IEEE
STANDARDS AND RECOMMENDED PRACTICES FOR CEM COMPUTER MODELING AND SIMULATION

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IEEE Project 1597 Working Group Meeting

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Standards Development Committee

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TOPICS

- Introduction/Background
- Project Overview
- Validation Issues
- Working Group Project Status
- Draft Outline of Standard and Recommended Practice
  - Coordinating Contributions and Writing Assignments
- Benchmarks
  - PC Boards/Subassemblies
  - Antenna Radiation
  - Large Body Scattering
- Summary

ABSTRACT

- The need for appropriate standards and guidelines for CEM computer modeling and simulation has been a topic of much discussion within the EM community in recent years.
- This encompasses a broad range of applications such as the analysis of PC board radiated and conducted emissions/immunity, assessing system-level EMC, and predicting the RCS of complex structures.
- Concerns exist regarding the lack of well-defined methodologies to achieve code-to-code or even simulation-to-measurement validations within a consistent level of accuracy.
- This has been prompted by the development and use of new CEM computer codes mainly over the past 20 years.
- This topic describes a project that is underway to guide the validation of CEM application models.
- The proposed standard is intended to address these concerns and provide a method for validating CEM codes and models.

WHICH IS ACCURATE?

- Although CEM codes have their basis in Maxwell’s equations of one form or another, their applicability and associated accuracies depend on:
  - the “applied” physics
  - numerical solver approach
  - mathematical basis functions
  - canonical modeling primitives (facets, wires, patches, canonical surfaces,…)
  - inherent modeling limitations and built-in approximations
  - desired “observables” (current or scattered fields)
  - other factors such as analysis frequency and time or mesh discretization further conspire to affect accuracy, solution convergence, and overall validity of computer models
- Concerns immediately arise when the results of predictions using one type of CEM code do not consistently agree with the results of other codes or against measurement benchmarks, begging the question, “*which is accurate?*”

NEW TERRITORIES

- The idea of a CEM standard is not a new one - the need for such was realized over 30 years ago and is influenced by several factors:
  - the growing complexity and sophistication of military and commercial systems designs.
  - the need to assure a balanced, cost-effective E^3 program in which computer analysis effectively complements measurements.
  - Requirements for developing consistent models and benchmarks to support life cycle EM code and measurement validations of real systems.
- Important technological advancements in computer hardware and use of structured code have accelerated the arrival of CEM technologies and applications, as we know them today.
- The fast track CEM M&S trend continues today and will grow as we further enter the age of <u>super high performance computing</u>.

QUESTIONS & PERSPECTIVES

- We need to eliminate (or at least significantly reduce) potential uncertainty in the modeling and simulation process.
- The EM community clearly needs a benchmark standard methodology that can assure consistency for M&S validations.
- What are the various methods that engineers use to solve CEM problems?
- What are some of the unique features of CEM methods and codes?
- The root of the problem - what seems appropriate to one expert may be inconsistent to another, yet both may (claim to) be "correct" based on their preferred tools and applied techniques.
- Although analysts may argue in favor of a given modeling approach, simulation technique or use of a particular CEM code, a consistent methodology for comparing results among codes or against empirically-based methods in a truly valid, objective way is oftentimes lacking.
- Obviously, the types of physics and solution method used for a given problem and the desired observables are central to the issue.
- Goal: determine how generalized computer models are represented or generated, and how they can be effectively converted into CEM models.
- Represent models using a common language or via a universal set of descriptors, and then specify methods to assure model and code validation based on these data?

PROJECT 1597.1

IEEE STANDARD FOR VALIDATION OF CEM COMPUTER MODELING AND SIMULATION

- Scope
  - A 4-year project to develop a standard for the validation of CEM computer M&S codes in differing applications. The standard will provide a basis for analytical and empirical validation of CEM codes and configurations. Several key areas will be addressed, including:
    - Validation by use of simple, canonical models – This refers to the specification of a common set of canonical modeling elements or building blocks as a function of ensemble parameters (frequency, desired accuracy or fidelity, physics and numerical solution method, etc.).
    - Validation by simulation versus measurement - Model- versus measurement-driven uncertainty estimation.
- Purpose
  - Guide the validation of CEM application models. The standard is intended to address concerns over the lack of well-defined methodologies to achieve code-to-code or simulation-to-measurement validations within a consistent level of accuracy, and provide a method for validating CEM codes and models.

PROJECT 1597.2
IEEE RECOMMENDED PRACTICE FOR CEM COMPUTER M&S APPLICATIONS

- Scope
  - A 4-year companion project to develop a recommended practice for use in CEM computer M&S applications to guide the EMC design of PC boards to large, complex systems. Areas to be addressed include:
    - General guidelines for creating CEM models.
    - Development of modeling methodologies for small-to-large scale “canonical” systems, platforms or composite models.
    - Methodologies for developing and applying collaborative, multi-disciplinary engineering modeling schemes.
    - Computation of uncertainty for modeling applications.

- This recommended practice will aid modelers and analysts in the selection and application of appropriate M&S methodologies, physics, and solution techniques to achieve accurate results and to complement measurements and design tasks for a wide range of problems.

RELEVANT RESEARCH

- This work will build upon prior analytical studies and research conducted by academic, government, commercial and professional institutions and consortia:
  - Applied Computational Electromagnetics Society (ACES)
  - IEEE EMC Society’s TC-9 Committee on CEM
  - IEEE’s AP, MTT and Magnetics Societies
  - EMCC and the DoD’s CHSSI/HPC Modernization Program
  - Other international groups concerned with advancing/applying CEM.
- These include studies on the modeling and simulation of multi-disciplinary engineering problems pertaining to:
  - fluid dynamics
  - laminar flow
  - structural and thermal engineering applications.
- Another key area of study is the development and use of analytical and measurement benchmarks.

VALIDATION ISSUES

- Reconciling differences among CEM codes as a function of their underlying physics, mathematical basis functions, numerical solution methods, associated precision, and the building blocks (primitives).
- Gauging convergence and “accuracy” against known/measured data.
- Results of predictions using one type of CEM code do not favorably or consistently agree with the results of other codes of comparable type or against measurement benchmarks
  - observing clear differences among analytically-based results over certain frequency regions and for certain simulation states
  - deviations between analytical and empirical methods.
- While differences are not unexpected, the lack of mutual or relative convergence in some cases cannot be readily explained nor easily discounted.
- Again, a consistent methodology for comparing results among codes or against empirically-based methods in a valid, objective way is often lacking.
- It is often difficult if not impractical to compare the results of certain codes even though they are based on Maxwell’s equations.

