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14. ABSTRACT

New fast time domain integral equation (TDIE) solvers for analyzing large-scale electromagnetic scattering and radiation phenomena were developed. These solvers were accelerated using a host of new Plane Wave Time Domain (PWTD) algorithms. PWTD augmented TDIE solvers accomplish for the time domain wave equation (and related Maxwell's equations) what fast multipole methods previously achieved for the Poisson and Helmholtz equations, viz. a significant reduction in computational cost of the integral equation based analysis of large-scale problems through a diagonal representation of field translation operators. The computational cost of analyzing transient surface scattering phenomena using PWTD-enhanced, MOT-based TDIE solvers scales nearly linearly in both the number of spatial and temporal degrees of freedom, that is, far more favorable than that of classical TDIE solvers. The new computational technologies developed were applied to the analysis of scattering and radiation from conducting, resistive, and impedance boundary condition surfaces, penetrable lossless, lossy, and dispersive volumes, potentially residing in layered media, and the analysis of hybrid lumped-distributed microwave circuits involving up to one million spatial unknowns, all this for thousands of time steps. In addition, the technology was successfully applied to the analysis of complex electromagnetic compatibility phenomena of interest to the Air Force and the analysis of surface plasmon polariton propagation problems.

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1. PROGRAM GOALS AND OVERVIEW

The University of Illinois VET effort entitled "Fast Time Domain Integral Equation Solvers for Large-Scale Electromagnetic Analysis" focused on building a *broadband* "Virtual Electromagnetic Testrange" (VET), i.e., a suite of algorithms and computational tools capable of accurately and efficiently analyzing large-scale *transient* electromagnetic scattering, radiation, and guidance phenomena.

The proposed VET components (primarily) targeted the fast solution of Time Domain Integral Equations (TDIEs) pertinent to the analysis of electromagnetic boundary value problems using Marching On in Time (MOT) schemes. Prior to the effort, MOT-based TDIE solvers were known to be computationally expensive as well as inaccurate and prone to instabilities. Plane Wave Time Domain (PWTD) technology, developed just prior to the start of the effort, promised to drastically alter this state of affairs. PWTD algorithms constitute extensions of frequency-domain Fast Multipole Methods (FMMs – Helmholtz equation) to the time domain (wave equation) and permit the fast and numerically rigorous calculation of electromagnetic fields produced by known, bandlimited source constellations (from their far-field expansions), viz. the computationally most expensive operation in MOT-based TDIE solvers. In addition, rudimentary PWTD-accelerated TDIE solvers had been shown to permit the analysis of transient perfect electrically conducting (PEC) surface scattering phenomena using $O(N_t N_s \log^2 N_s)$ computational/CPU resources (as opposed to $O(N_t N_s^2)$ for classical TDIE solvers); here, N_s and N_t denote the number of spatial unknowns and time steps in the analysis, respectively. Their promise notwithstanding, at the time, PWTD-accelerated TDIE solver technology was in its infancy; as a result, its advantages w.r.t. FMM-driven frequency-domain integral equation solver technologies developed in the decade prior to the start of the VET research program remained unclear. The principal goals of the University of Illinois VET effort consisted in advancing the state of the art in PWTD-enhanced TDIE solvers and to bring their performance on par with that of FMM-enhanced frequency-domain integral equation solvers. To accomplish these goals, the effort focused on

- Developing new parallel and memory efficient PWTD kernels that permit the fast evaluation of electromagnetic fields produced by temporally bandlimited sources embedded in lossless, lossy, dispersive, diffusive, nonlinear, layered, and quasi-planar media, that apply uniformly to low- (clustered), medium-, and high-frequency source distributions.
- Developing new higher-order, error-controllable, and grid-robust TDIE solvers that permit the analysis of electromagnetic wave interactions with dispersive and nonlinear objects, and comparing the performance of the resulting solvers to that of broadband fast multipole driven frequency domain solvers. (Transient electromagnetic phenomena can be analyzed not only by direct time domain methods, but also by combined frequency domain–Fourier transform schemes. The continued development of a broadband frequency domain based electromagnetic analysis capability was required in order to properly assess the performance of direct time domain methods.)
- Validating all new PWTD kernels and TDIE solvers by applying them to pressing scientific and engineering problems, including the analysis of scattering from rough surfaces, plasmonic interfaces and patterned/perforated plates, aircraft, and cavities, the design of complex (embedded) antennas and state of the art radar systems, and the

assessment of electromagnetic compatibility, interference, and high power microwave threats.

This Final Report is organized as follows. Section 2 describes the state of the art in MOT-based TDIE technology prior to the start of the Illinois DARPA VET program. Section 3 summarizes the program's principal accomplishments. Section 4 lists personnel supported by the program. Section 5 describes current use of computational technology develop under out VET effort and technology transitions. Finally, Section 6 contains references to all journal and selected conference papers published as a result of this study. An Appendix contains abstracts to all journal papers published.

2. STATE OF THE ART IN FAST TDIE SOLVERS PRIOR TO THE ILLINOIS DARPA VET EFFORT

The research accomplished under the Illinois DARPA VET program is situated best in the context of MOT-based TDIE solver technologies available prior to the program's start. These are described next.

2.1 Classical TDIE solvers

A classical TDIE solver for analyzing transient electromagnetic scattering from perfect electrically conducting (PEC) surfaces residing in unbounded 3D lossless environments operates as follows. The extinction theorem states that the electromagnetic field anywhere in space can be evaluated upon specification of the incident field and the total magnetic field, or, equivalently, the current, on the scatterer's surface. By enforcing the tangential component of the total electric field along the surface to vanish, the surface current can be related to the incident field through an electric field TDIE. To solve this TDIE by MOT methods, the surface current is represented in terms of N_s spatial basis functions with unknown amplitudes at N_t time steps. Then, the instantaneous total electric field is expressed as a superposition of the incident and scattered fields. The evaluation of the latter requires the computation of a retarded time boundary integral over the basis functions representing the field. This procedure leads to a system of equations that can be solved for the coefficients of the basis functions representing the surface field/current at a given time step. Depending on the choice of the time step size, the basis functions, and the testing procedure, the matrix to be inverted may be diagonal or sparse, yielding explicit or implicit time stepping schemes, respectively. It has been empirically shown that implicitness and accurate evaluation of retarded time boundary integrals contribute to the stability of a MOT scheme. Unfortunately, the overall computational cost of this procedure scales as $O(N_t N_s^2)$, which prevents the application of classical MOT-based TDIE solvers to the study of practical, real-world problems. It is noted that the above cost estimate is linear in N_t only because the 3D lossless medium Green propagator is local in time. When the above procedure is applied to the study of scattering from 2D objects, or surfaces embedded in dissipative or structured (e.g., layered) environments, then the computational complexity would scale as $O(N_t^2 N_s^2)$, as Green propagators in such media all have a wake.

2.2 Fast TDIE solvers and PWTD accelerators

In the year prior to the start of the Illinois VET effort, two of its PIs (Eric Michielssen and Balasubramaniam Shanker) jointly developed (rudimentary) PWTD schemes aimed at combating the computational complexity of classical MOT-based TDIE solvers. The scheme they developed constitutes the extension of the frequency-domain FMM (Helmholtz equation and related time-harmonic Maxwell equations) to the time-domain (wave equation and related time-dependent Maxwell equations) and permits the fast evaluation of transient fields produced by known, transient source densities. The PWTD scheme operates very much like the Helmholtz equation FMM from which it was derived. That is, starting from a hierarchical spatial decomposition of source densities, it computes the fields these sources produce from their far-field plane wave expansions. "Outgoing" plane waves carrying source signals are computed recursively and translated between source and observer spheres by using so-called diagonal translation operators. "Incoming" plane waves are aggregated to obtain observer fields. The primary difference between the PWTD scheme and its FMM predecessor stems from the fact that time-domain translation operators must account for the presence of so-called ghost signals, which significantly complicates the construction of the scheme. Classical MOT-based TDIE solvers are easily retrofitted with a PWTD accelerator, thereby reducing their computational complexity to $O(N_t N_s \log^2 N_s)$.

2.3 Applications

Unfortunately, prior to the start of the Illinois VET effort, the application of the above-described PWTD-accelerated TDIE solvers was limited to the analysis of relatively small scale scattering problems involving PEC scatterers devoid of geometric details and residing in lossless 3D environments. Indeed, the schemes available at that time did not permit more complex problems to be tackled due to a lack of PWTD extensions aimed at computing fields in other than 3-D lossless environments as well as their inability to resolve geometrically clustered source distributions. Even if these issues were resolved, the application of PWTD-accelerated TDIE solver technologies to real-world problems would be impeded by the lack of robustness and accuracy of classical TDIE solvers.

The Illinois DARPA VET program was aimed at eliminating all hurdles impeding the application of fast PWTD-accelerated TDIE technology to real-world problems.

3. ACCOMPLISHMENTS

Section 3.1 presents research highlights realized under the Illinois VET effort. A detailed breakdown of accomplishments is presented in Section 3.2. A self-assessment is presented in Section 3.3.

3.1 Research Highlights

This section describes the principal research results accomplished under the Illinois DARPA VET program relating to the development of new PWTD kernels and integral equation solvers, as well as to their validation and application. It also describes developments in broadband frequency domain integral equation solvers resulting from this effort.

3.1.1 Development of new PWTD kernels

As mentioned above, the PWTD algorithm permits the efficient evaluation of transient wave fields generated by temporally bandlimited sources. The original PWTD scheme developed prior to the start of the Illinois VET effort targeted nonclustered sources residing in 3D homogeneous and lossless backgrounds.

To widen the scheme's applicability, new PWTD schemes were developed that permit the computation of fields not only in 3D lossless media, but also in 2D and layered environments that can be lossy and/or dispersive. The capabilities of the new PWTD schemes developed under the Illinois VET effort mirror those of available FMMs, thereby extending virtually all FMM technology to the time-domain.

In addition, to permit the applicability of PWTD schemes to the computation of fields produced by potentially clustered source distributions, new hierarchically adaptive PWTD schemes were developed that resolve so-called low-frequency breakdown problems encountered in the classical PWTD through the use of either high-frequency bullet fields or multipoles. Again, these developments closely track those in frequency domain FMM technology.

Finally, to render PWTD technology applicable to the calculation of fields produced by very large source constellations that are potentially active for a very long time, parallel PWTD kernels were developed. Key hurdles in mapping the PWTD scheme on a parallel machine were overcome and parallel PWTD kernels capable of computing fields due to more than 10 million point/dipole sources were demonstrated.

In conclusion, the Illinois VET effort resulted in a suite of parallel PWTD schemes that permit the fast computation of fields produced by temporally bandlimited source constellations without any restriction on the environment these sources reside in or their spatial distribution. Our effort significantly narrowed if not eliminated the theory and implementation gap that existed between PWTD and FMM technologies prior to the start of the effort.

3.1.2 Development of new integral equation solvers

Time Domain Integral equation solvers.

Prior to the development of PWTD technology, the application range of TDIE solvers did not extend beyond the analysis of scattering from small-scale PEC objects. The implementation of PWTD-accelerated TDIE solvers provided an impetus for the development of stable and higher-order accurate TDIE solvers capable of analyzing geometrically intricate combined PEC/material structures.

Using VET funding, new TDIE solvers capable of analyzing homogeneous and inhomogeneous material objects were developed – these solvers use surface or volume equivalents, or a combination of both. The solvers developed also allow for the analysis of electromagnetic interactions with hybrid PEC/material objects with wire (antenna) attachments.

These solvers were rendered stable and higher-order accurate through the first-ever use of bandlimited basis temporal functions to represent current densities. Furthermore, they were implemented, together with the above-described PWTD accelerators, on MPI-based parallel clusters.

Finally, these solvers were successfully hybridized with circuit and cable solvers (the latter was realized in part under funding from an AFOSR MURI effort) to permit their application to the analysis of radiation from, and coupling into, nonlinearly loaded cavities and electronics.

In conclusion, the new PWTD-accelerated and MOT-based TDIE solvers resulting from the Illinois VET effort now permit the analysis of scattering and radiation from conducting, resistive and impedance boundary condition surfaces, penetrable lossless, lossy, and dispersive volumes, and the analysis of hybrid lumped-distributed circuits involving up to hundreds of thousands of spatial unknowns, all this for thousands of time steps and to higher-order accuracy.

Frequency domain integral equation solvers.

VET funding also was used to advance CEM frequency domain integral equation technology in two directions: (i) high-frequency scattering analysis (the analysis of scattering from electromagnetically (very) large bodies and (ii) low-frequency scattering analysis (the analysis of scattering from electromagnetically (very) small though geometrically intricate objects). Accomplishments in both areas further our goal, viz. the construction of broadband CEM tools.

(i) High-frequency scattering analysis. The robustness of our MLFMA-based fast frequency domain integral equation solvers (FISC) was further improved their applicability to problems involving up to 20 million unknowns – a 200 wavelength diameter sphere – was demonstrated. An elusive bug was removed from our MPI driven parallel ScaleME code that ultimately allowed us to demonstrate this tour-de-force computation. A target rotation scheme was developed to reduce memory usage for MLFMA, and extensive comparisons of results from ScaleME/MLFMA and Xpatch were made. In addition, it was demonstrated that by injecting ray physics into the MLFMA, it can be made more efficient by a factor of two with some memory savings. Finally, a thorough analysis of the error characteristics of the MLFMA and FIPWA was carried out. Even though these algorithm often were said to be error controllable, such never was demonstrated explicitly. Our work rigorously shows that these algorithms, if properly executed, can be error controlled to machine precision.

