Plane Wave Scattering From Three Dimensional Multiple Objects Using the Iterative Multiregion Technique Based on the FDFD Method

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***Abstract*—An iterative approach using the finite difference frequency domain method is presented in this paper in order to solve the problem of scattering from large three-dimensional electromagnetic scatterers. The idea of iterative multiregion technique is introduced to divide one computational domain into smaller subregions and solve each subregion separately. Then the subregion solutions are combined iteratively to obtain a solution for the complete domain. As a result, a considerable reduction in the computation time and memory has been achieved.**

***Index Terms*—Finite difference frequency domain (FDFD), iterative methods, scattering.**

I. Introduction

NUMERICAL analyzes of large-scale electromagnetic problems require long computational time and large computer memory. One of the goals of ongoing computational electromagnetic research is to develop time and memory efficient algorithms. A class of time and memory efficient algorithms divides the computational domain into smaller subdomains and then combines the subdomain solutions after introducing the effect of interactions between these subdomains. A group of methods that decomposes the computational domain into subdomains is known as the domain decomposition methods (DDM) [1]–[17]. These methods in general require common boundaries between subdomains and boundary conditions are enforced on subdomain interfaces. There are usually two approaches used with the applications of the coupling effects: the direct method imposes the continuity of the fields on the partition interfaces and generates a global coupling matrix [17], whereas the iterative method [1], [4] ensures the coupling between the adjacent elements by the transmission condition (TC) as described in [1]. It is possible to solve each subdomain with the same method such as with finite element method (FEM) [4] or finite difference frequency domain method [8]. However, some DDM methods have the flexibility that in each subdomain the most efficient method can be used independently to solve Maxwell's equations [7]. Therefore the complexity of the problem can be reduced, and a time and memory efficiency algorithm can be achieved. Another advantage of the DDM methods is that they are suitable to develop parallel processing techniques [14]–[16], and thus enable highly scalable algorithms.

In order to economically provide efficient solution to large-scale electromagnetic problems, especially those that involve open boundaries such as the scattering from multiple objects, decomposing the computation domain into separate subregions would be preferable. It is then necessary to develop accurate procedures to support the interaction between the unconnected subregions. Some hybrid-techniques based on combinations of method of moments (MoM), finite element (FE), finite difference time domain (FDTD), and physical optics (PO) have been used to solve a class of these problems, in which part of the problem is usually large compared to other parts [18]–[20].

In this paper, we present a new technique based on the finite difference frequency domain (FDFD) method and an iterative procedure between the subregions to calculate the scattering from multiple objects similar to that described in [21]. In this approach, the problem is decomposed into separated subregions, each subregion containing a scatterer or a group of scatterers. The scattered electromagnetic near fields are calculated due to the incidence of a time-harmonic wave in each subregion, using the FDFD method or any other appropriate method. Then fictitious electric and magnetic currents on imaginary surfaces surrounding the objects in these subregions are calculated, using the equivalence principle. Radiated fields by these currents are then considered as incident fields on the opposing subregions. The same procedure of calculating the subregion field components, the fictitious currents and the radiated fields on the opposing domains is repeated iteratively until a convergence is achieved. The iterative procedure developed here is similar to the procedure denoted as Iterative Field Bouncing (IFB) method and described briefly in [19], and the procedure described in [22]. References [19] and [22] touches on the subject but do not provide the details of a procedure that can be followed for general-purpose three-dimensional scattering problems.

The procedure presented in this paper, referred to as iterative multiregion (IMR) technique, requires solution of fields in the subregions a number of times instead of one solution of the complete domain. This technique effectively reduces the size of the required memory, especially for three-dimensional problems. Furthermore, the CPU time reduction can be achieved if the separation between some subregions is large and/or coarser grids are used in some of the subregions, which may not be possible to use if only one domain is used for the solution of the problem. The application of this technique is applied on three-dimensional scatterers and the verification of the gener-

Manuscript received March 28, 2005; revised October 2, 2005.

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Digital Object Identifier 10.1109/TAP.2005.863129

ated numerical data from the FDFD code is performed. The use of the FDFD provides the flexibility in defining composite (in shape and type) structures in each subregion. It also provides a much stable solution relative to other available methods and a more convenient procedure for performing the interaction between the subregions based on well-known theorems. The use of the FDTD technique was intentionally avoided in this work as the interaction process between subregions would involve complex bookkeeping for the source and its effect in the spatial and time domains from one subregion to the other. Despite that both FDFD and FDTD methods share a descritization constrain, the latest require more attention regarding the choice of the time step and the parameters of the source time domain waveform. Furthermore, the FDFD is free of dispersion, which is one of the drawbacks of the FDTD technique. The FDFD solution provided in this paper is similar to the two-dimensional FDFD analysis in [23]. Furthermore, the present formulation, only uses the E_x, E_y, and E_z components for a three-dimensional problem instead of using E_x, E_y, E_z, H_x, H_y, and H_z as one would expect following the formulation presented in [23]. Thus this FDFD formulation allows for additional memory saving.

