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# APPLIED COMPUTATIONAL ELECTROMAGNETICS SOCIETY (ACES)

## NEWSLETTER

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## NEWSLETTER ARTICLES AND VOLUNTEERS WELCOME

The ACES Newsletter is always looking for articles, letters and short communications of interest to ACES members. All individuals are encouraged to write, suggest or solicit articles either on a one-time or continuing basis. Please contact a Newsletter Editor.

## AUTHORSHIP AND BERNE COPYRIGHT CONVENTION

**ELECTION PROCEDURE:**

To vote for 3 new members of the ACES Board of Directors, go to the ACES web site (aces.ee.olemiss.edu), log in, and click on the "Elections" button at the bottom of the left-side menu. This will take you to a page where you may either view the candidates and their statements without voting, or vote. Follow the directions on the succeeding menus to complete the voting process.

Each year 3 new members are elected to the ACES BoD. This year, as we only have 3 nominees, they are by default elected to the board. We would ask, however, that you still go to the web site and vote so that we may test the on-line election system and be sure it is functioning properly. You do not have to vote for 3 candidates, but for any number that you wish. Write-in votes are no longer an option under this new system. In order to use the on-line system, you will need a username and password to get onto the members side of the website.

Thank you for your votes!

Rene Allard
Elections Committee

**Dr. Atef Z. Elsherbeni**

**GENERAL BACKGROUND**

Atef Z. Elsherbeni received an honor B.Sc. degree in Electronics and Communications, an honor B.Sc. degree in Applied Physics, and a M.Eng. degree in Electrical Engineering, all from Cairo University, Cairo, Egypt, in 1976, 1979, and 1982, respectively, and a Ph.D. degree in Electrical Engineering from Manitoba University, Winnipeg, Manitoba, Canada, in 1987. He was a Research Assistant with the Faculty of Engineering at Cairo University from 1976 to 1982, and from 1983 to 1986 at the Electrical Engineering Department, Manitoba University. He was a part time Software and System Design Engineer from March 1980 to December 1982 at the Automated Data System Center, Cairo, Egypt. From January to August 1987, he was a Post Doctoral Fellow at Manitoba University. Dr. Elsherbeni joined the faculty at the University of Mississippi in August 1987 as an Assistant Professor of Electrical Engineering. He advanced to the rank of Associate Professor on July 1991, and to the rank of Professor on July 1997. He spent a sabbatical term in 1996 at the Electrical Engineering Department, University of California at Los Angeles (UCLA).

Dr. Elsherbeni received The Mississippi Academy of Science 2003 Outstanding Contribution to Science Award, The 2002 IEEE Region 3 Outstanding Engineering Educator Award, The 2002 School of Engineering Outstanding Engineering Faculty Member of the Year Award, the 2001 Applied Computational Electromagnetic Society (ACES) Exemplary Service Award for leadership and contributions as Electronic Publishing Managing Editor 1999-2001, the 2001 Researcher/Scholar of the year award in the Department of Electrical Engineering, The University of Mississippi, and the 1996 Outstanding Engineering Educator of the IEEE Memphis Section.

Dr. Elsherbeni has conducted research in several areas such as: scattering and diffraction by dielectric and metal objects, inverse scattering, finite difference time domain analysis of passive and active microwave devices, field visualization and software development for EM education, dielectric resonators, interactions of electromagnetic waves with human body, and development of sensors for soil moisture and for monitoring of airports noise levels, reflector antennas and antenna arrays, and analysis and design of printed antennas for wireless communications and for radars and personal communication systems. His recent research has been on the application of numerical techniques to microstrip and planar transmission lines, antenna measurements, and antenna design for radar and personal communication systems. He has published 73 technical journal articles and 13 book chapters on applied electromagnetics, antenna design, and microwave subjects, and contributed to 210 professional presentations. He is the coauthor of the book entitled "MATLAB Simulations for Radar Systems Design", CRC Press, 2003 and the main author of the chapters "*Handheld Antennas*" and "*The Finite Difference Time Domain Technique for Microstrip Antennas*" in Handbook of Antennas in Wireless Communications, CRC Press, 2001.

Dr. Elsherbeni is a senior member of the Institute of Electrical and Electronics Engineers (IEEE). He is the Editor-in-Chief for the Applied Computational Electromagnetic Society (ACES) Journal, an Associate Editor to the Radio Science Journal, and the electronic publishing managing editor of ACES. He serves on the editorial board of the Book Series on Progress in Electromagnetic Research, the Electromagnetic Waves and Applications Journal, and the Computer Applications in Engineering Education Journal. He was the Chair of the Engineering and Physics Division of the Mississippi Academy of Science and the Chair of the Educational Activity Committee for the IEEE Region 3 Section. Dr. Elsherbeni's home page can be found at http://www.ee.olemiss.edu/atef and his email address is Elsherbeni@ieee.org.

**PAST AND CURRENT SERVICE TO ACES**

- Chair of ACES 2003 conference
- Co-chair of ACES 2004 conference
- ACES electronic publication manager editor, 2000-present
- ACES Journal Editor-in-Chief, 2002-present
- ACES pilot electronic publication project and website developer, 1999-present
- Presented papers at many ACES conferences
- Chaired and co-chaired, and organized sessions at ACES conferences
- Offered short courses at the last 5 ACES conferences
- ACES publications committee chair, 2004-present
- Member of ACES conference committee, 2003-present

**CANDIDATE'S PLATFORM**

For the coming few years, my continued service to ACES society will be focused on

- Enhancing the quality of the published journal articles,
- Expanding the scope of the Journal to include up to date applications addressing emerging technology,
- Expanding the annual conference activity and encouraging the participation from other electromagnetic communities in holding joint conferences in US and abroad,
- Continuing the development and enhancement of the on-line service provided by ACES web site, and
- Increasing the membership of the society.