(ii) Low-frequency scattering analysis. A broadband frequency domain integral equation solver for analyzing scattering from perfectly conducting objects that operates seamlessly from static to microwave frequencies was developed. The solver is accelerated by the low-frequency Fast Inhomogeneous Plane Wave Algorithm (LF-FIPWA). In addition, a method for stabilizing multi-dielectric/multi-region problem using loop-tree/loop-star (Helmholtz) decompositions was developed. It was demonstrated that, in order for a CEM solver to transition smoothly from a full-wave solver to a static solver, Helmholtz decomposition or loop-tree/loop-star decompositions are essential. This appears to be true even when second kind integral equations that show no obvious sign of low-frequency breakdown are used. These conclusions contrast those of many other researchers who have worked on stabilized electric field integral equations and who have claimed that this decomposition is not necessary.

In conclusion, the Illinois VET effort led to new broadband FMM-accelerated frequency domain integral equation solvers that, contrary to their predecessors, apply stably to both low and high-frequency scattering phenomena, thereby creating avenues for their use in the prediction of transient waveforms by Fourier transformation.

3.1.3 Validation and application

The fast, PWTD-accelerated TDIE solvers developed under the Illinois VET effort were successfully applied to a number of real-world scattering, radiation, and guidance problems. Some representative results are demonstrated below. Details regarding the various geometries and excitations studied can be found in the journal and conference papers listed in Section 7.

It should be stressed that the geometries and structures analyzed using the PWTD-enhanced TDIE solvers resulting from the Illinois VET program could not have been analyzed with classical MOT solvers available prior to its start. Indeed, these solvers were limited to the analysis of electromagnetic scattering and radiation from electromagnetically small objects devoid of dielectrics and nonlinear elements. The structures shown below, in contrast, are electromagnetically large composite PEC/dielectric objects that often contain fine geometric features (feedlines/wires/probes) and nonlinear elements (amplifiers/transistors).

In conclusion, the Illinois VET effort resulted in a suite of parallel PWTD-accelerated TDIE solvers capable of analyzing broadband electromagnetic interactions with nonlinearly loaded, geometrically intricate and electromagnetically large PEC/material scatterers. This technology will no doubt be useful in the analysis of novel antennas, complex electromagnetic compatibility/interference problems, nonlinear circuits, and radar cross sections.

Note: studies conducted on plasmon-polariton exitations on structured plates conducted under VET funding are detailed in Section 3.2 (detailed Task breakdown) as they somewhat fall outside the scope of the fast TDIE solver technology discussed here.

Example 1: radiation from array on 4-layer board.

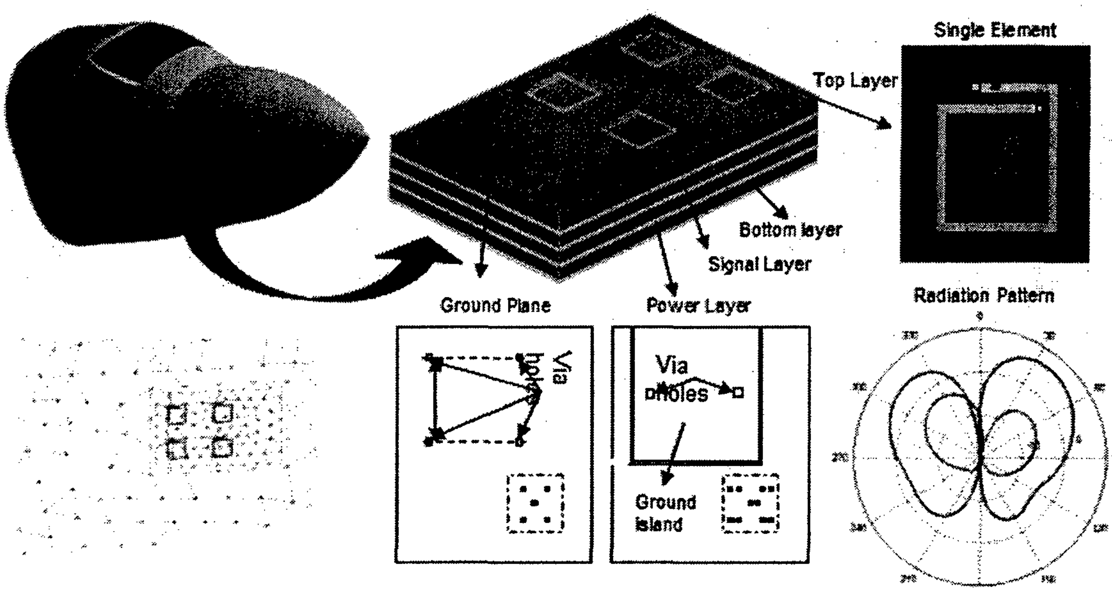
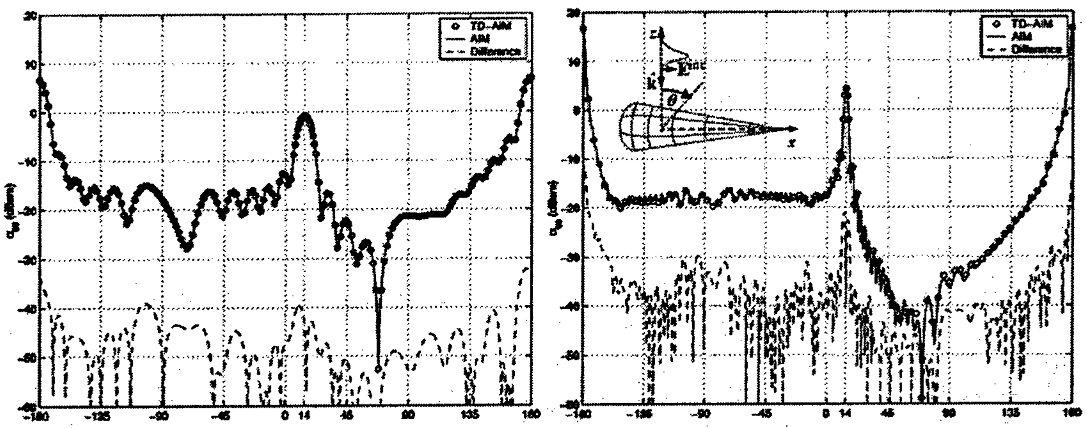


Figure 1. Radiation pattern of 2 by 2 spiral array residing on a four layer printed circuit board inclusive feed pins, signal traces, and switches..

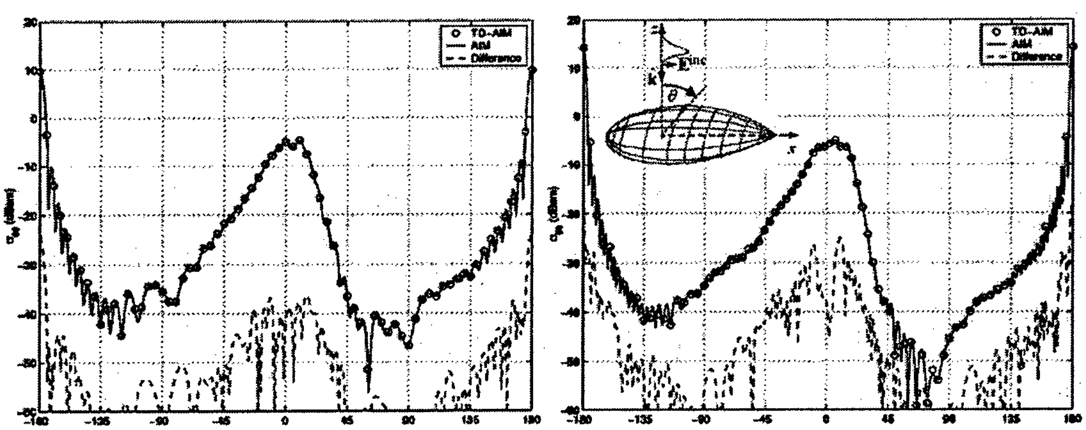
Example 2: Radar cross section of a cone-sphere



(a) (b)

Figure 2. Bistatic RCS (VV) of a benchmark conesphere in the $x-z$ plane: (a) $f_{\min}$ =2.5 GHz, (b) f_c =6 GHz , and (c) $f_{\max}$ =9.5 GHz . The cone is $19.2\lambda_{\min}$ long and the sphere part has a radius of $2.4\lambda_{\min}$. The surface of the conesphere is discretized using triangular patches, resulting in a total of N_s =62,340 RWG basis functions.

Example 3: Radar cross section of a NASA almond.



(a) (b)

Figure 3. Bistatic RCS (VV) of a NASA almond in the $x-z$ plane: (a) $f_{\min}$ =4 GHz and (b) $f_{\max}$ =24 GHz. The almond is about $20.2\lambda_{\min}$ long and its largest cross-section is an ellipse which is about $9.3\lambda_{\min}$ wide and $3.1\lambda_{\min}$ thick. The surface of the almond is discretized using triangular patches, resulting in a total of N_s =124,932 RWG basis functions.

Example 4: Range profile of a simple target

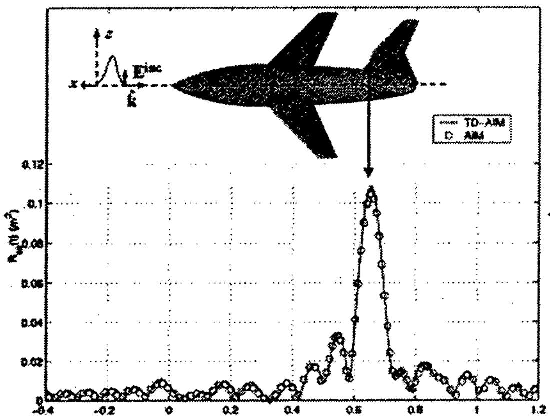


Figure 4 panels: (a) (b)

Figure 4. Range profile of a generic aircraft for (a) VV polarization and (b) HH polarization. The aircraft is of size $8.2\lambda_{\min} \times 8.1\lambda_{\min} \times 2.4\lambda_{\min}$.

Example 5: EMI/EMC analysis of electronics onboard an aircraft

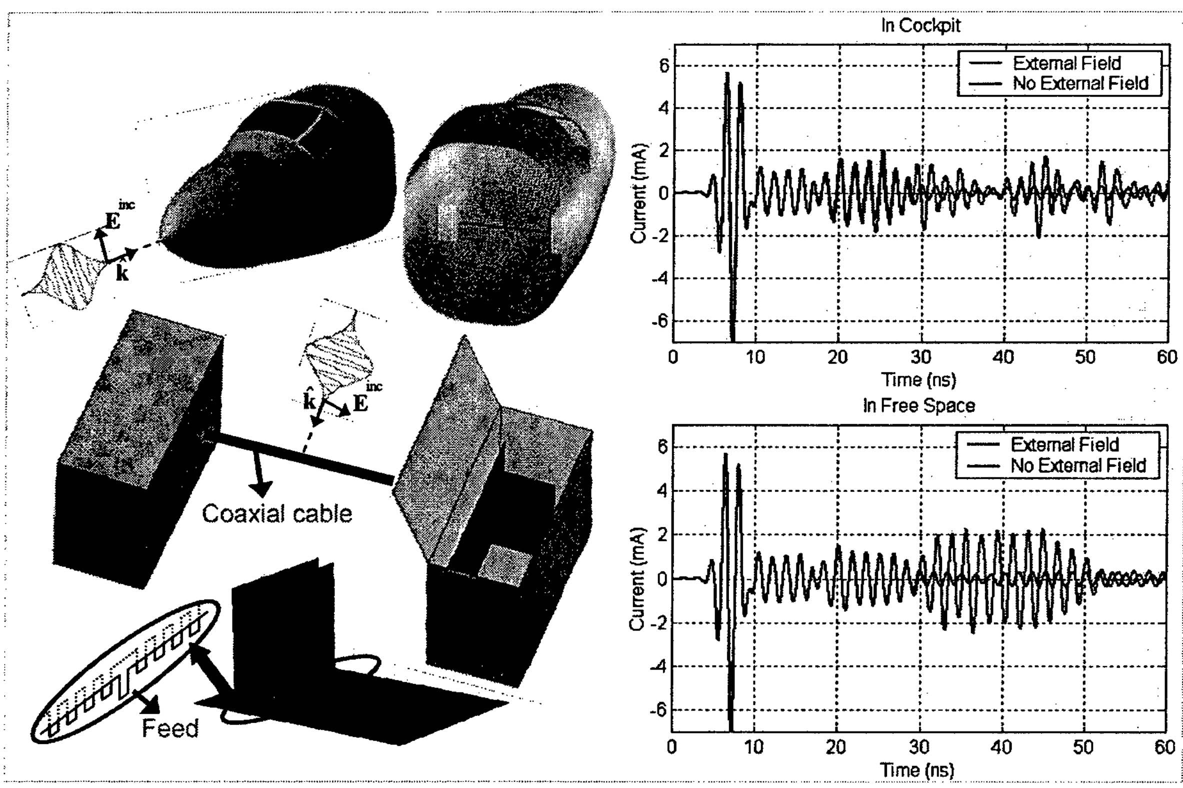


Figure 5. Current observed at the feed point of a PC-card configuration, which is completely shielded and connected to another shielded card-configuration via a coaxial cable for four different

scenarios: PC's located in cockpit with and without external field and PC's in free space again with or without external field.

