Computational Electromagnetics in Cartagena

selected sessions from
ICEAA 18 – IEEE-APWC 18 – FEM 18
Cartagena de Indas, Colombia, 10-14
September 2018

Amir Boag
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Introduction

This booklet contains selected abstracts of the contributions presented at the joint ICEAA 18 – IEEE-APWC 18 – FEM 18 Conference held on 10-14 September 2018 in Cartagena de Indias, Colombia.

In particular, in this 2018 edition of the usual ICEAA/IEEE-APWC joint conference, there is also the presence of the International Workshop on Finite Elements for Microwave Engineering (FEM).

The ICEAA/IEEE-AWPC joint conference is held outside Italy on even years, last edition was in Cairns, Australia, on September 19-23, 2016, chaired by R.D. Graglia (Politecnico di Torino, Italy), P.L.E. Uslenghi (University of Illinois at Chicago, Illinois, USA) and Paul D. Smith (Macquaire University, Sidney, Australia).

The International Workshop on Finite Elements for Microwave Engineering is a highly-focused biannual event. It provides an ideal meeting place for researchers and practitioners active in the theory and application of the Finite-Element Method in RF and microwave engineering. Its story dates back to 1992, when the first edition took place in Tuscany, jointly organized by the University of Florence, Italy and McGill University, Montreal, Canada.

The 13th edition was held in Florence, Italy, on 16-18 May 2016, chaired by R.D. Graglia (Politecnico di Torino, Italy) and G. Pelosi (University of Florence, Italy). In that edition, a decision was made to organize the 2018 edition in conjunction with the ICEAA offshore conference. This was mainly aimed at avoiding the dispersion caused by the high number of conferences held on the applied electromagnetics field topics in different places around the world and at attaining a larger audience by offering three topical conferences, ICEAA, IEEE-APWC and FEM, in the same place with just one subscription.

In this framework, this volume presents the abstracts submitted to the joint conferences in the specific topic of Computational Electromagnetics, broadening the scope from just Finite Elements to other Numerical techniques.

The booklet contains the abstracts of the three Numerical sessions at the Conference, followed by some recollections of the previous edition of FEM Workshop: a reprint of the report on the 13th edition of the Workshop appeared in 2016 in the *IEEE Antannas and Propagation Magazine* and some unpublished photos from that edition.

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Branislav Notaroš, ECE, Colorado State University, USA
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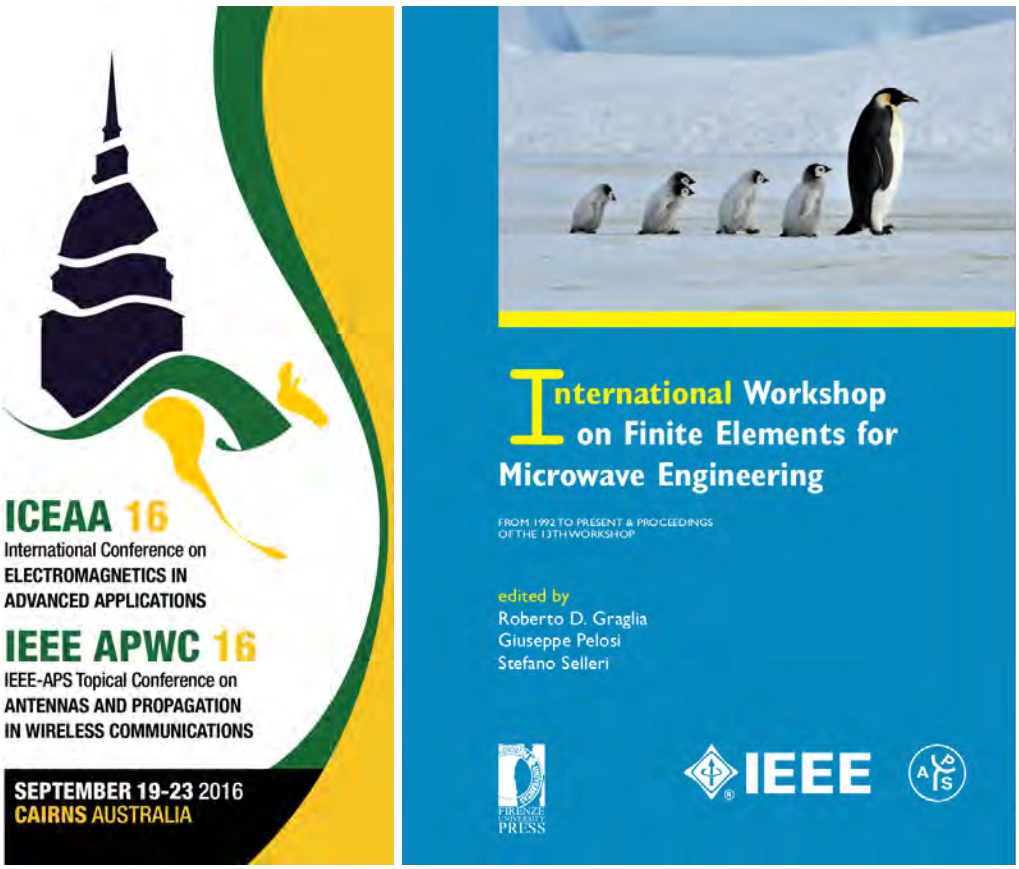
Cartagena de Indias, Colombia, September 2018.



ICEAA 2016 logo (left) and cover of the International Workshop on Finite Elements for Microwave Engineering book printed for the 13th edition and covering the history of the Workshop (right), Book was edited by Roberto D. Graglia (Politecnico di Torino, Italy), Giuseppe Pelosi (University of Florence, Italy) and Stefano Selleri (University of Florence, Italy) and is freely available at

`http://www.fupress.com/redir.ashx?RetUrl=3127_8833.pdf`.

Session:

FEM Workshop

Organized by

Branislav Notaroš and Stefano Selleri

An Efficient 2.5D Finite Element - Transformation Optics Approach to Morphed-BoR Objects

Gian Guido Gentili[(1)], *Misagh Khosrnonejad*[(1)], *Renzo Nesti*[(2)], *Giuseppe Pelosi*[(3)], *Stefano Selleri*[(4)]

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When an object exhibit some sort of symmetry, its exploitation in writing an ad-hoc formulation usually leads to greater efficiency with respect to a brute-force fully 3D approach. In particular, when an object exhibits a body-of-revolution (BoR) symmetry, its electromagnetic scattering properties can be analyzed by expanding the angular variation of the fields in harmonics and reduce the numerical FEM solution to the 2D half plane generating the structure, yielding a 2.5D formulations which is of course much more CPU and memory efficient than any full 3D solution. The same is also true for microwave waveguide devices exhibiting a BoR symmetry.

If the object, or the device, does not exhibit a BoR symmetry, but a coordinate transformation can be devised that morphs such an object into a true BoR then the object can be named Morphed-BoR (MBoR) and treated more efficiently. The key point is that the whole space around the object is subject to the same, continuous and differentiable, transformation. The way in which such a transformation reflects onto Maxwell's equations is known as Transformation Optics (TO - N. B. Kundtz *et. al.* Proceedings of the IEEE, vol. 99, no. 10, pp. 1622-1633, Oct. 2011). In TO the medium characteristic parameters transforms too with geometry according to relations containing the Jacobian matrix of the transformation. In general, the Jacobian leads to materials in the transformed system, which are anisotropic even if the original problem is in free space.

In this contribution a 2.5D BoR FEM code will be presented, allowing the analysis of MBoR structures immersed in a, possibly inhomogeneous, anisotropic material exhibiting tensor permeabilities and permittivities. This will be in particular applied to microwave two-port devices exhibiting nearly circular structures, and the approach validated via comparison with conventional fully 3D FEM simulations.

Applications of Adjoint Solutions for Predicting and Analyzing Numerical Error of Forward Solutions Based on Higher Order Finite Element Modeling

Branislav M. Notaroš[(1)], *Cam Key*[(1)], *Aaron Smull*[(1)], *Donald Estep*[(1)], *Troy Butler*[(2)]

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The finite element method (FEM) for discretizing partial differential equations in electromagnetics is an extremely powerful and versatile general numerical methodology for electromagnetic (EM) field modeling and computation in microwave engineering. This paper addresses numerical error estimation, model sensitivity prediction, and adaptive mesh refinement in the context of FEM solutions to EM scattering problems. The paper explains the concept of the adjoint operator and describes applications of adjoint solutions for predicting and analyzing numerical error of forward solutions based on higher order FEM modeling, with a perfectly matched layer (PML) boundary conditions for domain truncation. We present examples of application of an adjoint operator to quantify sensitivity of a quantity of interest (QoI) to perturbations in an input parameter in three-dimensional (3-D) higher order FEM-PML EM scattering computation, where we use the sensitivity information to predict the QoI over the parameter domain. In a large variety of illustrative one-dimensional (1-D) higher order FEM-PML EM scattering problems, we compute the error estimate from the numerical forward and adjoint solutions on an element-by-element basis and analyze element-wise contribution to the total error in a given QoI from the forward solution. We then discuss the usefulness of this information for adaptive mesh refinement, considering both h- and p-refinements. We demonstrate that developing efficient strategies for adaptive mesh refinement requires accounting for local cancellation of the element contributions to the error. We show that adjoint methods present a useful technique toward a posteriori error estimation and adaptive mesh refinement for the FEM computation of EM scattering

Characterizing Metamaterial Resonators and Finite Metasurfaces by the Method of Moments