## DR. MICHIKO KURODA

### GENERAL BACKGROUND

Michiko Kuroda was born in Osaka, Japan. She received the B. E. degree in Electrical Engineering from Shizuoka University, Shizuoka, Japan in 1973 and the M. E. and Ph.D. in Electrical Engineering from Waseda University, Tokyo, Japan, in 1975 and 1978, respectively. She was a visiting scholar of the Ohio State University, OH. She subsequently became an Associate Professor at Tokyo University of Technology. Since 1998, she has been a professor at the department of Information Networks and she became the Chair of the department of Information Networks in 2002. Since 2003, she has been a member of the steering committee of Tokyo University of Technology. Since 1994, she has been a Correspondent of URSI (International Union of Radio Science) in Japan. Since 2002, she has been a scientific advisor of guidance on the Ministry of Public Management, Home Affairs, Post and Telecommunications. Since 2004, she has been an advisory committee member of the Saitama Prefecture in Japan.

Her research interests include electromagnetic theory and numerical methods. Recently, her research interests are the FDTD method and the grid generation method. She proposed the numerical method for the analysis of the moving boundary problems and its application for the analysis of MEMS devices. She is a member of ACES, the IEEE Antennas and Propagation and Microwave Theory and Techniques Societies and Optical Society of America. She is also a member of IEICE and IEEJ in Japan.

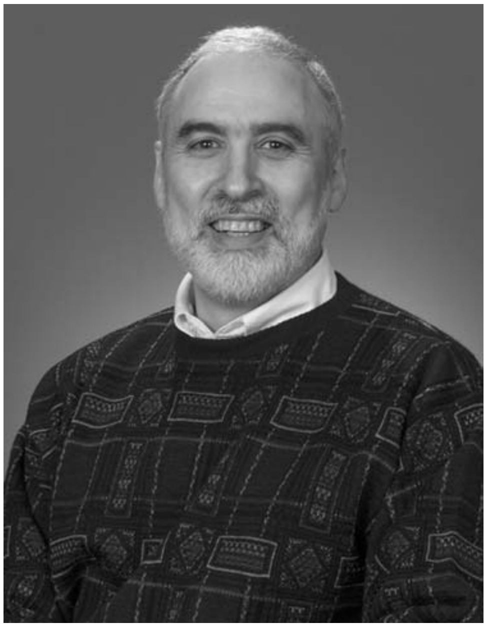
### PAST SERVICES TO ACES

The candidate has presented papers every year since 2001. She was also a session chair in 2001.

### CANDIDATE'S PLATFORM

Recently the field of electromagnetics has been developing widely in terms of sub-fields such as millimeter waves, computational electromagnetics, bioelectromagnetics, electromagnetic compatibility, microwave and high-speed digital circuits, nanotechnology, and optics. Therefore, Computational Electromagnetics should now become a very important area for any researcher, scientist, or engineer. Also, as the frequencies are becoming higher, engineers in the area of circuits or VLSI circuits have to consider the potential effects of the microwaves. For this reason, I believe that ACES will become one of the most important societies in the near future including various areas of engineering. With regard to computational methods, it is necessary for us to recognize that we are lagging behind the field of Fluid Mechanics, Structural Mechanics and Civil Engineering. In order to settle these problems, the field of computational electromagnetics is needed for collaboration with these different areas. As Computational Electromagnetics is making rapid progress nowadays, I am looking forward to contributing to the future development of ACES not only in the US but also especially in Japan.

## DR. ERIC L. MOKOLE



**GENERAL BACKGROUND**

Eric L. Mokole was born in Akron, OH, in 1949. He received the B.S. degree in applied mathematics from New York University (New York NY) in 1971, the M.S. degree in mathematics from Northern Illinois University (DeKalb IL) in 1974, the M.S. degrees in physics and applied mathematics from the Georgia Institute of Technology (Atlanta GA) in 1976 and 1978, respectively, and the Ph.D. degree in mathematics from the Georgia Institute of Technology in 1982.

For the 1982-1983 academic year, Eric was an Assistant Professor of Mathematics at Kennesaw College (Kennesaw GA). From 1982 to 1986 he held a position in the Electronic Warfare Division of the Naval Intelligence Support Center (now the Office of Naval Intelligence) in Washington DC. Since 1986 he has been employed by the Radar Division of the Naval Research Laboratory (NRL) in Washington DC. Currently, he is Head of the Surveillance Technology Branch. He has been conducting basic/applied research and system analyses on space-based radar, on shipboard Navy radars and the associated electronic countermeasures (ECM) and electronic counter-counter measures (ECCM), and on ultrawideband (UWB) radar. These efforts have involved information extraction, non-Gaussian detection theory, data analysis, system simulation/modeling, threat/electronic-attack modeling, antenna theory (element and arrays), electromagnetic propagation near the Earth's surface and through the ionosphere (deterministic and random), pulsed propagation in a dispersive medium, and RF scattering from the sea and land. On one effort, Eric is a member of a tri-service applications team for a project, sponsored by the DoD's High Performance Computer Modernization Office, to parallelize WIPL-D (WIPL-DP). He provided sufficiently difficult, but pertinent and numerically accessible, Navy applications to test the capability of WIPL-DP. In particular, to understand the target-like artifacts in radar returns called sea spikes that are induced by ocean scatter, Eric's group has been calculating the monostatic and bistatic radar cross sections of a 1-m trihedral corner reflector with WIPL-D and WIPL-DP at several frequencies between 1 and 11 GHz for vertically and horizontally polarized fields.

Eric is a member of the American Geophysical Union, the American Mathematical Society, the American Physical Society, the Applied Computational Electromagnetic Society, the Association of Old Crows, IEEE Societies on Aerospace and Electronic Systems, Antennas and Propagation, and Geoscience and Remote Sensing, Sigma Xi, and the Society for Industrial and Applied Mathematics. In addition, he is a Senior Member of the IEEE, a member of the Program Committee for the Tri-Service Radar Symposia, and a member of the High-Power Electromagnetics Committee. Eric has over 40 conference publications, journal articles, book chapters, and reports and is co-editor of the book *Ultra-Wideband, Short-Pulse Electromagnetics 6* (Kluwer Academic/Plenum Publishing, 2003).

