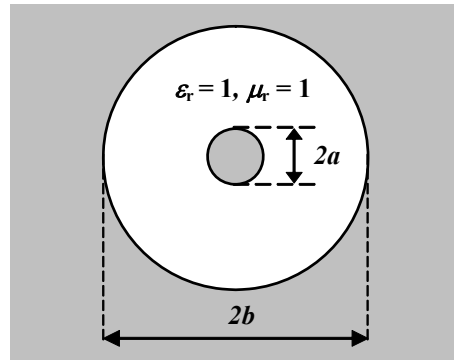


Figure 10—Coaxial problem geometry

Modeling and simulation results can be compared with the following theoretical results:

- Inductance per unit length (in F/m): $L' = \frac{\mu_0}{2\pi} \cdot \ln(b/a)$
- Capacitance per unit length (in H/m): $C' = \frac{2\pi\epsilon_0}{\ln(b/a)}$
- Characteristic impedance (in Ohm): $Z_0 = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{\mu_0}{\epsilon_0}} \cdot \frac{\ln(b/a)}{2\pi} = \eta_0 \cdot \frac{\ln(b/a)}{2\pi}$
- Phase velocity (in m/s): $v_{ph} = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{\mu_0\epsilon_0}} = c_0$

where

- a is the radius of the inner conductor
- b is the radius of the outer conductor
- μ_0 is the permeability of free space
- ϵ_0 is the permittivity of free space
- η_0 is the wave impedance of free space
- c_0 is the speed of light in free space

Reference

[B94] Pozar, David M., *Microwave Engineering*, 2nd edition, Wiley, New York, 1998

5.2.2.2 Parallel wire problem

The arrangement of two parallel, round wires of equal diameter, in a homogeneous dielectric medium, is another simple structure with well-known closed form expressions for the fundamental TEM mode. TEM mode propagation is, again, only possible for purely lossless, linear, and isotropic media and, for this problem, conductors are PEC and the dielectric is free space, as shown in Figure 11.

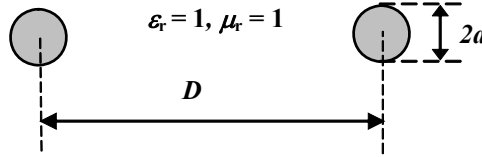


Figure 11—Parallel wire problem geometry

Modeling and simulation results can be compared with the following theoretical results:

- Inductance per unit length (in F/m): $L' = \frac{\mu_0}{\pi} \cdot \cosh^{-1}(D/2a)$
- Capacitance per unit length (in H/m): $C' = \frac{\pi\epsilon_0}{\cosh^{-1}(D/2a)}$
- Characteristic impedance (in Ω): $Z_0 = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{\mu_0}{\epsilon_0}} \cdot \frac{\cosh^{-1}(D/2a)}{\pi} = \eta_0 \cdot \frac{\cosh^{-1}(D/2a)}{\pi}$
- Phase velocity (in m/s): $v_{ph} = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{\mu_0\epsilon_0}} = c_0$

where

- a is the radius of each wire
- D is the separation between the centers of the two wires
- μ_0 is the permeability of free space
- ϵ_0 is the permittivity of free space
- η_0 is the wave impedance of free space
- c_0 is the speed of light in free space

Reference

[B94] Pozar, David M., *Microwave Engineering*, 2nd edition, Wiley, New York, 1998.

5.2.2.3 Strip line impedance problem

The symmetrical strip line trace on a PCB is a simple structure and very common in high-speed circuit designs. Its geometry is shown in Figure 12. The strip line characteristic impedance, which is a critical design aspect for SI, is a closed-form formula and is given in Equation (7). However, it should be noted that this is not a pure canonical problem, and that this equation is approximate and no exact solution is available.

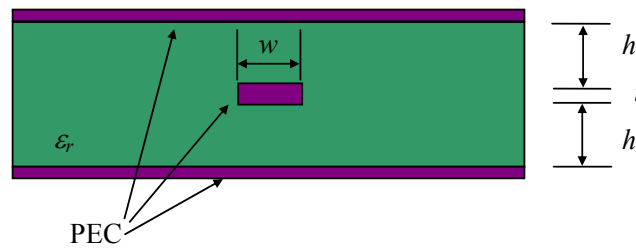


Figure 12—Strip line problem geometry

$$Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln \left[\frac{4(2h + t)}{0.67\pi(0.8w + t)} \right] \quad (7)$$

where

- Z_0 is the characteristic impedance of the strip line trace
- w is the width of the strip line trace
- t is the thickness of the strip line trace
- h is the distance between the trace and the planes
- ϵ_r is the relative permittivity of the dielectric material

Reference

[B68] IPC-2251; “Design Guide for the Packaging of High Speed Electronic Circuits,” Association Connecting Electronics Industries, Nov. 2003.

