ANALYSIS OF SCATTERING FROM COMPOSITE CONDUCTING AND DIELECTRIC TARGETS USING THE PRECORRECTED-FFT ALGORITHM

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Abstract—A precorrected-FFT algorithm is presented for the calculation of electromagnetic scattering from conducting objects coated with lossy materials. The problem is formulated using an EFIE-PMCHW formulation, which employs the electric field integral equation (EFIE) for conducting objects and the PMCHW formulation for dielectric objects. The integral equations are then discretized by the method of moments (MoM), in which the conducting and dielectric surfaces are represented by triangular patches and the unknown equivalent electric and magnetic currents are expanded using the RWG basis functions. The resultant matrix equation is solved iteratively and the precorrected-FFT method is used to speed up the matrix-vector products in iterations as well as to reduce the memory requirement. Numerical examples are presented to validate the implementation and to demonstrate the accuracy of the method.

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1. INTRODUCTION

Real-life scattering targets are usually a conglomeration of complicated shapes and materials. Numerical computations of such scatterers are often performed using surface integral equation (SIE) formulations in conjunction with the Method of Moments (MoM). With the SIE approach, the dimensionality of a problem is reduced from a 3-D volume to a 2-D surface. Despite this, the high computational complexity of MoM still renders the method computationally intractable when modeling complicated material and/or electrically large structures (the MoM analysis requires $O(N^3)$ computational complexity and $O(N^2)$ memory, where $N$ denotes the number of unknowns). A variety of methods such as the fast multiple method (FMM), the adaptive integral method (AIM), the conjugate gradient Fast Fourier Transform method (CG-FFT), and the precorrected-FFT (P-FFT) method, etc. have been developed to reduce CPU complexity and memory requirements. The initial focus of these fast methods was on solving problems related to scattering by large conducting bodies in free space. Recently, efforts have been made to extend some of them to penetrable scatterers [1–3] and multilayer penetrable scatterers [4]. In this paper, we present a method for fast analysis of electromagnetic scattering from 3-D composite conducting and dielectric objects by using the precorrected-FFT algorithm.

The precorrected-FFT method is a fast method associated with $O(N^{1.5}) \log N$ or less complexity. It was originally proposed by Philips and White [5, 6] to solve electrostatic integral equations and later extended to solve scattering from metallic targets in free space [7] and scattering and radiation of large microstrip antenna arrays [8]. In this paper, the precorrected-FFT method is further extended to the analysis of scattering from 3-D conducting bodies coated with lossy materials. We first formulate the problem using an EFIE-PMCHW formulation [9,10], employing the electric field integral equation (EFIE) for conducting surfaces and the Poggio, Miller, Chang, Harrington, and Wu (PMCHW) formulation [11] for dielectric surfaces. The surfaces are then modeled using triangular patches and the unknown equivalent electric and magnetic currents are expanded using the RWG basis functions [12]. By applying Galerkin’s technique, the integral equations are converted into a matrix equation. Finally, the matrix equation is solved iteratively and the precorrected-FFT method is used to speed up the matrix-vector multiplications in iterations. The resultant method has an accuracy comparable to the traditional MoM. It is also much faster and can analyze composite conducting and dielectric objects of much larger sizes efficiently.
2. FORMULATION

2.1. Integral Equation Formulation

Consider a general example of conducting bodies immersed in a dielectric material, as shown in Fig. 1. Let $S_{ci}, i = 1, 2, \ldots, N_c$, represent the surfaces of arbitrarily shaped conducting objects (either open or closed), $S_d$ represent the interface between the dielectric material coating and the external medium which is usually free space. The composite structure is illuminated by an incident plane wave ($E^{inc}, H^{inc}$).