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Metamaterials and metasurfaces use to be made of subwavelength resonators periodically arranged in 3D and 2D, respectively. Their unit cell may be a split ring resonator (J. B. Pendry *et al.*, IEEE Trans. Microwave Theory Techn., vol. 47, p. 2075, 1999), a spiral (J. D. Baena *et al.*, Phys. Rev. B 69, p. 014402, 2004; F. Bilotti *et al.* IEEE Trans. Antennas Propagation, vol. 55, p. 2258, 2007), an ELC resonator (D. Schurig *et al.*, Appl. Phys. Lett. 88, p. 041109, 2006), among others. Frequently, these particles are approximated as an equivalent RLC circuit presenting resonances for which the electric and magnetic polarizabilities and permeabilities can reach values which are not commonly found in Nature. By using the Method of Moments, in previous works we simulated single metamaterial resonators (J. L. Araque and J. D. Baena, 2013 Metamaterials Conference; J. L. Araque and J. D. Baena, 2014 Metamaterials Conference) to get their polarizability tensors from full wave simulations. Now we have simulated finite metasurfaces, at least of size 5×5 wavelengths, illuminated by plane waves. For this purpose, the Advanced Metal-Dielectric Solver (AMDS) code, developed at Universidad Nacional de Colombia was employed, which is a full-wave simulator based on the Method of Moments (MoM) technique (R. F. Harrington, *Field Computation by Moment Methods*, IEEE press, 1993.) with Multi-Level Fast Multipole Acceleration (ML-FMM) (R. Coifman *et al.*, IEEE Antennas Propagat. Mag., vol. 35, p. 7, 1993) and optimizations specific for finite-periodic structures such as the one under analysis. This code has been validated with well-known reference results, among which we could cite (O. Pea and U. Pal, Computer Physics Communications, vol. 180, p. 2348, 2009). This MoM implementation uses the Rao-Wilton-Glisson RWG basis (S. Rao *et al.*, IEEE Trans. Antennas Propagat., vol. 30, p. 409, 1982), which is defined on pairs of cells of meshes composed of triangular facets. Each basis element provides a piecewise linear approximation to surface currents and thanks to the div-conforming property, the overall representation correctly accounts for both charge and current contributions to the resulting fields.

Finite Elements Analysis of a Lightning-like Plasma Channel

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In this paper a lightning-like plasma channel is simulated to estimate the temperature increase caused by a 30kA, 10/350μs lightning current flowing through it. Additionally, the expanded channel dimensions interacting with the surrounding air are estimated. The energy liberated inside the cannel by the lightning current impulse is calculated by using equation (1):

$$Q = \iint_{V,t} \mathbf{J} \cdot \mathbf{E} dV dt \tag{1}$$

Where: Q is the energy dissipated as heat in the lightning channel, $\mathbf{J}$ is the current density and $\mathbf{E}$ is the electric field intensity. The lightning-like channel is simulated as a 10 mm in diameter and 2 km long vertical column, with a 13.4E6 S/m conductivity. The two-dimensional Finite Element simulation results, which integrates electromagnetic, turbulent flow and heat transfer models, are presented in Figs 1 and 2. The curves shown in Fig. 1 are both, the dissipated power in the lightning-like channel and the temperature increase in the lightning-like plasma channel. The maximum calculated temperature in the lightning-like channel is 19.23E3 °C. In Fig. 2 is presented the temperature distribution in the lightning-like channel, indicating the noticeable temperature reduction to 50% at just 30 mm from the channel centre. Due to this dramatic temperature reduction, the channel temperature is not expanded to the surrounding air. Additionally, as it is indicated in Fig. 1, the time constant at which the temperature increases in the plasma channel is in the order of a few ms, much slower than the current impulse rise time.

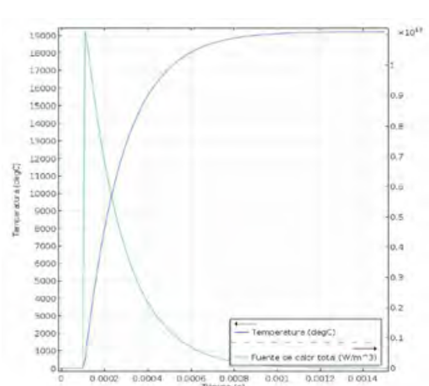

Figure 1: Temperature and 10/350μs impulse current injected in the lightning-like channel. Notice the delay between current and temperature.

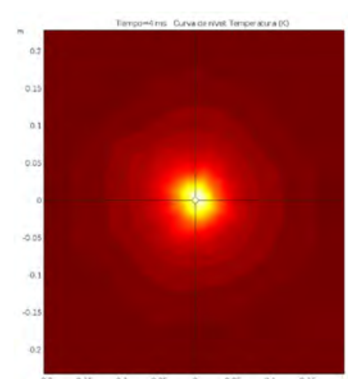

Figure 2: Temperature in the lightning-like cannel cross section. Notice the rapid temperature reduction.

FEM-based Detection of Moving Targets via Particle Filtering and Artificial Neural Network

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Detection of a moving target in a complex environment is a daunting task that is treated in several ways exploiting the band of electromagnetic waves from few MHz to optical frequencies. Radio-localization of targets in the microwave band has several advantages, among which low cost of the devices and the fact that the device is usually much less evident and have a wider angle of observation than a surveillance camera. Radio-localization can be passive, in the case in which what is detected and tracked is actually some mobile transmitting device held by the target (*e.g.* a mobile phone). This can be done by deploying several nodes in an area and guessing target position even on the basis of amplitude-only measurements (S. Maddio *et al.*, IEEE APS 2017 pp. 2523-2524). Radio localization can also be on noncooperating targets, meaning that they do not emit themselves a signal, and this is much more relevant in security applications, where targets must be assumed to be noncooperating. In this case active (radar) detection can be inappropriate since an active radar is itself easily detected by the non-cooperating target which can immediately take appropriate countermeasures. A fully passive system, relying only on the field existing in the environment, for example that due to radio or TV broadcasting, will not alert the target (A. Farina *et al.* ISMOT-2007, pp. 195-198). In this contribution, samples of the scattered field in a complex environment illuminated by a far-away radio source will be used to detect the presence of a target and track it by combining the finite element method (FEM) with particle filtering and artificial neural networks (ANNs). The FEM is used to simulate the values of the scattered field in a given number of sampling points (corresponding to the positions of the field sensor) for different positions of the target within the domain (including the case in which the target is not present). These data are used to train an ANN with the objective of learning the mapping from the target position to the samples of the scattered field. Then, a filter is designed to solve in real time the inversion problem of detecting the target and determining its kinematic state (*i.e.*, position and velocity) from the measurements of the scattered field in the sampling points. For this purpose, a particle filter is employed in which a set of particles is used to approximate the probability distribution of the target existence and kinematic state conditioned to the collected measurements. The FEMtrained ANN allows one to compute in real-time the likelihood of each particle (representing a hypothesis for the target existence and kinematic state) given the measured scattered field.

Efficient Electromagnetic Modeling of Wireless Signal Propagation in Underground Mine Tunnels

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Electromagnetic (EM) modeling and simulation of wireless signal propagation in underground mines presents extraordinary challenges and is an open EM research problem with unparalleled difficulty in many of its aspects. A working underground mine at modern wireless communication frequencies is electrically an extremely large (spanning hundreds and thousands of wavelengths) and complex EM system. The EM complexity is in both the geometry of the mine sections (tunnels of varying dimensions, with bends, corners, indents, rough walls, etc.) and obstacles (such as machinery, tools, mine wagons/carts, rail tracks, cables, piles of ore, debris, RF/microwave transmitters/receivers, and humans) and the material composition of the tunnel/chamber walls. To model and simulate wireless signal propagation through a complex network of mine tunnels and chambers in realistic scenarios, we use a hybridization of several approaches aimed for different sections of the mine. One approach is related to the generalized scattering matrix (GSM) computation of mine tunnel sections using a three-dimensional (3-D) finite element method (FEM) in conjunction with a mode matching (MM) technique at GSM ports. A large structure can be divided into smaller domains that are modeled separately and the final solution is obtained by connecting the GSMs of all domains into the large structure. The GSM results for one domain are computed using higher order three-dimensional (3-D) FEM. Modal expansion at a port is computed as an eigen problem solved using a higher order 2-D FEM. Another approach is constituted by the shooting-bouncing rays (SBR) ray tracing technique. Ray tracing, as an efficient high-frequency method, is advantageous for extremely electrically large scenes such as undergraduate mine sections at wireless communication frequency bands. The SBR approach involves launching a set of test rays in all directions in which propagation from the source can be expected, tracing the rays through the scene, and finding the electric field at a desired location in the scene by employing an ideal plane wave approximation for each ray and using the reflection coefficients based on surface parameters for each reflection. The SBR method is highly parallelizable which allows for efficient and expeditious computations and enables analysis of problems that require extremely high ray counts to achieve sufficient sample density for field convergence. We discuss GPU acceleration of SBR simulations, and demonstrate scalability and dramatic speedup with respect to CPU computations in examples of EM modeling of underground mine sections.

Non-Conformal Domain Decomposition Method supporting *hp* Discretizations

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In this communication, details about the implementation of a Domain Decomposition Method (DDM) with Second Order Transmission Conditions (F. Fuentes *et al.* Comput. & Math. Appl., vol. 70, no. 4, pp. 353–458, 2015.), on a Finite Element Code -called HOFEM- are included. The DDM formulation introduced is non-conformal to support independent meshes between domains to make *hp* adaptivity in 3D computationally feasible since DDM is inherently parallelizable. To achieve a generic approximation order, different families of higher-order curl-conforming elements -including hierarchical basis functions of order p, (D. Garcia-Donoro *et al.*, Proc. Comput. Sci., vol. 108, pp. 818-827, 2017 - Z. Peng, J.-F. Lee, SIAM J. Sci. Comput., vol. 34, no. 3, pp. A1266–A1295, 2012)- have been included in HOFEM along with three different shapes: triangular prisms, tetrahedra and hexahedra. An example of a cube of vacuum with a planewave as excitation is shown in Fig.1. Well-known paradigms for parallelization such as Message Passing Interface and OpenMP are included making HOFEM able to run in High-Performance Computing (HPC) environments.