5.2.2.4 Microstrip impedance and attenuation validation problem

The microstrip trace on a PCB is a simple structure and very common in high-speed circuit designs. Its characteristic impedance and attenuation, which are critical design aspects for SI, are known as closed-form formulas. This problem is not a pure canonical problem with an exact solution; however, it can be a meaningful validation tool, especially for PCBs.

For the microstrip geometry shown in Figure 13, the characteristic impedance, Z_0 , is given in Equation (8) (Wadell [B123]). It should be noted that this equation will not give an exact solution, but it will give a useful, “good” approximation.

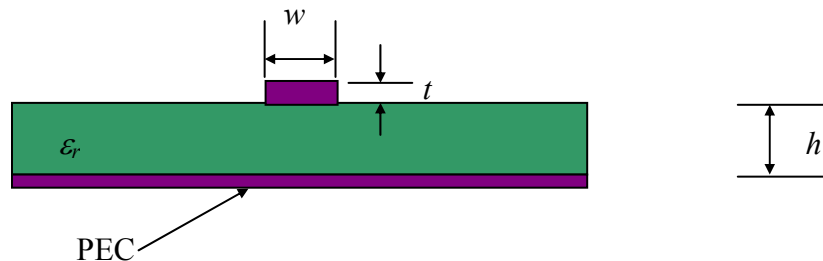


Figure 13—Microstrip problem geometry

$$Z_0 = \frac{60}{\sqrt{2}\sqrt{\varepsilon_{eff}+1}} \ln \left\{ 1 + \frac{4h}{w'} \left[\frac{14 + \frac{8}{\varepsilon_{eff}}}{11} \frac{4h}{w'} + \sqrt{\left(\frac{14 + \frac{8}{\varepsilon_{eff}}}{11} \right)^2 \left(\frac{4h}{w'} \right)^2 + \frac{1 + \frac{1}{\varepsilon_{eff}}}{2} \pi^2} \right] \right\} \quad (8)$$

where

Z_0 is the characteristic impedance of the microstrip trace
 H is the dielectric layer thickness
 ε_{eff} is the effective permittivity of the microstrip trace
 w is an intermediate term

The w' term is a function of the microstrip geometry and the relative permittivity as shown in Equation (9):

$$w' = w + \left(\frac{1 + \frac{1}{\varepsilon_r}}{2} \right) \frac{t}{\pi} \ln \left[\frac{4e}{\sqrt{\left(\frac{t}{h} \right)^2 + \left(\frac{\frac{1}{\pi}}{\frac{w}{t} + 1.1} \right)^2}} \right] \quad (9)$$

where

w is the width of the microstrip trace
 t is the thickness of the microstrip trace
 ε_r is the relative permittivity of the dielectric material
 e is the natural logarithm base

The effective permittivity (ε_{eff}) can be obtained from one of the two following equations, depending on the value of w/h . When $w/h \leq 1$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\left(1 + \frac{12h}{w} \right)^{-0.5} + 0.04 \left(1 - \frac{w}{h} \right)^2 \right] \quad (10)$$

When $w/h \geq 1$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left(1 + \frac{12h}{w} \right)^{-0.5} \quad (11)$$

The attenuation factors of the microstrip trace are also given as closed-form expressions as the characteristic impedance. Again it should be noted that these expressions are not exact solutions but are good approximations. The overall attenuation is caused by both conductor and dielectric losses (from Wadell [B123]). In other words, as shown in Equation (12):

$$\alpha = \alpha_c + \alpha_d \quad (12)$$

where

- α is the overall attenuation factor of the microstrip trace
- α_c is the attenuation factor of the microstrip trace due to conductor losses
- α_d is the attenuation factor of the microstrip trace due to dielectric losses

