Improved Fast Modeling of Scattering from Inhomogeneous Lossy Dielectric Bodies

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ABSTRACT

A new time domain integral equation (TDIE) scheme for analyzing scattering from lossy penetrable volumes is presented. TDIEs are derived using the volume equivalence theorem. The equivalent currents, which comprise of both conduction and polarization components, are expressed in terms of a pseudo-flux density that is normally continuous across material interfaces and that therefore can be represented accurately using divergence conforming basis functions. The TDIEs are solved using a novel marching-on-in-time scheme that is retrofitted with the plane wave time domain algorithm. Numerical results demonstrate the accuracy and efficacy of the proposed solver are presented.

INTRODUCTION

A new fast volume integral equation based scheme for simulating transient electromagnetic scattering from lossy inhomogeneous bodies is presented. Computational methods for analyzing scattering from, and propagation through, lossy media are important in applications ranging from medical diagnostics to the assessment of skin effect losses in high-speed circuits to the characterization of interactions between antennas and biological media. In the past, the finite difference time domain method has been *the* vehicle of choice for analyzing electromagnetic wave interactions with inhomogeneous penetrable volumes. Indeed, time domain integral equation (TDIE) based schemes for long were considered to be computationally expensive and prone to numerical instabilities. This is not surprising as the computational cost of a classical marching on in time (MOT) based TDIE solver scales as the square of the number of spatial unknowns times the number of simulation time steps. Recently, however, it has been shown that augmenting MOT based TDIE solvers for analyzing surface scattering problems with the multi-level plane wave time domain (PWTD) algorithm results in drastic reductions in computational complexity and memory requirements [1]. In addition, recent research has produced new strategies for mitigating MOT instabilities. Here, advantage is taken from these developments to construct a fast integral equation based scheme for analyzing scattering from lossy volumes; the proposed integral equation scheme is devoid of staircasing and boundary treatment problems inherent to many finite difference methods.

COMPUTATIONAL SCHEME

The proposed algorithm for analyzing transient scattering from lossy objects is an outgrowth of our earlier work in this area [2,3]. A TDIE that enforces the total field within the scatterer to equal the incident plus the scattered fields is constructed. To this end, the scatterer is replaced by equivalent volume electric currents that are proportional to the sum of the conduction currents and the time derivative of the polarization currents. In lossless media, this TDIE is typically cast in terms of the electric flux density as opposed to the electric field because the flux's normal components are continuous across interfaces. This, in turn, permits discretization of the TDIE by means of volume RWG basis functions, i.e., divergence conforming spatial basis functions defined over pairs of tetrahedral elements [4]. In lossy media, however, the flux density is discontinuous across an interface; this necessitates modeling of the flux in terms of like basis defined over a single tetrahedra. Alternatively, however, one can define a pseudo flux density in terms of an effective permittivity that includes both polarization and conduction terms. This pseudo flux density again has continuous normal components across interfaces and hence can be modeled using divergence conforming basis functions. Unfortunately, the effective permittivity is a function of frequency; in the time domain, the pseudo flux therefore equals the convolution of the electric field with the effective permittivity. Alternatively, the electric field is related to the flux density via a simple first order partial differential equation. The scheme proposed in this paper proceeds as follows: an MOT scheme is used to determine the pseudo-flux density, and this in turn is used to determine the electric fields that are associated with a basis function. The latter operation is done using a simple differential equation update scheme. The MOT scheme is also retrofitted with the PWTD algorithm that considerably accelerates the evaluation of fields due to bandlimited sources.

NUMERICAL RESULTS

In the examples presented herein, the incident field is a modulated Gaussian pulse that may be parameterized as

$$\mathbf{E}^{i}(\mathbf{r},t)=\hat{p}\cos\left[2\pi f_0\left(t-\hat{k}\bullet\mathbf{r}/c-t_p\right)\right]\exp\left[-\frac{\left(t-\hat{k}\bullet\mathbf{r}/c-t_p\right)^2}{2\vartheta^2}\right] \tag{1}$$

where $\hat{p}$ and $\hat{k}$ are the polarization and direction of propagation of the wave, respectively, f_0 is the center frequency of the wave, $\vartheta=6/(2\pi f_{bw})$, and f_{bw} is the bandwidth of the signal. At the maximum frequency, $f=f_0+f_{bw}$, the incident power is down by 160db relative to its peak value at the center frequency. As in most electromagnetic numerical simulations, the largest edge length is chosen to be a tenth of a wavelength in the medium. In what follows, the scheme described above has been used to generate time domain far-field data. This is then Fourier transformed to obtain frequency domain radar scattering cross-section (RCS) data that is then compared against either analytical or frequency domain methods of moments solutions. In all examples that follow, the relative permittivity and the loss tangent of the material are chosen to be 4 and 0.25, respectively.

First, we analyze scattering from a spherical shell with an inner radius of 0.8m and outer radius of 1.0m. This shell is discretized using 13,968 basis functions. The incident pulse is $\hat{p}=\hat{x}$ polarized and propagates in $\hat{k}=\hat{z}$ direction, has center frequency of $f_0=120$ MHz and bandwidth of $f_{bw}=80$ MHz. RCS data at 150 MHz and backscattered RCS over a range of frequencies, obtained using the time domain code is compared against analytical solutions in Fig. 1(a,b). As is evident, the agreement between both is very good.