WORKING GROUP STRATEGY

- Develop an outline of relevant focus areas to be covered by the standard and recommended practice
  - Modeling considerations
    - Primitive modeling elements
    - Simple canonical objects
    - Complex structures (electrically small-to-large)
  - Breadth and depth of physics and numerical solution methods
  - Matching method/tool to the problem conditions and problem type
  - Lessons learned from other computational engineering specs and standards
  - Error controllability
  - Use of trends and bounds, as necessary
  - Standardized input and output file formats
- Identify benchmarks for baseline validation purposes
- Produce drafts for review and balloting

A WEALTH OF CEM METHODS

- Boundary Element (Integral) Method (BEM)
- Finite Element Modeling/Analysis (FEM/A)
- Method of Moments (MoM)

- Shooting Bouncing Rays (SBR)
- Physical Optics (PO)
- Physical Theory of Diffraction (PTD)
- Geometrical Optics (GO)
- Geometrical/Uniform Theory of Diffraction (GTD/UTD)

- Transmission Line Method (TLM)
- Hybrid Lumped Circuit & Quasi-Transmission Line Method

- Finite Difference Time Domain (FDTD)
- Finite Volume Time Domain (FVTD)
- Finite Difference Frequency Domain (FDFD)
- Conjugate Gradient Method (CGM)
- Generalized Multi-pole Technique (GMT - Moment Method)
- Multiple Multi-Pole (MMP)
- Fast Multi-Pole Method (FMM)

- Partial Element Equivalent Circuit Model (PEEC)
- Perfectly Matched Layers using a Partial Differential Equation Solver Method (PML/PDE)

- Adaptive Integral Method (AIM)
- Bi-Conjugate Gradient Method w/Fast Fourier Transform (BCG-FFT)
- Thin-Wire Time Domain Method (TWTD)
- Time Domain Moment Method (TDMM)
- Vector Parabolic Equation Technique (VPE)
- Pseudo-Spectral Time Domain Method (PSTD)
- Multi-Resolution Techniques (MRT)
- Finite Integration Technique (FIT)
- Recursive Green’s Function Method (RGFM)

- Analytical Discrete Method(s)

- Hybrid Techniques (MoM/UTD,...)

“VIEWS” OF CEM MODELING

Structure Geometry

Finite-Element Mode

Figure 1: Finite-Element Modeling Example

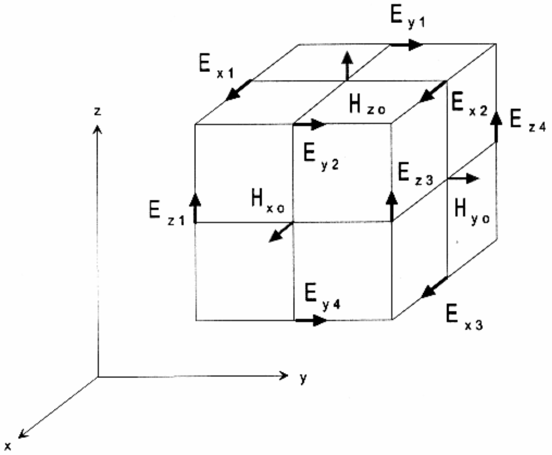


Figure 2: Basic Element of the FDTD Space Lattice

$$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

$$\nabla \times \boldsymbol{H} = \sigma \boldsymbol{E} + \varepsilon \frac{\partial \boldsymbol{E}}{\partial t}$$

$$\mathrm{F} = \int_v \frac{\mu|\mathbf{H}|^2}{2} + \frac{\varepsilon|\mathbf{E}|^2}{2} - \frac{\mathbf{J}\cdot\mathbf{E}}{2j\omega}\, dv$$

$$\begin{bmatrix} \mathrm{J}_1 \\ \mathrm{J}_2 \\ \cdot \\ \cdot \\ \mathrm{J}_n \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdot & \cdot \\ y_{21} & y_{22} & \cdot & \cdot \\ \cdot & \cdot & & \\ \cdot & \cdot & & \\ \cdot & \cdot & & y_{nn} \end{bmatrix} \begin{bmatrix} \mathrm{E}_1 \\ \mathrm{E}_2 \\ \cdot \\ \cdot \\ \mathrm{E}_n \end{bmatrix}$$

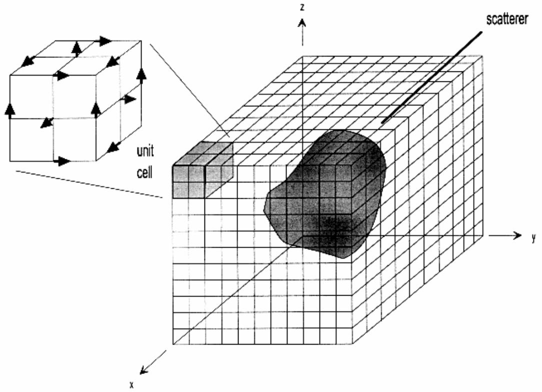
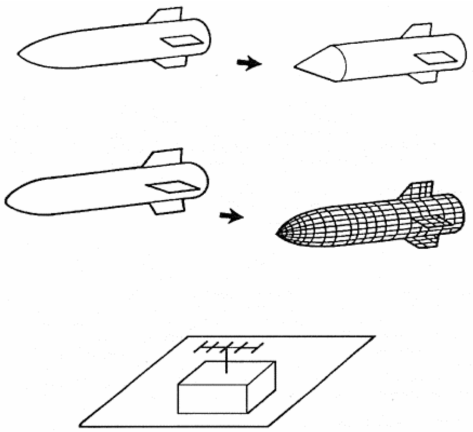


Figure 3: Scatterer in an FDTD Space Lattice

$$\nabla \times \boldsymbol{E} = -j\omega\mu \boldsymbol{H}$$

$$\nabla \times \boldsymbol{H} = (\sigma + j\omega\varepsilon)\boldsymbol{E}$$



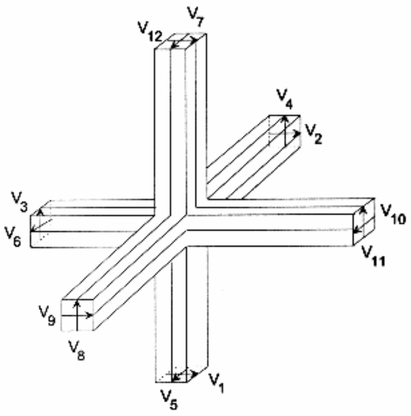


Figure 4: The Symmetrical Condensed Node

CEM MODELING ISSUES (1)