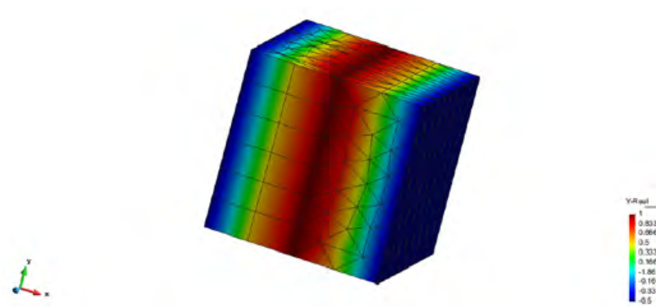

Figure 1: Cube discretized with a non-conformal mesh with triangular prisms and tetrahedra, both with p=2.

Checkerboard-like low profile antenna optimization

Marcello Zucchi(1), *Giorgio Giordanengo*(2) , *Marco Righero*(2), *Javier Leonardo Araque Quijano*(3), *Giuseppe Vecchi*(1)

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(2) *Istituto Superiore Mario Boella, Torino, Italy*
(3) *Universidad Nacional de Colombia, Bogotá, Colombia*

We apply a genetic algorithm (introduced in J. Araque, G. Vecchi, IEEE Trans. Antennas Propagat., vol. 57, no. 1, pp. 9-18, 2009.) to automatically design low profile antennas with emphasis on the radiated far-field (FF). The algorithm results in a checkerboard-like structure, as seen in Figure 1, left panel. The algorithm is based on the integral equation formulation. The matrix resulting from the discretization of a square plate of 2 wavelength at the frequency of interest of 2.44 GHz is computed once during the setup phase and then used at each iteration pruning the rows and columns corresponding to parts removed from the antenna. The fitness function takes into account both the return loss (RL) and the directivity on a solid angle of 5° around the broadside direction. No constraints are imposed to limit the complexity of the obtained geometry, resulting in the checkerboard structure depicted in Figure 1, left panel. Regions touching at a corner only are separated in a post processing phase after the optimization, to avoid mesh singularities, and the antenna is simulated again for final checks. The resulting directivity pattern is shown in Figure 1, right panel. Analysis of the robustness of the obtained layout, insertion of a dielectric between the checkerboard-like part and the ground plane, and realization of the antenna are ongoing activities.

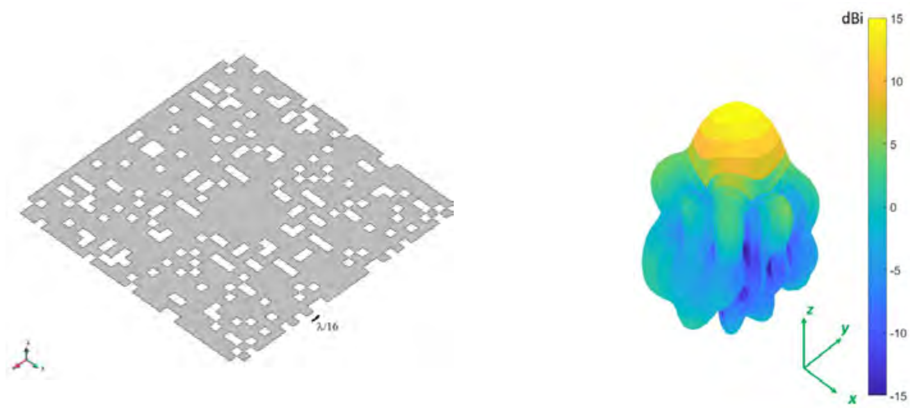

Figure 1: Left: optimized checkerboard (ground plane not shown to enhance clarity). Right: Directivity pattern [dBi].

Multi-Objective Optimal Design of Meandering Antenna Through Low Discrepancy Sequences

Andres Felipe Uribe Ávila, David Sebastián Pulido Suárez, Germán Felipe Giraldo Villa, Sebastián Velásquez Suárez, Luis Ernesto Muñoz Camargo, Juan Carlos Bohórquez Reyes, Néstor Misael Peña Traslaviña

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A methodology for incorporating a low-discrepancy sequence in the solution of a multi-objective optimization problem is used for the optimal design of a dipole meandering antenna for RFID-SAW applications. The objectives of the optimization are the antenna's gain, resonance frequency and reflection coefficient parameter. Optimization is performed on a parametric finite element analysis model, and responses are calculated with a computer-intensive simulation in ANSYS HFSS. A global sensitivity analysis is performed in order to identified the variables that affect the most the response of the antenna (Y. Zhang, *et al* ,2012 IEEE Radio and Wireless Symposium, pp. 47–50). The method is proposed to obtain Pareto efficient designs (G. Mastinu *et al., Optimal Design of Complex Mechanical Systems: With Applications to Vehicle Engineering*, 15th ed. Springer-Verlag Berlin Heidelberg, 2006). An experimental validation is finally performed to observe the behavior of a Pareto efficient design in a real application. The experimental validation consisted of determining the normalized radiation pattern and comparing the maximum reading distance of two antennas.

Session:

Numerical Methods in Electromagnetics

Organized by

Roberto D. Graglia and Donald R. Wilton

SIE-DDM based Direct and Iterative Solvers for Multiscale Problems

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In the past few years, surface integral equation based domain decomposition method (SIE-DDM) has emerged as one of the most attractive approaches for modeling multiscale problems, which splits a large and complicated structure into a set of smaller and easier solvable sub-domains according to their geometrical properties. Some appropriate transmission conditions are employed to ensure the continuity of electric and magnetic fields between adjacent sub-domains. In the convention framework of SIE-DDM, an inner-outer iterative method is utilized to solve the final matrix equation. Essentially, this kind of iterative method can be viewed as a multiple right hand sides (MRHS) problem. However, if one sub-domain encounters the convergence problem, it is prohibitive for the whole solve process. Therefore, there are two particular motivations to develop a fast direct method as a sub-solver for SIE-DDM:

1. It is particularly efficient for MRHS problems. Iterative solution of SIE-DDM can be viewed as a situations involving MRHS problems. Matrices inversion for each sub-domain just need to be performed once by the present algorithm. During the outer iteration, applying its inverse to each additional updated right-hand side is inexpensive.

2. It is suitable for problems involving relatively ill-conditioned matrices. Although SIE-DDM decomposes the original large problem into smaller ones. It does not guarantee that every sub-domain can be solved by iterative methods successfully at any time.

In this paper, SIE-DDM hybridizing both fast direct and iterative solvers for multiscale electromagnetic modeling and simulation is proposed. Here, a fast algorithm based on hierarchically off-diagonal low rank (HODLR) structure using a modified compression technique is developed to solve sub-domain directly in SIE-DDM. For each sub-domain, the dense off-diagonal matrices can be split into small sub-matrices with the admissible condition instead of a direct factorization of off-diagonal matrices. Then the low-rank off-diagonal matrices can be reconstructed through aggregating all sub-matrices. Subsequently, Sherman-Morrison-Woodbury formula (SMWF) is applied to construct the hierarchical factorization of the inverse. This method has computational complexity of $O(n^2)$. Numerical results will be shown to demonstrate the accuracy and efficiency of the proposed method.

Equivalence Principle Algorithm for Potential Integral Equations

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Potential integral equations (PIEs), which are based on enforcing boundary conditions for the electric scalar potential and the magnetic vector potential on surfaces, enable accurate and stable solutions of low-frequency problems involving perfect electric conductors without resorting to special discretization functions. Following their solutions using the standard method of moments, fast algorithms, such as the multilevel fast multipole algorithm (MLFMA) using multipoles, scaled plane waves, and other stable expansions of far-field interactions, have been used to solve densely discretized structures with subwavelength details. While PIEs theoretically do not suffer from ill-conditioning, as an advantage in contrast to the electric-field integral equation that has a well-known lowfrequency breakdown, they may still lead to matrix equations that require preconditioning and/or matrix balancing for quick iterative convergences, especially as the problem size grows. Alternatively, PIEs can be solved with more stable methods, such as the equivalence principle algorithm (EPA), as described in this contribution. EPA implementations have been developed particularly to handle densely packed structures that can be partitioned into small parts. As opposed to MLFMA, EPA involves discretized surfaces that enclose the parts of the given structure. Thanks to the extended freedom in choosing the mesh size on EPA surfaces, it becomes possible to generate stable matrix equations involving self interactions of surfaces and cross interactions between them. The translations between EPA surfaces can also be accelerated via suitable expansion methods, as in MLFMA. As a general drawback and limitation, EPA implementations require the direct inversion of matrix equations for sub-problems, while the main solutions often need only a few iterations, making them much more efficient than other fast solvers.

In this contribution, we present a novel implementation of EPA for PIEs to analyze perfectly conducting objects. The equivalence relationships are extended by including potentials on equivalence surfaces, while PIEs are used to solve sub-problems without any low-frequency breakdown. Radiations from equivalence surfaces to objects and objects to equivalence surfaces, as well as solutions of sub-problems using PIEs together with the self equation of the electric scalar potential, are studied in detail. The developed implementation provide accurate, stable, and also efficient solutions of large-scale problems with dense discretizations with respect to wavelength.