**PAST SERVICES TO ACES**

The candidate's involvement with ACES is fairly recent. He has attended ACES conferences and was a co-author of a paper and a session co-chair at the 2004 ACES Conference.

**CANDIDATE'S PLATFORM**

Although computational electromagnetics (CEM) has had some success in predicting scattering from objects, antenna radiation, and propagation through media, the field is still very young. To increase CEM's role and importance for future technologies and related systems, I would like to see the ACES intensify emphases in three areas: comparing numerical results against benchmark analytical results and measurements; conducting more error analyses; and combining numerical electromagnetics and information-extraction methods. For a computational result to have greater credibility in my opinion, it needs to be compared to carefully taken measurements and analytically derived solutions. With respect to electromagnetic systems like radar, much greater integration of CEM and information-extraction methods for system performance/design is needed to obtain accurate, realistic characterizations of such systems. For example, determining the antenna pattern in a Compact Range or from a numerical simulation is usually inadequate for knowing the pattern on a platform (UAV, ship, satellite, pedestal, etc.), because the electromagnetic interactions with structures in an antenna's near-field, although essential to realistic characterization, are often ignored. I believe that addressing such issues more frequently in ACES conferences and publications will enhance the society's prestige and usefulness.

# SOME SOURCES OF ERROR IN CEM MODELING AND SIMULATION

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## Abstract

The modeling and solution of large-scale problems in computational electromagnetics (CEM) requires the application of the *right tool for the right job* in order to minimize the potential for error generation and propagation during each step of the process. The subtleties of this issue are associated with knowing where sources of error can arise, how to quantify them, and what methods can be used to control errors. Sources of error can be categorized as *procedural*, *model-limited*, *technique-limited*, *problem dependent*, *numerical*, and *interpretive*. These by no means represent a complete taxonomy of error sources in CEM, but provide a means of better understanding error budgets and how these may be controlled. This article provides a brief overview of some of the sources of error to be mindful of and the potential pitfalls that may lend to computational uncertainty.

## INTRODUCTION

Generally, CEM techniques can be subdivided into two categories: frequency domain and time-domain. These can be further expressed as either integral or differential formulations of Maxwell's equations. Solutions to these equations fundamentally involve a series of partial differential equations that are subject to boundary constraints, except for some variations that are particular to the physics of a given problem. For instance, a CEM technique can be used to solve the Laplace equation that describes the potential distribution of a closed boundary. Also, a CEM technique can be applied to solving the Helmholtz wave equation, which arises in many electromagnetic radiation problems in open space. Clearly, there are different techniques and formulations for different problem solving applications.

Integral equation methods traditionally involve a dense matrix system, in which tens of millions of unknowns can now be solved with today's high performance computers [1]. Differential equation methods involve a sparse matrix system, in which problems with billions of unknowns have been solved [1]. In some problems, the unknowns are volumetrically distributed, whereas in others, they are distributed over a surface.

In volumetric methods, grid dispersion error has been shown to be a significant issue [1]. As the authors in [1] have shown, in the case of a differential equation solver, the field is propagated from point to point via a numerical grid, giving rise to errors. In volume integral equations, the Green's function in an inhomogeneous region usually can have the incorrect phase velocity to propagate the field from point to point, which is also a source of grid dispersion error. In surface integral equations, an exact closed-form Green's function is used to propagate the field through space. Hence, as reference [1] reports, grid dispersion error is greatly mitigated except for surface waves that propagate on the numerical grid on the surface of the scatterer.

The authors in [1] also cite the effects of numerical noise due to round off errors in ultra large-scale computational electromagnetics. For CEM problems involving hundreds of wavelengths, the solution is particularly sensitive to the phase velocity error. As the authors point out, an error in the phase velocity can generate numerical noise that is intolerable if the goal is to achieve high accuracy computations. It becomes incumbent upon the analyst to find ways of validating computed results using high-quality measurements (in which the measurement errors and uncertainty are also reasonably well quantified), or sometimes even comparing computed results to theoretical closed-form solutions such as the Mie series solution in the case of electromagnetic scattering from a sphere, to check the integrity of the calculations [1]. Once again, the goal is to eliminate as much uncertainty in the computational process as is possible. In other words, it's all about the accuracy.

Indeed, there have been many such studies performed in recent years to identify and quantify the sources of error in CEM modeling in an attempt to find effective ways of countering their effect. Clearly, the main goal of research into controllable error methods is to increase the confidence factor in CEM modeling and simulation since we are relying more and more on simulation-based acquisition to procure new systems. This involves the development of new standards and recommended practices for CEM [2] which are in process, as well as the application of novel mathematical algorithms and numerical methods to assure accuracy as well as computational efficiency. Although much progress has been made in implementing new computational methods such as the multi-level fast multipole algorithm (MLFMA), there is still much work ahead of us in terms of further stabilizing error budgets for state-of-the-art CEM techniques and codes.

Nonetheless, the CEM community remains steadfast in its pursuit of developing new, highly accurate fast solvers. Today's methods exploit variations on the Gaussian elimination method, matrix partitioning and pruning schemes, parallel computing, and other potentially effective methods. This remains an evolving branch of electromagnetics that continues to deal with the dichotomy of ensuring efficient computing without forsaking accuracy. Unfortunately, as the problem size becomes larger, numerical instabilities and computational errors begin to emerge and cannot be ignored─even with today's sophisticated fast solvers. As mentioned above, this is the numerical *noise* due to inherent approximations, limited precision, and round-off error. This numerical noise is proportional to the number of floating point operations that is performed. This noise can be particularly devastating in ultra large scale computing as well as problems that are ill conditioned [1].

In addition to numerical noise error due to precision and round off, other sources of error can be attributed to the geometry, applied physics and mathematical algorithms utilized in the solvers. These and other sources of error are covered next within the context of the taxonomy mentioned earlier.

## CEM Error Budgets

Sources of error can be categorized as *procedural*, *model-limited*, *technique-limited*, *problem dependent*, *numerical*, and *interpretive*. These are described below.