The attenuation factor due to dielectric losses (α_d) is expressed as shown in Equation (13):

$$\alpha_d = \frac{20\pi}{\ln 10} \frac{\epsilon_r}{\epsilon_{eff}} \frac{\epsilon_{eff} - 1}{\epsilon_r - 1} \frac{\tan \delta}{c} \sqrt{\epsilon_{eff}} f \quad (13)$$

where

- $\tan \delta$ is the loss tangent of the dielectric material
- f is the frequency
- c is the velocity in free space

The attenuation factor due to conductor losses (α_c) can be obtained from one of the two following equations, depending on the value of w/h . When $w/h \leq 1$

$$\alpha_c = \frac{10R_s}{\pi \ln 10} \frac{\left(\frac{8h}{w} - \frac{w}{4h}\right) \left(1 + \frac{h}{w} + \frac{h}{w} \frac{\partial w}{\partial t}\right)}{hZ_0 \exp(Z_0/60)} \quad (14)$$

When $w/h \geq 1$

$$\alpha_c = \frac{Z_0 R_s}{720\pi^2 h \ln 10} \left[1 + \left(\frac{0.44h^2}{w^2} \right) + \frac{6h^2}{w^2} \left(1 - \frac{h}{w} \right)^5 \right] \left(1 + \frac{w}{h} + \frac{\partial w}{\partial t} \right) \quad (15)$$

where

- R_s is the surface resistance of the conductor
- $\frac{\partial w}{\partial t}$ is an intermediate term

The $\frac{\partial w}{\partial t}$ term is determined from one of the two following expressions, depending on the value of w/h .

$$\text{When } \frac{w}{h} \leq \frac{1}{2\pi} \quad \text{then} \quad \frac{\partial w}{\partial t} = \left(\frac{1}{\pi} \right) \ln \frac{4\pi w}{t}$$

$$\text{When } \frac{w}{h} \geq \frac{1}{2\pi} \quad \text{then} \quad \frac{\partial w}{\partial t} = \left(\frac{1}{\pi} \right) \ln \frac{2h}{t}$$

The surface resistance of the conductor (R_s) is given as shown in Equation (16):

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \quad (16)$$

where

μ is the permeability of the dielectric material
 σ is the conductivity of the conductor

While many different full-wave simulation techniques can be used for this problem, it is likely that a volume-based technique, such as the *finite-difference time-domain* (FDTD) technique, is best suited for this problem. This is because the volume of the dielectric is important to the solution. Surface-based techniques may be able to solve this problem using equivalent surface currents at the air-dielectric interface, or by other methods.

References

- [B123] Wadell, Brian C., *Transmission Line Design Handbook*, Artech House, 1991, Chapter 3.
[B44] Edwards, T. C., *Foundations for Microstrip Engineering*, John Wiley, New York, 1981.
[B91] Paul, C. R., *Introduction to EMC*, John Wiley, New York, 1992.

5.2.3 Scattering canonical validation problems

5.2.3.1 Reflection/scattering from a PEC sphere

The scattering of a plane wave by a sphere is a classic problem and is often used as the reference because of its symmetry. This is used to measure the scattering properties like the RCS of other targets. As the problem has been extensively studied by many authors, only an outline of the problem is sketched and references will be provided for the interested reader. The RCS, or scattering cross section, σ_s , (in square meters) can be defined as shown in Equation (17):

$$\sigma_s = \lim_{r \rightarrow \infty} \left[4\pi r^2 \frac{|\vec{E}^s|^2}{|\vec{E}^i|^2} \right] \quad (17)$$

where

r is the distance from the target to the observation point
 $\vec{E}^s$ is the scattered electric field
 $\vec{E}^i$ is the incident electric field

For a sphere of radius a , it can be shown that, assuming geometrical optics ($a \gg \lambda$) and a perfectly reflecting sphere, the incident plane-wave radiation is uniformly scattered in all directions (isotropic scattering) and the RCS is given as $\sigma_s = \pi a^2$.