Introduce equivalent electric currents $J_{ci}, i = 1, 2, \ldots, N_c$ on the conducting surfaces and equivalent electric and magnetic currents ($J_d, M_d$) and ($-J_d, -M_d$) on the outer and the inner side of the dielectric surface respectively. By enforcing the boundary conditions of continuity of the tangential components of electric field on the conducting surfaces and both electric and magnetic fields on the dielectric surface, we can obtain a set of coupled integral equations in terms of the unknown equivalent electric and magnetic currents [10]:

\[
\sum_{i=1}^{N_c} \mathbf{E}_{S_{ci}}^2 (J_{ci}) + \mathbf{E}_{S_{ci}}^2 (-J_d) + \mathbf{E}_{S_{ci}}^2 (-M_d) \bigg|_{\text{tan}} = 0, \quad i = 1, 2, \ldots, N_c
\]

\[
\sum_{i=1}^{N_c} \mathbf{E}_{S_d}^2 (J_{ci}) - \mathbf{E}_{S_d}^1 (J_d) + \mathbf{E}_{S_d}^2 (-J_d) - \mathbf{E}_{S_d}^1 (M_d) + \mathbf{E}_{S_d}^2 (-M_d) \bigg|_{\text{tan}} = \mathbf{E}_{S_d}^{inc} \bigg|_{\text{tan}} \quad (1b)
\]
\[
\left[ \sum_{i=1}^{N_c} \mathbf{H}_d^2 \left( \mathbf{J}_{ci} \right) - \mathbf{H}_d^1 \left( \mathbf{J}_d \right) + \mathbf{H}_d^2 \left( -\mathbf{J}_d \right) - \mathbf{H}_d^1 \left( \mathbf{M}_d \right) + \mathbf{H}_d^2 \left( -\mathbf{M}_d \right) \right]_{\text{tan}} = \mathbf{H}_{\text{inc}}^\ast \bigg|_{\text{tan}}
\]

where the superscript represents the medium in which the scattered fields are evaluated and the subscript represents the surface on which the equations are enforced. Eqn. (1a) is the electric field integral equation (EFIE) for conducting objects and Eqn. (1b) and (1c) are known as the PMCHW formulation for dielectric objects. The PMCHW formulation has been shown to be free of interior resonances and yield a unique and stable solution.

### 2.2. Method of Moments Solution

For the MoM solution of the integral equations (1), we first discretize all the conducting and dielectric surfaces into planar triangular patches and expand the equivalent electric and magnetic currents by the RWG basis functions [12]:

\[
\mathbf{J}_c(r') = \sum_{n=1}^{N_t} I_{cn} f_n(r')
\]

\[
\mathbf{J}_d(r') = \sum_{n=1}^{N_d} I_{dn} f_n(r')
\]

\[
\mathbf{M}_d(r') = \eta_0 \sum_{n=1}^{N_d} M_{dn} f_n(r')
\]

where \(N_d\) and \(N_t\) denote the number of edges on the dielectric and all \(N_c\) conducting surfaces of the triangulated model, respectively. For the convenience of both coding and description, we treat the \(N_c\) conducting surfaces as one overall conducting surface \(S_c\). The factor of \(\eta_0\) is required since the \(H\)-field equation is normalized by \(\eta_0\). Substituting (2) into (1) and using the Galerkin’s testing technique yield an \(N \times N\) \((N = N_t + 2N_d)\) matrix equation:

\[
\mathbf{ZI} = \mathbf{V}
\]
The matrices $Z$, $I$ and $V$ can be written in the following partitioned form,

\[
Z = \begin{bmatrix}
[Z_{cJ_c}] & [Z_{cJ_d}] & [T_{cM_d}]
\end{bmatrix}, \quad I = \begin{bmatrix}
[I_{cn}]
\end{bmatrix}, \quad V = \begin{bmatrix}
[V_{dm}]
\end{bmatrix}
\]

(4)

Considering the expressions of the scattered electric and magnetic field in terms of the electric and magnetic current, elements of the above submatrices can be written out as:

\[
Z_{mn}^{J_cJ_c} = -j \omega \int_{T_m} f_m(r) \cdot A_{2mn}(r) dr + \int_{T_m} \nabla_s \cdot f_m(r) \Phi_{2mn}(r) dr, \quad r \in S_c
\]

