Guest Editorial for the Special Issue on Large and Multiscale Computational Electromagnetics

IT IS ALREADY eleven years since the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION published its special issue on "Advanced Numerical Techniques in Electromagnetics" (March 1997). During this time, the state of the art in computational electromagnetics (CEM) has evolved tremendously. Both the algorithmic complexity and predictive power of today's CEM tools have advanced well beyond what anyone could have imagined a decade ago. Without a doubt, the sustained growth in computer power fueled by Moore's law played an important role in this development. However, it is the multitude of CEM breakthroughs—ranging from novel integral- and differential-equation formulations, to ingeniously designed hybrid algorithms and effective domain decomposition techniques and preconditioners, to parallel solvers and physics-inspired basis functions—that has contributed most to this transformation. Today, CEM has gained a strong foothold in many academic and industrial settings seeking to analyze and design high-frequency circuits, antennas and wireless communication systems, characterize EMI/EMC phenomena, compute scattering cross sections, and understand bio-electromagnetic effects.

The objective of this Special Issue is to report on recent advances in the areas of differential and integral equation solvers, their hybridization, and application to challenging real-world problems. The 28 papers appearing in this Special Issue were selected from those submitted in response to the Call for Papers (23) and papers accepted by the Editorial Board in the Spring of 2008 (five). Considerably more papers were submitted in response to the Call but after a rigorous process of review the present set of papers remained.

This Special Issue starts with five papers on the finite-difference time-domain (FDTD) method, then proceeds with five on the finite-element method (FEM) and eighteen on integral equation (IE) solvers. A brief overview of their contribution to the CEM state of the art follows.

I. FDTD

The FDTD papers in this issue review the state of the art in the field, introduce new FDTD stencils with improved accuracy, describe implementations targeting the analysis of ultra-large scale phenomena on parallel computers, and demonstrate the power of the FDTD method in multiphysics simulations. First, Teixeira reviews the state of the art in both finite-difference and finite-element time-domain solvers for anisotropic, dispersive, and nonlinear media. His paper provides an up-to-date and comprehensive list of references on the subject. Then Chilton and Lee present a high-order accurate FDTD scheme that uses the Lobatto cell to reduce numerical dispersion and improve on the convergence of the classical Yee scheme. Specifically, they illustrate the use of the Lobatto cell to enable the modeling of discontinuous interfaces without sacrificing accuracy. Bettencourt and Greenwood demonstrate the performance of a parallel algorithm for simulating electromagnetic and low-density plasma phenomena using thousands of processors and discuss issues key to achieving optimal parallel FDTD performance. Their paper is followed by that of MacGillivray, which describes an FDTD mesh generation technique capable of generating a trillion-cell mesh on a single workstation. The last FDTD paper is by Buerkle and Sarabandi, who applied the FDTD method to study two-dimensional electromagnetic interactions with vibrating objects. Their technique potentially can be applied in the field of nondestructive testing.

II. FEM

The FEM papers in this issue introduce highly efficient domain decomposition and massively parallel methods for analyzing large-scale phenomena, and review the state of the art in FEMs for antenna analysis and high-order accurate simulations. Lü *et al.* describe a domain decomposition algorithm based on partial solution vectors for the FEM simulation of large-scale electromagnetic problems. They applied their method to the analysis of a variety of finite arrays, exploiting geometric repetitions whenever possible to further accelerate the analysis. Another domain decomposition method proposed by Zhao *et al.* decomposes the entire problem domain into disjoint subregions, partitions each subregion into subdomains, and then couples the subregions using boundary IEs. Their method gains the upper hand over existing ones when analyzing scattering from multiple separated targets. The next paper by Jin *et al.* reviews FEMs for analyzing complex antennas and arrays. Specifically, these authors discuss a host of technical issues critical to the successful FEM analysis of antenna problems, including the modeling of complex materials and antenna feeds, mesh truncation techniques, and schemes for analyzing infinite and finite arrays, and antenna-platform interactions. The paper by Stowell *et al.* describes the implementation of the finite-element time-domain method on a massively parallel computer and demonstrates the power of the method by simulating radar wave propagation inside buildings involving over 10 billion Cartesian elements. Finally, Notaroš provides an extensive review of high-order accurate frequency-domain FEM and IE methods, discusses both high-order geometrical and field/current representations, and demonstrates the advantages of high-order methods through a variety of examples

III. IE METHODS

The IE methods in this issue introduce new techniques for modeling singular currents on nonsmooth scatterers, discuss progress in fast iterative solvers, and propose novel techniques for analyzing array antennas. In addition, they present new preconditioners and fast direct solvers, and a novel scheme for solving time-domain IEs.