- Potential sources of modeling error and associated factors
  - Limitations in the physics
    - Edge and surface traveling waves
    - Knife edge vs. wedge, tip and point diffraction
    - Phase error (loss) over large distances or dimensions at high frequencies
    - High-frequency asymptotic ray tracing approximations (*ansatz* error)
    - Limited current expansion functions
    - Inability to handle material discontinuities at interfaces (multilayer, anisotropic or inhomogeneous materials, FSS)
    - Shadow boundaries, creeping wave and dispersion loss effects
    - Singularity or caustic conditions where levels rapidly collapse or dramatically increase (ill conditioned, non-convergent, unstable)
    - Radiator feed modeling, FSS and mutual coupling (multi-region)
  - Solution error
    - Banded matrices, iterative convergence, full vs. partial wave solutions

CEM MODELING ISSUES (2)

- Geometry model limitations
  - Existence of multilayer regions and material interfaces
  - Ill-defined (open, closed) boundaries, region or material discontinuities
  - Gross modeling primitives described with improper resolution, elemental length or cell area (discretization scheme and geometry basis)
  - Staircasing at edges and curved surfaces
  - Inability to model the effects of doubly-curved surfaces accurately
  - Flaws in CAD model or CEM geometry model construction procedures (incomplete definitions, voids, overlaps, intersection, union, subtraction)
  - Neglecting physically small surface features at high frequencies

- Modeling procedures
  - Ill-conditioned near field problem leading to caustics, singularities, resonances, etc. due to insufficient sampling
  - Use of canonical modeling objects (high-frequency ray tracing approximation) instead of actual shapes and contours

- Computation of observables
  - Singularities, caustics, resonances, discontinuity of currents, field point mismatch at/between region interfaces for multiple regions or layers

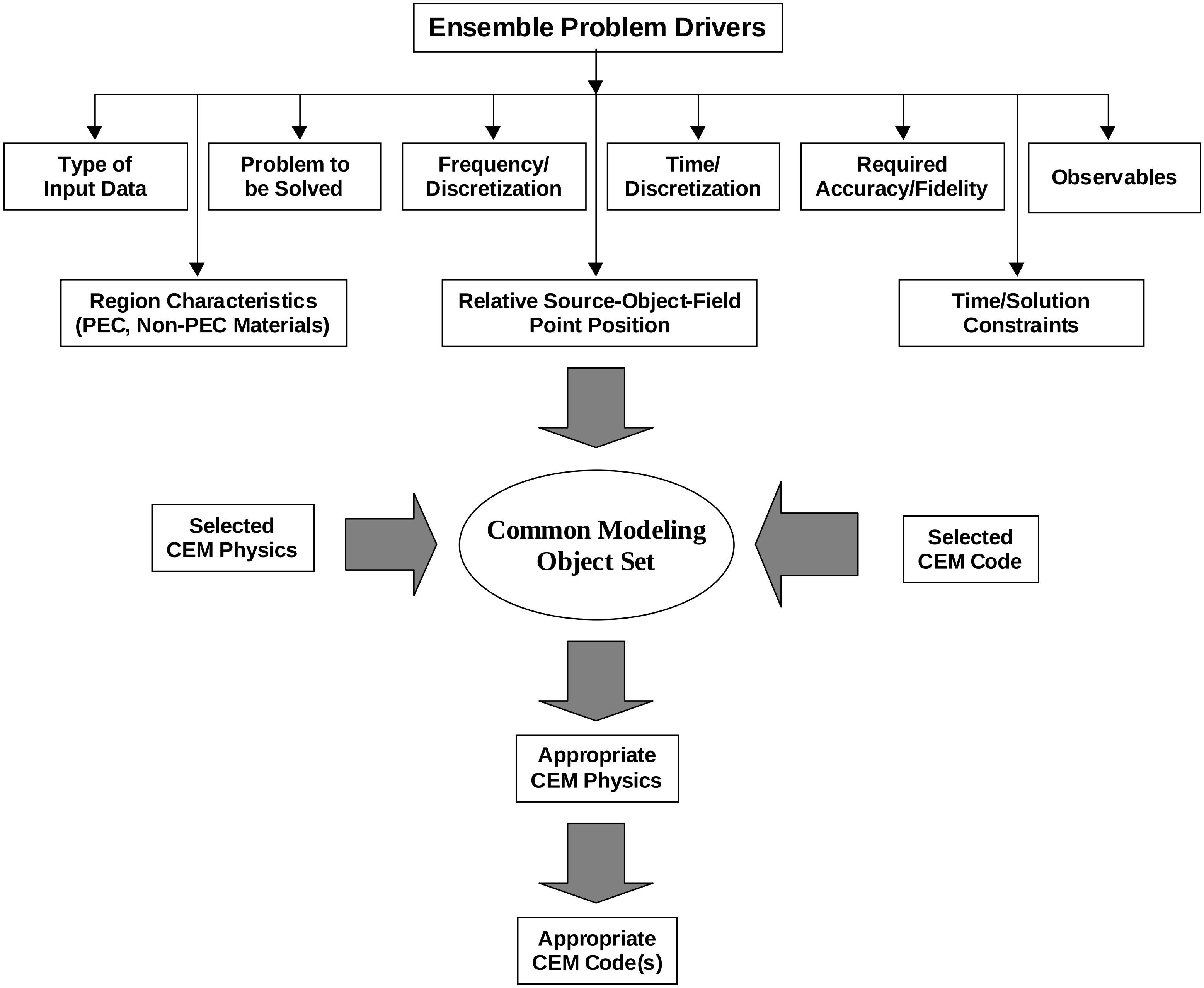
CEM MODELING ISSUES (3)