(5a)

\[
Z_{mn}^{J_cJ_d} = j \omega \int_{T_m} f_m(r) \cdot A_{2mn}(r) dr - \int_{T_m} \nabla_s \cdot f_m(r) \Phi_{2mn}(r) dr, \quad r \in S_c
\]

(5b)

\[
T_{mn}^{J_cM_d} = \int_{T_m} \eta_0 f_m(r) \cdot \frac{\nabla \times F_{2mn}(r)}{\varepsilon_2} dr, \quad r \in S_c
\]

(5c)

\[
Z_{mn}^{J_dJ_c} = -j \omega \int_{T_m} f_m(r) \cdot A_{2mn}(r) dr + \int_{T_m} \nabla_s \cdot f_m(r) \Phi_{2mn}(r) dr, \quad r \in S_d
\]

(5d)

\[
Z_{mn}^{J_dJ_d} = j \omega \int_{T_m} f_m(r) \cdot [A_{1mn}(r) + A_{2mn}(r)] dr
\]

\[
- \int_{T_m} \nabla_s \cdot f_m(r) [\Phi_{1mn}(r) + \Phi_{2mn}(r)] dr, \quad r \in S_d
\]

(5e)

\[
T_{mn}^{J_dM_d} = \int_{T_m} \eta_0 f_m(r) \cdot \nabla \times \left[ \frac{F_{1mn}(r)}{\varepsilon_1} + \frac{F_{2mn}(r)}{\varepsilon_2} \right] dr, \quad r \in S_d
\]

(5f)

\[
T_{mn}^{M_dJ_c} = \int_{T_m} \eta_0 f_m(r) \cdot \frac{\nabla \times A_{2mn}(r)}{\mu_2} dr, \quad r \in S_d
\]

(5g)

\[
T_{mn}^{M_dJ_d} = - \int_{T_m} \eta_0 f_m(r) \cdot \nabla \times \left[ \frac{A_{1mn}(r)}{\mu_1} + \frac{A_{2mn}(r)}{\mu_2} \right] dr, \quad r \in S_d
\]

(5h)

\[
Y_{mn}^{M_dM_d} = j \omega \int_{T_m} f_m(r) \cdot \eta_0^2 [F_{1mn}(r) + F_{2mn}(r)] dr
\]

\[
- \int_{T_m} \nabla_s \cdot f_m(r) \cdot \eta_0^2 [\Psi_{1mn}(r) + \Psi_{2mn}(r)] dr, \quad r \in S_d
\]

(5i)
where the various vector and scalar potential integrals take the following form, for \( i = 1, 2 \):

\[
A_{imn}(r) = \frac{\mu_i}{4\pi} \int_{T_n} f_n(r') G_i(r, r') dr'
\]

\[
\Phi_{imn}(r) = -\frac{1}{4\pi j \omega \varepsilon_i} \int_{T_n} \nabla' \cdot f_n(r') G_i(r, r') dr'
\]

\[
F_{imn}(r) = \frac{\varepsilon_i}{4\pi} \int_{T_n} f_n(r') G_i(r, r') dr'
\]

\[
\Psi_{imn}(r) = -\frac{1}{4\pi j \omega \mu_i} \int_{T_n} \nabla' \cdot f_n(r') G_i(r, r') dr'
\]

\( G_i(r, r') \) is the scalar Green’s function in medium \( i \) defined by

\[
G_i(r, r') = \frac{e^{-jk_i|r-r'|}}{|r-r'|}
\]

where \( k_i \) is the propagation constant in medium \( i \). The time variation, \( e^{j\omega t} \), is assumed and suppressed throughout. Elements of the electric and magnetic field excitation are given by:

\[
V_{dm} = \int_{T_m} f_m(r) \cdot E_{inc}^{\text{inc}}(r) dr
\]

\[
H_{dm} = \int_{T_m} f_m(r) \cdot \eta_0 H_{inc}^{\text{inc}}(r) dr
\]