Example 6: A Reflect-array configuration (nonlinearly fed antennas)

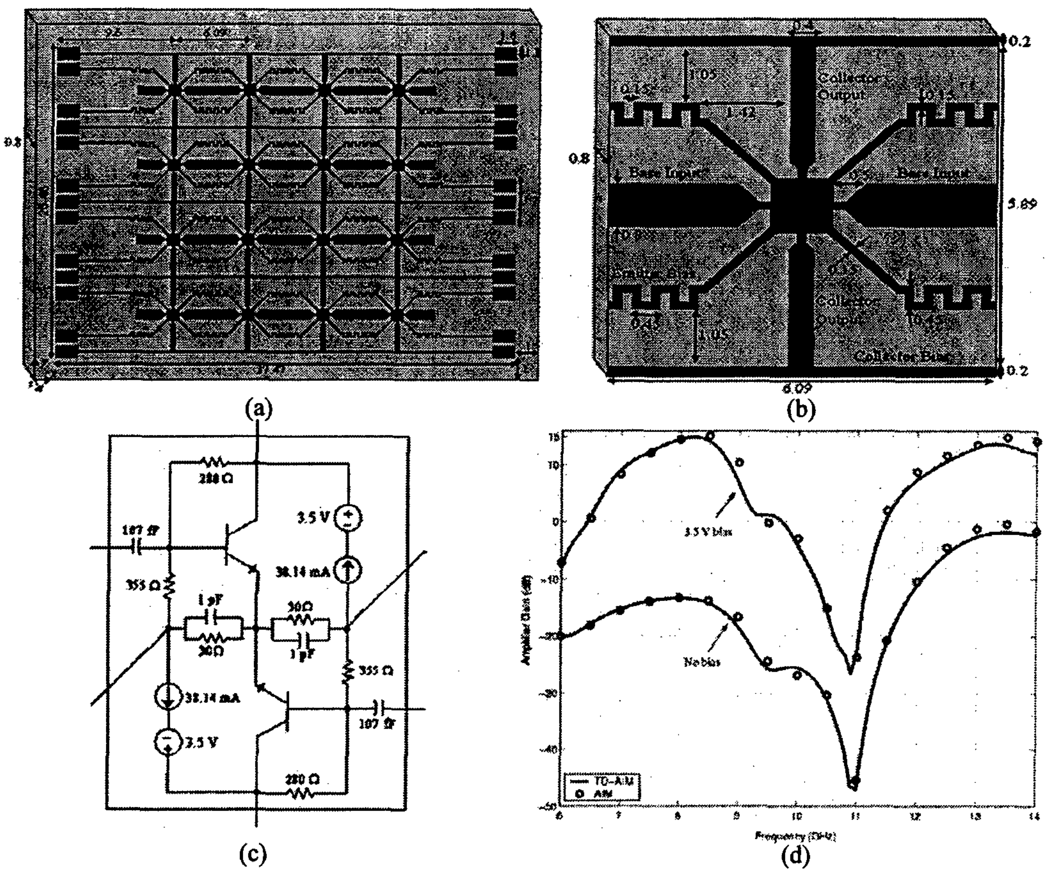


Figure 6. Reflection-grid amplifier. The dimensions in millimeters of (a) entire structure, (b) a single element. (c) The six-terminal differential-amplifier model of the chips and the DC bias values. (d) Amplifier gain with respect to the frequency with no bias or 3.5 V bias when the ground plane is 13.6 mm below the dielectric and the grid is illuminated at normal incidence.

3.2 Detailed Breakdown of Accomplishments

Itemized below (in italics) are all (sub)tasks proposed in VET proposal "Fast Time Domain Integral Equation Solvers for Large-Scale Electromagnetic Analysis". Research accomplishments for each (sub)task (or lack thereof and reasons why) follow each (sub)task description.

Task A. PWTD Kernel Development.

All PWTD kernels developed to date target free-space phenomena and assume discretized source distributions devoid of clusters. These assumptions limit the application range of our present PWTD-enhanced TDIE solvers.

Tasks A.1.x. To render PWTD technology applicable to other than free-space environments, we will

- *Task A.1.1. Develop PWTD Kernels for Lossy Media that evolve ray spectra through solution of one-dimensional lossy wave equations as opposed to lateral field displacement as is possible in lossless media.*

  Accomplishments. Effort successfully completed. A new PWTD kernel that permits the evaluation of scalar and vector fields generated by known source constellations residing in homogeneous lossy media was developed. As anticipated, this kernel updates rays, viz. plane wave spectra of fields produced by sources, by evolving one dimensional PDEs long straight lines. This new kernel permits the application of PWTD-enhanced TDIE solvers to the analysis of scattering from, and the broadband characterization of, structures embedded in lossy backgrounds, e.g. underground bunkers and landmines. The scheme potentially can be generalized to weakly inhomogeneous media by solving 1-D PDEs along eikonal paths.

- *Task A.1.2. Develop PWTD Kernels for Constant Loss Tangent/Dispersive/Nonlinear Media that rely on multiresolution decompositions of temporal source signatures with controlled material variability within several frequency bands.*

  Accomplishments: Effort partially completed. A dispersive medium PWTD formulation that generalizes the above lossy medium formulation was developed; a proof of concept kernel was implemented also. This kernel, once fully developed, will permit the application of PWTD-enhanced TDIE solvers to the analysis of scattering from penetrable dispersive structures that are embedded in dispersive backgrounds. Application examples include the broadband characterization of underwater targets and the analysis of optical components. Unfortunately, all efforts to date to construct PWTD kernels for constant loss-tangent and nonlinear media have failed.

- *Task A.1.3. Develop PWTD Kernels for Layered Environments by decomposing fields in layered media in direct and reflected components and by representing the tail of the reflected field in terms of a Hilbert transform.*

  Accomplishments: Effort successfully completed. A new PWTD kernel for rapidly computing fields due to both scalar and vector sources residing in layered media was developed. This kernel constitutes a generalization of a two-dimensional PWTD kernel, developed by our group in 1998. Specifically, the kernel considers the plane wave spectrum of a source, then acts on it with angle dependent reflection and transmission coefficients; when the latter are imaginary a Hilbert transform too acts on the spectrum. While nontrivial to implement, the resulting kernel is highly efficient. Note: our paper on this topic coauthored by Mingyu Lu and Eric Michielssen received the Best Student Paper award at the 2001 IEEE Antennas and Propagation International Symposium, Boston, July 2001.

- *Task A.1.4 Develop PWTD Kernels for Quasi-Planar Environments by representing the far-field spectrum of sources residing on such structures in terms of plane waves with complex time delays.*

  Accomplishments: Effort successfully completed. A new PWTD kernel that specifically targets source distributions arranged in a quasi-planar constellation was developed. The kernel effectively windows the plane wave spectrum of the source distributions and only retains waves grazing the horizon, without loss of accuracy of the observed fields. The scheme can be thought of as the generalization of so-called ray-propagation fast multipole kernels developed by Chew and Rokhlin, to the time domain. Contrary to what was anticipated in the Task description, the kernel does not use complex time delays. Instead, it relies on a multiresolution, wavelet-like decomposition of the fields produced by quasi-planar source constellations in both propagation direction and time. This new PWTD kernel opens the door to the effcicient simulation of transient scattering from rough surfaces and gratings.

- *Task A.1.5. Develop PWTD Kernels for Diffusive Phenomena through application of Q-transform theory.*

  Accomplishments: Effort failed. Numerical experiments indicated that it will be difficult for PWTD-based kernels that track diffusive phenomena to outperform fast FFT kernels developed for the same purpose by Greengard and Strain. Resources originally allocated to this Task were redirected to Task C.1.2. (Applications; Plasmons).

Tasks A.2.x. We propose to develop PWTD kernels that do not assume spatial discretizations commensurate with the wavelength at the highest frequency measurably present in the excitation waveform. This assumption makes sense when analyzing scattering phenomena induced by excitations with DC component in systems devoid of fine geometric details. However, the performance of present PWTD kernels suffer when these conditions are not met (antennas/circuits with small features, bandlimited radar, etc.) To remedy this situation, we propose to:

- *Task A.2.1. Develop Low-Frequency PWTD Kernels that "shoot" short pulses from sources to observers only at times requires by the solver.*

  Accomplishments: Task successfully completed. Frequency domain fast multipole kernels are known to suffer from the so-called low-frequency breakdown problem. Classical PWTD kernels suffer from a similar problem, albeit in disguise. Specifically, classical PWTD kernels impose a CFL-like limit on the time step proportional to the source separation if fields are to be reconstructed ghost-free. To remedy this situation, a new low-frequency PWTD kernel that does not suffer from this drawback was developed. This kernel effectively shoots short high-frequency pulses from source to observer regions (whenever field information is called for by the TDIE solver within which the kernel operates). This scheme permits the fast, PWTD-like eveluation of transient wave fields without CFL limitation and without increase in computational cost. Moreover, the scheme gracefully transitions into the classical PWTD scheme when sources are not clustered. At present, full multipole competitors to this plane wave based scheme are being developed and the two approaches are being compared on their relative merits and drawbacks. These schemes, when coupled to TDIE solvers, permit the analysis of scattering from structures with fine geometric details, e.g. antenna feeds.

- *Task A.2.2. Develop Bandlimited PWTD Kernels that save on computational resources by limiting source sampling rates through specialized representations of time domain translation functions.*

  Accomplishments: Effort failed. No specialized representations of time domain translation functions that suit this purpose were found.

• *Task A.2.3. Develop High Frequency PWTD Kernels that marry high frequency diffraction theory with low-frequency integral equation solvers.*

Accomplishments: Effort partially completed. A new PWTD kernel that couples to a TDIE solver using the physical optics (PO) paradigm was developed. This kernel permits the rapid analysis of complex scatterers with large, smooth surfaces and edges. Smooth surfaces are modelled using PO, and edges are modeled rigorously using the TDIE solver. This solver has been applied to the analysis of scattering from large cavities, e.g., engine inlets. To date, no high-frequency PWTD kernels that exploit asymptotics beyond PO have been developed. Their development would solve many long standing problems in high-frequency scattering analysis and, in the opinion of the PIs, ought to be pursued in the future.

Tasks A.3.x. Present PWTD kernels are tuned for execution on a serial machine. This prevents the application of PWTD enhanced TDIE solvers to the analysis of truly large-scale phenomena, e.g., aircraft scattering at X-band. Moreover, the efficiency of present PWTD kernels is limited by the fact that they do not exploit space-time redundancies in far-field source signatures. To render PWTD technology applicable to the analysis of very large-scale scattering phenomena, we propose to:

• *Task A.3.1. Develop Parallel PWTD Kernels that execute on a variety of parallel/distributed machines. These kernels will be based on extensions to the ScaleMe frequency domain fast multipole kernel developed at UIUC.*

Accomplishments: Effort successfully completed. A parallel PWTD kernel that executes under MPI was developed. Not unlike parallel Helmholtz FMM kernels, this parallel PWTD kernel uses a spatial paralellization strategy for low levels, and a directional strategy for high levels. New local filtering methods for processing portions of plane wave spectra residing on different processors were developed; in contrast to commonly used filters, these new filters use "uniform sampling along both theta and phi". This parallel PWTD kernel was coupled to a parallel TDIE kernel. Current efforts are aimed at solving problems involving 2 million spatial unknowns using this parallel PWTD-emhanced TDIE solver.

• *Task A.3.2 Develop Memory Efficient and Adaptive PWTD Kernels that exploit spatial source smoothness (beamforming) and deactivate quiet portions of the scatterer/spectrum (temporal gating.)*

Accomplishments: Effort partially completed. Memory efficient, adaptive PWTD kernels that exploit the existence of high-frequency scattering phenomena on large relatively smooth bodies, were proposed in several white papers submitted to DARPA. To date, no implementations have been attempted.

Task B. Novel Fast TDIE Solvers.

Our present PWTD-enhanced TDIE solvers analyze scattering from stationary perfect electrically conducting and linear penetrable (homogeneous and inhomogeneous) scatterers. Scattering from stationary and linear inhomogeneous objects is analyzed using volume integral equations. The majority of our present solvers rely on separable source expansions in which spatial and temporal variations are assumed linear and low-order polynomial, respectively.

Tasks B.1.x. To extend the range of application and accuracy of our present PWTD-enhanced TDIE solvers, we will

- Task B.1.1 Develop Higher-Order TDIE Solvers, Capable of Analyzing Low and High Frequency Scattering Phenomena. *We will pursue the development of solvers that rely on both space-time separable and non-separable source expansions. The separable representations will rely on divergence-conforming Nedelec elements defined on geometrically curved triangular or quadrilateral patches and approximate prolate interpolants to represent spatial and temporal source signatures, respectively. (We expect others funded under the DARPA-VET program to study higher-order surface representations; hence, we propose to focus our effort on studying extensions of prolate-based temporal representation schemes and their impact on time marching.) Non-separable source representations will be studied in view of their expected usefulness in the analysis of high-frequency scattering phenomena. The proposed TDIE solvers will be grid-robust, i.e., they will not require matching meshes at material/surface interfaces.*

  Accomplishments: Effort successfully completed. A new TDIE solver that uses higher order spatial basis functions and approximate prolate temporal basis functions was developed. This solver was applied to the analysis of scattering from relatively simple, canonical shapes and shown to exhibit algebraic convergence in space and exponential convergence in time. A hybrid PWTD-TDIE solver that uses this discretization technology and that is applicable to the analysis of large-scale scattering problems remains to be implemented.