First, consider the following fact: all CEM techniques are not necessarily alike even though they are all fundamentally cast from Maxwell's equations. Recall the earlier discussion on the integral and differential formulations of Maxwell's equations, frequency and time domain methods, and Laplace and Helmholtz equations. Specific implementations of electromagnetic theory and CEM techniques are usually aimed at solving certain problems in a certain way for a certain set of boundary conditions and for a certain range of electromagnetic problems. For instance, some techniques are more apt to be used in analyzing exterior radiation and scattering problems, whereas other techniques are better suited to analyzing interior cavity coupling problems. Therefore, even though CEM techniques are based on Maxwell's equations, it is often difficult if not impossible to interchange them for practical problem solving applications or even to compare them in any valid and consistent way.

The "accuracy" of any one CEM technique clearly depends on a number of inter-related factors. These are: (i) the applied physics i.e., how the theoretical equations are cast and what method is used to "map" Maxwell's equations for an infinite space to a finite geometrical space (e.g., boundary element or moment method integral form, finite difference time domain form, finite element method, transmission line model, etc.); (ii) inherent limitations associated with the geometry modeling approach and the procedures followed in building a CEM model; (iii) the numerical solver method used (e.g., full-wave solution, full or banded matrix decomposition, non-matrix solutions, etc.); (iv) the type of problem to be solved (EMI/C, scattering cross section, antenna radiation, printed circuit board trace coupling, etc.); and (v) the methods used to interpret results for computed observables (total and scattered fields, normalized radiation patterns, surface currents, charge densities, etc.).

Hence, the underlying physics formalism, model building blocks (primitives such as canonical surfaces, wires, patches, facets, etc.) and the procedures used to construct models as well as the solution method all conspire to affect the convergence, accuracy, and overall validity of the computed results. The analysis frequency (mesh discretization) and time steps, mathematical basis functions, computer precision, and approximations employed further compound the problem.

***Model-Limited Errors***. This refers to the errors that arise because of limitations associated with the geometrical elements that are used to construct computational models. Sometimes the modeling elements are too gross or simplistic to faithfully represent the geometry at the frequency of interest. For instance, the use of canonical objects in high-frequency ray tracing simulations offers a computationally efficient solution, but does not accurately represent the actual geometry, which in turn leads to approximate solutions. To overcome such difficulties, techniques have been developed to adapt detailed computer-aided design (CAD) models directly in order to derive high-fidelity CEM models. However, this results in a new source of error in that the CAD models themselves may contain subtle flaws that are not readily detected and which can result in errors downstream of the modeling and simulation process.

Research of late has led to the use of curved elemental facets and higher order basis functions, which result in more accurate geometry descriptions and more uniform current distributions on the surfaces of these elements. However, with the exception of certain high-fidelity CEM techniques used for radar cross section simulations, certain limitations still exist with regard to consistently handling the following special cases, which can significantly contribute to the model-limited error budget:

- Multilayer materials, interfaces and discontinuities involving dielectrics
- Open vs. closed boundaries or regions including incomplete geometry definitions, voids, and overlaps (geometrical intersection, union, and subtraction)
- Presence of long, skinny facets
- Modeling doubly-curved surfaces
- Adaptive, non-uniform mesh discretization
- Staircasing at edges and over curved surfaces.

***Procedural Errors***. This refers to the step-by-step approach used in generating and analyzing a CEM model. How one goes about modeling and analyzing a real-world problem is dependent on the type of problem to be solved and what electromagnetic phenomena and observables are of interest among other considerations.

For example, consider the problem of assembling a computational model, and integrating components and their individual electromagnetic contributions to compute a *total budget solution*—not to be confused with *error budget*. This problem is one of resolving a complex system into its parts, analyzing the electromagnetic interactions or relative contributions, and then integrating results in order to arrive at an accurate system analysis—a procedure called *combinatorial* modeling. First, this is an approximate idea. Linear superposition does not work. By solving a problem in components, finding its component radar cross section, for instance, and later adding up the contributions, the total budget solution found this way is a lower bound to the true solution. The difference between the budget solution and the true solution is a function of how strongly the parts interact. The stronger they interact, the larger the difference between the budget solution compared to the true total solution.

For example, five walls of a cavity are not strong scatterers individually, but when the five walls cooperate with each other to form a cavity, they can give rise to resonance scattering, which is much stronger than the scattering from the individual walls. So, a possible approach is to break the system up into weakly interacting components. Then the budget solution is not too different from the true solution. This method can be modified to suit the requirements of subdividing a complex system into weakly interacting components.

This is just one of many illustrations of the importance of defining the step-by-step procedures for modeling and analyzing a problem in order to reduce errors and ensure accuracy in the computed results. An ill-posed problem can result in computational instabilities and numerical inaccuracies, for example, when improper sampling is used to try and capture electromagnetic phenomena at resonance or about singularities or at near field caustic points.

Yet other procedural errors again point back to how the basic geometry and CEM model were built─as in the case of canonical modeling objects that are used to approximate a physical system for high-frequency ray tracing computations. Here we can see the relationship between procedural errors and model-limited errors.

The lesson to be learned is this: building and analyzing a CEM model without some a priori understanding of the type of problem to be solved, the basic physics of the problem, and what observables are most appropriate based on the boundary conditions, frequency, and so forth, will likely lead to errors and lend to the uncertainty. In other words─one needs to properly define the problem and the desired "metrics."

***Technique-Limited Errors***. This category pertains to the approximations and potential errors that are introduced when Maxwell's equation are constrained to a particular subset of boundary conditions and modeling problems (also referred to by some as *quadrature* error), expressed either in differential or integral form. As a result, the applied physics can have certain limitations. Examples of the limitations in the physics include:

- Lack of edge and surface traveling wave models
- Approximations to knife-edge, wedge, tip and point diffraction models
- Phase error (loss) over large distances or dimensions at very high frequencies
- High-frequency asymptotic ray tracing approximations (*ansatz* error)
- Lack of a robust set of current expansion or basis functions
- Inability to handle material discontinuities at interfaces (multilayer, anisotropic or inhomogeneous materials, frequency selective surfaces or FSS, etc.)
- Approximated near-to-far-field extrapolation techniques
- Shadow boundaries, creeping wave and related dispersion losses
- Consistent models and techniques for computing rapidly-varying current or field levels in the vicinity of singularities or caustics
- Radiator feed modeling, FSS and mutual coupling for multi-region problems.