In the above equations, \( f_m \) and \( f_n \) represent the testing and basis functions, respectively, while \( T_m \) and \( T_n \) denote their supports. \( \eta_0 \) stands for the characteristic impedance in free space. As we know, the definitions of the vector potentials \( A_i(r) \) and \( F_i(r) \) are similar except that the former is produced by the electric currents and the later by the magnetic currents. When the same basis functions are used for the expansion of both the electric and magnetic currents, they are essentially the same except for a constant, which is also revealed in (6a) and (6c). The scalar potentials \( \Phi_i(r) \) and \( \Psi_i(r) \) have the same property. Therefore, although both electric and magnetic currents exist in the problem, in the following P-FFT approach, we need only to construct the projection operators for one current, say electric current without loss of generality, the projection of the magnetic currents can be performed using the same projection operators. However, the potentials produced by different currents still need to be computed separately because the values of the currents are different.
Solving the matrix equation (3), we can obtain the unknown coefficients $I_{cn}$, $I_{dn}$, and $M_{dn}$, then the equivalent electric and magnetic currents, the scattered electric field in the far field and the RCS can be successively computed. It should be noted that only $\mathbf{J}_d$ and $\mathbf{M}_d$ on the outer dielectric surface contribute to the scattered fields and the scattered fields should be computed in the external medium.

### 2.3. Precorreted-FFT Approach

To solve the MoM equation (3) efficiently, one way is to combine an iterative method with a fast approach to compute the matrix-vector products of the form $\mathbf{Z}\mathbf{I}$. Computing $\mathbf{Z}\mathbf{I}$ is equivalent to computing the interactions between $N$ sources. The interactions between the sources can be divided into the near-zone and far-zone interactions. The near-zone interactions correspond to a sparse matrix $\mathbf{Z}^{\text{near}}$ and $\mathbf{Z}^{\text{near}}\mathbf{I}$ can be computed directly. The far-zone interactions correspond to a dense matrix $\mathbf{Z}^{\text{far}}$ and will be approximated by the precorrected-FFT approach. To implement the P-FFT algorithm, we first enclose the whole geometry in a rectangular region and then recursively subdivide it into a regular Cartesian grid so that each small cell contains only a few triangular patches. By replacing the original current and charge distribution with an approximately equivalent set of point-like currents and charges located at nodes of the Cartesian grid (a procedure which is referred to as “projection”), we can compute the vector and scalar potentials generated by these currents and charges using the FFT. Then the potentials on the triangular patches can be obtained from knowledge of the potentials on the grid points via interpolation. Since the near-zone interactions have been poorly approximated in the above procedure, it is necessary to remove the inaccurate contribution from the use of the grid as well as compute the near-zone interactions directly. This step is referred to as “precorrection”.

Assume $W_u(k)$ and $W_c(k)$ respectively represent the projection operators that project the $u$ component of the original current distributions and the original charge distributions on the triangular patches onto the uniform grid, $V^T$ denotes the interpolation operator that interpolates the grid point potentials onto the triangular patches, the approximations $A_G(k)$ and $\Phi_G(k)$ to the vector and scalar potentials can be obtained by

\begin{align}
A_{u,G}(k) &= V^T DFT^{-1} \{DFT\{G\} \cdot DFT\{W_u J_u\}\}, \quad u = x, y, z \\
\Phi_G(k) &= V^T DFT^{-1} \{DFT\{G\} \cdot DFT\{W_c \nabla \cdot J\}\}
\end{align}

where $DFT$ and $DFT^{-1}$ denote the FFT and inverse FFT, respectively. The entries of $G$ are the Green’s functions between grid points in
the corresponding medium. Both the projection and the interpolation operators are represented by sparse matrices and the discrete Fourier transform of the kernel matrix $G$ need be computed only once. The far-field interactions can be accurately approximated by (9a) and (9b), but the near fields radiated by the grid sources do not match those radiated by the original patch sources. Therefore, to get more accurate results, it is necessary to compute the near-field interactions directly and remove the errors introduced by the far-field operator. A “precorrected” direct interaction operator is defined as,

$$
\hat{P}(k,l) = P(k,l) - V(k)^T H(k,l) W(l)
$$

Then the exact vector potential $A(k)$ and scalar potential $\Phi(k)$ for each cell $k$ can be obtained by