- Some possible solutions to improve accuracy and control error
  - Use of high-fidelity geometry models
  - Use of higher-order surface modeling elements and robust current expansion functions (e.g., RWG type)
  - Application of hybrid techniques to accurately model multiple regions (enforcing continuity of current and field point matching)
  - Careful exploitation of symmetry and BOR techniques
  - Accounting for or eliminating artifact “noise”
  - Use of “adaptive” optimization algorithms that maintain accuracy
    - Efficient partitioning and decomposition of submatrices
    - Streamline solutions (order reduction, increase speed, eliminate bottlenecks)
    - Sift out and suppress “off diagonal” error sources (noise)
    - Ensemble parameter reasoning (building valid CEM models)
    - Smoothing functions to control staircasing error
  - Extended precision computing and controlling error propagation
  - Use of matrix-free fast solvers and HPCs to handle large, high-resolution problems at low and high frequencies accurately

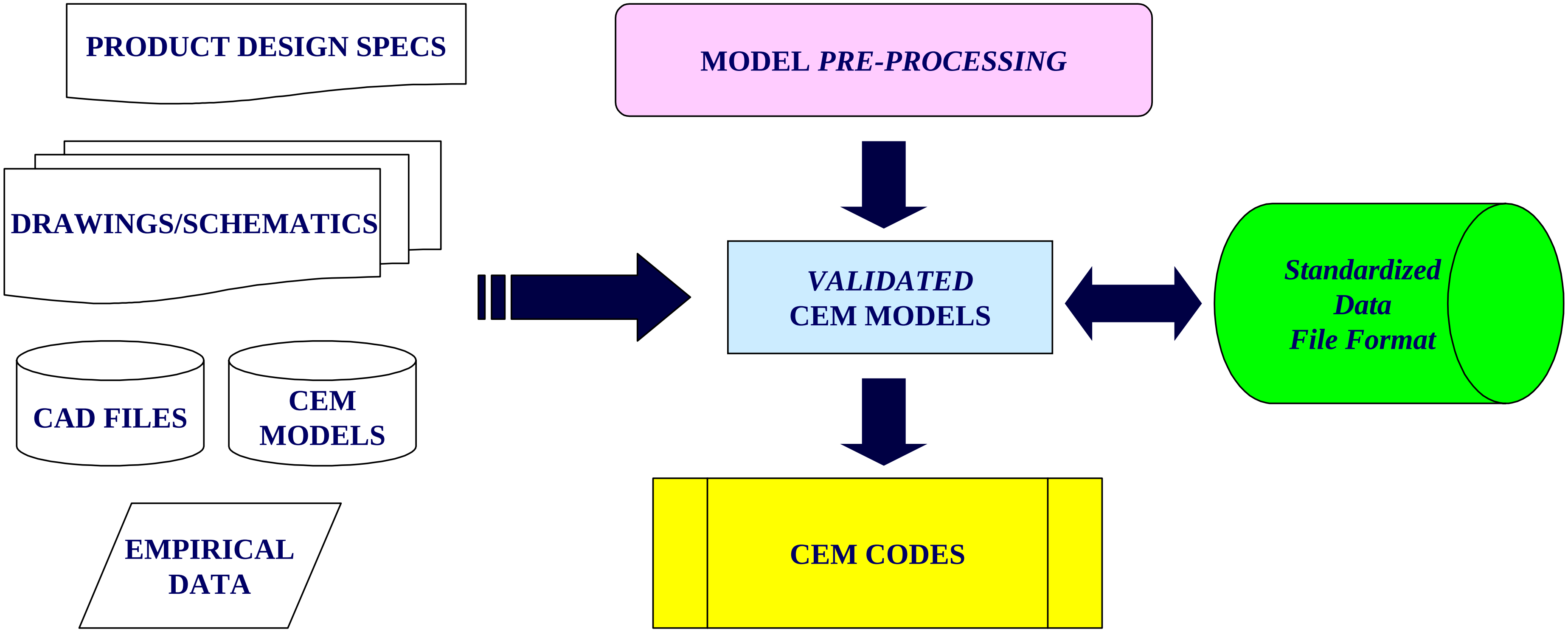
STANDARDIZED DATA FORMATS

- Support data sharing and reuse for various codes
- Definitions of modeling primitives used to describe the EM problem
- Generalized notation system (formats) for model data
  - Standard Interface Data Structures (SIDS) (CFD)
  - CFD General Notation System" (CGNS)*
- Standardized output data formats for computed "observables"

***CGNS, The CFD General Notation System Overview and Entry-Level Document*, CGNS Project Group, 15 May 1998.


Ensemble Problem Drivers
Type of Input Data
Problem to be Solved
Frequency/ Discretization
Time/ Discretization
Required Accuracy/Fidelity
Observables
Region Characteristics (PEC, Non-PEC Materials)
Relative Source-Object-Field Point Position
Time/Solution Constraints
Selected CEM Physics
Common Modeling Object Set
Selected CEM Code
Appropriate CEM Physics
Appropriate CEM Code(s)