Comparison of Two Methods for the Study of Three-Media Junctions Using the Method of Moments

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In computational electromagnetics, the Method of Moments (A. Poggio and E. Miller, *Computer techniques for electromagnetics.*,Oxford UK: Pergamon Press, 1973) is a spectral method that is particularly convenient for the simulation of open problems and geometries that are homogeneous by blocs. First, the surface of each bloc is discretized, traditionally using linear Basis Functions (BF) such as the Rao-Wilton-Glisson (RWG) (S. Rao *et al.*, IEEE Trans. on Antennas and Propagat., Vol. 30, no. 3, pp. 409-418,

1982) or rooftop BF. Then, using the equivalence principle, the global problem is subdivided into several smaller problems corresponding to the different homogeneous blocs present in the geometry. The unknown equivalent currents on the boundary of each sub-problem is expanded using the previously defined set of BF. For each sub-problem, the interaction through the medium consider between the BF and a given set of Testing Functions (TF) is computed. Last, the value of the equivalent currents on every surface is found by enforcing some boundary conditions, whose choice depends both on the physics of the problem and the formulation considered. A given pair of BF and TF may be involved in more than one sub-problem, and therefore their interaction computed more than once. However, when three different media are sharing a common edge, it may happen that one half of a BF is part of a sub-problem, while the other half is not. In that case, a specialized formulation is required (P. Ylä-Oijala *et al.*, PIER, Vol. 52, pp. 81-108, 2005; and D.M. Solis *et al.*, IEEE Trans. Antennas Propogat., Vol. 63, no. 5, pp. 2141-2152, 2015). In this paper, we compare the results obtained for such a three-medium interface using two different formulations.

- The first method used is the one proposed in the aforementioned papers, where specialized BF are devised for the treatment of these 3-media junctions. On one hand, these specialized BF allow for an optimal treatment of the junction from a numerical point of view. On the other hand, the introduction of such specialized BF may require special code in order to properly treat the interaction of these functions with themselves and others.

- The second method presented consists in introducing an infinitely thin gap between the third medium and the two others. On one hand, a higher number of unknowns is required, since the presence of the air gap is generating the appearance of a twin surface. On the other hand, this formulation only requires the computation of the classical MoM impedance matrix and of the Magnetic Field Integral Equation (MFIE) singular term. The singular term corresponds to the 2D integral of a smooth function and can be obtained in closed-form. For that reason, this method is less problem dependent and is easier to implement. Moreover, it may also be used for touching objects whose meshes are not conformal. It is worth mentioning that the singular term of the MFIE naturally appears in the Müller formulation of the method of moments (P. Ylä-Oijala and M. Taskinen, IEEE Trans. Antennas Propagat., Vol. 53, no. 10, pp. 3316-3323, 2005) and may therefore be already available depending on the formulation used.

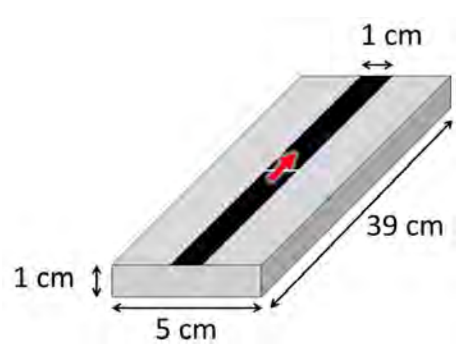

Figure 1: Geometry studied. The red arrow in the middle of the dipole corresponds to the port.

As preliminary results we already compared the results obtained from the second method with CST in the case of a dipole antenna with a port impedance of 50Ω. The dipole is made of a metallic strip deposited on a FR-4 slab. The metallic strip is modeled as a Perfect Electric Conductor (PEC), while the FR-4 is modeled with a relative permittivity $\varepsilon = 4.3 - 0.108j$, the imaginary part corresponding to the losses. The geometry and the results obtained for the impedance of the antenna and the S-parameter are illustrated below. The fit is very good considering that the simulations are based on totally different methods (Finite Elements Method vs. Method of Moments). In the full paper, a complete comparison between the two methods using the more complex geometry of an MRI birdcage will be conducted.

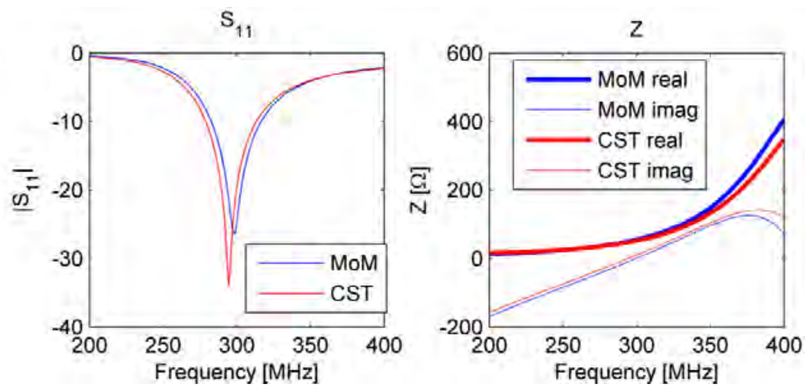

Figure 2: Comparison between the S-parameters and antenna's impedance for several frequencies using CST and the second method presented here above.

Deep Thinning of MoM Matrices with the Balanced Electromagnetic Absorber Method in Three Dimensions

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This work presents a numerical approach (the balanced electromagnetic absorber (BEMA) method) to economizing and conditioning the classic electric or magnetic field integral equation (EFIE or MFIE) formulation of surface electromagnetic scattering. In the conventional approach, the free space Green's function (GF) is used, as afforded by the èequivalence principle, which replaces conducting or homogeneous scatterers by currents radiating in free space. The equivalence principle provides more, however: Since the sources provided by the principle generate a null field inside the scatterer volume, the door is open for the inclusion of arbitrary media (termed "fillers" herein) within the volume. Here, balanced absorbers are proposed for this purpose. The idea of balanced electromagnetic absorbers dates back to Salisbury in the 1940's and to Weston in the 1960's. It was later elaborated into the seminal perfectly matched layer (PML) by Berenger. Balanced absorbers can work with very high or very low permittivities and permeabilities, and even work with small inherent loss.

Balanced absorbing media are created by matching their intrinsic impedance to that of the embedding lossless homogeneous medium with permittivity and permeability ε_r, μ_r. If the lossy medium is characterized by electric and magnetic conductivities σ and σ^*, implying

$$Z = \sqrt{\frac{\mu'}{\varepsilon'}}\sqrt{\frac{1 - j\frac{\sigma^*}{\omega\mu'}}{1 - j\frac{\sigma}{\omega\varepsilon'}}} = \sqrt{\frac{\mu'}{\varepsilon'}} \qquad (2)$$

so that a balanced material must satisfy the condition

$$\frac{\sigma}{\varepsilon'} = \frac{\sigma^*}{\mu'} \tag{3}$$

Equation (2) s a sufficient condition for a 100% absorption of a normally incident plane wave at a planar interface between the embedding and absorbing media.

No matter what medium is used for the filler material, the inclusion of a substance other than free space alters the algorithm. Most importantly, it modifies the GF that must be used at several different places in the formulation. When the filler chosen is a balanced absorber, interactions between pairs of basis and testing functions at opposite sides of the filler are virtually eliminated. Indeed, the matrix elements corresponding to these interactions need not be computed at all. As a result, the MoM matrix created with the new GF is significantly sparser than that based on the free space GF. The inherent well-conditioning of the BEMA-derived EFIE can be seen in the elimination of the spurious solutions associated with internal resonance, without resorting, say, to the conventional remedy of the combined field integral equation (CFIE). Examples of scattering from two-dimensional perfect electric conductors (PECs) have been presented in the recent past, and a demonstration of a three-dimensional problem will be given here. One of the outcomes of these simulations is a possible preference for the usage of the MFIE since the Green's matrix appears to be very highly localized in this case. In fact, the matrix can be deeply thinned to the level of retaining just about the diagonal entries.

A Hybrid Time-Frequency Domain Algorithm for Broadband Monostatic RCS Computation of Large and Deep Open Cavities

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A hybrid algorithm that combines the finite-element time-domain (FETD) method and generalized scattering matrix (GSM) technique is proposed to efficiently compute the broadband monostatic radar cross-section (RCS) of a large and deep open cavity. The formulation and implementation for the numerical modal analysis of arbitrary cross-sections and the FETD method equipped with complex frequency shifted perfectly matched layers (CFS-PML) for transient simulations are presented. The broadband monostatic RCS is evaluated using a broadband GSM obtained by the FETD solutions. Several examples are presented to demonstrate the accuracy and efficiency of the proposed hybrid FETD-GSM algorithm for broadband monostatic RCS computation and inverse synthetic aperture radar (ISAR) imagery of large and deep open cavities.

The Flammer Solution for the Circular PEC Disk: Computations and Comparisons

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A circular, perfectly conducting disk is one of only a few three-dimensional problems amenable to exact electromagnetic (EM) analysis. This makes it potentially useful as a benchmark geometry for assessing EM analysis software and various types of higher order basis functions. In addition, the induced tangential current components and charge density are singular at the disk edge, enabling the evaluation of basis functions that attempt to better model edge singularities.

Exact solutions for EM wave scattering from circular, perfectly conducting disks were first proposed by Andrejewski and Meixner in 1950 and Flammer in 1953, in terms of oblate spheroidal functions. The problem of scattering from a disk is related to the problem of a circular aperture by Babinet's principle, and similar efforts were directed at the aperture problem. The vector Helmholtz equation is not separable in general spheroidal coordinates; however the disk is a special case (like the prolate spheroidal dipole antenna) where exact solutions may be constructed. The analysis includes an explicit enforcement of the edge condition on the disk rim. Because the solutions can be constructed in more than one way, the Andrejewski and Flammer solutions have very different forms.

The first modern computer implementation of the exact disk solution for scattering cross section (SCS) computations was published by Mattson in 1970, based on the Flammer formulation, while another based on the Andrejewski formulation was published by Hodge in 1979. These appeared to be motivated by the need to determine the range of validity of asymptotic solutions. To date, other than comparisons with quasi-static solutions for disk currents, there appears to be no use of the exact disk solution to evaluate numerical solutions.