The FDFD equations are constructed based on the scattered field formulation, that is, the total field is assumed to be the sum of incident and scattered fields. The use of these equations requires the computation of incident field components at all grid nodes in the computation space. However, it has been realized that, a considerable amount of computation time is spent for calculation of the incident field components in a region due to the fictitious current sources in the other regions. Therefore, the idea of using the *total-field / scattered-field* (TF/SF) formulation [24], is introduced in this work. The TF/SF technique requires the computation of incident field components on a surface boundary rather than the whole computational domain. Therefore, the (TF/SF) formulation provides the IMR technique with the advantage of a tremendous time saving of around 50%, compared to the scattered field formulation.

II. FDFD Formulation

Starting from Maxwell's equations for the total electric and magnetic fields with time harmonic convention $e^{j\omega t}$

$$\nabla \times \overline{E}^{tot} = -j\omega\mu\overline{H}^{tot}, \quad \nabla \times \overline{H}^{tot} = j\omega\varepsilon\overline{E}^{tot} \tag{1}$$

and by separating the total field into incident and scattered field components, we obtain

$$\begin{aligned} \nabla \times (\overline{E}^{i} + \overline{E}^{s}) &= -j\omega\mu(\overline{H}^{i} + \overline{H}^{s}), \\ \nabla \times (\overline{H}^{i} + \overline{H}^{s}) &= +j\omega\varepsilon(\overline{E}^{i} + \overline{E}^{s}). \end{aligned} \tag{2}$$

The superscripts i and s are used to denote the incident and scattered fields, where the incident field is the field that would exist in the computational domain with no scatterers. If the computational domain is free space then the incident field satisfies Maxwell's equations, such that

$$\nabla \times \overline{E}^{i} = -j\omega\mu_0\overline{H}^{i}, \quad \nabla \times \overline{H}^{i} = j\omega\varepsilon_0\overline{E}^{i}. \tag{3}$$

Substitution of (3) into (2) yields

$$\overline{E}^{s} = \frac{1}{j\omega\varepsilon}\nabla \times \overline{H}^{s} - \frac{(\varepsilon - \varepsilon_o)}{\varepsilon}\overline{E}^{i} \tag{4}$$

$$\overline{H}^{s} = -\frac{1}{j\omega\mu}\nabla \times \overline{E}^{s} + \frac{(\mu_o - \mu)}{\mu}\overline{H}^{i}. \tag{5}$$

In this paper, the FDFD scattered field formulation for the three-dimensional case is developed and the presented method is applied to problems that belong to this case, without loss of generality. The incident plane wave field component for both, θ and ϕ polarization can be given as

$$\begin{aligned} E_x^i(x,y) &= E_\theta^i \cos\theta^i \cos\phi^i - E_\phi^i \sin\phi^i \\ E_y^i(x,y) &= E_\theta^i \cos\theta^i \sin\phi^i + E_\phi^i \cos\phi^i \\ E_z^i(x,y) &= -E_\theta^i \sin\theta^i \\ H_x^i(x,y) &= \frac{1}{\eta_0}\left(E_\phi^i \cos\theta^i \cos\phi^i + E_\theta^i \sin\phi^i\right) \\ H_y^i(x,y) &= \frac{1}{\eta_0}\left(E_\phi^i \cos\theta^i \sin\phi^i - E_\theta^i \cos\phi^i\right) \\ H_z^i(x,y) &= \frac{1}{\eta_0}\left(-E_\phi^i \sin\theta^i\right) \end{aligned} \tag{6}$$

where E_θ^i and E_ϕ^i indicates the polarization type; thus can be written as

$$E_{\theta,\phi}^i = E_{\theta,\phi}^0 e^{-j\beta(x\sin\theta^i\cos\phi^i + y\sin\theta^i\sin\phi^i + z\cos\theta^i)} \tag{7}$$

where E_θ^0 and E_ϕ^0 are the magnitude of the incident electric field, indicating whether the polarization is θ or ϕ polarized by assigning $E_\theta^0 = 1$ and $E_\phi^0 = 0$ or vice versa, k_0 is the wave number, ε_0, and μ_0 are the permittivity and the permeability of free space. The incident angle with respect to the x-axis of the global coordinates system is ϕ^i, while θ^i is the incident angle with respect to the z-axis. Having defined the incident fields, (4) can be written for the scattered electric field components in the form