CODE VALIDATION



PRODUCT DESIGN SPECS

DRAWINGS/SCHEMATICS

CAD FILES

CEM MODELS

EMPIRICAL DATA

MODEL *PRE-PROCESSING*

***VALIDATED* CEM MODELS**

Standardized Data File Format

CEM CODES

-Facilitates Analytic Code Validation
Benchmarking Efforts
Standard Definitions

BENCHMARKS

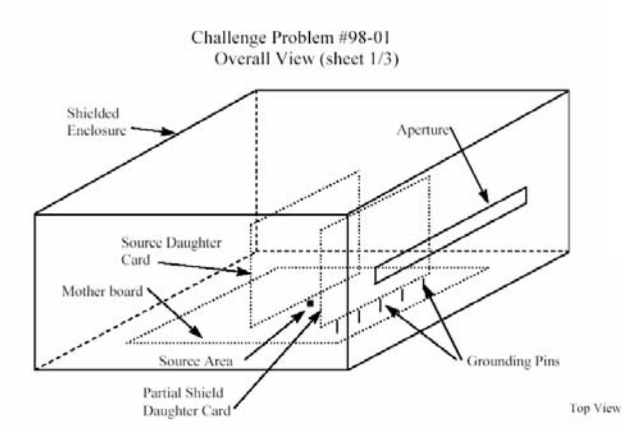
http://aces.ee.olemiss.edu/

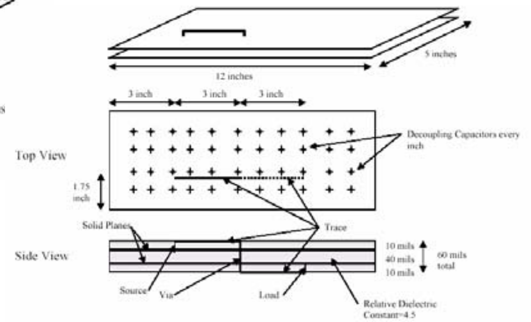
- The purpose of this web site is to provide data for EMC modeling validation. Measurement data and modeling data will be provided with enough detail so the user can repeat the work, and compare new results to the previous results.
- This site is a joint effort between the Applied Computational Society (ACES) and the IEEE EMC Society TC-9 subcommittee. All papers and data on this site have been reviewed by a special committee for completeness, technical content, and value to the EMC modeling community.
- All papers and data may be downloaded and used as desired, as long as proper credit to the source is recognized in any publication of new results using this data.
- In addition to the test/model data results, a section is provided for 'Standard' EMC modeling problems. These problems have been documented with sufficient detail so that a user can easily create these models, and potentially analyze commercial or new software codes for their ability to perform meaningful EMC simulations.
- Questions concerning this site should be addressed to the Joint EMC Model Validation Committee chairman, Bruce Archambeault at barch@us.ibm.com

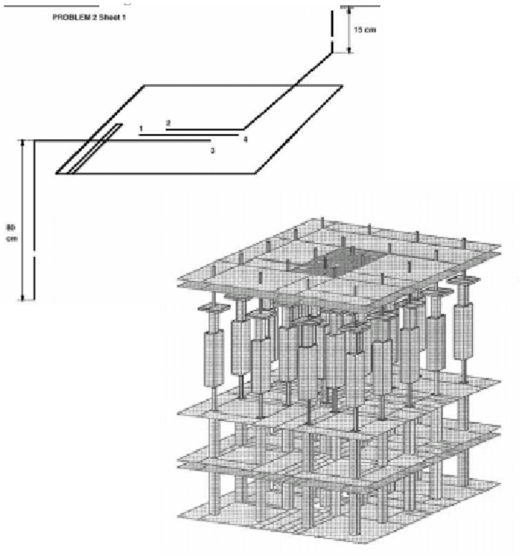
ACES STANDARD MODELING PROBLEMS

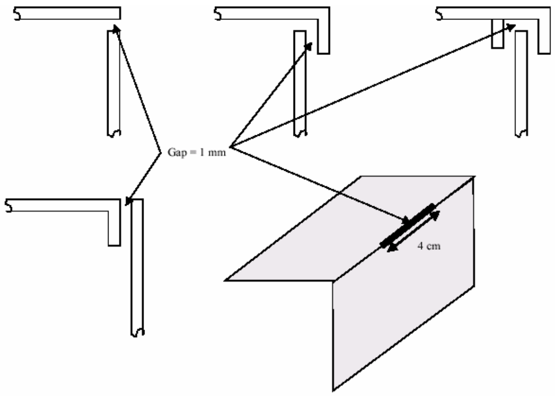
- Review of 1998 TC-9 Challenging Problems Results and 1999 TC-9 Challenging Problems Introduction *(by Dr.Bruce Archambeault, Albert Ruehli)*
  - Shielded Mother/Daughter Board Application
  - Calculation of Currents (Voltages) and Radiated Fields for PC Board with Attached Wires
  - Edge Emissions from a PC Board Structure
  - Seam Shape Shielding Effectiveness
  - Emissions from a PC Board and Attached Shielded Enclosure
  - Crosstalk within a Complex Connector
  - Differential Pair over Split Plane
  - Delay Line Performance
- **Standard Problems**
  - Decoupling Power/Ground-Reference Plane
  - Trace-Over-Split-in-Ground-Plane
  - Enclosure Problem Definition
  - Heat Sink Grounding Problem Definition

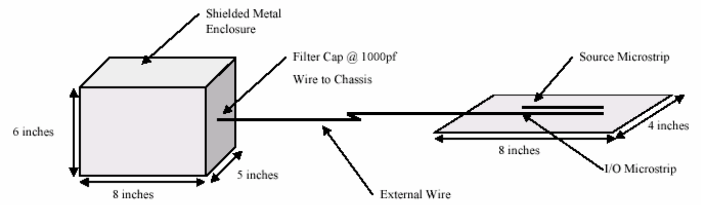
BENCHMARK ILLUSTRATIONS

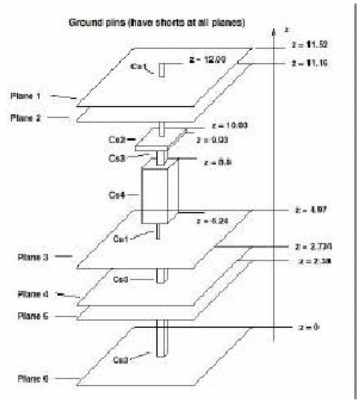












Ref.: B. Archambeault and J. Druniak, "EMI Model Validation and Standard Challenge Problems" on ACES Web Site.

MODEL VALIDATION PAPERS (ACES/TC-9) (1)

- **Shielding**
  - "EMI from Shielding Enclosures—FDTD Modeling and Measurements", Min Li
  - "EMI from Airflow Aperture Arrays in Shielding Enclosures", Min Li

- **PC Board Design**
  - Plane Decoupling "Technical Report --- Printed Circuit Board Decoupling Capacitor Performance For Optimum EMC Design", Bruce Archambeault, Doug White
    "Power Bus Modeling Using a Circuit Extraction Approach Based on a Mixed-Potential Integral Equation", Jun Fan, *et.al*
    Multiple Board Configurations "EMI Associated with Inter-board Connections for Module-on-backplane and stacked-card Configuration", Xiaoning Ye
  - General Coupling and Crosstalk "EMI Modeling of Coupling From High-Speed Digital to I/O Lines", Wei Cui, *et.al*
  - "Coupling between a Microstrip Trace Pair", Ted Zeeff, *et.al*
  - Microstrip / Stripline "Numerical Modeling of Segmented Signal Return Planes", Yun Ji
  - "EMI Modeling of Coupling From High-Speed Digital to I/O Lines", Wei Cui, *et.al*
  - "Coupling between a Microstrip Trace Pair", Ted Zeeff, *et. al*

MODEL VALIDATION PAPERS (ACES/TC-9) (2)