In this presentation we will review the Flammer formulation for the disk, develop expressions for the surface currents and SCS, and describe an implementation based on the use of software from (S. Zhang and J.-M. Jin, Computation of Special Functions, Wiley, 1996). We will use those results to evaluate several method of moments approaches based on the electric field integral equation, employing basis functions that contain singular terms to properly model the behavior of current density at disk edges. We will also discuss the accuracy limits of the spheroidal function computations as a function of the disk circumference ka, based on the use of several precision levels, the computation of reference functions such as a plane wave with the spheroidal functions, and direct substitution of the functions back into the spheroidal differential equation.

Reducing the Dimensionality of Volume-Volume (6-D) Integrals for Numerical Evaluation by Multiple Applications of the Divergence Theorem

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Advances in fast solution methods have made the application of volumetric integral equations more attractive. However, the rigorous solution of radiation and scattering problems using integral equation formulations requires the accurate and efficient numerical evaluation of double volumetric reaction integrals. Recently Bleszynski et al. presented a method allowing an analytical conversion of expressions for matrix elements of the tensor and vector Green functions from 6-D volumetric to 4-D surface integrals with nonsingular integrands (see e.g. E. H. Bleszynski *et al.*, IEEE Trans. Antennas Propagat., vol. 61, no. 7, 2013).

For surface integral equations, the authors recently showed an approach in which the divergence theorem is applied twice (once each for the source and test domains) to obtain a general formula valid for self, edge-, and vertex-adjacent, as well as separated element pairs for co-planar and non-coplanar elements (see e.g. J. Rivero et al., ICEAA 2017). The resulting 4-D surface integrals are expressed as two radial integrals plus two contour integrals over the source and observation domain boundaries.

In the present paper, we instead apply the surface divergence theorem for the integration of double volumetric integrals for both source and test domain of the 6-D reaction integrals. The resulting 6-D volume integrals are expressed as two radial integrals plus two surface integrals over the source and observation domain boundaries. The radial integrations in the physical domain should be well-behaved and easily performed for arbitrary polyhedral domains. Unlike the surface case, in the volumetric case, points in the source or test element plane do not need to be imaged in the plane of the other element. Preliminary results have shown good accuracy of the proposed method. The surface integrals can be performed numerically, or by applying the previously-developed scheme for surface integral equations.

LEGO Brick Boundary with a Penetrating PEC Structure

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Printed circuit boards (PCBs) and integrated circuits (ICs) are the foundation of virtually any kind of modern technology and there is a constant need for a better understanding of such structures through modelling. To design a PCB and include the effect of the environment, while ensuring electromagnetic compatibility (EMC), is a complex process. EM interaction between an IC and the rest of the PCB is an important aspect and it has to be taken into account from the beginning of the PCB design. Despite the impressive evolution and wide-ranging capabilities of commercial 3D-EM-full-wave tools based of finite techniques (FIT, FDTD, FEM, etc.), the final results may be unreliable.

For all these reasons, a modelling strategy that exploits a domain decomposition technique is advantageous because:

- the treatment of local strong EM interactions and related fine details can be separated from that of weaker, more distant interactions;
- the introduction of separation equivalence surfaces and scattering operators can make the recalculation of similar problems much easier by recalculating just the response of the domains that contain differences.

In particular, the domain decomposition can be realized with the linear embedding via Green's operator (LEGO) method (V. Lancellotti *et al.*, IEEE Trans. Antennas Propagat., vol. 57, no. 11, pp. 3575–3585, 2009), in which different parts of a composite larger problem are included inside "EM bricks". The latter are then combined to describe the behavior of the original structure by means of an operator equation. We will present modelling of multi LEGO bricks with PEC structures penetrating brick boundaries, where LEGO solves the electric field integral equation (EFIE) through the Method of Moments. To make this work we have:

1. created brick boundaries in a way to touch and follow the shape of a PEC penetrable structure;
2. defined a port at every place where the PEC structure penetrates the brick boundary to ensure the connectivity and smooth flow of the current.

We shall present a current distribution comparison of a LEGO solution together with the direct solution that solves the EFIE directly over the structure for different shapes of PEC structures. To validate the scattering operators, far-field comparison for the LEGO approach and the direct solution will be shown.

A Stochastic Green's Function – Integral Equation Method for Communication Through Diffusive Environments

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Transmission of information through complicated environments is a topic of both fundamental and practical importance to wireless communication. Representative applications include indoor communications within large and complicated enclosures, communications in metropolitan areas, radar systems over rough or glistening surfaces, transmission through disordered media, etc. As the wavelength is much shorter than the typical size of the structures (scatterers) in the environment, the wave scattering process may exhibit chaotic ray dynamics. Consider two propagating rays with slightly different incident directions. Their trajectories start out very close to each other and separate significantly over time. In a finite number of bounces the results become completely different, even though the scattering environment is deterministic. On the other hand, the complexity of the scattering environment creates an extremely large number of multiple paths between transmitters and receivers. Attributed to the distinguished characteristics and unique behaviors, applied scientists and engineers has found diverse applications, including multiple-input and multiple-output (MIMO) communications, time-reversal systems, wavefront shaping and focusing, sensing and targeting, et al. These intriguing systems and experiments are realized by taking advantage of chaotic sensitivity, ergodicity, and broadband spectra of dynamics in phase space. Yet, much potential is not fully exploited due to a lack of comprehensive, firstprinciples mathematical theory explaining wave-chaotic propagation physics. The goal of this work is to investigate the first-principles mathematical model which statistically replicates the multipath, diffusive propagation between transmitters and receivers. The objective is attained by cutting across traditional disciplinary boundaries between electromagnetic theory, wave chaos physics, random statistical analysis and information theory. The methodology is to first establish fundamental statistical representations of complex diffusive media, then integrate component-specific features of transmitters and receivers, and finally encode the governing physics into the mathematical information theory.

Analytical Treatment of the Near Field Term of the Green Function of Planarly Stratified Media

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We present an approach allowing accurate and efficient evaluation of the near-field con- tribution to the matrix elements of the electric and magnetic field operators for planar conducting structures embedded in a layered medium. The method is applicable to Rao- Wilton-Glisson (RWG) (S.M. Rao 1em et al., IEEE Trans. Antennas Propagat., vol. 30, pp. 409-418, 1982.) basis functions supported on parallel interfaces in the medium. Our approach makes use of the technique introduced in (E.H. Bleszynski *et al.*, IEEE Trans. Antennas Propagat., vol. 64, pp. 4760-4769, 2016) and applied, in the present context, to the most singular components of the stratified-medium EFIE and MFIE Green functions involved in matrix elements for basis functions supported on either the same interface or on two nearby interfaces separated by a small distance d in the z direction. Those Green function components are due to asymptotic terms of the integrand in the Sommerfeld representation and have a form similar to the infinite-space Green functions with appropriate wave numbers and z components of spatial arguments.

The described method consists of representing a Green function $G(\rho, z_1, z_2)$, for fixed z coordinates on interfaces, as a two-dimensional Laplacian of an auxiliary function M, $G(\rho, z_1, z_2) = \nabla_\rho \cdot \nabla_\rho M(\rho, z_1, z_2)$. This representation is then used to convert quadruple surface integrals with singular integrands to double contour integrals over the perimeters of the surface elements involving simple closed-form auxiliary non-singular functions. The line integrals can be either evaluated analytically, resulting in rather lengthy expressions involving elementary functions, or by means of standard numerical quadratures. The latter task is facilitated by the fact that the function M being a solution of an appropriate differential equation, is not unique and can be chosen to ensure a smooth behavior for small ρ and for either $z_1 = z_2$ (when the points are located on the same interface) or small $d = |z_1 - z_2|$

We describe both analytic and numerical quadrature-based procedures for evaluation of the line integrals and compare their relative advantages for various geometrical configurations of basis functions' supports.

Numerical Modeling of a Wind Turbine Blade Deflection Sensing System Using the Moving Frame FDTD Method

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A wireless system capable of measuring deflection of a wind turbine blade has recently been introduced. The deflection (bending) of the blade is determined from the time of arrival of short pulses launched by an antenna near the blade tip and received by an antenna close to the root. The system is based on an existing ultrawideband (UWB) technology in the range 3.1-4.8 GHz. It detects the pulse arrival by using a modified correlator that locks onto the rising edge of the received pulse. Due to aerodynamic

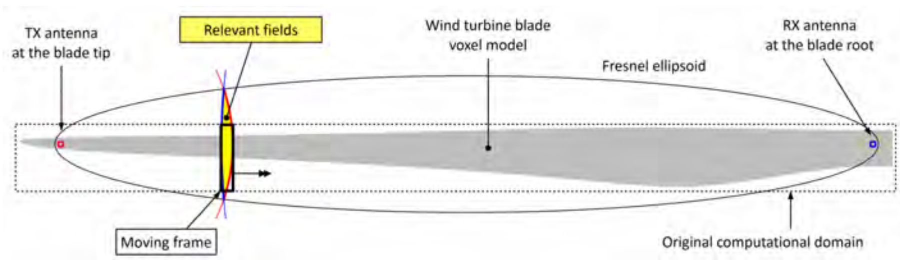

Figure 3: Geometry studied. The red arrow in the middle of the dipole corresponds to the port.

noise and protection from lightning strikes, the tip antenna is placed inside the blade tip. This poses a challenge for the wireless link as it has to operate on non-line-of-sight conditions. The electromagnetic waves radiated from the tip antenna must penetrate the fiberglass shell of the blade and then travel towards the root with very low elevation angle from the fiberglass-air boundary. The multipath components of the received signal may then become very strong and prevent reliable detection of the pulse time of arrival. In order to predict the link budget and to determine the optimum location of the root antennas, we have modeled the wave propagation along the 58.7m long blade using the finite-difference time-domain (FDTD) method. The computational domain consisted of more than 10 billion cubical mesh cells with cell size of 5 mm, including 50 cell thick perfectly matched layers (PML) necessary to suppress reflections from the outer 1 boundaries under low elevation angles. Total simulation time on a parallel cluster was 26 hours, after load balancing the parallel processes. Since the wave traveling along the wind turbine is created by an UWB pulse, the portion of cells in the computational domain with non-negligible magnitude of the fields is small during the entire simulation and the active region is steadily moving along the blade from the tip towards the root. Moreover, as the correlator locks onto the rising edge only, the amount of cells whose fields are important for the result is quite limited. By exploiting these properties we could significantly reduce the simulation time and speed up the optimizations. In the proposed paper, we demonstrate the application of the moving frame FDTD method to reduce the computation time of an UWB pulse traveling along a 58.7m long wind turbine blade. We present concrete formulas for determining the extent of the moving frame and the expected speedup, based on the geometrical constellation of the wireless link, parameters of the UWB pulse and material properties and their distribution along the propagation path. It is also shown that on the right circumstances it is even possible to remove the PML layers from the simulation frame without affecting the results, and thus reduce the computational burden even further. The findings and practical considerations presented here are applicable to efficient computation of other problems with similar arrangement.