When the wavelength is not small compared with the sphere radius, the calculation is much more complicated. This region where the wavelength is not small compared to the radius is called the *Mie region*.

or *resonance region*. After several developments from different authors (Mie [B83], Stratton [B110], Kerr et al. [B72], and Blake [B17]), the solution is given in Equation (18):

$$\frac{\sigma_s}{\pi a^2} = \frac{1}{k^2} \left| \sum_{n=1}^{\infty} (-1)^n (2n+1) (a_n + b_n) \right|^2 \quad (18)$$

where

σ_s is the RCS
 a is the radius of the sphere
 k is the wave number
 n is an index referring to the order of the spherical Bessel function used to express the solution behavior

a_n and b_n (for a perfectly conducting sphere) are given by

$$a_n = \frac{j_n(\alpha)}{h_n^{(2)}(\alpha)}$$

$$b_n = \frac{-[\alpha j_n'(\alpha)]}{[\alpha h_n^{(2)'}(\alpha)]}$$

where

j_n is the spherical Bessel function of the first kind
 $h_n^{(2)}$ is the spherical Hankel function of the second kind, respectively
 α is ka , the argument of the Bessel and Hankel functions

The primes denote the differentiation with respect to the argument of the Bessel and Hankel functions, α . The plot of the RCS is given in Figure 14 (Barton [B12]).

The RCS for a sphere of radius a is calculated and the results are reported in the Excel file *rsc_sphere.xls* (see IEEE EMC-S Web site). The behavior is indeed oscillatory with a peak of approximately 5.4 dB at $a = \lambda / 2\pi$.

While many different full-wave simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem versus a volume-based technique where the surrounding air, as well as the air to the distant observation point in the far field, would be required to be part of the model. Another useful technique could be the Geometrical Theory of Diffraction (GTD).

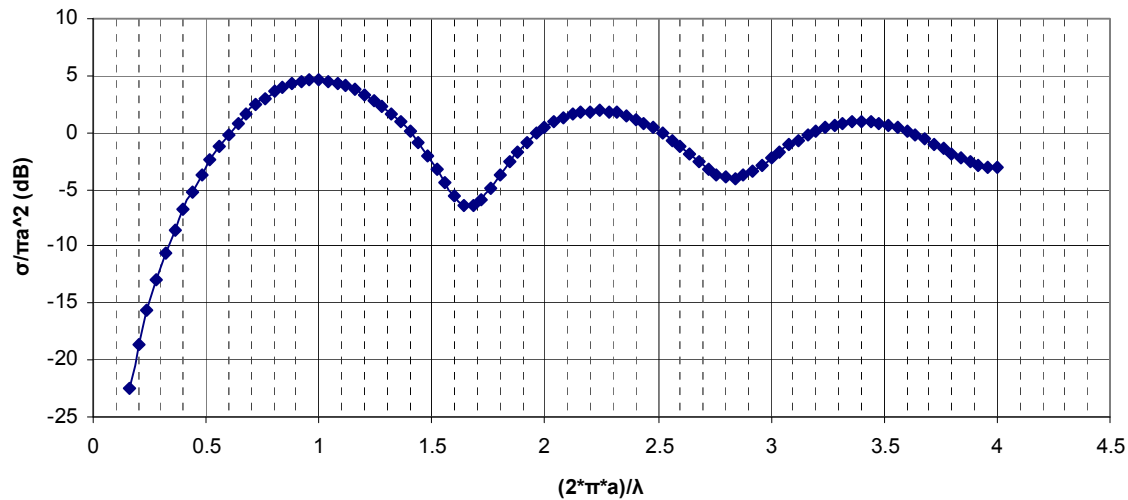


Figure 14—RCS of a perfectly conducting sphere

References

- [B113] Sullivan, Roger J., *Microwave Radar: imaging and advanced concepts*, Norwood, MA: Artech House, 2000.
- [B12] Barton, D. K., *Modern Radar System Analysis*, Norwood, MA: Artech House, 1988. (Updated version: *Radar System Analysis and Modeling*, Artech House, 2005.)
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- [B35] Crispin, J. W., and Siegel, K. M., *Methods of Radar Cross Section Analysis*, New York: Academic Press, 1968.
- [B83] Mie, G., "A Contribution to the Optics of Turbid Media, Especially Colloidal Metallic Suspensions," *Annals of Physics*, Vol. 25, 1908, pp. 377-445
- [B110] Stratton, J. A., *Electromagnetic Theory*, New York: McGraw-Hill, 1941. (Re-issued by Wiley-IEEE, Jan. 2007.)
- [B72] Kerr, D. E., et al., *Propagation of Short Radio Waves*, New York: Dover Publications, 1965. (Rev Sub edition by P. Peregrinus, 1987; also by IEE, 1987.)
- [B17] Blake, L. V., *Radar Range-Performance Analysis*, Norwood, MA: Artech House, 1986. (Reprinted by Munro Publishing, 1991.)