- Task B.1.2 Develop Nonlinear TDIE solvers. *We will develop TDIE solvers for analyzing electromagnetic wave interaction with bulk and lumped nonlinear structures. Bulk nonlinearities will be initially assumed to be of the Kerr-type; more general nonlinearities will be studied later. Lumped nonlinearities will be analyzed through hybridization of a classical TDIE solver with a circuit simulator, e.g., SPICE.*

  Accomplishments: Effort successfully completed. A TDIE-SPICE hybrid was implemented. This solver permits the analysis of electromagnetic platforms/passives loaded with nonlinear circuitry. The solver was accelerated by PWTD, thereby realizing, to our knowledge, the first ever application of a wave based fast solver to the analysis of nonlinear phenomena This effort connects years of fast multipole development to the world of nonlinear circuit analysis.

- Task B.1.3 Develop Volumetric TDIE Solvers for lossy/dispersive media. *We will develop volume PWTD solvers to account for media losses and/or dispersive/diffusive effects. We will develop a novel TDIE scheme that performs updates of both the electric field and the flux density through recursive convolution.*

  Accomplishments: Effort successfully completed. Two types of PWTD-enhanced TDIE solvers for analyzing scattering from lossy and dispersive media were developed. The first one uses a recursive convolution scheme to account for the effect of losses on the fields produced by dielectric polarization currents. The second one achieves the same goal by evolving a set of ODEs along with the TDIE solver. This effort demonstrates the applicability of PWTD-enhanced TDIE solvers to volume scatterers comprising non-ideal materials. These codes currently are being hybridized with others for analyzing perfect electrically conducting structures, this to permit the analysis of coated objects.

- *Task B.1.4 Develop TDIE Solvers for Moving Media. We propose to develop PWTD-based TDIE solvers for analyzing scattering from moving targets. Moving/gyrating targets give rise to Doppler shifts, and coupling of electric and magnetic fields, effectively creating a bianistropic medium.*

  Accomplishments: Effort failed. It became clear early on that this effort was much harder than anticipated. Resources originally allocated to this Task were redirected to Task C.1.2. (Applications; Plasmons).

Tasks B.2.x. To ensure accuracy of our new TDIE solvers, and to calibrate their efficiency, we will:

- *Task B.2.1 Study Error Control/Propagation in TDIE Solvers. Many TDIE solvers exhibit unstable behavior if not carefully implemented. Proving the stability of carefully implemented discretized time marching schemes remains an open problem. We will attempt to rigorously analyze stability of TDIE schemes (old and new) by generalizing the tools proposed in [1-3].*

  Accomplishments: Effort partially completed. Two avenues for stabilizing TDIE solvers were studied. (i) Full space-time Galerkin PWTD codes were implemented. As suggested by the work of Ha-Duong/Aboud/Nedelec, such solvers, when carefully implemented, are stable. Their implementation however is very difficult; moreover, even when accelerated by PWTD kernels, these solvers remain computationally expensive. (ii) Therefore, stable kernels that use bandlimited curreent expansion functions were developed, too (See Task B.1.1).

- *Task B.2.2 Comparison of MLPWTD and Broadband MLFMA Based Integral Equation Solvers. We will compare the performance of our PWTD-enhanced TDIE to that of state of the art broadband frequency domain solvers. These solvers will be constructed by equipping the Fast Illinois Solver Code (FISC) with fast frequency-sweep model-order reduction techniques, e.g. asymptotic waveform evaluation (AWE) and Pade via Lanczos methods, to minimize the number of frequencies required for characterizing broadband scattering mechanisms. To fully exploit the AWE method, we propose to develop algorithms that automatically determine the frequency expansion points for a given frequency band using bisection schemes. Finally, we will study automatic mesh-coarsening algorithms to reduce the unknown count at lower frequencies in the band.*

  Accomplishments: Effort partially completed. The performance of parallel PWTD-enhanced TDIE solvers was compared to that of parallel FMM-enhanced method of moment solver. The relative performance of both technologies depends heavily on the problem at hand, the discretization strategy used, etc. The relative merits of frequency and time domain computational technologies for analyzing electromagnetic transients will be determined by their future users: This is because frequency domain solver technologies themselves continuously are being refined to render them more suitable to tackle broadband problems. See Section on overview of accomplishments.

Task C. Application to Pressing Scientific and Engineering Problems.

To validate and tune the TDIE solver codes developed under Task B, they will be applied to difficult/important scientific and engineering problems.

Tasks C.1.x. Scientific Realm. We will apply our PWTD-enhanced TDIE solvers to the analysis of broadband electromagnetic scattering from natural surfaces and composites. Specifically, we will

- *Task C.1.1. Rough surfaces. We will analyze scattering from large-scale rough surfaces at near-grazing incidence.*

  Accomplishments: Effort canceled in favor of C.1.2, Plasmons.

- *Task C.1.2. Plasmons. We will study the interaction between the electromagnetic fields and surface plasmons. Our analysis will be restricted to rough surfaces and diffraction gratings. Understanding material-field interactions will allow for the development of better sensors that exploit resonances to measure surface quality, characterize thin film gratings, predict particle distributions by exploiting localized field intensities, etc.*

Accomplishments: Effort successfully completed. Physical phenomena associated with electromagnetic field scattering from metallic plates perforated by apertures of subwavelength size find use in many applications in physics and engineering. For example, probes with subwavelength apertures are used in near-field imaging and microscopy, small holes are used to excite and couple energy between various waveguide and cavity systems, perforated plates often serve as cost-effective ground planes and electromagnetic shields, arrays of small apertures are used as photonic band gap structures to improve operation of printed antennas. Identification of new phenomena associated with scattering from perforated plates is expected to open a host of new practical applications.

Classical scattering (Bethe) theory predicts that the scattering from non-interacting apertures is very weak. In many applications the weak scattering constitutes a restrictive characteristic. It is therefore important to identify novel plate / subwavelength aperture geometries that lead to various extraordinary scattering phenomena. It was realized that when apertures interact strongly/resonantly the perforated plates permit various extraordinary phenomena. For instance, in recent years, phenomena of enhanced transmission of plane waves, viz. high peaks in transmitted field magnitude for special frequency/angular ranges, through arrays of subwavelength holes in metal plates have been identified. The ability to pump significant electromagnetic power through tiny holes opens up new possibilities for numerous applications. In addition, phenomena of electromagnetic wave guidance on arrays/chains of densely spaced elements (e.g. resonant dipoles and spheres) have been studied spurred by their potential applications in physics and engineering. Similar to free standing chains of scatterers, it is anticipated that chains of scatterers (e.g. apertures) patterning a metal-dielectric plate also can support guided waves. The study of these phenomena of enhanced transmission through small holes and wave guidance along chains of small apertures are goals of our proposed study.

Originally the phenomena of enhanced transmission were believed to occur only in the optical regime and were associated with the existence of surface plasmon polaritons, viz. surface waves supported by metal surfaces modeled as plasmas in the optical regime. Recently, we have identified several structures leading to enhanced transmission through subwavelength holes not only in the optical but also in the microwave regime. These structures include plates embedded in free-space or layered medium background and perforated by apertures having simply or multiply connected cross-sections. All these structures have in common that they support some type of a slow wave and have a special periodic grating that can be tuned to interact in such a manner as to lead to the desired (exotic) scattering properties. The enhanced transmission mechanism is associated with hole grating-assisted resonant coupling between the incident field and leaky waves/resonance supported by the structures. We have explored responses of the identified structures to time-harmonic and transient plane waves, as well as localized (beam and line source) excitations. The enhanced transmission of time-harmonic plane waves was shown to occur in one of two regimes. In the single resonance regime, a GW residing in a single slab couples to the incident field. The transmission coefficient magnitude peaks as the excitation frequency scans through the resonance; however the peak magnitude decays exponentially with plate thickness. In the double resonance regime, GWs in both slabs simultaneously couple to the incident field. The transmission coefficient magnitude exhibits twin peaks whose magnitudes typically are larger than those resulting from single resonances and that remain large even for plates of moderate thickness. It was demonstrated that double resonances may occur for symmetric as well as for asymmetric structures, i.e. when the two slabs are identical or different. The transmission response of the perforated plates to an incident beam comprises of a geometrical ray, leaky waves, and lateral waves. The existence of the leaky waves is identified as the origin of the transmitted field enhancement. The transmission response of the perforated plates to a transient plane wave also is comprised of three contributions: early time arrival – a time domain counterpart of the geometrical ray, resonant contributions – a counterpart of the leaky waves, and a term leading to a long time tail – a counterpart of the lateral waves. These studies elucidated the physics behind the enhanced transmission phenomena and provide a unified explanation of resonant and Rayleigh types of Wood anomalies existing on any periodic grating supporting leaky waves/resonances. We also have demonstrated that plates perforated by apertures with simply and multiply-connected cross-sections lead to different scattering properties. The understanding of the above phenomena allowed developing simple models, dependent solely on the hole distribution's first and second Fourier components, that permit tuning these structure's dispersion relations and transmission coefficient.

Given the significant application promise of enhanced transmission phenomena, we intend to continue developing precise theoretical models and sophisticated numerical techniques that allow predicting and tuning the scattering properties of complex plate-like structures. We will consider infinite periodic planar structures as well as truncated planar and curved structures incorporating various scatterers. Attention will be paid to mechanisms of coupling between incident fields and different types of bounded fields supported by the structures, e.g. surface and guided waves, surface plasmon polaritons, and whispering gallery modes. Given our successes in developing integral equation techniques we will examine and improve several existing approaches for efficiently computing fields in periodically perforated/modulated plates based on integral equation methods. We anticipate that the aforementioned scattering mechanisms leading to enhanced transmission phenomena will find uses in a wide range of applications. For example, the phenomenon of near field enhancement will be used for signal amplification and generation. The phenomenon of transmitted far field enhancement will be used for construction of microwave and optical filters and frequency selective surfaces. Enhanced transmission phenomena can be used for efficient coupling of electromagnetic field from/into metallic cavities/buildings. The subwavelength size of the holes will allow their use in construction of novel probes for near field imaging and microscopy. Special arrangements of small apertures can be used as "signatures" for target identification and interrogation.

In addition to enhanced transmission phenomena, we intend to study the phenomena of wave guidance on chains of subwavelength apertures. We will examine the conditions under which traveling waves can be supported by straight chains of apertures and study the phenomena of wave guidance along bended chains of apertures are studied. It is anticipated that interaction between apertures along a chain have a strong near-field component which results in efficient guidance of traveling waves past appropriately designed bends. Applications of the investigated structures include the construction of aperture chain communication links, straight and bended waveguides with subwavelength channels, subwavelength probes and lenses, antennas, etc.

- *Task C.1.3. Composites. We will study field propagation in composite materials, i.e., structures that comprise of a myriad of dielectric and PEC materials. Such material combinations are ubiquitous and present in modern aircraft, antennas, circuits, , etc.*

  Accomplishments: Effort partially completed.

Tasks C.2.x. Engineering Realm. We will apply our PWTD-enhanced TDIE solvers to the analysis of broadband electromagnetic interactions on a variety of complex platforms that are not only electromagnetically large but that also contain many detailed features packed within a fraction of a wavelength. Specifically, we will

- *Task C.2.1. Aircraft. We will analyze scattering from a realistic aircraft illuminated by an X-band radar.*

  Accomplishments: Effort still under way. Aircraft scattering has been analyzed up to 600 MHz. At present, the above described parallel and hybrid PWTD-TDIE codes are being readied for pplication to the anaysis of aircraft scattering at higher frequencies. We anticipate to break through the 1 GHz mark by December 2005.

- *Task C.2.2. Complex Antennas. We will analyze complex (embedded) antenna systems on mobile platforms (aircraft, ships, and land-based vehicles; many of the targeted antenna systems involve complex feeds/layered supports.)*

  Accomplishments: Significant progress was made; specifically, a low frequency TDIE solver that allows the analysis of small geometric details, was developed and successfully applied to the analysis of coax-driven antennas.

- *Task C.2.3. Electromagnetic Compatibility/Interference (EMC/EMI). We will assess EMC/EMI issues in aircraft cockpits.*

  Accomplishments: Significant progress made (this effort is also, separately, supported by an AFOSR MURI allocation). Specifically, we demonstrated that PWTD-enhanced TDIE solvers permit the analysis of wave interactions with nonlinear electronic circuitry. This is important because it provides a mechanism for analyzing (hostile) EMC/EMI issues in aircraft; see examples above.

- *Task C.2.4. High Power Microwave (HPM). We will study high-power microwave penetration into aircraft through windows, wheel bays, and cracks and seams.*

Accomplishments: Effort being pursued under AFOSR MURI effort.