Some of the subtle issues here pertain to the applied mathematical algorithms and methods for truncating infinite series and controlling the number of second and higher order electromagnetic interactions (i.e., bounces) to be considered. Government and academic institutions are presently conducting research to find ways of overcoming these and other limitations in the applied physics formalisms and mathematical algorithms.

***Problem-Dependent Errors***. Understanding the physical problem to be solved goes a long way in reducing the potential for errors. For example, one would not necessarily want to use a full-matrix decomposition moment method technique to solve a simple antenna coupling problem at 10 GHz (recall that the effects of numerical noise become more pronounced due to round off and phase velocity errors in ultra large scale computational electromagnetics!). However, for scattering cross section problems at 10 GHz, moment method based techniques in conjunction with the use of fast solvers are desirable in order to obtain highly accurate results. Similarly, a transmission line modeling (TLM) technique may be quite suitable to analyzing an internal cable coupling problem for a closed or bounded cavity, but may not be appropriate for calculating antenna radiation effects for exterior problems involving large, complex structures.

In this case, it is imperative that one defines the problem to be solved. The most suitable physics formalism(s) and solution method(s) can then be determined with a greater degree of confidence. Generally, at a very high level, problems can be classified as one of he following types: EMI/C, scattering cross section, antenna radiation, signal integrity, shielded enclosure problems, and materials problems. These categories can be further subdivided as necessary. EMI/C, for instance, can apply to printed circuit boards or devices as well as to large-scale systems. Remember the rule─*use the right tool for the right job!*

***Numerical Errors***. Solution error is closely tied to the category of technique-limited error in that the physics and the numerical solvers work together to provide a total budget solution. However, in ultra large scale computational electromagnetics, a variety of errors can arise. Solution errors are attributed to the solver method employed e.g., banded matrix iteration, full wave or lower-upper decomposition (LUD) of matrices, exploitation of block Toeplitz matrices, and additional forms of partitioning in conjunction with the application of the Green's function and other methods to arrive at a total solution.

In [1], the authors describe errors arising from an inconsistent Green's function for an MLFMA based technique in which there was a 4th-digit error in the wave number as a result of the speed of light constant, c, which was defined in two different ways. In this case, the following equations apply.

$$f(\mathbf{r}) = \int_{\Omega} g(\mathbf{r}, \mathbf{r'})_S(\mathbf{r'})\, d\mathbf{r'}$$

and where

$$\mathbf{y} = A\mathbf{x}.$$

Here, the MLFMA used the exact value (299,792,458 m/s) whereas the triangular mesh algorithms used the approximate value ($3\text{x}10^8$ m/s). Therefore, extinction theorems will not apply with an inconsistent Green's function. Hence, surface currents may not be correctly calculated in such a way to cancel the internal fields resulting in residual *noise*. This noise and error propagation can be enhanced with large-scale problems and dense matrix systems [1].

The enhancement of numerical noise and round off error propagation stems from the application of the Green's function and the process of solving for the large number of current or field unknowns (N) for a dense matrix system. A**x** typically requires $N^2$ operations, whereas MLFMA can perform the action in O(N) or O(NlogN) operations for densely packed sources and sparsely packed sources, respectively [1]. Therefore, one could conclude that a fewer number of operations would result in less error propagation. However, there are actually various numerical noise contributions at play in solving for the unknowns. These are product noise, subtraction noise, Gaussian elimination noise, matrix error noise (quadrature error in evaluating matrix coefficient terms), as well as phase velocity error where the phase velocity is incorrectly defined, which in turn can give rise to errors in the exponential function calculations [1]. This is related to the process of solving an integral equation which formulates a cooperative behavior among the current elements so as to produce a field that exactly cancels the incident field within a metallic scatterer, for instance. The authors in [1] point out that this cooperative behavior requires that all the current elements "talk" to each other on the same "wavelength" or the same phase velocity. Hence, any inconsistency in the phase velocity will not allow the current elements to cooperate effectively with each other.

Next, the sources of matrix error can be traced to the problem of (i) geometrical modeling error; (ii) integral equation discretization (including basis function expansion error and quadrature error); (iii) matrix equation solution error (using iterative solvers, LUD, and banded matrices); (iv) matrix vector product error due to matrix equation factorization error (in the case of fast algorithms) and pre-corrected FFT errors; and (v) associated round off and numerical precision errors [1, 3].

***Interpretive Errors***. The human's own ability to interpret the computed observables can invoke a *Heisenberg uncertainty* principle of sorts. The process of modeling and analyzing problems that reveal singularities, caustics, and harmonic resonance behavior as well as situations where abrupt discontinuities of currents or field point mismatches exist at/between multiple region (multilayer material) interfaces, can call into question the suitability of the technique and/or the solution method let alone the accuracy of the computed results. Oftentimes, there is a balance of objective and subjective reasoning at play at this stage of the modeling and simulation task. The proof comes in validating the results against ground truth or measurement benchmarks.

Research has been conducted to establish a standardized method of interpreting computed data results in a highly objective and consistent way using novel technique comparison and Feature Selective Validation (FSV) methods that are design to reduce uncertainty [4, 5].

## Controlling Error

Some possible ways to enhance accuracy and control error in the CEM modeling and simulation process include:

- Use of high-fidelity geometrical models and automated CAD healing capabilities

- Incorporating additional physics models to more accurately handle special cases such as surface and edge traveling waves
- Using higher-order surface modeling elements
- Applying robust current expansion functions (e.g., RWG type)
- Applying new hybrid techniques to accurately model multiple regions (enforcing current continuity and field point matching at interfaces)
- Novel exploitation of symmetry and bodies of revolution (BOR) techniques
- Using "adaptive" optimization algorithms for accuracy and computational efficiency
- Utilizing novel partitioning and decomposition of submatrices
- New and effective ways of sifting out, ranking, and suppressing "off diagonal" noise error sources
- Applying ensemble parameter reasoning (using AI/expert systems to automatically build valid CEM models)
- Applying novel smoothing functions to control staircasing error
- Using extended precision computing
- Exploiting matrix-free fast solvers and HPCs to handle large problems across a broad frequency range
- Developing component-level techniques that can be integrated and extrapolated to provide accurate system-level (total budget) solutions.