An Efficient Galerkin Scheme to Solve the Time Domain Integral Equation for Wire-Grid Models Involving Multiple Incident Pulses

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Until recently a time-stepping process, popularly known as the Marching-on-in-Time (MOT) method (S.M. Rao, *Time Domain Electromagnetics*, Academic Press, New York, 1999), has been the main technique for solving the numerical solution of Time Domain Integral Equation (TDIE) for electromagnetic field problems. The main advantage of MOT method is that, when used as an explicit scheme, it requires no matrix inversion, a computationally intensive step in any numerical algorithm (S.M. Rao, *Time Domain Electromagnetics*, Academic Press, New York, 1999). Unfortunately, the MOT procedure is prone to late-time instabilities. The source of instability is primarily the method itself where the accumulation of error occurs at each time step. Over the last 50 years, there have been several proposed remedies to overcome this problem. However, most of the proposed remedies only try to arrest the instabilities, work only for simple problems, and invariably fail for complex objects. Even the implicit schemes in time domain, which require a matrix inversion, are vulnerable to the instability problem and hence are of little use to a practicing engineer. Recently, a new type of algorithm was developed and applied to wire-grid models of arbitrary bodies to solve the time domain integral equation (TDIE) using the conventional method of moments (MOM) solution procedure (M. Rao, IET Microw., Antennas Propagat. J. *accepted*). In the MOM numerical solution scheme, the arbitrary wire was divided into subdomains and the standard pulse functions were used to represent the space variable along the length of the wire. The time variable is approximated by a set of time-shifted Gaussian functions. Note that the time-shifted Gaussian functions represent entire domain functions and decay as time extends to infinity. As a result, the time domain signature stays stable even at a late time. For testing purposes, point matching was used for both the space and time variables. Because of the conventional MOM procedure, the new method can handle multiple incident pulses, with varying frequency signature bands and directions of incidence, with only a fractional additional cost as compared to a single incident field. We note that the new method, as described in the aforementioned paper, is based on an entirely a new line of thinking where the error is suppressed in both time and space. There is no time marching involved in this procedure. The method can handle multiple incident pulses with varying frequency content in a single run, which even the frequency-domain MOM cannot do. However, one disadvantage of this new procedure is the required inversion of large real matrix with the dimension $N = N_t \times N_s$, where N_t and N_s represent the number of time functions and number of wire subdomains, respectively. Thus, the matrix dimension N could be quite large even for moderately complex wire models and hence can be computationally expensive. In the present work, we alleviate this problem by modifying the testing procedure. The expansion procedure is identically the same as in the aforementioned paper, i.e. we retain the use of Gaussian functions for expressing the time variable and pulse functions to represent the wire subdomains. In contrast to the previous work, instead of point matching, we adopt the Galerkin procedure in the MOM scheme, implying usage of Gaussian and Pulse functions for testing time and space variables, respectively. The Galerkin procedure offers several advantages and makes the algorithm extremely efficient. First of all, in the new procedure the MOM matrix of dimension N is a block-wise lower triangular matrix and hence easily solvable without a computationally expensive matrix-inversion. Next, the lower triangular matrix is also a block Toeplitz matrix with each block of dimension N_s. Thus, we need to compute only $N \times N_s$ elements compared to N^2 elements as in the aforementioned paper. Since the matrix inversion step is eliminated, the new algorithm is very efficient and remains stable for very long solution times. Several numerical results are obtained using the new procedure and compared with other methods for accuracy and efficiency.

Accuracy-Controlled and Structure-Preserved $\mathcal{H}^2$-Matrix-Matrix Product in Linear Complexity

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The $\mathcal{H}^2$-matrix (S. Börm, Computing, vol. 77, pp. 1–28, 2006) is a general mathematical framework for compact representation and efficient computation of large dense systems. Both partial differential equation and integral equation operators in electromagnetics can be represented by $\mathcal{H}^2$-matrices with controlled accuracy. For example, the matrix structure resulting from a fast multipole method (FMM) (W. C. Chew *et al.*, Fast and efficient algorithms in computational electromagnetics, Norwood, MA: Artech House, 2001.) is an $\mathcal{H}^2$-matrix, which has a sparse transfer matrix, diagonal coupling matrix, although its rank is full asymptotically for analyzing electrically large problems. The development of H2- matrix arithmetic such as addition, multiplication, and inverse are of critical importance to the development of fast solvers in electromagnetics (W. Chai, D. Jiao, IEEE Trans. MTT, vol. 59, no. 10, pp. 2404–2421, Oct. 2011). Under the $\mathcal{H}^2$-matrix framework, it has been shown that an $\mathcal{H}^2$-matrix-based addition, matrix-vector product (MVP), and matrix-matrix product (MMP) all can be performed in linear complexity for constant-rank $\mathcal{H}^2$(S. Börm, Computing, vol. 77, pp. 1–28, 2006). However, the accuracy of existing $\mathcal{H}^2$-MMP algorithm like (S. Börm, Computing, vol. 77, pp. 1–28, 2006) is not directly controlled. This is because given two $\mathcal{H}^2$-matrices $\mathbf{A}_{\mathcal{H}^2}$ and $\mathbf{B}_{\mathcal{H}^2}$, the matrix structure and cluster bases of their product $\mathbf{C} = \mathbf{A}_{\mathcal{H}^2} \times \mathbf{B}_{\mathcal{H}^2}$ are assumed, and a formatted multiplication is performed, whose accuracy is not controlled. For example, the row cluster bases of $\mathbf{A}_{\mathcal{H}^2}$ and the column cluster bases of $\mathbf{B}_{\mathcal{H}^2}$ are assumed to be those of $\mathbf{C}$. This treatment lacks accuracy control since the original cluster basis may not be able to represent the new content generated during the MMP procedure. One can find many cases where a formatted multiplication can fail. The posterior multiplication in (S. Börm, Europ. Math. Soc. Tracts Math., 14, 2006.) is more accurate than the formatted multiplication in (S. Börm, Computing, vol. 77, pp. 1–28, 2006). But it is only suitable for special $\mathcal{H}^2$-matrices. In addition, this posterior multiplication requires much more computational time and memory than the formatted one. In this work, we propose a new algorithm to perform the $\mathcal{H}^2$matrix-matrix multiplication with controlled accuracy. The cluster bases are updated based on the prescribed accuracy during the computation of the matrix-matrix product. Meanwhile, we are able to keep the computational complexity to be linear for constant-rank $\mathcal{H}^2$. For variable-rank cases such as those for electrically large analysis, the proposed MMP is also efficient since it only involves $O(2^l)$ computations at level l, each of which costs $O(r_l^3)$ only, where r_l is the rank at tree level l. This algorithm serves as a fundamental arithmetic in the error-controlled fast inverse, LU factorization, solution for many right hand sides, etc. Numerical experiments have demonstrated its accuracy and low complexity.

Session:

Fast computational methods for forward and inverse problems

Organized by

Amir Boag, Xudong Chen and Jian-Ming Jin

Accelerating the DGFM Active Impedance Matrix Calculation with the Equivalent Dipole-Moment Method

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The Domain Green's Function Method (DGFM) and its enhancement through the iterative Jacobi approach (D.J. Ludick et al., IEEE Trans. Antennas Propagat., vol. 62, no. 4, pp. 1-11, 2014) is a novel method-of-moment based domain decomposition technique to analyse finite antenna arrays consisting of identical, disconnected elements. Fundamental to the DGFM is the calculation of the active impedance matrix for each array element. This matrix is formulated as a weighted summation of the self-interaction matrix for the array element, to which the coupling sub-matrices are added that account for the surrounding array environment. When considering the computational runtime for the algorithm, this step in the solution process dominates the runtime. In (D.J. *et al.*, ICEAA 2014, pp. 636-639, 2014), the Adaptive Cross Approximation (ACA) was used to obtain a low-rank approximation for the coupling terms that significantly accelerated this summation. In this work, an alternative approach is proposed to accelerate this calculation based on representing the reaction between two separated basis functions with the Equivalent Dipole-Moment (EDM) method (J. Yuan, *et al.* IEEE Antennas Wireless Propagat. Lett., vol. 8, pp. 716-719, 2009).