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A. Singular Current Representations

Peterson *et al.* propose new expansions for singular currents to render electric field IE solvers high-order accurate even when applied to structures with corners. Their technique appears easily extendable to three dimensions and therefore promises to remove an important hurdle towards the construction of high-order accurate IE solvers for real-world structures.

B. Fast Iterative Solvers

The issue comprises seven papers that report on fast iterative solvers that are more accurate and/or CPU efficient than their predecessors. Kim and Meincke report on a new adaptive integral method-accelerated IE solver that uses high-order basis functions to drastically improve on the accuracy and CPU/memory efficiency of previous implementations. Rius *et al.* report on an extension of the multilevel matrix decomposition algorithm that uses singular value decompositions to compress its operators. Contrary to fast multipole method-accelerated solvers, their technique can be applied on top of existing integral equations solvers irrespective of the Green function used. In a similar vein, Rodriguez *et al.* present a singular value compression algorithm to improve the efficiency of fast multipole methods. By applying a singular value decomposition to the plane-wave fast multipole aggregation matrix, they achieve an order-of-magnitude reduction in computational cost and memory requirements without compromising the solution accuracy. Ergul and Gurel describe a state-of-the-art parallel fast multipole solver capable of handling tens of millions of degrees of freedom on widely available computer platforms. Their solution to well-known fast multipole parallelization bottlenecks is sure to assist many fast multipole practitioners in extending the reach of their codes. Their parallelization strategy should be contrasted with that of Fostier and Olyslager, whose first of a kind asynchronous implementation avoids communication bottlenecks and appears highly suited when using slow interconnection networks. Hannien proposes a new scheme to evaluate the fast multipole translation operator at minimal computational cost that uses a fast Fourier transform to oversample and then interpolate tabulated operators. He provides tables detailing optimal parameter choices that could find widespread use by fast multipole implementers aiming to further hone their codes. Finally, Catedra *et al.* propose a new solver that hybridizes the characteristic basis function method and the fast multipole algorithm to significantly extend the reach of both schemes.

C. Antenna Analysis

The accurate analysis of antennas invariably calls for IE solvers that are quite different from those targeting scattering applications. This issue contains two papers on the topic. First, Dardenne and Craeye describe an efficient method for simulating infinite doubly periodic structures with elements comprising dielectric and perfectly conducting components. By incorporating fast summation methods into IE formulations applicable to both components, they successfully analyze arrays of tapered-slot antennas embedded in dielectric slabs. Second, Mumcu *et al.* present a technique for analyzing finite layered uniaxial structures. Their technique extends upon existing methods for analyzing scattering from dielectric objects and enables the characterization of antennas printed on anisotropic substrates.

D. Preconditioning

Iterative IE solvers, whether accelerated or not, often converge slowly (or not altogether) when applied to the analysis of real-world, multiscale and/or low-frequency problems. The development of powerful preconditioners is a very active research topic, as evidenced by the following five papers in this issue. Chew and Li develop an improved version of their equivalence principle algorithm that uses a new high-order field sampling scheme to more efficiently and accurately treat metal-to-dielectric interfaces. Their technique not only proves to be more error controllable than previous ones, but also lowers condition numbers when analyzing multi-scale structures. Andriulli *et al.* describe a new Calderon preconditioner for the electric field IE that eradicates dense mesh breakdown phenomena. Contrary to its predecessors, their preconditioner is purely multiplicative, easily integrated into existing solvers, and applicable to open structures. In a separate paper, Andriulli *et al.* elucidate the construction of hierarchical, multi-scale functions, which are linear combinations of the well-known Rao-Wilton-Glisson functions. The preconditioner that results from the use of these basis functions produces well-conditioned linear systems immune from low-frequency breakdown. Hesford and Chew propose a new block preconditioner that operates hand-in-glove with multilevel fast multipole algorithms to facilitate the analysis of structures with highly nonuniform meshes. They apply their technique to the analysis of various real-world antennas intractable by unpreconditioned solvers. Finally, Naenna and Johnson propose a new non-algebraic preconditioner for accelerating the analysis of rough surface scattering phenomena. Their preconditioner implements an approximate solution to the scattering problem at hand using spectral methods, and is shown to outperform banded matrix preconditioners for surfaces of small to moderate roughness.