- **Standard Modeling Problems**
  - "A Proposed Set of Specific Standard EMC Problems To Help Engineers Evaluate EMC Modeling Tools ", Bruce Archambeault, Juan Chen, Satich Pratepeni, Lauren Zhang, David Wittwer
  - "Comparison of Various Numerical Modeling Tools Against a Standard Problem Concerning Heat Sink Emissions - Standard Modeling Paper 3", Bruce Archambeault, Juan Chen, Satich Pratepeni, Lauren Zhang, David Wittwer

OTHER BENCHMARK-RELATED INFORMATION

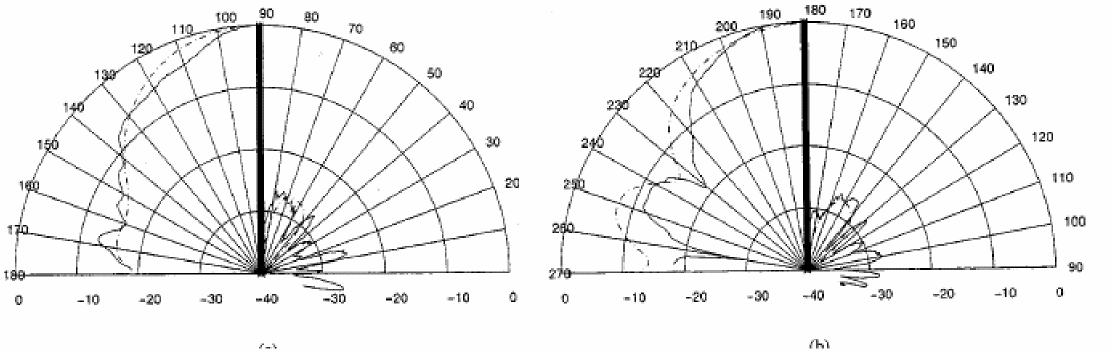
- German IEEE Benchmark problems (Singer, Buecker, Brüns, et. al., Tech. University Hamburg-Harburg, University of Stuttgart, Germany)
  - Homogeneous lossy dielectric sphere illuminated by a plane wave, near–field computation inside the sphere
  - Homogeneous lossy dielectric sphere illuminated by a plane wave, near–field computation inside the sphere.
  - Microstrip line above a finite ground
  - Dipole in the presence of a hollow sphere
  - Thin panel with wire connection above a ground plane
  - Cable coupling
  - Transients in a multi-conductor configuration
  - Shielding effectiveness
- EMC measurement technology (H. Garbe, University of Hannover, Germany)
- Analysis of techniques to compare complex data sets (A. Duffy, De Montfort University, Leicester, UK)

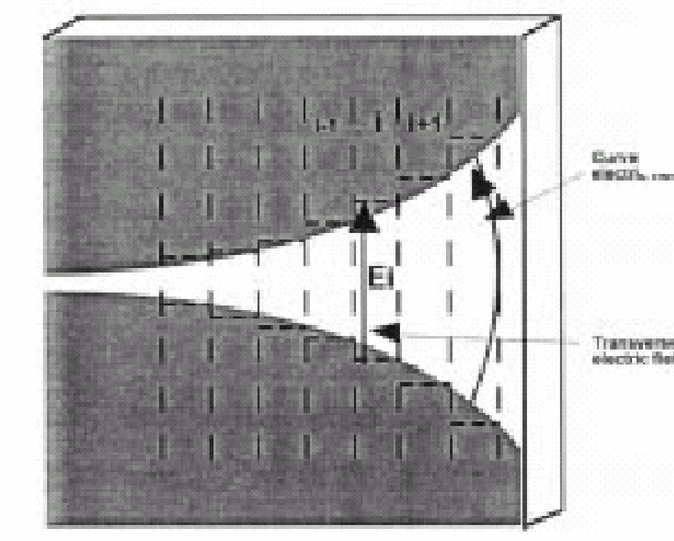
ANTENNA BENCHMARKS

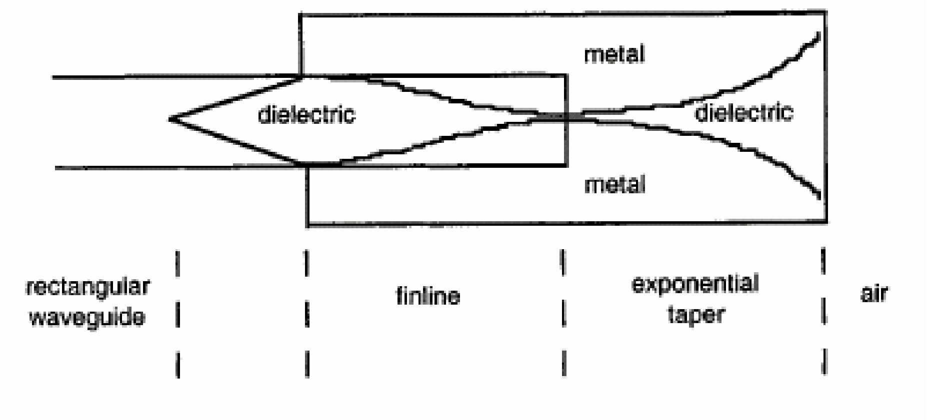
- Tapered slot antenna [2, 3, 7]
- Rectangular patch antenna [8]
- Multilayer printed antenna [1]
- Microstrip array [5]
- Printed annular ring antenna [4]
- Fractal antenna [6]
- Slant cut or Vlasov antenna placed on the end of a TM_{01} wave launcher

CO- AND CROSS-POLAR RADIATION OF VIVALDI ANTENNA ON DIELECTRIC SUBSTRATE [7]

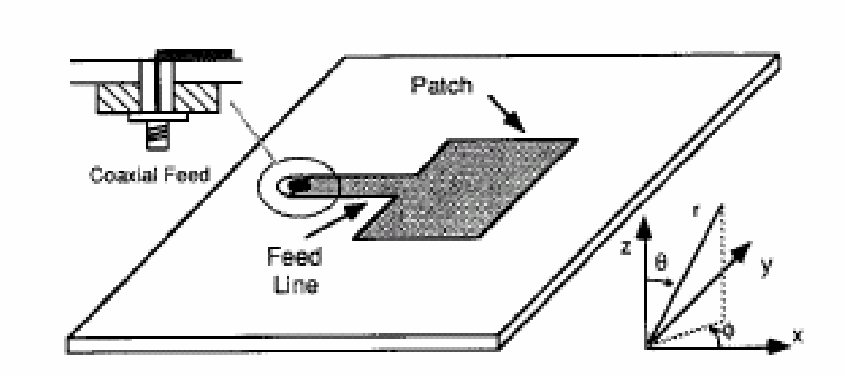
Measured (–) and calculated (--) radiation patterns: (a) E-plane and (b) H-plane