Some errors can be easily removed by extending bit precision. Other errors can only be removed by employing better algorithms and methods.

## SUMMARY

This article highlighted the various sources of error in the overall CEM modeling and simulation process. An overview of some of the sources of error and the potential pitfalls that may lend to computational uncertainty was provided. This is applicable to a broad range of problems ranging from the modeling of printed circuit board radiated and conducted emissions/immunity to analyzing large, complex system electromagnetic effects. Concerns have been raised regarding the lack of well-defined methodologies to achieve CEM technique validations within a consistent level of accuracy. This points to the need to identify and quantify the sources errors and to employ controllable error schemes when and where feasible.

The modeling and solution of large-scale problems in CEM requires the application of the *right tool for the right job* in order to minimize the potential for error generation and propagation. This starts by knowing where sources of error can arise, how to quantify them, and what methods can be used to control errors. Sources of error were generally categorized as *procedural*, *model-limited*, *technique-limited*, *problem dependent*, *numerical*, and *interpretive*. These are by no means complete and inclusive, but these provide insights into better understanding error budgets and how these may be controlled.

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# Coupled-Pair Transmission Line Termination Revisited: An MTL Approach

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**Abstract**

**In this paper, the proper termination of a coupled stripline geometry is revisited. Termination guidelines are determined by treating the coupled pair and its associated ground reference as a multi-conductor transmission line and subsequently performing a modal analysis of the line. It is shown that terminating the line in its differential impedance alone is not sufficient from an EMC perspective. Results are demonstrated using a modal FDTD implementation of the of the multi-conductor transmission line equations.**

## Introduction

The differential pair is a dominant transmission line geometry for high-speed data communications systems. Its popularity exists primarily due to its robustness with respect to noise rejection. Commonly, the signals comprising the differential pair are implemented as a set of microstrip or stripline transmission lines which reference a common ground or power plane. Under this scenario the geometry becomes not a simple two conductor coupled line problem but a three-conductor multi-conductor transmission line which support two modes of propagation. Though either or both of these modes may exist on the line, designers typically only properly terminate one of the supported modes. The proper termination of both of the supported modes is the subject of this paper.

The coupled stripline of Figure 1(a) is the simplest of configurations within the multi-conductor transmission line (MTL) class of TEM transmission lines [1]. In general, a multi-conductor transmission line is comprised of N+1 conductors within a background media $\varepsilon_r$ where N is the number of signal conductors in the system. Each of the conductors within the system is coupled to all other conductors within the system through the per-unit-length (PUL) parameters of the line. The PUL parameters are determined using quasi-static techniques from the cross-sectional description of the MTL geometry. The coupled time domain transmission line equations for a *lossless* MTL line are given by

$$\frac{\partial}{\partial z}\mathbf{V}(z,t) = -\mathbf{L}\frac{\partial}{\partial t}\mathbf{I}(z,t) \qquad (1.1)$$

$$\frac{\partial}{\partial z}\mathbf{I}(z,t) = -\mathbf{C}\frac{\partial}{\partial t}\mathbf{V}(z,t) \qquad (1.2)$$

where for a symmetric three-conductor stripline and a homogeneous media

$$\mathbf{C} = \begin{bmatrix} c + c_{12} & -c_{12} \\ -c_{12} & c + c_{12} \end{bmatrix}, \tag{1.3}$$

$$\mathbf{L} = \begin{bmatrix} l & l_{12} \\ l_{12} & l \end{bmatrix} \tag{1.4}$$

In order to easily analyze the propagation characteristics of a MTL structure, it is necessary to decouple the transmission line equations into the N voltage and current modes which are supported by the line. In general, a rigorous eigenmode analysis is required. For the special case of a three-conductor line with two identical signal conductors, the decomposition procedure is quite simple and the two resulting modes are typically referred to as the even and odd modes of the line [[ii]] (differential and common mode in the EMC community). These two modes of propagation are distinguished by their current and voltage distributions. For the even mode, equal, symmetric currents exist on the two signal lines with the return current on the reference conductor. For the odd mode, the currents on the two signal lines are anti-symmetric with their mirror image on the reference conductor. The even/odd decomposition for this symmetric three conductor line is defined by the simple relations [i],[[iii]].

$$\mathbf{V}(z,t) = \mathbf{T_v V_m}(z,t) \tag{1.5}$$

$$\mathbf{I}(z,t) = \mathbf{T_I I_m}(z,t) \tag{1.6}$$

where

$$\mathbf{T}_I = \mathbf{T}_v = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}. \tag{1.7}$$

Substituting (1.5) and (1.6) into (1.1), (1.2) leads to

$$\frac{\partial}{\partial z}\mathbf{V}_m(z,t) = -\mathbf{L}_m \frac{\partial}{\partial t}\mathbf{I}_m(z,t), \tag{1.8}$$

$$\frac{\partial}{\partial z}\mathbf{I_m}(z,t) = -\mathbf{C_m} \frac{\partial}{\partial t}\mathbf{V_m}(z,t) \tag{1.9}$$

where

$$\mathbf{L_m} = \begin{bmatrix} l_{odd} & 0 \\ 0 & l_{even} \end{bmatrix}, \quad \mathbf{C_m} = \begin{bmatrix} c_{odd} & 0 \\ 0 & c_{even} \end{bmatrix}. \tag{1.10}$$

For the special case of a stripline where the media is homogeneous, the odd and even mode characteristic impedances may be computed directly from (1.10) and the relationship $\mathbf{CL} = \frac{1}{v^2}\mathbf{I}$ where $\mathbf{I}$ is the identity matrix. The even mode impedance is given by

$$Z_{even} = \frac{1}{vC_{even}} = \frac{1}{vC_{11}} \tag{1.11}$$

whereas the odd mode impedance is given by

$$Z_{odd} = \frac{1}{vC_{odd}} = \frac{1}{v(C_{11} + 2C_{12})} \tag{1.12}$$

where $v$ is the speed of light in the homogeneous medium. Equations (1.11) and (1.12) are of the same form as given by many microwave reference texts [iv].