Generalized Source Integral Equations with Improved Shields

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The Generalized Source Integral Equations (GSIE) is a family of integral formulations, designed to produce inherently compressible matrices, and thus enable fast direct solution. These formulations employ highly directional sources with complex radiation patterns rather than the conventional non-directional sources. Such sources suppress line-of-sight interactions between basis and testing functions on opposite sides of essentially convex scatterers, thus effectively reducing the problem's dimensionality. The dimensionality reduction enables compression and solution of two- and three-dimensional problems at $O(N \log N)$ and $O(N^{3/2})$ complexity, respectively, (N designates the number of unknowns in the discretized problem). In an attempt to design such directional sources, we focus on sources that make use of elliptical scatterers as "shields". For these sources, a modified Green's function (MGF) comprising the direct free-space elemental source radiation and a contribution from the currents on the "elliptic shield" is computed. Having shields associated with each of the original geometry's basis functions, rather than a single large shield that is fixed in position and orientation, enables geometrical adaptivity and the extension of the method beyond essentially circular problems (Y. Brick, *et al.*, IEEE Trans. Antennas and Propagation, vol. 62, no. 8, 2014, pp. 4314-4324). For the Green's function of a PEC or a dielectric elliptic cylinder we follow the standard procedure of separating the Helmholtz equation in elliptic coordinates. The field outside the PEC elliptic cylinder or the fields inside and outside the dielectric elliptic cylinder are each expressed by means of products of radial and angular Mathieu functions. Radial Mathieu functions are expanded by Bessel functions to ensure a rapid convergence while angular Mathieu functions are developed as harmonic series. The boundary value problem is solved by enforcing the continuity of the tangential field components on the elliptic cylinder, i.e., by equating angular Mathieu functions. Different from the case of a dielectric circular cylinder the angular functions in domains with different material properties are not orthogonal which has to be considered in case of the dielectric elliptic cylinder. To enable fast direct solution at an $O(N \log N)$ cost, several botlenecks should be removed. The GSIE based direct solver's performance and accuracy will be demonstrated.

Self-Dual Wideband Absorbers

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Electric-magnetic homogeneous media obeying the Weston condition $\varepsilon_r = \mu_r$ produce zero backscattering at a planar interface with free space in response to a normally incident plane. Since both ε_r and μ_r may be complex, the incident power can be made to be fully absorbed in the structure over a very wide range of frequencies. In order to facilitate possible realizations, such structures have been approximated by checkerboard-like partitioning of the medium into finite electric-only and magnetic-only regions across the interface. Our previous studies have demonstrated, however, that this type of partitioning can be designed to yield inherently zero backscatter on its own merits, not merely as an approximation to the homogeneous case. In addition, when the structure is embedded in a single mode environment, e.g., a periodic arrangement whose unit cell is smaller than the wavelength, all the incident power is transferred across the interface with no reflection, i.e., the medium is "perfectly matched". To achieve this, all cross sections parallel to the interface should be designed as self-dual. Self-duality means that the cross section remains unchanged when the electric and magnetic regions are interchanged, except for a 90° rotation around the axis of propagation. Checkerboard-like structures with square regions are then perceived as a special case of the above.

Cross sections can vary in shape and mutual electric-magnetic orientation, with abrupt changes also possible. Yet, no local reflections are observed, thanks to buildup of local evanescent modes that support this smooth transition. Specific designs have made it possible, for example, to funnel the energy though very narrow bores when the structure has low losses. Here, we make use of complex constitutive parameters to achieve superior absorption relative to conventional absorbers. Many configurations are possible, making the design process quite flexible and adaptive.

Back-Projection Cortical Potential Imaging Using a Multi-Resolution Optimization Algorithm

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Over the last decade, electroencephalogram (EEG) has evolved to be a well-established brain activity imaging tool. This progress is mainly due to high-resolution (HR) EEG methods. These methods aim to reduce the smearing of the scalp potentials, which is the effect of the low-conductive skull. One type of these HR-EEG is the cortical potential imaging (CPI) that estimates the detailed cortical potential distribution from the measured scalp EEG potentials, known as the inverse problem. Even though some of these methods exhibit good performance, most of them holds inherent inaccuracies and limits out-coming from their principle of operation, which is mostly based on a set of constraints on the solution. Some other CPI methods exhibit good results but are computational exhaustive. The back-projection CPI (BP-CPI) method (D. Haor, *et al.*, IEEE Trans. Medical Imaging, vol.36, No.7, July 2017.) has the advantages of being constraint free and computation inexpensive along with good estimation accuracy. However, better performance must be achieved. This study proposes two improvements to the BP-CPI algorithm. Both improvements are successive stages to the BP-CPI and based on the multi-resolution (MR) optimization approach. The proposed techniques take the BP-CPI solution and cluster it to N regions. These regions potentials are optimized, in the N-dimensional space to fit the measured EEG. When this optimization is done, the regions are divided into smaller regions and the procedure repeats until no more divisions can be done. This yields very fast and accurate optimization scheme. The two techniques presented are the random multi-resolution CPI (rMR-CPI) and the discrete multi-resolution (dMR-CPI). The difference between the two techniques comes in the division approach. In the dMR, in each stage each group of cortical nodes are divided into two. In the rMR in each stage smaller independent groups are created, having the same area as the once generated in the dMR, but with their center-point moved by a predefined random factor. A series of simulations were performed to examine the proposed improvements. The results have shown fast convergence to highly accurate cortical potential estimations, demonstrating accuracy of 96% (rMR-CPI) and 93% (dMR-CPI), relative to the BP-CPI which has shown accuracy of 85%. The MR-CPI methods were shown to be reliable CPI methods enabling researchers fast and robust high-resolution EEG. References

A Parallelized Multi-Solver Algorithm for Solving Large and Complex Electromagnetic Problems

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A parallelized multi-solver algorithm based on Robin transmission condition (MS-RTC) is developed on distributed computing systems. To solve large and complex electromagnetic problems using the MS-RTC method, the object with its background is partitioned into multiple non-overlapping subdomains based on their respective material properties, which are modeled by either the finite element method or the method of moments (MoM). Each subdomain problem in the MS-RTC method is solved in parallel to achieve a better efficiency. In particular, for the subdomains modeled by the MoM, the parallelized multilevel fast multipole algorithm is applied to accelerate the computation on many processors. Numerical examples are given to show the parallel efficiency and modeling capability of the proposed algorithm.

Effects of Multiple Scattering on Resolution of Full-Wave Inverse-Scattering Solver

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Inverse-scattering techniques have wide applications in quantitatively determining either physical or geometrical properties in various fields. For example, since one only needs to collect the scattered fields outside of the unknown objects without drilling holes into them, inversion methods act as a powerful tool in non-destructive evaluation/testing. Nevertheless, the inverse-scattering problem is very challenging due to its ill-posed and nonlinear properties. In this paper, we study and analyze the effects of multiple scattering on the resolution of full-wave reconstructions in inverse-scattering problems, where both theoretical analyses and numerical simulations have been done. In the numerical experiments, subspace-based optimization method is used to reconstruct permittivities of scatterers from scattered fields for weak, moderate, and strong scatterers under different noise levels. It is found that, for weak scatterers, inversion is unstable, especially when noise is high. For strong scatterers, one can hardly obtain a solution that is close to the exact one even when the noise level is low. Furthermore, for moderate scatterers, the inversion is more stable than weak scatterers and one is able to find a solution that is close to the exact one with the optimization method.

Fast Direct Solution of Electromagnetic Scattering with An Enhanced Skeletonization Scheme

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Fast direct solvers based the skeletonization algorithm have been proposed in the last few years. These solvers have several attractive features over iterative solvers because they do not suffer from convergence problems and are very suitable to solve multiple right-handsides vectors. In general, this kind of algorithm involves two main processes: selecting skeletons and computing inverse. The interpolative decomposition is utilized to select the skeleton basis functions in each group. With the use of the Huygens' principle and the proxy surface, the skeletons will be selected efficiently. And, the inverse of impedance matrix can be executed in a recursive manner. However, these solvers can be further improved in terms of the computational efficiency. (1) Conventionally, the dense proxy matrices for selecting skeletons are solved by the standard MoM with $O(N^2)$ complexity. Since such implementation must be repeated for each group, it is very time consuming. (2) The inverse process involves many direct sub-matrices inverse and matrix-matrix multiplication. With the dimension of the sub-matrices increasing, the cost for computing inverse grows high.

In this work, an enhanced skeletonization scheme is proposed to further improve the computational efficiency for analyzing scattering from electrically conducting objects. The contributions for the present algorithm involves two aspects: reducing the cost for filling proxy matrices and modifying the inverse process. To reduce the filling time of proxy matrices, the proxy surface is discretized by the points rather than the auxiliary RWG basis functions. The number of points is considerably small compared with RWG basis functions. Moreover, the selected skeleton basis functions in neighboring groups are used to construct the local matrices instead of all basis functions. So the dimension of the dense proxy matrices for each group can be reduced remarkable in this way. On the other hand, a multiplicative factorization technique is utilized in the inverse process, which is based on the property of the projection matrices obtained by interpolative decomposition in each level. Then the redundant basis functions can be removed in the modified inverse process. Finally, the block diagonal sub-matrices can be easily solved by LU decomposition. The accuracy and efficiency of the proposed method will be validated by several numerical results.

Florence FEM2016 Recollection

Some FEM2016 Memories

This last section hold few memories from last workshop edition, the 13th, held in Florence, Italy, on 16-18 May 2016, chaired by R.D. Graglia (Politecnico di Torino, Italy) and G. Pelosi (University of Florence, Italy).

Image from FEM2016 call for papers

In that occasion a silver "Fiorino" coin, a licensed reproduction of the original currency minted in Florence since 1252 up to mid XIX century and which was the preferred currency all over Europe during the reinassance.

The reproduction of the "Fiorino" coin still minted by hand in Florence by licensed goldsmiths.

On next two pages the report appeared on IEEE AP Magazine (Vol. 58, No. 5, 2016) is reproduced, while the last pages reproducs few photos taken during the workshop.

13th International Workshop on Finite Elements for Microwave Engineering

Stefano Selleri

The 13th International Workshop on Finite Elements for Microwave Engineering (FEM2016) was held 16–18 May 2016 in Florence, Italy. It was co-organized by the Politecnico di Torino under Cochair Roberto D. Graglia and the University of Florence under Cochair Giuseppe Pelosi. This biannual workshop returned to it origins after traveling the world for 26 years, growing and maturing.

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It began as a national workshop organized by the University of Florence in San Miniato, Pisa, in 1992. Many foreign speakers were invited to attend, the most notable of which was Prof. Peter P. Silvester. On that occasion, a fruitful collaboration began between Prof. Pelosi and his group at the University of Florence and Prof. Silvester and his group at McGill University in Canada. This alliance was concretized by the decision to organize a second, truly international symposium in 1994 in Siena, Italy.