5.2.3.2 Transverse electric (TE) reflection/scattering from an infinitely long conducting cylinder

The TE (magnetic field parallel to the axis of the cylinder, permitting the electric field to be considered transverse) scattering of a plane wave by an infinitely long conducting cylinder is a classic problem and is often used as the reference because of its symmetry. As the problem has been extensively studied by many

authors, only an outline of the problem is sketched and references will be provided for the interested reader. The scattering cross section, σ_s , or RCS, for two dimensional problems is considered a scattering width (in meters). See Equation (19).

$$\sigma_s = \lim_{\rho \rightarrow \infty} \left[2\pi\rho \frac{|\vec{E}^s|^2}{|\vec{E}^i|^2} \right] \quad (19)$$

where

- ρ is the distance from the target to the observation point
- $\vec{E}^s$ is the scattered electric field
- $\vec{E}^i$ is the incident electric field

Cylindrical coordinates will be used in the problem description to follow.

Since the cylinder is infinitely long, the problem is two dimensional as shown in Figure 15. We can express the time factor $e^{j\omega t}$ throughout the analysis. For the sake of convenience, we need to express the plane wave in terms of cylindrical waves.

The incident wave may be written as shown in Equation (20):

$$E_z^i = E_0 e^{-jkx} = E_0 \sum_{n=-\infty}^{\infty} (-j)^n J_n(k\rho) e^{jn\phi} \quad (20)$$

where

- E_z^i is the incident wave on the cylinder
- E_0 is the electric field, treated as a constant amplitude
- k is the wave number
- J_n is the cylindrical Bessel function of n^{th} order
- ρ is the separation between the observer and the centre of the cylinder
- ϕ is the angle measured from the x-axis

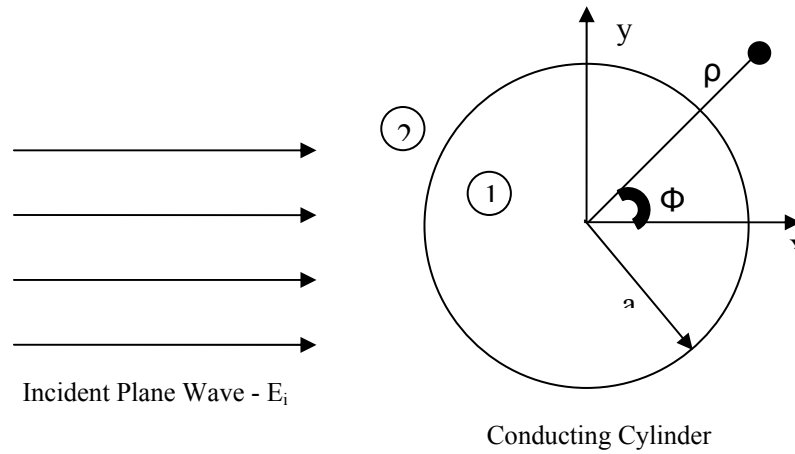


Figure 15—Conducting cylinder scattering canonical problem geometry

The total field in medium 2 is shown in Equation (21):

$$E_2 = E_z^i + E_z^s \quad (21)$$

While the total field in medium 1 is $E_1 = 0$ since medium 1 is conducting. At $\rho = a$, the boundary condition requires that the tangential components of E_1 and E_2 be equal. Hence, as shown in Equation (22):

$$E_z^i(\rho = a) + E_z^s(\rho = a) = 0 \quad (22)$$

Substituting the values for the incident and scattered fields, where A_n is a constant,

$$\sum_{n=-\infty}^{\infty} [E_0 (-j)^n J_n(ka) + A_n H_n^{(2)}(ka)] e^{jn\phi} = 0 \quad (23)$$

From this we obtain Equation (24):

$$A_n = -\frac{E_0 (-j)^n J_n(ka)}{H_n^{(2)}(ka)} \quad (24)$$

Finally substituting A_n and introducing the time factor leads to the scattered wave as shown in Equation (25):

$$E_z^s = -E_0 e^{j\omega t} a_z \sum_{n=-\infty}^{\infty} (-j)^n \frac{J_n(ka) H_n^{(2)}(k\rho) e^{jn\phi}}{H_n^{(2)}(ka)} \quad (25)$$

where

E_z^s is the scattered wave on the cylinder
 a is the radius of the cylinder
 ρ is the separation between the observer and the center of the cylinder
 k is the wave number
 J_n is the cylindrical Bessel function of n^{th} order
 H_n is the cylindrical Hankel function of n^{th} order

The excitation is chosen to be an incoming plane wave of unit amplitude incident normally from the left and the monostatic backscattering angle is ϕ equal to 180 degrees. Figure 16 shows the bistatic RCS of an infinite conducting cylinder with electric radius equal to one wavelength. The results are provided in an Excel file, *rscs_cylinder.xls* (see IEEE EMC-S Web site).