- <u>Task C.2.5. Chip Interconnects and Nonlinear Circuitry</u>. *We will analyze electromagnetic coupling into chip interconnects and nonlinear circuits (this subtask, along with the previous one is important to determine upset or damage levels for electronic circuitry in aircraft illuminated by an enemy radar.)*

  Accomplishments: Effort nearing completion. The applicability of "low-frequency PWTD kernels to stuctures with fine geometric detail, was demonstrated. This development is significant as it demonstrates the possibility of operating a transient solver using a time step dictated solely by the bandwidth of the temporal excitation and not by the spatial discretization. In other words, our solvers operate without CFL limit.

- <u>Task C.2.6. Near-Resonant Structures</u>. *We will analyze scattering from near-resonant structures, e.g., engine inlets.*

  Accomplishments: Effort partially completed. In collaboration with SAIC engineers, our PWTD-accelerated TDIE solvers were applied to the analysis of scattering from straight and bent inlets. The possibility of extracting late-time information from Prony-fitted scattering data was demonstrated. A robust code implementing these ideas was not developed, however.

- <u>Task C.2.7. Radar</u>. *Assess the effectiveness of (wideband) foliage penetration radar systems (FOPEN; see also Task C.1) and analyze scattering from foliage-covered and buried targets.*

  Accomplishments: Effort canceled in favor of C.1.2, Plasmons

3.3 Self-assessment

Chart I below details all program Tasks described in the original proposal. An estimate of the degree to which each task was completed is listed next to each task (in %). Areas where results were obtained beyond those anticipated in our original proposal are marked by a star (*).

4. PERSONNEL AND INFRASTRUCTURE SUPPORTED

4.1 Faculty

1. Eric Michielssen, Center for Computational Electromagnetics, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign.
2. Weng Cho Chew, idem.
3. Jianming Jin, idem.
4. Balasubramaniam Shanker (initially, for FY01, with the Department of Electrical and Computer Engineering at Iowa State University, and for FY02 and FY03 with the Department of Electrical and Computer Engineering at Michigan State University). Balasubramaniam Shanker received ¼ of total funding for this project.

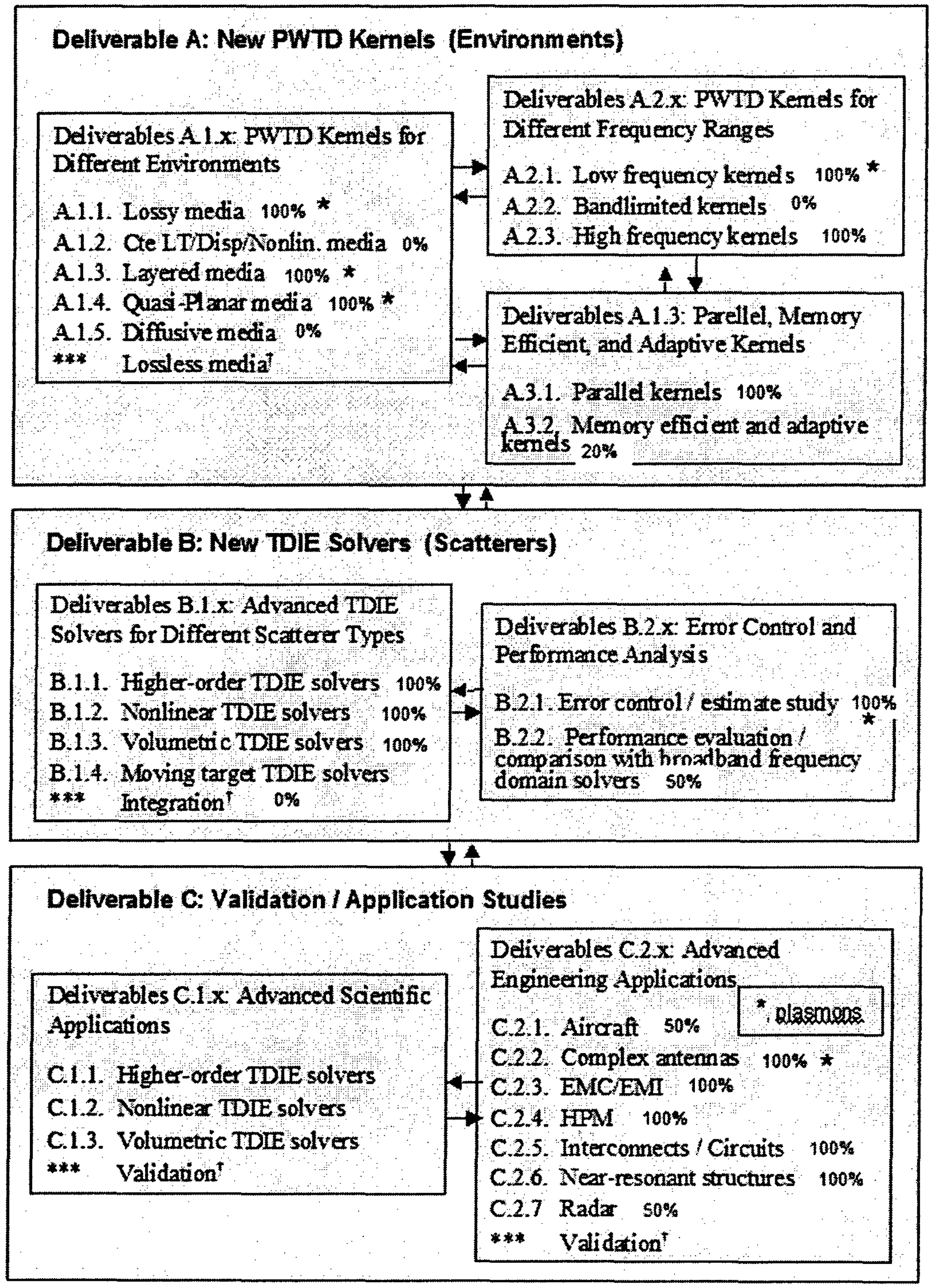


Chart I: Deliverables (copied fro proposal "Fast Time Domain Integral Equation Solvers for Large-Scale Electromagnetic Analysis" along with estimated % completion rates; stars indicate tasks that were investigated in more depth than described in the original proposal (self-evaluation).

4.2 Postdocs and Students

Students listed below were supported, entirely or in part (salary and/or infra-structure), by the VET grant. (UIUC = University of Illinois at Urbana-Champaign, ISU = Iowa State University, MSU = Michigan State University).

1. Y.C. Pan, Ph.D. UIUC, May 2002, Intel.
2. M. Delaquil, M.S. UIUC, May 2002, Northrop Grumman Corporation.
3. E.A. Forgy, Ph.D. UIUC, September 2002, self-employed.
4. H.Y Chao, Ph.D. UIUC, January 2003, National Chiao Tung University, Taiwan.
5. M.L. Hastriter, Ph.D. UIUC, June 2003, Air Force Institute of Technology.
6. Subramaniam Lalgudi, M.S. ISU, 2003, Georgia Institute of Technology (Ph.D. student).
7. M.K. Li, M.S. UIUC, May 2004, current Ph.D. student at UIUC.
8. A. A. Aydiner, Ph.D., June 2004, Intel.
9. L.J. Jiang, Ph.D., August 2004, IBM.
10. Y.H. Chu, Ph.D., August 2004, Agilent.
11. Thomas Rylander, PostDoc, 2003, Chalmers University of Technology, Sweden.
12. Ali Yilmaz, Ph.D., 2005, University of Illinois at Urbana-Champaign
13. Matthys Botha, Postdoctoral Fellow, 2004, University of Stellenbosch, South Africa.
14. Shuqing Li, 2004, Postdoctoral Fellow.
15. Christopher Trampel, M.S., 2004, Iowa State (Ph.D. student in Mathematics)
16. Nan-Wei Chen, Ph.D., 2004, National Central University, Taiwan.
17. Yu Zhong, current Ph.D. student at UIUC.
18. Yujia Li, current Ph.D. student at UIUC.
19. Mingyu Lu, current Postdoctoral Fellow at UIUC.
20. Vitaliy Lomakin, current Postdoctoral Fellow at UIUC.
21. Hakan Bagci, current Ph.D. student at UIUC.
22. Gao Jun, current Ph.D. student at MSU.
23. Yuan Jun, current Ph.D. student at MSU.
24. Lu Chuan, current Ph.D. student at MSU.

4.3 Infrastructure

During FY1, VET funds were used to purchase a small Unix-based Sunblade cluster, comprising 10 Model 900 machines with 4-8 MB RAM. This cluster, while no longer competitive with new Linux based clusters available to CCEM researchers, was instrumental to our effort: its large memory permitted us to run very large time- and frequency domain problems in-house.

5. CONTINUING APPLICATIONS - TECHNOLOGY TRANSITIONS

With funding from AFOSR MURI grant "Analysis and Design of Ultrawide-Band and High-Power Microwave Pulse Interactions with Electronic Circuits and Systems", (managed by Dr. Witt, AFOSR), computational technologies developed with VET funding have been, and are continuing to be applied to electromagnetic compatibility/interference (EMC/EMI) and high power microwave (HPM) problems of interest to the DoD. Specific phenomena studied include the penetration of wideband electromagnetic pulses into enclosures containing sensitive electronics (e.g., a personal computer containing multiple circuit boards or a missile cone containing a nonlinear amplifier) and cable-loaded airframes containing such systems. Given the broadband nature of the electromagnetic threats to these often nonlinear systems, the fast time domain integral equation solvers developed with VET funding have proven instrumental in tackling these problems. Our methodologies now are recognized as one of very few possible avenues for analyzing the above phenomena using numerically rigorous tools.

With funding from AFOSR MURI grant "Electromagnetics of Antennas and Arrays Designed Using Novel Electronic Materials and Conformal to Large Complex Bodies", (managed by Dr. Arje Nachman, AFOSR), computational technologies developed with VET funding are being applied to the study of complex and potentially nonlinear antenna feed networks. This effort, though only in its early stages, has demonstrated the applicability of computational technologies developed under the VET program to the time-domain analysis of broadband, airframe installed, log-periodic monopole antennas fed by complex cable networks. Current efforts focus on applying the same technology to the characterization of nonlinearly loaded microstrip antennas.

With funding from DEMACO-SAIC grant "Time Domain Integral Equation Solvers for Analyzing Large Cavities", computational technologies developed with VET funding are being applied to the study of broadband field penetration into deep cavities / engine inlets. Frequency domain integral equation solvers converge slowly when applied to such near-resonant problems. Time domain integral equation solvers, in contrast, trade this slow convergence for long simulation times. Prony and Pade-approximant based techniques for reducing these simulation times are currently being studied.

Other grants that leverage computational technologies developed with VET funding include:

1. A DOE grant via the US Geological Survey for subsurface sensing (Chew),
2. An SRC-customization grant from Intel for low-frequency modeling of electronic systems (Chew),
3. An SRC for time-domain modeling of on-chip interconnects modeling of chip interconnects (Cangellaris/Michielssen),
4. A Boeing grant for frequency-domain modeling of scattering from wedges and the development of applicable generalized impedance boun dary conditions (Michielssen).
5. An Air Force education scholarship for Hastriter for RCS with large scale computing (Chew).
6. A GM industry grant for antenna modeling on cars (Chew).

6. PUBLICATIONS

Journal Papers

Note: only papers published to date are listed. Approximately 15 additional papers acknowledging DARPA VET support under AFOSR Program contract F49620-01-1-0228 are under review.

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13. B. Shanker, A. A. Ergin, M. Lu and E. Michielssen, "Fast analysis of transient electromagnetic scattering phenomena using the multilevel plane wave time domain algorithm," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 3, pp. 628-641, March 2003.
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37. M. K. Li and W. C. Chew, "A new Sommerfeld-Watson transformation in 3D," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 5, pp. 75-78, 2004.
38. M. Lu, B. Shanker, and E. Michielssen, "Elimination of spurious solutions associated with exact transparent boundary conditions in FDTD solvers," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 4, pp. 59-62, 2004.
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40. H. Bagci, A. E. Yilmaz, V. Lomakin, and E. Michielssen, "Fast solution of mixed-potential time-domain integral equations for half-space environments," to appear in *IEEE Transactions on Geoscience and Remote Sensing.*
41. N.-W. Chen, M. Lu, F. Capolino, B. Shanker, and E. Michielssen, "Floquet-wave-based analysis of transient scattering from doubly periodic perfectly conducting bodies," to appear in *Radio Science.*
42. B. Shanker, M. Lu, A. A. Ergin and E. Michielssen, "Acceleration of global exact boundary conditions for truncation of FDTD domains," submitted to *IEEE Transactions on Antennas and Propagation.*
43. A. E. Yilmaz, J. M. Jin, and E. Michielssen, "A parallel FFT accelerated transient field-circuit simulator," submitted to *IEEE Transactions on Microwave Theory and Techniques.*

Selected Refereed Conference Papers

1. Nan-Wei Chen, K. Aygun, and Michielssen, "Transient analysis of a canted sector antenna with the modeling of fine feed features," *2001 IEEE Antennas and Propagation Society International Symposium*, vol. 2, pp. 384-387, 2001.
2. B. Shanker, K. Aygun, N. Gres, and E. Michielssen, "Fast integral equation based analysis of transient electromagnetic scattering from three-dimensional inhomogeneous lossy

dielectric objects," *2001 IEEE Antennas and Propagation Society International Symposium*, vol. 4, pp. 532-535, 2001.