$$
A(k) = A_G(k) + \sum_{l \in M(k)} \hat{P}(k,l) J_l, \quad (11a)
$$

$$
\Phi(k) = \Phi_G(k) + \sum_{l \in M(k)} \hat{P}(k,l) (\nabla \cdot J_l) \quad (11b)
$$

where $A_G(k)$ and $\Phi_G(k)$ are the respective grid-approximations to $A(k)$ and $\Phi(k)$. $P(k,l)$ denotes the close interactions which are computed directly, and $H$ denotes the overall inverse and direct FFT operations in (9). $M(k)$ is the indices of the set of cells which are “close” to cell $k$. For each cell $k$, $M(k)$ is a small set and each matrix $\hat{P}(k,l)$ is also small, so this precorrection step is also a sparse operation. The steps of FFT, interpolation and precorrection are similar to those for the conducting objects [7] although there are more terms to be treated in the present problem. The projection procedure will be explained in detail.

As can be seen from (5) and (6), there are three kinds of sources need to be projected onto the uniform grid, i.e., the basis function $f_n$, which is corresponding to patch currents (either electric or magnetic), the divergence operator $\nabla \cdot f_n$, which is corresponding to patch charges, and the curl operator $\nabla \times f_n$, which is corresponding to $\nabla \times \mathbf{A}_{imn}$ and $\nabla \times \mathbf{F}_{imn}$. As having mentioned that the vector (scalar) potentials produced by the electric and magnetic currents are essentially the same, we need only to construct the projection operators for the electric currents and charges.

Assume that the $n^{th}$ RWG basis function, $f_n$, is contained in a given cell $k$. The current and charge distributions on the two patches associated with the $n^{th}$ edge are then projected onto the grids surrounding this edge. Point sources on the grids can be set at the cell
vertices (grid-order \( p = 2 \)), or at half the spacing of the vertices (grid-order of \( p = 3 \)), etc., as desired for accuracy. Select \( N_{te} \) test points on the surface of a sphere of radius \( r_c \) whose center is coincident with the center of the cell \( k \). Enforcing the vector potential \( \mathbf{A}_i \) produced by the currents at the \( p^3 \) grid points to match that produced by the original current distributions on the triangular patches at the test points, we obtain

\[
\mathbf{A}^\text{pt}_{i,q} = \tilde{\mathbf{A}}^\text{gt}_{i,q}, \quad q = 1, 2, \ldots, N_{te}, \quad i = 1, 2
\]

where \( \mathbf{A}^\text{pt}_{i,q} \) and \( \tilde{\mathbf{A}}^\text{gt}_{i,q} \) denote the vector potentials at the \( q \)th test point due to the original patch current distributions and the grid currents respectively, whose expressions are given by

\[
\mathbf{A}^\text{pt}_{i,q}(\mathbf{r}^t_q) = \frac{\mu_i}{4\pi} \int_S I_n f_n(\mathbf{r}^t) e^{-jk_i|\mathbf{r}^t_q - \mathbf{r}^t'|} |\mathbf{r}^t_q - \mathbf{r}^t'| dS'
\]

\[
\tilde{\mathbf{A}}^\text{gt}_{i,q}(\mathbf{r}^t_q) = \frac{\mu_i}{4\pi} \sum_{s=1}^{p^3} (\mathbf{J}_{x,s} \hat{\mathbf{x}} + \mathbf{J}_{y,s} \hat{\mathbf{y}} + \mathbf{J}_{z,s} \hat{\mathbf{z}}) e^{-jk_i|\mathbf{r}^t_q - \mathbf{r}_s|} |\mathbf{r}^t_q - \mathbf{r}_s|
\]

with \( \mathbf{r}^t_q \) and \( \mathbf{r}_s \) being the position vectors at the \( q \)th test point and the \( s \)th grid point, respectively, and \( \mathbf{J}_{x,s}, \mathbf{J}_{y,s}, \mathbf{J}_{z,s} \) being the three components of the current at the \( s \)th grid point. The subscript \( i \) represents the medium in which the vector potentials are computed. Substituting (13) into (12) and also decomposing the patch currents into three components yield