$$E_x^s = \frac{1}{j\omega\varepsilon_{xy}}\frac{\partial H_z^s}{\partial y} - \frac{1}{j\omega\varepsilon_{xz}}\frac{\partial H_y^s}{\partial z} - \frac{(\varepsilon_{xi} - \varepsilon_o)}{\varepsilon_{xi}}E_x^i \tag{8-a}$$

$$E_y^s = \frac{1}{j\omega\varepsilon_{yz}}\frac{\partial H_x^s}{\partial z} - \frac{1}{j\omega\varepsilon_{yx}}\frac{\partial H_z^s}{\partial x} - \frac{(\varepsilon_{yi} - \varepsilon_o)}{\varepsilon_{yi}}E_y^i \tag{8-b}$$

$$E_z^s = \frac{1}{j\omega\varepsilon_{zx}}\frac{\partial H_y^s}{\partial x} - \frac{1}{j\omega\varepsilon_{zy}}\frac{\partial H_x^s}{\partial y} - \frac{(\varepsilon_{zi} - \varepsilon_o)}{\varepsilon_{zi}}E_z^i. \tag{8-c}$$

Using (5) the magnetic field components can be expressed in terms of the scattered electric field as

$$H_x^s = \frac{1}{j\omega\mu_{xz}}\frac{\partial E_y^s}{\partial z} - \frac{1}{j\omega\mu_{xy}}\frac{\partial E_z^s}{\partial y} + \frac{(\mu_o - \mu_{xi})}{\mu_{xi}}H_x^i \tag{9-a}$$

$$H_y^s = \frac{1}{j\omega\mu_{yx}}\frac{\partial E_z^s}{\partial x} - \frac{1}{j\omega\mu_{yz}}\frac{\partial E_x^s}{\partial z} + \frac{(\mu_o - \mu_{yi})}{\mu_{yi}}H_y^i \tag{9-b}$$

$$H_z^s = \frac{1}{j\omega\mu_{zy}}\frac{\partial E_x^s}{\partial y} - \frac{1}{j\omega\mu_{zx}}\frac{\partial E_y^s}{\partial x} + \frac{(\mu_o - \mu_{zi})}{\mu_{zi}}H_z^i \tag{9-c}$$

In (8) and (9) the permittivity and permeability parameters are indexed in such a way that these equations will be used for the absorbing boundary based on the perfectly matched layer (PML), that will be used to truncate the computational domain, and the non-PML regions as well. Equations (8) and (9) are

the starting points to the construction of the FDFD equation for a three-dimensional problem. Based on the Yee's [25] grid and after applying the central difference approximations to the derivatives in (8) and (9), we get

$$\begin{aligned} E_x^s(i,j,k) = {} & \frac{1}{j\omega\varepsilon_{xy}(i,j,k)\Delta y} H_z^s(i,j,k) \\ & - \frac{1}{j\omega\varepsilon_{xy}(i,j,k)\Delta y} H_z^s(i,j-1,k) \\ & - \frac{1}{j\omega\varepsilon_{xz}(i,j,k)\Delta z} H_y^s(i,j,k) \\ & + \frac{1}{j\omega\varepsilon_{xz}(i,j,k)\Delta z} H_y^s(i,j,k-1) \\ & - \frac{(\varepsilon_{xi}(i,j,k)-\varepsilon_o)}{\varepsilon_{xi}(i,j,k)} E_x^i(i,j,k) \qquad \text{(10-a)} \end{aligned}$$

$$\begin{aligned} E_y^s(i,j,k) = {} & \frac{1}{j\omega\varepsilon_{yz}(i,j,k)\Delta z} H_x^s(i,j,k) \\ & - \frac{1}{j\omega\varepsilon_{yz}(i,j,k)\Delta z} H_x^s(i,j,k-1) \\ & - \frac{1}{j\omega\varepsilon_{yx}(i,j,k)\Delta x} H_z^s(i,j,k) \\ & + \frac{1}{j\omega\varepsilon_{yx}(i,j,k)\Delta x} H_z^s(i-1,j,k) \\ & - \frac{(\varepsilon_{yi}(i,j,k)-\varepsilon_o)}{\varepsilon_{yi}(i,j,k)} E_y^i(i,j,k) \qquad \text{(10-b)} \end{aligned}$$

$$\begin{aligned} E_z^s(i,j,k) = {} & \frac{1}{j\omega\varepsilon_{zx}(i,j,k)\Delta x} H_y^s(i,j,k) \\ & - \frac{1}{j\omega\varepsilon_{zx}(i,j,k)\Delta x} H_y^s(i-1,j,k) \\ & - \frac{1}{j\omega\varepsilon_{zy}(i,j,k)\Delta y} H_x^s(i,j,k) \\ & + \frac{1}{j\omega\varepsilon_{zy}(i,j,k)\Delta y} H_x^s(i,j-1,k) \\ & - \frac{(\varepsilon_{zi}(i,j,k)-\varepsilon_o)}{\varepsilon_{zi}(i,j,k)} E_z^i(i,j,k) \qquad \text{(10-c)} \end{aligned}$$