While many different full-wave simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem versus a volume-based technique where the surrounding air, as well as the air to the distant observation point in the far field would be required to be part of the model. Another useful technique could be the GTD.

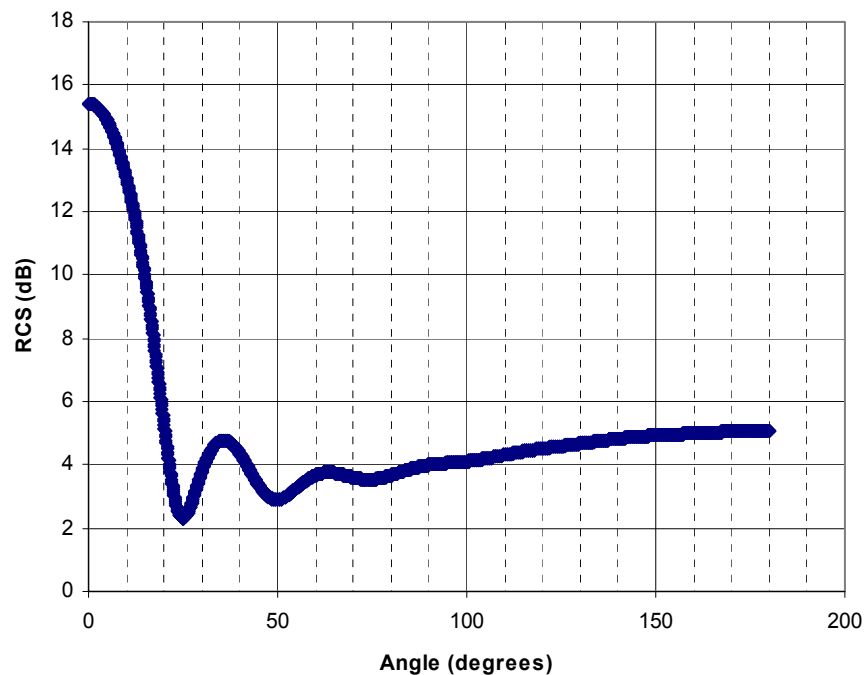


Figure 16—RCS of an infinitely long PEC cylinder

Reference

[B97] Sadiku, Matthew N. O., *Numerical Techniques in Electromagnetics*, Boca Raton, FL: CRC Press, 2001.

5.3 Benchmark validation problems

5.3.1 Antenna benchmark validation problems

5.3.1.1 Antenna calibration

In this benchmark validation problem, the effects of imperfect ground planes on the measurement in a typical open area test site (OATS) (as per ANSI C63.5-2006 [B1]) are found for a frequency of 600 MHz as the receive antenna height is varied from 1 m to 4 m above the ground reference. The results of the electric field over height are compared to the theoretical value for a perfect ground (image) plane.

The problem geometry is shown in Figure 17. The dipole antennas are aligned parallel to the y -axis and have a length of one-half the wavelength at 600 MHz. The wire radius for the dipole is set to $\lambda/1000$. The distance, R , from the coordinate system origin to the antennas is 3 m. The transmit antenna is at a height of 1 m, and the receive antenna height is varied from 1 m to 4 m.