\[
P^\text{gt}_{i,u} \mathbf{J}_{i,u} = P^\text{pt}_{i,u} I_n, \quad u = x, y, z
\]

where \( \mathbf{J}_{i,u} \in R^{p^3 \times 1} \) denote the vectors consisting of the \( u \) component of the grid currents, \( P^\text{gt}_{i,u} \in R^{N_{te} \times p^3} \) represent the mappings between the grid currents and the test-point potentials given by

\[
P^\text{gt}_{i,u}(q, s) = \frac{\mu_i}{4\pi} e^{-jk_i|\mathbf{r}^t_q - \mathbf{r}_s|} |\mathbf{r}^t_q - \mathbf{r}_s|
\]

By construction, the relative positions of the grid points and the test points are identical for each cell, and therefore \( P^\text{gt}_{i,u} \) are the same for each cell. The components, \( P^\text{pt}_{i,u} \in R^{N_{te} \times N(k)} \), are the mappings between the patch currents and the test point potentials, \( N(k) \) is the number of the basis functions contained in cell \( k \). \( P^\text{pt}_{i,u} \) can be written
The contribution of the \(n\)th basis function in cell \(k\) to \(\hat{J}_{i,u}\) can be represented by three column vectors \(W_{i,u}(k,n)\) given by

\[
W_{i,u}(k,n) = [P_{i,u}^{gt}]^+ P_{i,u}^{pt,n}
\]  

(17)

where \(P_{i,u}^{pt,n}\) denotes the \(n\)th column of \(P_{i,u}^{pt}\) and \([P_{i,u}^{gt}]^+\) indicates the generalized inverse of \(P_{i,u}^{gt}\). \(W_{i,u}(k,n)\) identifies the current projection operator computed in medium \(i\). By using the projection operators, we can project the patch current \(I_n f_n\) onto the \(p^3\) grid points surrounding cell \(k\).

The foregoing formulae are made for the projection of the patch current. Similarly, by matching the scalar potential due to the \(p^3\) grid charges and that due to the actual patch charge distribution at the test points, we can construct the charge projection operator \(W_{i,c}(k,n)\). The accuracy of the above projection scheme depends on the proper selection of the test points \(\mathbf{r}^t\). The criteria for the choice of the test points can be found in [13, 14].

As for the operator \(\nabla \times f_n\), we employ a simplified approach which avoids the projection of the \(\nabla \times f_n\) operator. Replacing the partial derivatives of the vector potential \(A_{imn}\) with the corresponding differences, i.e.,

\[
\nabla \times A_{imn} = \left( \frac{\partial A_{imn,z}}{\partial y} - \frac{\partial A_{imn,y}}{\partial z} \right) \hat{x} + \left( \frac{\partial A_{imn,x}}{\partial z} - \frac{\partial A_{imn,z}}{\partial x} \right) \hat{y} + \left( \frac{\partial A_{imn,y}}{\partial x} - \frac{\partial A_{imn,x}}{\partial y} \right) \hat{z}
\]

(18)

The required differences of the components of \(A_{imn}\) can be computed through the vector potentials at several vicinal points of the observation point. Knowledge of these potentials can be readily obtained through interpolation once the vector potentials at grid points have been computed by the FFTs. This approach only requires several extra interpolations and avoids the efforts to project the \(\nabla \times f_n\) operator and to perform extra FFTs.

Note that since the Green’s functions is a function of the constitutive properties of different mediums, the projection must be performed for each medium separately. In other words, when the vector or scalar potentials in medium \(i\) are to be computed, the projection operators...
corresponding to medium $i$ are used to project the patch currents and charges unto the uniform grid. After obtaining the required projection operators, the vector and scalar potentials generated by the electric and magnetic currents can be evaluated efficiently following the steps represented by (9) to (11). Then all the required submatrix-vector products in the iterative solution of (3) can be computed according to (5).

3. NUMERICAL EXAMPLES

In this section, some numerical examples are presented to validate the implementation procedure and to demonstrate the accuracy of the present method. The actual memory reduction and speed-up attained by this fast method has already been demonstrated in [7, 8], so it is omitted here.