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16. A. E. Yilmaz, J. M. Jian-Ming, and E. Michielssen, "Time domain adaptive integral method for the combined field integral equation," *2003 IEEE Antennas and Propagation Society International Symposium*, vol. 3, pp. 543-546, 2003.
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18. J. Gao, G. Kobidze, and B. Shanker, "Higher-order FDTD algorithm using tetrahedral tessellation," *2003 IEEE Antennas and Propagation Society International Symposium*, vol. 4, pp. 364-367, 2003.
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26. V. Lomakin and E. Michielssen, "Efficient calculation of transient fields in multilayered media," *2004 IEEE Antennas and Propagation Society Symposium*, vol. 4, pp. 4232-4235, 2004.
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29. D. Vande Ginste, E. Michielssen, F. Olyslager and D. De Zutter, "Towards a PML-based MLFMA for planar microwave circuits," *2004 IEEE Antennas and Propagation Society Symposium*, vol. 2, pp. 1191-1194, 2004.
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structures," *2004 IEEE Antennas and Propagation Society Symposium,* vol. 4, pp. 4535-4538, 2004.

31. M. Lu and E. Michielssen, "A local filtering scheme for FMM/PWTD algorithms," *2004 IEEE Antennas and Propagation Society Symposium*, vol. 4, pp. 4523-4526, 2004.
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33. G. Kobidze, K. Aygun and B. Shanker, "Efficient integral equation based analysis of scattering from PEC-anisotropic bodies," *2004 IEEE Antennas and Propagation Society Symposium*, vol. 4, pp. 3887-3890, 2004.
34. C. Trampel, G. Kobidze, B. Shanker and D. P. Nyquist, "A novel algorithm for analysis of surface plasmon polaritons in metallic thin films," *2004 IEEE Antennas and Propagation Society Symposium*, vol. 3, pp. 3159-3162, 2004.

APPENDIX: ABSTRACTS OF JOURNAL PUBLICATIONS

1 N. T. Gres, A. A. Ergin, B. Shanker, and E. Michielssen, "Volume integral equation based analysis of transient electromagnetic scattering from three-dimensional inhomogeneous dielectric objects," *Radio Science*, vol. 36, no. 3, pp. 379-386, May-June 2001.

Abstract: A novel technique for analyzing transient electromagnetic scattering from three-dimensional inhomogeneous dielectric targets is proposed. An integral equation for the electric flux density throughout the scatterer is constructed by invoking the electromagnetic volume equivalence principle. This equation is solved using a marching-on-in-time scheme in which the electric flux density is expanded in space by volumetric rooftop basis functions defined on a tetrahedral mesh and in time by piecewise polynomials. The proposed method is validated for representative dielectric structures by comparison via Fourier transformation of scattering data obtained with this method and various frequency domain techniques.

2 Z. J. Liu, W.C. Chew, and E. Michielssen, "Numerical modeling of dielectric-resonator antennas in a complex enviroment using the method of moments," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 1, pp. 79-82, Jan. 2002.

Abstract: Aperture coupled dielectric resonator antennas (DRAs) that reside above a layered background are analyzed using the method of moments (MoM). Dyadic Green's functions for the layered medium are derived in a simple and effective manner and the Rao-Wilton-Glisson (RWG) function is used to expand both electric and magnetic currents. A transmission-line technique is used to compute the antenna-input impedance. Numerical results obtained for both hemispheric and rectangular DRAB agree well with published measurement results.

3 K. Aygün, B. Shanker, A. A. Ergin, and E. Michielssen, "A two-level plane wave time domain algorithm for fast analysis of EMC/EMI problems," *IEEE Transactions on Electromagnetic Compatibility*, vol. 44, no. 1, pp. 152-164, Feb. 2002.

Abstract: In this paper, a fast time-domain integral equation (IE)-based scheme for analyzing transient electromagnetic compatibility and interference (EMC/EMI) problems involving printed circuit boards and cables/connectors that reside in shielding enclosures is presented. The proposed algorithm hybridizes a classical marching-on-in-time (MOT) solver for analyzing radiation from perfect electrically conducting (PEC) surface/wire geometries with the recently introduced two-level plane wave time-domain (PWTD) algorithm. The accuracy and efficacy of the resulting MOT-PWTD algorithm are validated via analysis of the radiation characteristics of a number of structures including a loaded motherboard that resides in a chassis. For a problem with spatial and temporal unknowns, the computational complexity of the two-level MOT-PWTD algorithm scales as $O(N_t N_s \log^2 N_s)$ as opposed to $O(N_t N_s^2)$ for a classical MOT scheme.

4 T. J. Cui and W. C. Chew, "Accurate analysis of wire structures from very-low frequency to microwave frequency," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 3, pp. 301-307, March 2002.

Abstract: Based on the accurate model developed in our previous paper, a general method is proposed to analyze wire structures in the free space or above multilayered media, which is valid from very-low to microwave frequencies. In this method, loop-tree basis functions have been applied to overcome the low-frequency breakdown problem, which can represent the nature of the Helmholtz decomposition of the current. The proposed method can be used to study wire antennas, or it can be incorporated with other methods to analyze circuit problems containing wire structures.

5 B. Shanker, A. A. Ergin and E. Michielssen, "Analysis of transient scattering from penetrable bodies using the multilevel plane wave time domain algorithm," *Journal of the Optical Society of America A*, vol. 19, no. 4, pp. 716-726, April 2002.

Abstract: A novel and fast integral-equation-based scheme is presented for analyzing transient electromagnetic scattering from homogeneous, isotropic, and nondispersive bodies. The computational complexity of classical marching-on-in-time (MOT) methods for solving time-domain integral equations governing electromagnetic scattering phenomena involving homogeneous penetrable bodies scales as $O(N_t N_s^2)$. Here, N_t represents the number of time steps in the analysis, and N_s denotes the number of spatial degrees of freedom of the discretized electric and magnetic currents on the body's surface. In contrast, the computational complexity of the proposed plane-wave-time-domain-enhanced MOT solver scales as $O(N_t N_s \log^2 N_s)$. Numerical results that demonstrate the accuracy and the efficacy of the scheme are presented.

6 T. J. Cui, W. C. Chew, J. S. Zhao and H. Y. Chao, "Full-wave analysis of complicated transmission line circuits using wire models," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 10, pp. 1350-1360, Oct. 2002.

Abstract: Three existing wire models based on the method of moments are used to analyze a transmission-line circuit. Simulation results show that the wire model where the current is assumed to flow along the axis and the testing is on the whole surface (around 2/spl pi/) has the best performance when two wires are close. However, this model is still inaccurate when two wires are very close, which is the case in computer chip and circuit problems. We then develop a new wire model that is valid for many cases. Using the new wire model, complicated transmission-line circuits can be accurately analyzed and simulated. Many numerical simulations are given to test the validity of the new model.

7 W. C. Chew, T. J. Cui and J. M. Song, "A FAFFA-MLFMA algorithm for electromagnetic scattering," *IEEE Transactions on Antennas and Propagation*, vol. 50, no. 11, pp. 1641-1649, Nov. 2002.

Abstract: Based on the multilevel fast multipole algorithm (MLFMA), an efficient method is proposed to accelerate the solution of the combined field integral equation in electromagnetic scattering and radiation, where the fast far-field approximation (FAFFA) is combined with MLFMA. The translation between groups in MLFMA is expensive because spherical Hankel functions and Legendre polynomials are involved and the translator is defined on an Eward sphere with many k/spl circ/ directions. When two groups are in the far-field region, however, the translation can be greatly simplified by FAFFA where only a single k/spl circ/ direction is involved in the translator. The condition for using FAFFA and the way to efficiently incorporate FAFFA with MLFMA are discussed. Complexity analysis illustrates that the computational cost in FAFFA-MLFMA can be asymptotically cut by half compared to the conventional MLFMA. Numerical results are given to verify the efficiency of the algorithm.

8 A. Yilmaz, D. S. Weile, B. Shanker, J. M. Jin and E. Michielssen, "Fast analysis of transient scattering in lossy media," *IEEE Antennas and Wireless Propagation Letters*, vol. 1, no. 1, pp. 14-17, 2002.

<u>Abstract</u>: The solution of time-domain integral equations pertinent to scattering from perfectly conducting objects residing in unbounded lossy media is considered. The computational cost of classical marching-on-in-time (MOT) schemes for the solution of such equations scales as $O(N_t^2 N_s^2)$, where N_t and N_s are the number of temporal and spatial unknowns, respectively. In this letter, a fast Fourier transform (FFT)-based algorithm that reduces the computational complexity to $O(N_t N_s^2 \log^2 N_t)$ is introduced. When combined with spatial FFT algorithms, the proposed scheme further reduces the complexity of MOT-based integral equation solvers, for example to $O(N_t N_s \log(N_t N_s) \log(N_t))$ if the objects are uniformly meshed. Numerical simulations that demonstrate the accuracy and efficiency of the algorithm are presented.

9 K. Aygün, B. Shanker, and E. Michielssen, "Fast time-domain characterization of finite size microstrip structures," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 15, no. 5-6, pp. 439-457, 2002.

<u>Abstract</u>: A new fast integral equation-based scheme for analyzing electromagnetic transients on finite size microstrip structures is described. The scheme permits the analysis of perfectly conducting surfaces and wires along with lossless but potentially inhomogeneous dielectric regions. For typical microstrip structures, the computational complexity of the proposed analysis tool grows as $O(N_t N_{sv} \log^2 N_{sv})$, where N_t denotes the number of time steps in the analysis, $N_{sv} = N_s + N_v$, N_s and N_v represent the number of spatial unknowns that model currents on conducting surfaces/wires/junctions and in penetrable volumes, respectively. This complexity estimate is in start contrast with that for classical marching-on-in-times solvers, which require $O(N_t N_{sv}^2)$ CPU resources.

10 S. Ohnuki and W. C. Chew, "Truncation error analysis of multipole expansion," *SIAM Journal on Scientific Computing*, vol. 25, no. 4, pp. 1293-1306, 2003.

<u>Abstract</u>: The multilevel fast multipole algorithm is based on the multipole expansion, which has numerical error sources such as truncation of the addition theorem, numerical integration, and interpolation/anterpolation. Of these, we focus on the truncation error and

discuss its control precisely. The conventional selection rule fails when the buffer size is small compared to the desired numerical accuracy. We propose a new approach and show that the truncation error can be controlled and predicted regardless of the number of buffer sizes.

11 S. Ohnuki and W. C. Chew, "Numerical analysis of local interpolation error for 2D MLFMA," *Microwave and Optical Technology Letters*, vol. 36, no. 1, pp. 8-12, January 2003.

Abstract: The error control of local interpolation for a 2D MLFMA will be discussed. The way to select proper parameters is proposed in terms of both numerical accuracy and computational cost. Satisfying the conditions derived in this paper, error can be controlled at the same level as global interpolation, and the computational cost becomes less expensive than the global one.

12 H. Y. Chao, J. S. Zhao, and W.C. Chew, "Application of curvilinear basis functions and MLFMA for radiation and scattering problems involving curved PEC structures," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 2, pp. 331-336, Feb. 2003.

Abstract: The curvilinear surface and wire basis functions have been applied to solve radiation and scattering problems of various shapes of curved metallic structures with the method of moments. However, a suitable form of junction basis function that can connect the curvilinear wire and the curvilinear Rao-Wilton-Glisson (RWG) surface basis functions has not been found. We present a novel curvilinear junction basis function that can fill the gap. The convergence tests reveal that the curvilinear junction basis function, in conjunction with curvilinear wire and surface basis functions, can reduce the radar cross section (RCS) error by one order of magnitude more than their reduced linear forms for a curved structure. The curvilinear basis functions are applied to solve the radiation from wire antennas attached to curved surfaces. We will demonstrate that the curvilinear basis functions with the multilevel fast multipole algorithm can significantly reduce the computational resources for simulating electrically large objects with curved features.

13 B. Shanker, A. A. Ergin, M. Lu and E. Michielssen, "Fast analysis of transient electromagnetic scattering phenomena using the multilevel plane wave time domain algorithm," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 3, pp. 628-641, March 2003.

Abstract: The computational complexity of classical marching-on-in-time (MOT) methods for solving time domain integral equations (TDIEs) pertinent to the analysis of transient scattering phenomena involving perfectly conducting targets grows as $O(N_t N_s^2)$ (N_t and N_s denote the number of temporal and spatial degrees of freedom (DOF) of the electric current on the target). This scaling law impedes the application of these schemes to the analysis of large-scale scattering phenomena. The recently developed plane wave time domain (PWTD) algorithm permits the rapid evaluation of transient wave fields generated by temporally bandlimited sources and hence the acceleration of marching on in time based TDIE solvers. Previously, we described a two-level PWTD enhanced TDIE solver for analyzing electromagnetic scattering from perfectly conducting targets; the computational complexity of this algorithm scales as $O(N_t N_s^{1.5} \log N_s)$. Here, a multilevel PWTD scheme for rapidly evaluating electric fields due to temporally bandlimited electric current sources is described. In addition, a multilevel PWTD enhanced TDIE solver for analyzing electromagnetic scattering from perfectly conducting scatterers using $O(N_t N_s \log^2 N_s)$ CPU resources is outlined. Last, the accuracy and CPU/memory efficiency of this solver are demonstrated by analyzing transient scattering from electrically large bodies.