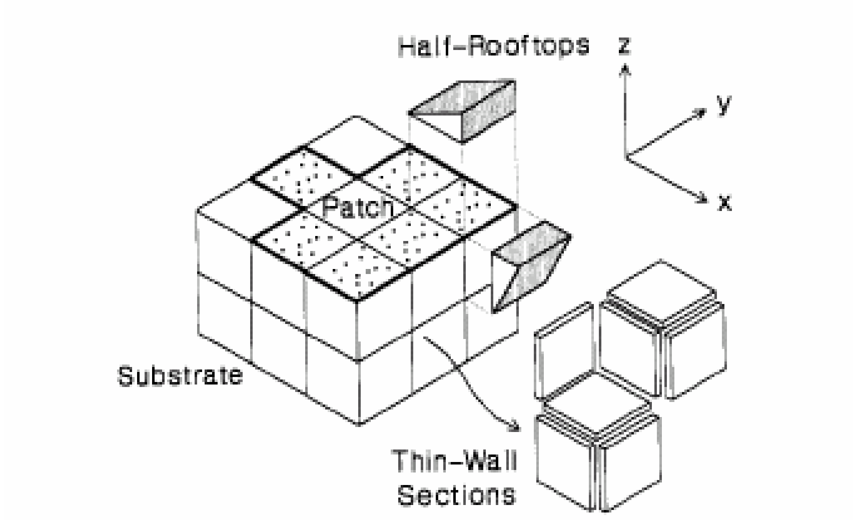




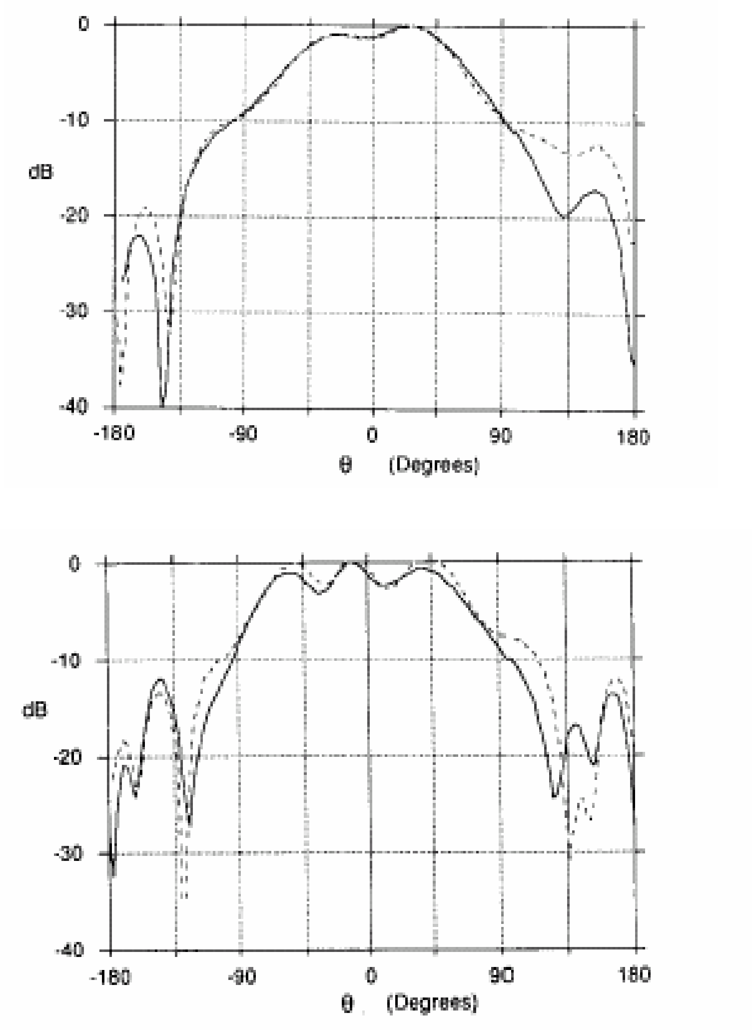
MICROSTRIP PATCH ANTENNA [8]



Microstrip Patch Geometry



Use of Thin Wall Sections and
Rooftop Basis Functions to Model
Current Density in a Structure Including the Conductive Patch



E_θ Far Field Patterns
Measured vs. Calculated

BENCHMARK RADAR TARGET DATABASE*

- Several benchmark targets have been designed, fabricated, measured, and calculated over the last 15 years
    - Four target classes included: flat plates, low cross-section targets, simple cavities, dielectric slab
    - Selected aircraft
    - Measurements/calculations performed in late 1980’s & early 1990’s

- Objective of this effort is to compile this data into a format that is easily understood and distributable

- Data has been compiled for four sets of targets
    - Azimuth and frequency “cuts” of measured/calculated data available
    - Several formats, all are easily understood ASCII files

*NASA, Navy, and Air Force.