E. Direct Solvers

Direct as opposed to iterative solvers represent an important new research direction in CEM. Schaefer applies the popular adaptive cross approximation scheme to rapidly invert impedance matrices stemming from the IE analysis of low- to mid-frequency scattering problems. He demonstrates the power of his scheme by inverting impedance matrices involving over a million unknowns on a PC! Adams *et al.* review their efforts towards constructing fast direct solvers by exploiting the notion of "local-global solution modes." They show that in an h-refinement environment, their technique permits factorization and storage of an IE impedance matrix using O(N log N) CPU resources and O(N) memory resources, respectively. As such, their solver directly competes with iterative fast multipole ones.

F. Time-Domain IEs

The issue contains a single paper on time-domain IEs, in which Wang *et al.* present a radically new technique to time advance solution vectors that relies on a frequency-domain inspired finite-difference delay scheme. Without a doubt, their scheme opens up new avenues for constructing fast and unconditionally stable time-domain IE solvers.

IV. Conclusion and Acknowledgment

The progress reported in this Special Issue notwithstanding, many long-standing CEM problems remain unsolved. In addition, new opportunities as well as challenges are introduced on a continuous basis as simulation needs and hardware evolve. The CEM holy grail, viz. the construction of a fast solver, whether differential or integral equation based, that seamlessly applies across spatial and frequency/temporal scales and interfaces with multiphysics simulators originated in other disciplines, remains as elusive as ever before. Not surprisingly, the CEM field continues to attract new researchers worldwide.

We close this Editorial by expressing our thanks to all the authors and the 80-plus reviewers, who completed their effort in a mere eight months, thus ensuring the timely publication of this Special Issue. We also sincerely thank the Editor-in-Chief, Dr. Trevor Bird, and the Editorial Assistant, Ms. Dallas Rolph, for their advice, help, and the occasional nudge. Their immeasurable contributions to this Special Issue are greatly appreciated.

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Prof. Michielssen is an elected Fellow of the IEEE and a member of URSI Commission B. He received a Belgian American Educational Foundation Fellowship in 1988 and a Schlumberger Fellowship in 1990. Furthermore, he was the recipient of a 1994 International Union of Radio Scientists (URSI) Young Scientist Fellowship, a 1995 National Science Foundation CAREER Award, and the 1998 Applied Computational Electromagnetics Society (ACES) Valued Service Award. In addition, he was named 1999 URSI United States National Committee Henry G. Booker Fellow and selected as the recipient of the 1999 URSI Koga Gold Medal. He also was awarded the UIUC's 2001 Xerox Award for Faculty Research, appointed 2002 Beckman Fellow in the UIUC Center for Advanced Studies, named 2003 Scholar in the Tel Aviv University Sackler Center for Advanced Studies, and selected as UIUC 2003 University and Sony Scholar. He served as the Technical Chairman of the 1997 Applied Computational Electromagnetics Society (ACES) Symposium (Review of Progress in Applied Computational Electromagnetics, March 1997, Monterey, CA, and served on the ACES Board of Directors (1998-2001 and 2002-2003) and as ACES Vice-President (1998-2001). From 1997 to 1999, he was as an Associate Editor for *Radio Science*, and from 1998 to 2005 he served as Associate Editor for the IEEE Transactions on Antennas and Propagation.

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