The first example is a perfectly conducting sphere with a coating having the relative permittivity of $4.0 - j0.01$. The radius of the conducting sphere is $0.3\lambda_0$ and the coating thickness is $0.05\lambda_0$. The conducting and dielectric spheres are modeled with 350 and 478 triangular patches respectively, which results in 1959 unknowns. For the precorrected-FFT method, a grid spacing of $0.08\lambda_0$ is used and the near-field threshold distance is set to be $0.24\lambda_0$. This choice of the near field threshold has been demonstrated to produce accurate results in [8] and is used throughout this paper. The bistatic RCS computed is shown in Fig. 2. Very good agreement is observed between the traditional MoM solution, the precorrected-FFT solution and the exact Mie series solution [15], validating both our MoM and precorrected-FFT codes.

The second example is a conducting disk embedded in a dielectric cylinder. The radius of the disk and the cylinder is $0.4\lambda_0$ and $0.45\lambda_0$ respectively, and the height of the cylinder is $1.6\lambda_0$. The triangular patch model of the disk contains 179 edges and the dielectric cylinder contains 1914 edges, resulting in 4007 unknowns. The bistatic RCS obtained from the precorrected-FFT method and the traditional MoM are given in Fig. 3. Again near perfect agreement is observed.

As a larger example, we consider the bistatic RCS of another coated sphere. The conducting sphere has a radius $a = 2\lambda_0$ and the coating has a thickness $t = 0.05\lambda_0$, a relative permittivity $\varepsilon_r = 4.0 - j9$. The conducting and dielectric surfaces are modeled by 12,378 and 12,868 triangular patches respectively, resulting in 57,171 unknowns in all. The results calculated by the precorrected-FFT method are shown in Fig. 4. The exact Mie series solution [15] is also given for comparison. It is observed that the agreement between the results is
Figure 2. Bistatic RCS of a conducting sphere coated with a lossy dielectric material.

Figure 3. Bistatic RCS of a conducting disk imbedded in a lossy dielectric cylinder.
Figure 4. Bistatic RCS of a large coated sphere ($\theta \theta$ polarization).

Figure 5. The monostatic RCS of a coated finite cylinder in the $y$-$z$ plane ($\phi = 90^\circ$).
reasonably good.

Fig. 5 gives an additional example of scattering by a coated cylinder. The conducting cylinder has a diameter $d = 1.0\lambda_0$ and a length $l = 2.0\lambda_0$. The coating has a thickness $t = 0.1\lambda_0$, a relative permittivity $\varepsilon_r = 2.0 - j1.0$, and a relative permeability $\mu_r = 1.5 - j0.5$. The surfaces of the conducting and dielectric cylinder are modeled using 1600 and 2132 triangles respectively, and the number of unknowns is 8796. The calculated monostatic RCS in the $y$-$z$ plane for both the coated and uncoated object are shown in the figure. The results obtained by Sheng et al. from the FEM-MLFMA [16] are also given for comparison. Good agreement is observed. It also can be seen that the RCS for the coated object is smaller than that for the uncoated one. In other words, the coating has effectively reduced the RCS of the cylinder.

4. CONCLUSIONS

In this paper, a precorrected-FFT algorithm has been presented for the calculation of electromagnetic scattering from 3-D bodies comprising both conducting and dielectric objects. The problem was formulated using the PMCHW formulation for dielectric objects and the EFIE for conducting objects. The conducting and dielectric surfaces are modeled by triangular patches and the unknown equivalent electric and magnetic currents are expanded using the RWG basis functions. The resultant numerical system was solved iteratively and the matrix-vector products were accelerated by the precorrected-FFT method, which was tailored to accommodate the material properties of composite conducting and dielectric scatterers. Some numerical examples were presented to validate the implementation of the algorithm and illustrate the accuracy of this approach.

REFERENCES

3. Catedra, M. F., E. Gago, and L. Nuno, “A numerical scheme to obtain the RCS of three-dimensional bodies of resonant size using


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