## Line Termination

The coupled lines described in the previous section can support a combination of even and odd mode signals simultaneously. Clearly, from a functional perspective, one is interested primarily in the odd mode as this mode has more robust transmission characteristics with regards to noise rejection. From a realistic standpoint, however, some even mode energy will exist. The even-mode or common-mode energy can be the result of imperfect drivers or asymmetric routing of the differential pair. While the even mode energy can easily be rejected by differential mode receivers, its existence can lead to significant EMC problems if not treated carefully. Specifically, if the even mode (common mode) is not terminated correctly, a portion of the even mode signal will resonate along the length of the line leading to higher radiated emissions. By implementing proper multi-mode termination, both even and odd mode currents can be terminated and such resonances are avoided.

As is the case with single conductor transmission lines, a multi-conductor transmission line is ideally terminated with the characteristic impedance(s) of the line. Unlike a single line, the characteristic impedance of the multi-conductor line is represented by an N x N characteristic impedance matrix. There are several equivalent formulations for obtaining this matrix, all of which are determined from the constitutive parameters of the line. For the two conductor line discussed here, it is most easily found by first constructing the modal characteristic impedance matrix. This is given in terms of modal capacitances and inductances as

$$\mathbf{Z_c^m} = \begin{bmatrix} \dfrac{1}{vC_{odd}} & 0 \\ 0 & \dfrac{1}{vC_{even}} \end{bmatrix}. \tag{1.13}$$

In order to implement a termination circuit, the fully coupled characteristic impedance matrix must be formed from (1.13) and is

$$\mathbf{Z_c} = \mathbf{T_v Z_c^m T_I^{-1}} = \frac{1}{2}\begin{bmatrix} Z_{odd}+Z_{even} & Z_{even}-Z_{odd} \\ Z_{even}-Z_{odd} & Z_{odd}+Z_{even} \end{bmatrix} \tag{1.14}$$

which is in general a full matrix.

Proper implementation of the above termination is easily accomplished by mapping this termination to a known termination scheme. Specifically, consider the termination scheme shown in Figure 1 (b). The terminal constraints at the load are expressed in matrix form as

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_1+R_3 & R_3 \\ R_3 & R_2+R_3 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}. \tag{1.15}$$

By equating the elements of (1.15) to those in (1.14) the resistive values of the termination are easily found and are

$$R_1 = R_2 = Z_{odd}, \qquad R_3 = \frac{Z_{even}-Z_{odd}}{2}. \tag{1.16}$$

This subject is discussed in detail in [i].

## Observations

For a purely differential propagating mode , it is seen by a simple application of Kirchoff's current law at the junction of $R_1$, $R_2$, and $R_3$, that no current will flow in $R_3$, thus it is effectively isolated from the differential mode termination. The common mode termination value, $R_3$, diminishes as the coupling between the two lines vanishes, i.e. as $C_{12} \rightarrow 0$. Therefore, in those cases where the two lines of the differential pair are routed separately in an isolated fashion, the inclusion of a common mode termination has a diminishing effect. One hazard of the common mode termination is common impedance coupling [1] which can occur when significant even mode signal is present. In such cases, one must weigh the EMI advantages of this termination scheme against the possible increase in crosstalk voltage.

## Example: The Coupled Stripline

To demonstrate the effectiveness of proper coupled-line termination, a simple vertically coupled stripline geometry is studied. The geometry is homogeneous and symmetric thus the even/odd mode field structure discussed previously will be supported. The physical geometry and electrical description of the example is illustrated in Figure 1. The reference plane separation, d, is 12 mils, the signal line separation, S, is 4 mils, and the line width, W, is 6 mils. Each conductor is assumed infinitely thin and perfectly conducting.

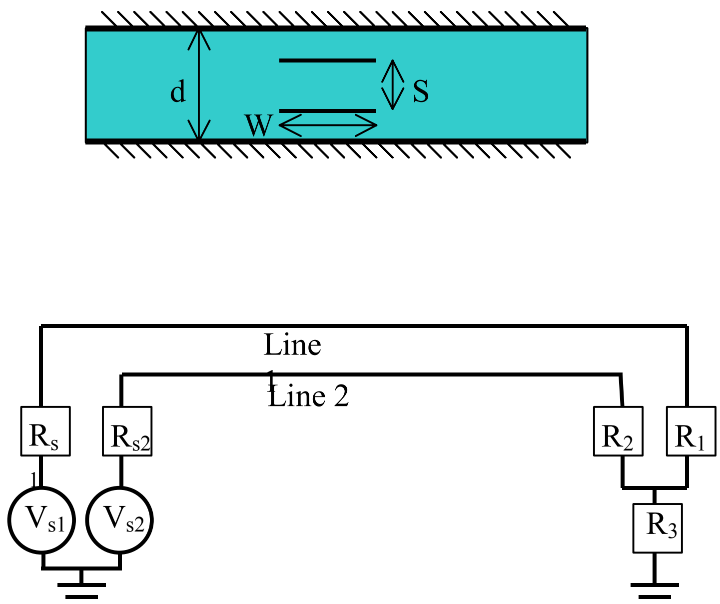


**Figure 1 Coupled slotline a) Physical geometry.**
**b) Electrical Circuit**

The approximate capacitance matrix is determined analytically using methods described in [iv] and is

$$C = \begin{bmatrix} 83.67 & -55.78 \\ -55.78 & 99.16 \end{bmatrix} pF . \qquad (1.17)$$

From (1.13) and (1.17), the modal characteristic impedance matrix found to be

$$Z_c^m = \begin{bmatrix} 49.16 & 0 \\ 0 & 245.76 \end{bmatrix} ohms , \qquad (1.18)$$

and the fully coupled characteristic impedance matrix is

$$Z_c = \begin{bmatrix} 147.45 & 98.3 \\ 98.3 & 147.45 \end{bmatrix} \; ohms\,. \tag{1.19}$$