Since that time, the FEM has matured to be a highly focused, biannual event that provides an ideal place for researchers in the finite-element area. It is now an itinerating workshop that takes place in many countries (Figure 1).

The 2016 conference featured 70 papers, divided into 12 technical sessions, plus two keynote speeches by Prof. Jon P. Webb of McGill University and Prof. John L. Volakis of The Ohio State University in Columbus. At the end of their lectures, the invited speakers were given a sterling silver fiorino, a perfect and licensed reproduction of

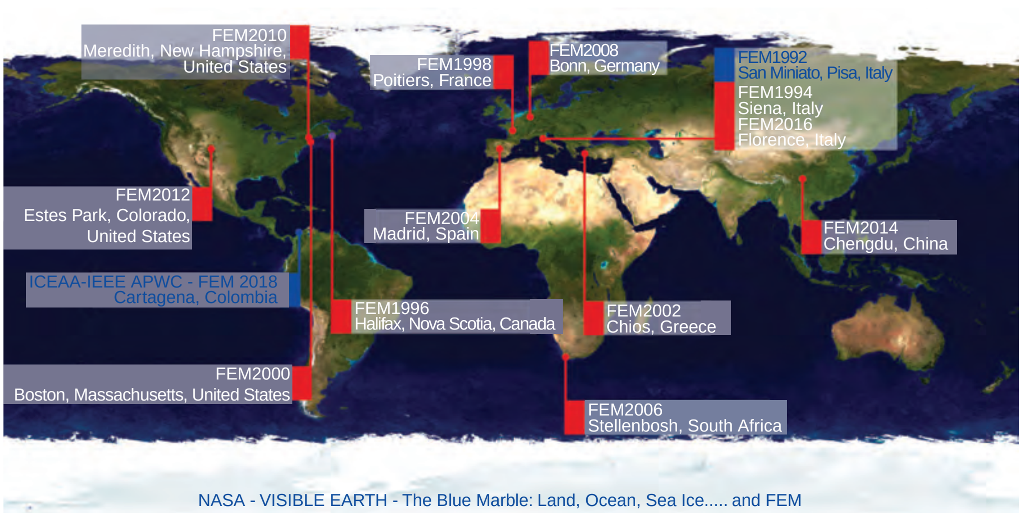


FIGURE 1. The past FEM locations and the proposed location for FEM2018. (Image courtesy of NASA.)

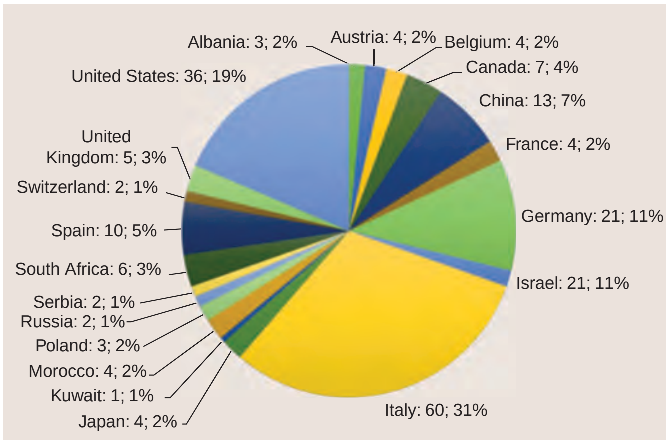


FIGURE 2. The FEM2016 authors grouped by country.

FIGURE 3. Prof. Roberto D. Graglia, past president of the IEEE Antennas and Propagation Society, welcomes all participants to the opening session held in the Aula Magna Rectorate of the University of Florence.

FIGURE 4. Prof. Jon P. Webb gives his keynote speech in the Aula Magna Rectorate of the University of Florence.

FIGURE 5. FEM2016 attendees dine in the Mirror Room at Palazzo Borghese, one of the preeminent neoclassical palaces in Florence.

the original fiorino coin, which was the currency in Florence from the 13th to 19th centuries and one of Europe's main currencies. The coin was either 24-karat gold or sterling silver and weighed 3.54 g, and it is still minted one by one by hand and hammer. The University of Florence has decided that a fiorino will be bestowed as an award, according to the rules to be defined, at FEM2018, which will be held in conjunction with the 2018 International Conference on Electromagnetics in Advanced Applications–IEEE Antennas and Propagation Society Topical Conference on Antennas and Propagation in Wireless Communications in Cartagena, Colombia (Figure 1).

From a technical point of view, the 70 papers were written by 194 authors who came from 20 countries and four continents (Figure 2). Nine of the 12 sessions were special sessions:

- "Multi-Physics FEM Techniques in the Simulation of Semiconductor Devices," organized by G. Ghione
- "Advanced FEM and Hybrid Techniques I and II," organized by B. Notaros and J. Zapata
- "Optimization Techniques and Parameter Space Sweep," organized by R. Dyczij-Edlinger
- "FEM in Italy I and II," organized by A. Toscano and A. Laudani
- "Acceleration/Preconditioning Techniques for Large Problems," organized by A. Boag and B. Shanker
- "Integral Equation/BEM Methods," organized by A. Boag and B. Shanker
- "Parallel Computation on Multi- and Many-Core Computers," organized by A.E. Yılmaz.

The three regular sessions were "FEM Applications," "Domain Decomposition and Non-Linear FEM," and "FEM Theory."

Because FEM2016 was a special conference, its proceedings are available as a book (which also contains memorabilia covering the previous workshops) and as an open-access PDF document from Firenze University Press at http://www.fupress.com/catalogo/international-workshop-on-finite-elements-for-microwave-engineering/3127.

Figures 3–5 show some events of FEM2016, both technical and social. The chairs and I thank all of the attendees, speakers, and session organizers for contributing to its success, and we invite all of you to Cartagena in 2018.

May 16, 2016

People attending the opening session in the *Aula Magna* of the Rectorate of the University of Florence.

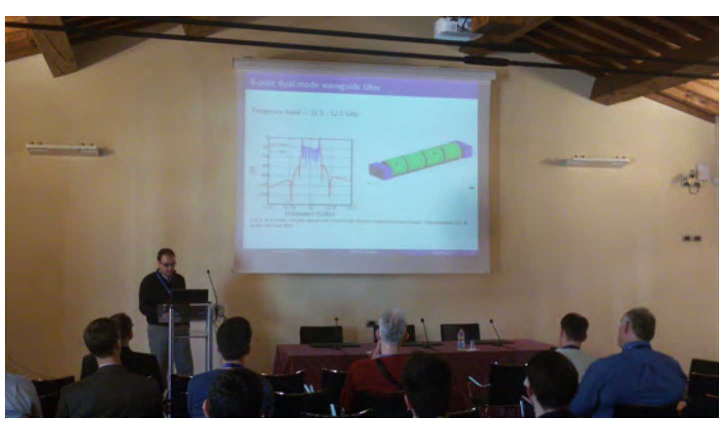
Invited lecture by J.L. Volakis (then: Ohio State University, USA, now Florida International University, USA) in the *Aula Magna* of the Rectorate of the University of Florence.

Welcome drink in the cloister of the Rectorate of the University of Florence.

Registration desk at the Rectorate of the University of Florence, members of the local commitee E. Agastra (left - Polytechnic University of Tirana, Albania) and M. Righini (right - University of Florence, Italy) at work.

May 17, 2016

R.D. Graglia (Politecnico di Torino, Italy) presenting a paper in the morning session in Room B of the *Centro Arte e Cultura* in front of the Baptistery and the *Duomo* of Florence.



V. de la Rubia (Universidad Politecnica de Madrid, Spain) presenting a paper in the afternoon session in Room A of the *Centro Arte e Cultura* in front of the Baptistery and the *Duomo* of Florence.

Musical welcome in Reinassance costumes at *Palazzo Borghese*, for the social dinner.

Social dinner in the mirrors room in *Palazzo Borghese*.

May 18, 2016

Closing remarks by the Workshop Scientific Secretary S. Selleri (University of Florence, Italy) at the *Centro Arte e Cultura* in front of the Baptistery and the *Duomo* of Florence.

About the Conferences:

ICEAA 18 :: The twentieth edition of the International Conference on Electromagnetics in Advanced Applications (ICEAA 2018) is supported by the Politecnico di Torino, by the National University of Colombia, and by the Torino Wireless Foundation, with the principal technical cosponsorship of the IEEE Antennas and Propagation Society and the technical cosponsorship of the International Union of Radio Science (URSI).

IEEE-APWC 18 :: The eighth edition of the IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications.

FEM 18 :: The fourteenth International Workshop on Finite Elements for Microwave Engineering (FEM 2018) organized in cooperation with ICEAA. The Workshop is a highly-focused biannual event. It provides an ideal meeting place for researchers and practitioners active in the theory and application of the Finite-Element Method in RF and microwave engineering.

These Conferences are co-sponsored by the IEEE Antennas and Propagation Society and consist of invited and contributed papers. They share a common organization, registration fee, submission site, workshops and short courses, banquet, and social events. The proceedings of the conferences will be submitted to the IEEE Xplore Digital Library.

About the Session Organizers:

Amir Boag :: Department of Physical Electronics, Tel Aviv University, Israel.
Xudong Chen :: Department of Electrical and Computer Engineering, National University of Singapore, Singapore.
Roberto D. Graglia :: Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, Turin, Italy.
Jian-Ming Jin :: Electrical & Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
Branislav Notaroš :: Electrical & Computer Engineering Department, Colorado State University, Fort Collins, CO, USA
Stefano Selleri :: Department of Information Engineering, University of Florence, Florence, Italy.
Donald R. Wilton :: Department of Electrical and Computer Engineering, University of Houston, Houston, TX, USA