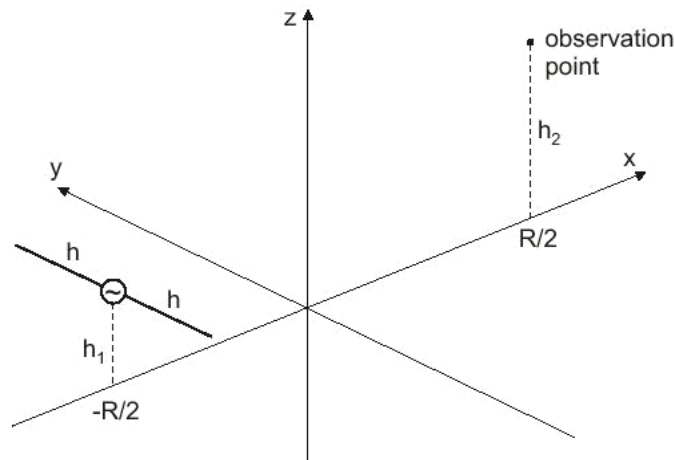


Figure 17—Antenna calibration benchmark problem geometry

The ground (image) plane conditions are varied as follows:

- Ground 1: Perfectly conducting infinite ground plane at $z = 0$.
- Ground 2: Perfectly conducting ground plane at $z = 0$ with finite dimensions of 2 m $\times$ 4 m. The ground plane is located from $x = \pm 2$ m and $y = \pm 1$ m.
- Ground 3: Wet soil modeled by a homogeneous dielectric media for $z < 0$ with a relative permittivity of 12 and conductivity of 0.04 S/m. The relative permeability is 1.
- Ground 4: Dry soil modeled by a homogeneous dielectric media for $z < 0$ with a relative permittivity of 8 and conductivity of 0.04 S/m. The relative permeability is 1.

The excitation is applied to the transmitting dipole antenna at a frequency of 600 MHz so that a total power of 1 pW is radiated.

The task requires the electric field (in dB μ V/m) for each type of ground be plotted for the receive antenna heights of 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 3.5 m, and 4.0 m.

While many different full-wave simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem as opposed to a volume-based technique where the surrounding air, as well as the air between the source and observation point in the far field, would be required to be part of the model.

References

IEEE German EMC Chapter, *Numerical Benchmark Problem #11*.¹⁴

[B1] ANSI C63.5-2006, American National Standard for Electromagnetic Compatibility—Radiated Emission Measurements in Electromagnetic Interference (EMI) Control—Calibration of Antennas (9 kHz to 40 GHz).

5.3.1.2 Coupling from transmitting antenna into transmission line

In this benchmark validation problem, the effect of a nearby monopole antenna on a transmission line is found. Figure 18 shows the physical geometry and dimensions. The entire configuration is placed above an infinite, perfectly conducting, ground (image) plane. The transmission line represents a cable close to the antenna and the antenna dimensions are for a typical high-frequency (HF) antenna. The conductors are considered to be perfect conductors. The transmission line is terminated to the ground plane through a 1 k Ω resistor at the right hand end of the transmission line, and is shorted at the left-hand end.

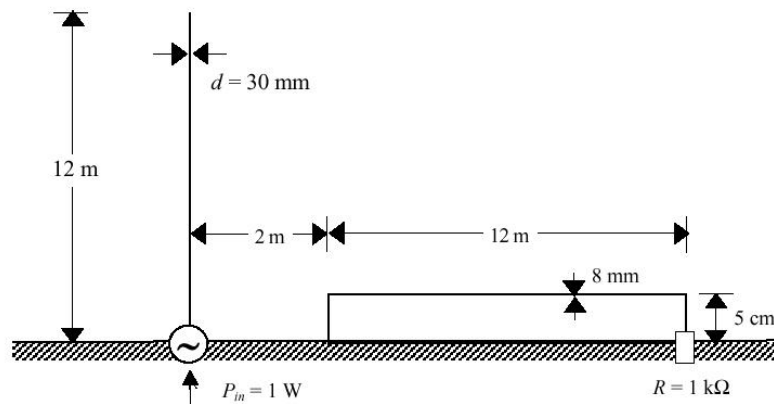


Figure 18—Coupling benchmark problem geometry

The antenna is fed with a 1 W sine wave that varies over the frequency range of 1 MHz to 30 MHz. The internal impedance of the antenna is assumed to be zero.

The results should include the real and imaginary part of the current at the right-hand end of the transmission line (load end), and the real and imaginary part of the monopole antenna's impedance.

While many different full-wave simulation techniques can be used for this problem, it is likely that a surface-based technique, such as the MoM, is best suited for this problem. This is because only a few unknowns (surface currents) would be needed for this problem as opposed to a volume-based technique where the surrounding air, as well as the air to the distant observation point in the far field would be required to be part of the model.

¹⁴ Available at Web site http://www.ewh.ieee.org/r8/germany/emc/ag_num/benchmark.html. See also Clause 2.