Electrically, each of the two coupled lines is driven by an independent voltage source. Ideally, these two sources would be of equal magnitude but opposite phase. In such a case, the even mode is not excited. Here, both modes are excited by setting $V_{s1}$ to one volt and $V_{s2}$ to negative one and one half volts. The source waveforms are each step functions with a risetime of 174 picoseconds. The source impedance of each line is set to fifty ohms. The termination values are given by (1.16) and are

$$R_1 = R_2 = 49.16 \; ohms, \quad R_3 = 98.3 \; ohms\,. \tag{1.20}$$

The MTL equations given in (1.1), (1.2) are easily solved using the FDTD technique with exact termination and load conditions [v]. These coupled equations are solved using a time step governed by the Courant Friedrich Lewy (CFL) condition which requires $\Delta_t <= \frac{\Delta_z}{v}$ where $\Delta_z$ is the spatial discretization of the MTL line, $\Delta_t$ is the time step at which the solution is advanced, and $v$ is the maximum velocity of propagation along the line. For a transmission line within a homogeneous media, a 'magic' time step exists and is given by $\Delta_t = \frac{\Delta_z}{v}$. In this special case, $\Delta_z$ may be chosen arbitrarily and the resulting solution is *exact*. This is the case for the homogeneous stripline. Therefore an accurate and extremely efficient solution is available.

The results of the even mode termination scheme of (1.16) using the values given in (1.20) are shown in Figure 2. Also shown here is the more commonly used differential termination scheme where $R_1$ and $R_2$ are equal to $Z_{odd}$, and $R_3$ is set to zero ohms. The differential mode signal proved to be perfectly terminated regardless of the common mode termination. As is demonstrated here, significant ringing exists in both the voltage and current waveforms as a result of the improper termination of the common mode signal. Clearly, the oscillating current will increase the radiation of the topology.

## Conclusion

In this paper the proper termination of symmetric coupled transmission lines was demonstrated and validated. Though the example presented was a homogeneous stripline, the same theory is applicable to coupled microstrip lines and in a more limited sense to shielded twisted-pair transmission lines. Though functional currents may be terminated using a simple two resistor scheme, proper common mode termination requires a slightly more complicated topology where a third resistor to ground is used. It was shown that this termination provided a more robust termination from an EMC standpoint since common mode current resonances were eliminated.

Finally, it is important to note that the common mode current discussed in this work is not equivalent to the highly radiating antenna currents with which EMI engineers often do battle. In this work, the currents and voltages are purely TEM in nature thus their radiation will usually be small compared to true antenna mode currents.

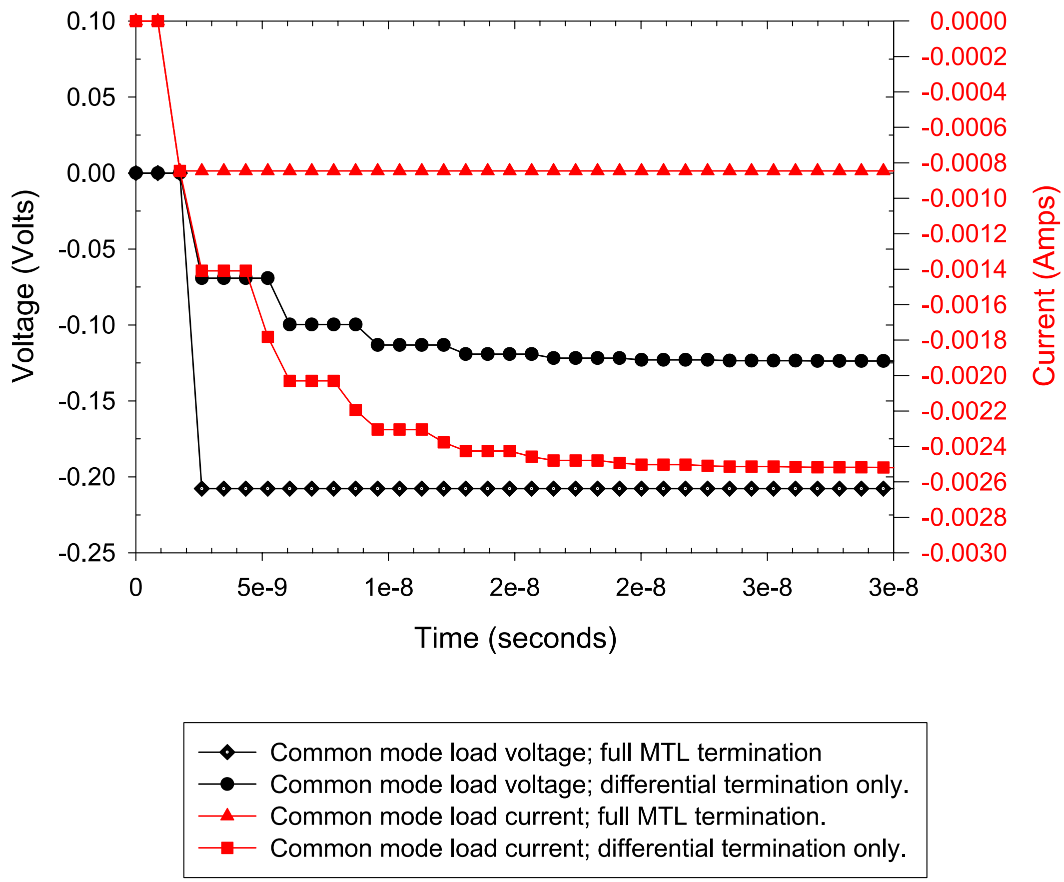


**Figure 2 Common mode load voltage $(V_1+V_2)/2$ and Load Current $(I_1+I_2)/2$ for the homogeneous coupled stripline geometry of Figure 1 (b).**

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## Last Word

The only reason for time is so that everything doesn't happen at once.
----Albert Einstein