14 S. Velamparambil, W. C. Chew, and J. M. Song, "10 million unknowns, is it that big," *IEEE Antennas Propagation Magazine*, vol. 45, no. 2, pp. 43-58, April 2003.

Abstract: At the Center for Computational Electromagnetics at the University of Illinois, we recently solved a very-large-scale electromagnetic scattering problem. We computed the bistatic radar cross-section of a full-size aircraft at 8 GHz, involving the solution of a dense matrix equation with nearly 10.2 million unknowns. We regarded this as the "ultimate test" of a massively parallel implementation of the multilevel fast multipole algorithm (MLFMA), called ScaleME. In this paper, we narrate the technical difficulties faced and the experience gained from a very informal point of view. We describe the various methods developed for surmounting each of the obstacles.

15 N.-W. Chen, B. Shanker, and E. Michielssen, "Integral-equation-based analysis of transient scattering from periodic perfectly conducting structures," *IEE Proceedings - Microwaves, Antennas and Propagation*, vol. 150, no. 2, pp. 120-124, April 2003.

Abstract: A marching-on-in-time algorithm for solving a time-domain electric field integral equation pertinent to the analysis of plane-wave scattering from doubly periodic, perfectly conducting bodies is presented. For obliquely incident waves, a classically constructed marching-on-in-time solver leads to a non-causal system of equations that requires the knowledge of future current values to solve for the present ones. Here, time-shifted temporal basis functions and bandlimited extrapolation procedure that mitigate and eliminate the non-causal nature of marching-on-in-time system of equations are introduced. The validity and effectiveness of the resulting algorithm are demonstrated through a number of examples.

16 M. L. Hastriter, S. Ohnuki, and W. C. Chew, "Error control of the translation operator in 3-D MLFMA," *Microwave and Optical Technology Letters*, vol. 37, no. 3, pp. 184-188, May 2003.

Abstract: This paper presents an extension of a new approach to select the truncation number for translation operators in a 3D multilevel fast multipole algorithm (MLFMA). Although error is harder to control in 3D than in 2D problems, this recently developed new approach provides better error control in 3D problems over the excess bandwidth formula.

17 Y. Zhang, T. J. Cui, W. C. Chew and J. S. Zhao, "Magnetic field integral equation at very low frequencies," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 1864- 1871, Aug. 2003.

Abstract: It is known that there is a low-frequency breakdown problem when the method of moments (MOM) with Rao-Wilton-Glisson (RWG) basis is used in the electric field integral equation (EFIE); it can be solved through the loop and tree basis decomposition. The behavior of the magnetic field integral equation (MFIE) at very low frequencies is investigated using MOM, where two approaches are presented based on the RWG basis and loop and tree bases. The study shows that MFIE can be solved by the conventional MOM with the RWG basis at arbitrarily low frequencies, but there exists an accuracy problem in the real part of the electric current. Although the error in the current distribution is small, it results in a large error in the far-field computation. This is because a big cancellation occurs during the far field computation. The source of error in the current distribution is easily detected through the MOM analysis using the loop and tree basis decomposition. To eliminate the error, a perturbation method is proposed, from which a very accurate real part of the tree current has been obtained. Using the perturbation method, the error in the far-field computation is also removed. Numerical examples show that both the current distribution and the far field can be accurately computed at extremely low frequencies by the proposed method.

18 S. Ohnuki and W. C. Chew, "Numerical accuracy of multipole expansion for 2D MLFMA," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 8, pp. 1883-1890, August 2003.

Abstract: A numerical study of the multipole expansion for the multilevel fast multipole algorithm (MLFMA) is presented. In the numerical implementation of MLFMA, the error comes from three sources: the truncation of the addition theorem; the approximation of the integration; the aggregation and disaggregation process. These errors are due to the factorization of the Green's function which is the mathematical core of the algorithm. Among the three error sources, we focus on the truncation error and a new approach of selecting truncation numbers for the addition theorem is proposed. Using this approach, the error prediction and control can be improved for the small buffer sizes and high accuracy requirements.

19 Y. Chu, W. C. Chew, S. Chen, and J. Zhao, "A surface integral equation method for low-frequency scattering from a composite object," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 10, pp. 2837-2844, Oct. 2003.

Abstract: A surface integral equation formulation is derived for low-frequency scattering from a composite object. This formulation allows those algorithms for finding the loop-tree basis on simple surfaces to be applied to the complicated interfaces of a composite object. By including the residue term in the K operator, the present formulation induces the interface boundary conditions automatically, and the resultant matrix equation can be solved directly without using the O(N/sup 2/) number-of-unknowns-reduction scheme.

Numerical results validate that the algorithm is stable even at extremely low frequencies and for closely spaced structures.

20 T. J. Cui and W. C. Chew, "A full-wave model of wire structures with arbitrary cross sections," *IEEE Transactions on Electromagnetic Compatibility*, vol. 45, no. 4, pp. 626-635, Nov. 2003.

Abstract: Transmission lines with rectangular cross sections are usually used in integrated circuit (IC) and computer chip problems. In this paper, a full-wave method is proposed based on an efficient wire model to analyze transmission-line circuits, where the cross sections of wires can be arbitrary. Comparing the existing wire models in the method of moments, it has been shown that the best performance occurs when the current is assumed to flow along the electrical axis of a wire and the testing is on the whole surface if two wires are very close. The physical significance of such modeling implies that the surface current on a wire is equivalent to a current filament along the electrical axis. For a single round wire, the electrical axis is exactly the same as its geometrical axis. For two parallel round wires, the electrical axis of each wire is located at the image position of the other wire. In this paper, a general wire model is proposed to determine electrical axes of wires with arbitrary cross sections by solving a static problem. Then, full-wave formulations are derived for wire structures with rectangular cross sections, which are the most important for IC and computer-chip problems. Numerical simulations are given to test the validity and accuracy of the proposed method.

21 A. Aydiner, W.C. Chew, J. M. Song, and T. J. Cui, "A sparse data fast Fourier transform (SDFFT)," *IEEE Transactions on Antennas and Propagation*, vol. 51, no.11, pp. 3161-3170, November 2003.

Abstract: A multilevel algorithm that efficiently Fourier transforms sparse spatial data to sparse spectral data with controllable error is presented. The algorithm termed "sparse data fast Fourier transform" (SDFFT) is particularly useful for signal processing applications where only part of the k-space is to be computed - regardless of whether it is a regular region like an angular section of the Ewald sphere or it consists of completely arbitrary points scattered in the k-space. In addition, like the various nonuniform fast Fourier transforms, the O(NlogN) algorithm can deal with a sparse, nonuniform spatial domain. In this paper, the parabolic reflector antenna problem is studied as an example to demonstrate its use in the computation of far-field patterns due to arbitrary aperture antennas and antenna arrays. The algorithm is also promising for various applications such as backprojection tomography, diffraction tomography, and synthetic aperture radar imaging.

22 W. C. Chew, H. Y. Chao, T. J. Cui, C. C. Lu, S. Ohnuki, Y. C. Pan, J. M. Song, S. Velamparambil, and J. S. Zhao, "Fast integral equation solvers in computational electromagnetics of complex structures," *Engineering Analysis with Boundary Elements*, vol. 27, no. 8, pp. 803-823, 2003.

Abstract: This paper reviews the recent progress of fast integral equation solvers at the Center for Computational Electromagnetics and Electromagnetics laboratory, University of Illinois at Urbana-Champaign. We will demonstrate the ability to solve a variety of electromagnetic problems for complex structures and low-frequency structures as well as large scale scattering problems with over 10 million unknowns.

23 M. Lu, K. Yegin, B. Shanker, and E. Michielssen, "Fast time domain integral equation solvers for analyzing two-dimensional scattering phenomena; Part I: temporal acceleration," *Electromagnetics*, vol. 24, no. 6, pp. 425-449, 2004.

Abstract: The primary impediment to analyzing two-dimensional transient scattering phenomena using classical marching-on-in-time-based integral equation solvers is these schemes' high computational complexity that scales as $O(N_s^2 N_t^2)$, where N_s and N_t denote the number of spatial and temporal degrees of freedom of the current on the scatterer. Here, three schemes that reduce this cost by permitting the rapid evaluation of the temporal convolution of a bandlimited transient source signature with the two-dimensional wave equation Green function are studied; these three methods rely on (i) blocked fast Fourier transforms, (ii) truncated singular value decompositions, and (iii) multiresolution concepts. The computational cost of all three proposed algorithms scales as $O(N_s^2 N_t \log^\alpha N_t)$ with $\alpha \leq 2$. The three schemes are compared on their respective multiplicative constants inherent in this cost estimate, their memory requirements, and their ease of implementation.

24 M. Lu, B. Shanker, and E. Michielssen, "Fast time domain integral equation solvers for analyzing two-dimensional scattering phenomena; Part II: full PWTD acceleration," *Electromagnetics*, vol. 24, no. 6, pp. 451-470, 2004.

Abstract: The primary impediment to using marching-on-in-time (MOT) schemes for solving time domain integral equations pertinent to the analysis of large-scale two-dimensional (2D) transient electromagnetic scattering phenomena is their high computational complexity. If N_s and N_t are the number of spatial and temporal degrees of freedom in the analysis, then this computational complexity scales as $O(N_s^2 N_t^2)$. Recently, it has been theoretically demonstrated that if classical MOT schemes are augmented with 2D plane wave time domain (PWTD) algorithms, their computational complexity can be reduced to $O(N_s N_t \log N_s \log N_t)$. This article elucidates key steps in implementing such a scheme within the context of 2D transient TM_z and TE_z electromagnetic scattering analysis. Several numerical examples that demonstrate the efficacy of the proposed schemes and also confirm the aforementioned computational complexity are presented.

25 L. J. Jiang and W. C. Chew, "Low frequency inhomogeneous plane wave algorithm -LF-FIPWA," *Microwave and Optical Technology Letters*, vol. 40, no. 2, pp. 117-122, Jan. 2004.

Abstract: A new method, the low-frequency fast inhomogeneous plane-wave algorithm (LF-FIPWA) is presented to extend the traditional multilevel fast multipole algorithm

(MLFMA) and fast inhomogeneous plane-wave algorithm (FIPWA) seamlessly into the low-frequency range. It uses evanescent-wave extrapolation and translation techniques to overcome the low-frequency breakdown problem. The accuracy can be well controlled over a broad frequency range. Numerical examples show the effectiveness of this new algorithm.

26 L. Xuan, B. Shanker, Z. Zeng, and L. Udpa, "Element-free Galerkin method for static and quasi-static electromagnetic field computation," *IEEE Transactions on Magnetics*, vol. 40, no. 1, pp. 12-20, Jan. 2004.

Abstract: Conventional finite-element methods (FEMs) rely on an underlying tessellation to describe the geometry and the basis functions that are used to represent the unknown quantity. Alternatively, however, it is possible to represent both the geometry and basis as a set of points. This alternative scheme has been used extensively in solid mechanics to compute stress and strain distributions. This paper presents an adaptation of the scheme to the analysis of electromagnetic problems in both the static and quasi-static regimes. It validates the proposed model against both analytical solutions and benchmarked FEMs. The paper demonstrates the efficacy of the proposed method by applying it to a range of problems.

27 K. Aygün, B. C. Fisher, J. Meng, B. Shanker and E. Michielssen, "A fast hybrid field-circuit simulator for transient analysis of microwave circuits," *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 2, pp. 573-583, Feb. 2004.

Abstract: A plane-wave-time-domain accelerated time-domain integral-equation solver is coupled to a SPICE-like transient circuit simulator to analyze electromagnetic platform-circuit interactions. The hybrid field-circuit simulator simultaneously solves surface-wire-volume time-domain integral equations that model electromagnetic interactions with the platform and modified nodal analysis equations that govern the behavior of the potentially non-linear lumped circuits. A shielded nonlinear microwave amplifier is analyzed using the proposed scheme, and its immunity to electromagnetic interference is assessed.

28 B. Shanker, K. Aygün and E. Michielssen, "Fast transient analysis of scattering from lossy inhomogeneous dielectric bodies," *Radio Science*, vol. 39, no. 2, Art. No. RS2007, March 2004.

Abstract: A time domain integral equation (TDIE)-based approach for analyzing transient wave scattering from linear lossy media is proposed. The pertinent TDIEs are cast in terms of a "conduction current corrected flux density" and are solved using a marching-on-in-time (MOT) scheme that incorporates a differential equation update algorithm for the aforementioned flux. The scheme is accelerated by the PWTD algorithm and it is shown that the computational complexity and memory requirements of the resulting solver scale as $O(N_t N_s)$ and $O(N_s)$, where N_t and N_s denote the number of temporal and spatial degrees of freedom in the flux expansion, respectively. Numerical results that validate the accuracy and efficacy of the proposed method are presented.

29 V. Lomakin, N.-W. Chen, S. Li and E. Michielssen, "Enhanced transmission through two-period arrays of subwavelength holes," *IEEE Microwave and Wireless Components Letters*, vol. 14, no. 7, pp. 355-357, July 2004.