One of our principal objectives is to determine computational complexity of the proposed algorithm. To this end, a series of boxes with increasing number of unknowns were analyzed. The next example compares the RCS data of a box that was obtained using both the time and frequency domain codes. The box is of dimension $1\times1\times20\ m^3$, and is discretized using 11,834 spatial basis functions. A pulse that is polarized along $\hat{p}=\hat{x}$, propagating along $\hat{k}=\hat{z}$ direction with center frequency $f_0=65$ MHz, and bandwidth $f_{bw}=62.5$ MHz is incident upon the scatterer. Figure 2 (a) demonstrates the excellent agreement between the RCS data obtained using the time and frequency domain codes at 90 MHz. Finally, the computational complexity of the proposed scheme is reported. All the timing data was obtained by running these codes on an SGI Origin2000 machine that has a theoretical performance rating of 360 Mflops. As is evident from Fig. 2 (b), the computational cost scales linearly with the number of unknowns, and has a breakeven point of about 2500 unknowns.

SUMMARY

The contributions of this paper are two-fold. (i) A new MOT scheme for solving a TDIE in terms of a pseudo flux density is described; this scheme exploits the fact that the psuedo flux density and the electric field are related by a first order differential equation. (ii) This solver is augmented with a PWTD accelerator. Numerical results demonstrate the accuracy and efficacy of the proposed solver. Specifically, these numerical experiments demonstrate that the solver's computational cost scales proportionally to the number of spatial unknowns rather than its square.

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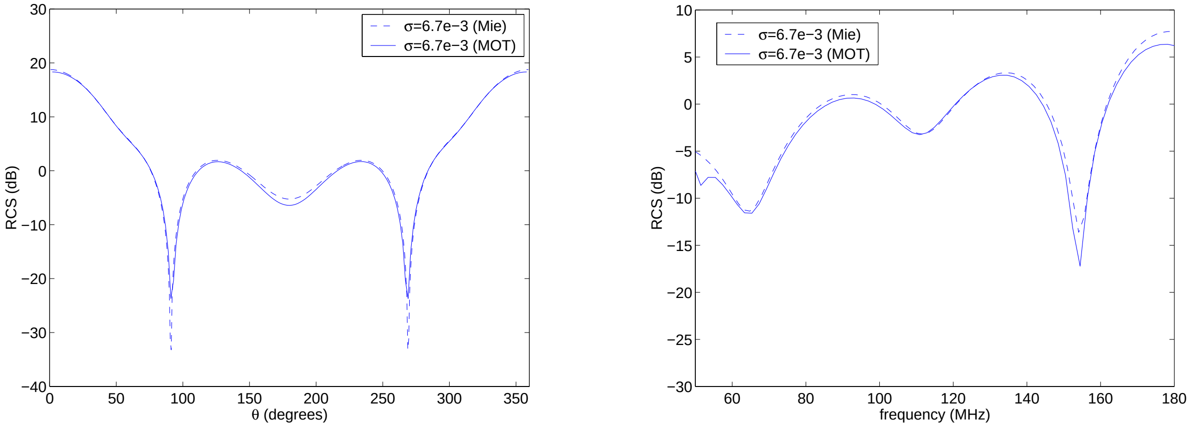
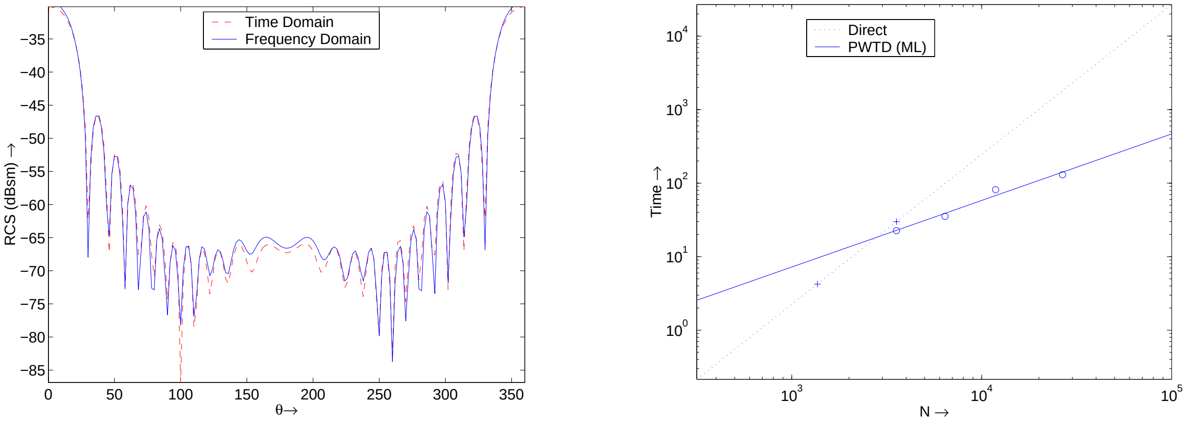


(a) 150 MHz

(b) Back scattered sweep

Figure 1. Comparison of RCS data obtained by the time domain code against analytical results



(a) 90 MHz

(b)

Figure 2: (a) Comparison of RCS data obtained using both the time and frequency domain codes; (b) Computational complexity of the proposed scheme.