BENCHMARK RCS DATABASE

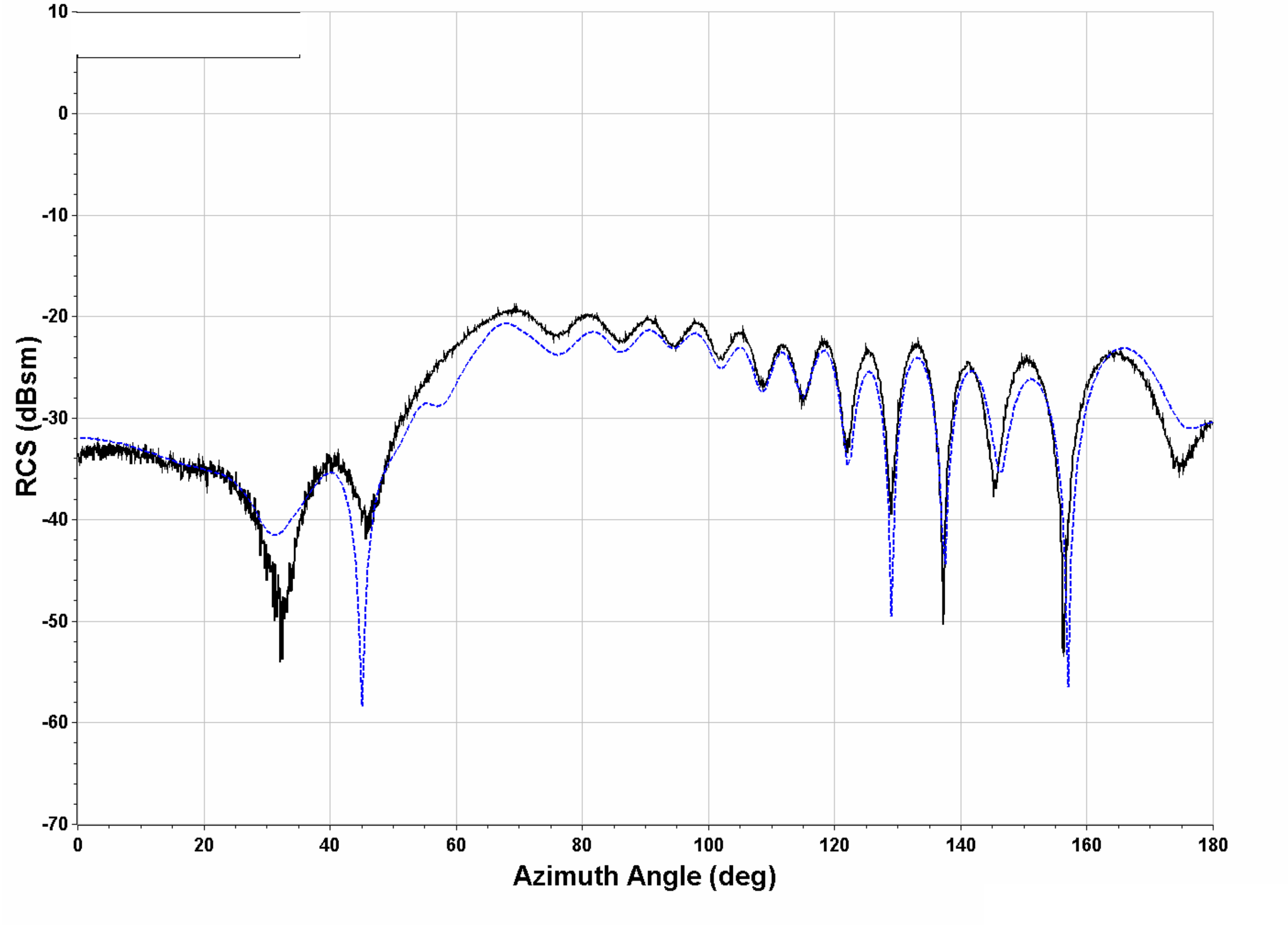
- Plate targets
  - Wedge cylinder
  - Wedge-plate cylinder
  - Plate cylinder
  - Business card
  - Wedge cylinder gap

- “Exotic” targets
  - Almond
  - Ogive
  - Double Ogive
  - Cone-sphere
  - Cone-sphere gap

- Cavities
  - Square aperture
  - Cylindrical cavity

- Ice cream sandwich
  - Dielectric slab only
  - Dielectric slab with one PEC face
  - Dielectric slab with two PEC faces

STANDARD OUTPUT FORMATS



REFERENCES

[1] Das, N K and D M Pozar. “Multiport Scattering Analysis of General Multilayered Printed Antennas Fed by Multiple Feed Ports: Part II – Applications,” *IEEE Transactions on Antennas and Propagation*, *40* (5):482–491 (May 1992).

[2] Janaswamy, Ramakrishna. “An Accurate Moment Method Model for the Tapered Slot Antenna,” *IEEE Transactions on Antennas and Propagation*, *37* (12):1523 (December 1989).

[3] Janaswamy, Ramakrishna and Daniel H. Schaubert. “Analysis of the Tapered Slot Antenna,” *IEEE Transactions on Antennas and Propagation*, *AP-35*(9):1058 (September 1987).

[4] Kokoto®, D M, et al. “Rigorous Analysis of Probe-Fed Printed Annular Ring Antennas,” *IEEE Transactions on Antennas and Propagation*, *47* (2):384–388 (February 1999).

[5] Pozar, D M and S D Targonski. “A Shared-Aperture Dual-Band Dual-Polarized Microstrip Array,” *IEEE Transactions on Antennas and Propagation*, *49* (2):150–157 (February 2001).

[6] Romeu, Jordi and Jordi Soler. “Generalized Sierpinski Fractal Multiband Antenna,” *IEEE Transactions on Antennas and Propagation*, *49* (8):1237 (August 2001).

[7] Stockbroeckx, B and A Vander Vorst. “Copolar and Cross-Polar Radiation of Vivaldi Antenna on Dielectric Substrate,” *IEEE Transactions on Antennas and Propagation*, *48* (9):19–25 (January 2000).

[8] York, Robert A., et al. “Experimental Verification of the 2-D Rooftop Approach for Modeling Microstrip Patch Antennas,” *IEEE Transactions on Antennas and Propagation*, *39* (5):690 (May 1991).

ADDITIONAL REFERENCES

- B. Archambeault and J. Drewniak, “*EMI Model Validation and Standard Challenge Problems*”, *http://aces.ee.olemiss.edu/.*

- Electromagnetic Code Consortium Web Site *http://www.asc.hpc.mil/PET/CEA/emcc/benchmark/benchmark.html.*

- *IEEE Antennas and Propagation Magazine, Vol. 34, No. 6, December 1992*

CONCLUSION

- A CEM standard will provide a consistent methodology for developing valid models, performing M&S validations as well as validating codes.
- Provide a guide for the validation of CEM application models i.e., when and how to apply certain code-specific modeling techniques in view of the physics and nuances of the CEM codes to control (manipulate) error and optimize accuracy and fidelity.
- Provide a basis for representing models possibly by using a common language or via a universal set of descriptors, and then specifying methods to assure model and code validation utilizing these data.
- Assure flexibility to cover a broad range of applications.
- Fill any voids in current methods and practices to achieve code-to-code or simulation-to-measurement validations within a consistent level of accuracy, and provide a method for validating CEM codes and models.

http://grouper.ieee.org/groups/emc/emc/ieee_emcs_-_sdcom/ieee_emcs_-_sdcom_mainpage.htm

- Web site for P1597 projects
- Pointer to various benchmarks to support this standards work
- Source to download WG meeting minutes, agendas, WG rosters, and to post information