Abstract: A two-period array of subwavelength holes in a perfect electrically conducting plate permits enhanced transmission of incident plane waves with wavenumbers near those of leaky waves supported by the array. A simple periodic impedance sheet model explains this phenomenon and provides an approximate expression for the transmission peak location. Transmission through thin perforated plates is studied using a full-wave solver to verify model-theoretic observations. Transmission coefficient peak splitting and narrowing phenomena, associated with thick perforated plates, are explored.

30 T. Rylander and J. M. Jin, "Stable coaxial waveguide port algorithm for the time domain finite element method," *Microwave and Optical Technology Letters*, vol. 42, no. 2, pp. 115-119, July 2004.

Abstract: A new coaxial waveguide-port algorithm is developed and tested for the time-domain finite-element method. The electric field is modeled by edge elements and, for part of a coaxial cable or a similar transmission line, the full Maxwell's equations are reduced to the one-dimensional transmission-line equation through the use of macro elements, which represent the dominant waveguide mode. The port algorithm converges quadratically with the cell size for geometries with smooth boundaries, which is demonstrated by tests on a coaxial cable with a short-circuit termination. The port algorithm is proven to be stable up to the Courant limit of the explicit scheme used for the transmission-line equation, without any added artificial dissipation. The proposed port algorithm preserves, by construction, the reciprocity of Maxwell's equations. For a 2 × 2-array of patch antennas, computation of the coupling of the antenna elements demonstrates that the scattering matrix is symmetric or, equivalently, that the proposed algorithm preserves reciprocity.

31 M. Lu, M. Lv, A. A. Ergin, B. Shanker, and E. Michielssen, "Multilevel plane wave time domain-based global boundary kernels for two-dimensional finite difference time domain simulations," *Radio Science*, vol. 39, no. 4, Art. No. RS4007, Aug. 2004.

Abstract: Time domain boundary integrals are used to impose global transparent boundary conditions in two-dimensional finite difference time domain solvers. Augmenting classical methods for imposing these conditions with the multilevel plane wave time domain scheme reduces the computational cost of enforcing a global transparent boundary condition from $O(\tilde{N}_s^2 \tilde{N}_t^2)$ to $O(\tilde{N}_t \tilde{N}_s \log \tilde{N}_t \log \tilde{N}_s)$; here $\tilde{N}_s$ and $\tilde{N}_t$ denote the number of equivalent source boundary nodes and their time samples used to integrate external fields, respectively. Numerical results demonstrate that for thin and concave material objects, plane wave time domain-accelerated global transparent boundary kernels outperform perfectly matching layer-based absorbing boundary schemes without loss of accuracy.

32 Q. Chen, M. Lu and E. Michielssen, "Integral-equation-based analysis of transient scattering from surfaces with an impedance boundary condition," *Microwave and Optical Technology Letters*, vol. 42, no. 3, pp. 213-220, Aug. 2004

Abstract: A marching-on-in-time (MOT)-based scheme for the analysis of transient scattering from closed surfaces characterized by an impedance boundary condition (IBC) is described. The time-domain integral equations being solved involve no analytical approximation and are free of spurious solutions. The proposed scheme is validated by a host of numerical examples.

33 T. Rylander and J. M. Jin, "Perfectly matched layers for the time domain finite element method applied to Maxwell's equations," *Journal of Computational Physics*, vol. 200, no. 1, pp. 238-250, Oct. 2004.

Abstract: A new perfectly matched layer (PML) formulation for the time domain finite element method is described and tested for Maxwell's equations. In particular, we focus on the time integration scheme which is based on Galerkin's method with a temporally piecewise linear expansion of the electric field. The time stepping scheme is constructed by forming a linear combination of exact and trapezoidal integration applied to the temporal weak form, which reduces to the well-known Newmark scheme in the case without PML. Extensive numerical tests on scattering from infinitely long metal cylinders in two dimensions show good accuracy and no signs of instabilities. For a circular cylinder, the proposed scheme indicates the expected second order convergence toward the analytic solution and gives less than 2% root-mean-square error in the bistatic radar cross section (RCS) for resolutions with more than 10 points per wavelength. An ogival cylinder, which has sharp corners supporting field singularities, shows similar accuracy in the monostatic RCS.

34 A. E. Yilmaz, J. M. Jin and E. Michielssen, "Time domain adaptive integral method for surface integral equations," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 10, pp. 2692-2708, Oct. 2004.

Abstract: An efficient marching-on-in-time (MOT) scheme is presented for solving electric, magnetic, and combined field integral equations pertinent to the analysis of transient electromagnetic scattering from perfectly conducting surfaces residing in an unbounded homogenous medium. The proposed scheme is the extension of the frequency-domain adaptive integral/pre-corrected fast-Fourier transform (FFT) method to the time domain. Fields on the scatterer that are produced by space-time sources residing on its surface are computed: 1) by locally projecting, for each time step, all sources onto a uniform auxiliary grid that encases the scatterer; 2) by computing everywhere on this grid the transient fields produced by the resulting auxiliary sources via global, multilevel/blocked, space-time FFTs; 3) by locally interpolating these fields back onto the scatterer surface. As this procedure is inaccurate when source and observer points reside close to each other; and 4) near fields are computed classically, albeit (pre-)corrected, for errors introduced through the use of global FFTs. The proposed scheme has a computational complexity and memory requirement of $O(N_t N_s \log^2 N_s)$ and $O(N_s^{3/2})$

when applied to quasiplanar structures, and of $O(N_t N_s^{3/2} \log^2 N_s)$ and $O(N_s^2)$ when used to analyze scattering from general surfaces. Here, and denote the number of spatial and temporal degrees of freedom of the surface current density. These computational cost and memory requirements are contrasted to those of classical MOT solvers, which scale as $O(N_t N_s^2)$ and $O(N_s^2)$, respectively. A parallel implementation of the scheme on a distributed-memory computer cluster that uses the message-passing interface is described. Simulation results demonstrate the accuracy, efficiency, and the parallel performance of the implementation.

35 G. Kobidze and B. Shanker, "Fast computational scheme for analyzing scattering from inhomogeneous anisotropic bodies," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 10, pp. 2650-2658, Oct. 2004.

Abstract: This paper presents an integral equation based scheme to analyze scattering from inhomogeneous bodies with anisotropic electromagnetic properties. Both the permittivity and permeability are assumed to be generalized tensors. Requisite integral equations are derived using volume equivalence theorem with the electric and magnetic flux densities being the unknown quantities. Matrix equations are derived by discretizing these unknowns using three-dimensional Rao-Wilton-Glisson basis functions. Reduction of the integral equation to a corresponding matrix equation is considerably more involved due to the presence of anisotropy and the use of vector basis function; methods for evaluation of the integrals involved in the construction of this matrix is elucidated in detail. The method of moments technique is augmented with the fast multipole method and a compression scheme. The latter two enable large scale analysis. Finally, several numerical results are presented and compared against analytical solutions to validate the proposed scheme. An appendix provides analytical derivations for the formulae that are used to validate numerical method, and the necessary formulae that extends the approach presented herein to the analysis of scattering bianisotropic bodies.

36 L. Xuan, Z. Zheng, B. Shanker and L. Udpa, "Meshless methods for modeling pulsed eddy currents," *IEEE Transactions on Magnetics*, vol. 50, no. 6, pp. 3457-3462, Nov. 2004.

Abstract: Meshless methods have attracted great attention due to their advantage in geometric representation. In this paper, a meshless element-free Galerkin method is applied for the first time to solve pulsed eddy-current problems. Detailed mathematical derivations and the numerical implementation are discussed. The model is validated against analytic solutions for two canonical cases.

37 M. K. Li and W. C. Chew, "A new Sommerfeld-Watson transformation in 3D," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 5, pp. 75-78, 2004.

Abstract: A new formula on the scalar wave scattering by a sphere at high frequency is presented. A new Sommerfeld-Watson transformation is used to construct a new residue series. In the derivation, a spherical traveling wave is defined and used to reduce the complexity of the solution. Furthermore, the new solution offers a clearer physical picture.

38 M. Lu, B. Shanker, and E. Michielssen, "Elimination of spurious solutions associated with exact transparent boundary conditions in FDTD solvers," *IEEE Antennas and Wireless Propagation Letters*, vol. 3, no. 4, pp. 59-62, 2004.

Abstract: An analysis of spurious solutions that often plague finite-difference time-domain solvers supplemented with certain transparent boundary conditions (TBC) is presented. It is shown that the electric- and magnetic-field TBC kernels may support undesired spurious modes. A combined-field TBC kernel is proposed that does not allow for the buildup of resonant modes. Its functionality is demonstrated by two numerical examples.

39 G. Kobidze, G. Jun, B. Shanker and E. Michielssen, "Fast scheme for analyzing scattering from dispersive media," to appear in *IEEE Transactions on Antennas and Propagation,* Feb. 2005.

Abstract: A fast integral equation based scheme for analyzing transient scattering from inhomogeneous dispersive bodies is presented. A time domain integral equation in terms of the electric flux inside the body is constructed by invoking the volume equivalence principle, i.e., by equating the sum of the incident electric field and that radiated by equivalent volume polarization currents to the total electric field. The proposed algorithm for solving this time domain integral equation incorporates a recursive convolution scheme that updates the polarization current from knowledge of the electric flux. To reduce the computational cost and memory requirement of the resulting marching-on-in-time scheme, it is augmented with the plane wave time domain algorithm. Numerical results that validate the proposed approach and demonstrate its accuracy are presented.

40 H. Bagci, A. E. Yilmaz, V. Lomakin, and E. Michielssen, "Fast solution of mixed-potential time-domain integral equations for half-space environments," to appear in *IEEE Transactions on Geoscience and Remote Sensing.*

Abstract: An FFT-accelerated integral-equation based algorithm to efficiently analyze transient scattering from planar perfect electrically conducting objects residing above or inside a potentially lossy dielectric half-space is presented. The algorithm requires O(NtNs(logNs+log^2Nt)) CPU and O(NtNs) memory resources when analyzing electromagnetic wave interactions with uniformly meshed planar structures. Here, Nt and Ns are the number of simulation time steps and spatial unknowns, respectively. The proposed scheme is therefore far more efficient than classical time-marching solvers, the CPU and memory requirements of which scale as O(Nt^2Ns^2) and O(NtNs^2). Inthe proposed scheme, all pertinent time-domain half-space Green functions are (pre-) computed from their frequency-domain counterparts via inverse discrete Fourier Transformation. In this process, in-band aliasing is avoided through the application of a smooth and interpolatory window. Numerical results demonstrate the accuracy and efficiency of the proposed algorithm.

41 N.-W. Chen, M. Lu, F. Capolino, B. Shanker, and E. Michielssen, "Floquet-wave-based analysis of transient scattering from doubly periodic perfectly conducting bodies," to appear in *Radio Science.*

Abstract: A Floquet-wave-based algorithm for solving a time-domain electric field integral equation pertinent to the analysis of transient plane wave scattering from doubly periodic, discretely planar, perfect electrically conducting structures is presented. The proposed scheme accelerates the evaluation of fields generated by periodic constellations of bandlimited transient currents via their expansion in time-domain Floquet waves and use of blocked fast Fourier transforms. The validity and effectiveness of the resulting algorithm are demonstrated through a number of examples.

42 B. Shanker, M. Lu, A. A. Ergin and E. Michielssen, "Acceleration of global exact boundary conditions for truncation of FDTD domains," submitted to *IEEE Transactions on Antennas and Propagation.*

Abstract: Truncating finite difference time domain meshes using exact radiation boundary conditions is computationally expensive. The computational bottleneck stems from the global nature of the resulting boundary update scheme, which calls for the evaluation of retarded-time boundary integrals at each time step. The classical evaluation of such integrals requires $O(N_s^2)$ operations per time step where N_s is the number of spatial field sampling points on the boundary. Here, the plane wave time domain algorithm is used to evaluate retarded-time boundary integrals in $O(N_s \log^2 N_s)$ operations per time step and thereby accelerate finite difference time domain solvers that impose exact radiation boundary conditions. The effectiveness of the resulting approach and its computational complexity are demonstrated through several numerical examples.

43 A. E. Yilmaz, J. M. Jin, and E. Michielssen, "A parallel FFT accelerated transient field-circuit simulator," submitted to *IEEE Transactions on Microwave Theory and Techniques.*

Abstract: A novel fast electromagnetic field-circuit simulator that permits the full-wave modeling of transients in nonlinear microwave circuits is proposed. This time-domain simulator is composed of two components: (i) A full-wave solver that models interactions of electromagnetic fields with conducting surfaces and finite dielectric volumes by solving time-domain surface and volume electric field integral equations, respectively; (ii) A circuit solver that models field interactions with lumped circuits, which are potentially active and nonlinear, by solving Kirchoff's equations through modified nodal analysis. These field and circuit analysis components are consistently interfaced and the resulting coupled set of nonlinear equations is evolved in time by a multidimensional Newton-Raphson scheme. The solution procedure is accelerated by allocating field- and circuit-related computations across the processors of a distributed-memory cluster, which communicate using the message-passing interface standard. Furthermore, the electromagnetic field solver, whose demand for computational resources far outpaces that of the circuit solver, is accelerated by an FFT based algorithm, viz. the time-domain adaptive integral method. The resulting parallel FFT accelerated transient field-circuit

simulator is applied to the analysis of various active and nonlinear microwave circuits, including power-combining arrays.