$$\begin{aligned} H_x^s(i,j,k) = {} & \frac{1}{j\omega\mu_{xz}(i,j,k)\Delta z} E_y^s(i,j,k+1) \\ & - \frac{1}{j\omega\mu_{xz}(i,j,k)\Delta z} E_y^s(i,j,k) \\ & - \frac{1}{j\omega\mu_{xy}(i,j,k)\Delta y} E_z^s(i,j+1,k) \\ & + \frac{1}{j\omega\mu_{xy}(i,j,k)\Delta y} E_z^s(i,j,k) \\ & + \frac{(\mu_o-\mu_{xi}(i,j,k))}{\mu_{xi}(i,j,k)} H_x^i(i,j,k) \qquad \text{(11-a)} \end{aligned}$$

$$\begin{aligned} H_y^s(i,j,k) = {} & \frac{1}{j\omega\mu_{yx}(i,j,k)\Delta x} E_z^s(i+1,j,k) \\ & - \frac{1}{j\omega\mu_{yx}(i,j,k)\Delta x} E_z^s(i,j,k) \\ & - \frac{1}{j\omega\mu_{yz}(i,j,k)\Delta z} E_x^s(i,j,k+1) \\ & + \frac{1}{j\omega\mu_{yz}(i,j,k)\Delta z} E_x^s(i,j,k) \\ & + \frac{(\mu_o-\mu_{yi}(i,j,k))}{\mu_{yi}(i,j,k)} H_y^i(i,j,k) \qquad \text{(11-b)} \end{aligned}$$

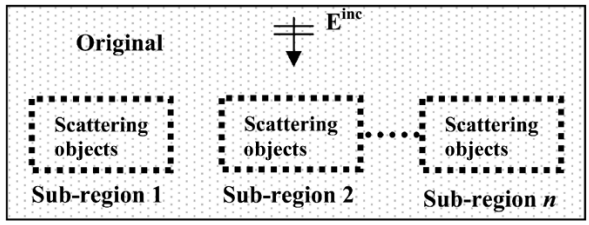

Fig. 1. Original domain showing possible decomposition to n regions.

$$\begin{aligned} H_z^s(i,j,k) = {} & \frac{1}{j\omega\mu_{zy}(i,j,k)\Delta y} E_x^s(i,j+1,k) \\ & - \frac{1}{j\omega\mu_{zy}(i,j,k)\Delta y} E_x^s(i,j,k) \\ & - \frac{1}{j\omega\mu_{zx}(i,j,k)\Delta x} E_y^s(i+1,j,k) \\ & + \frac{1}{j\omega\mu_{zx}(i,j,k)\Delta x} E_y^s(i,j,k) \\ & + \frac{(\mu_o-\mu_{zi}(i,j,k))}{\mu_{zi}(i,j,k)} H_z^i(i,j,k) \qquad \text{(11-c)} \end{aligned}$$

where i, j, and k represent the indices of the grid points of the Yee cell, Δx, Δy, and Δz, represents the spatial increments in the Cartesian computational domain that contains a total of N grid points.

Equations (10) and (11) can be reduced to three equations, in terms of the three scattered electric field components by eliminating the scattered magnetic field terms, which can then construct a linear set of equations. These equations can be arranged in a matrix form as [A][E] = [Y], where [A] is a $(3N \times 3N)$ highly sparse coefficients matrix, [E] is the unknown vector, in which the first (N) elements represent the E_x scattered electric field components, the second (N) elements represent the E_y scattered electric field components and the third (N) elements represent the E_z scattered electric field components in the computation grid, thus the total size of the vector [E] is $(3N)$. The [Y] vector is the excitation vector, and is a function of incident field components, E_x^i, E_y^i, E_z^i, H_x^i, H_y^i and H_z^i. The solution of this matrix equation for the vector [E] yields the E_x^s, E_y^s, and E_z^s field components in the computational grid. Once the electric field components are determined the corresponding magnetic field components can be evaluated using (9).

III. Iterative Procedure Between Multiple Domains

The developed iterative technique is based on dividing the original electromagnetic scattering problem of a large domain into smaller problems in separated subregions, where the latest are to interact with each other in order to take in consideration the effect of the coupling between them. A huge saving in memory is achieved due to the fact; that dividing the original problem into smaller problems provides the benefit of minimizing the domain size, in addition to the saving in the computational time, especially with large separation between some regions. Therefore instead of dealing with one large region, which may not be possible in some problems due to limited computing resources, one would be dealing with multiple smaller regions.

The problem illustrated in Fig. 1 shows the construction of the original domain, where the IMR techniques is to be applied on. First, the original problem domain is divided into sub-

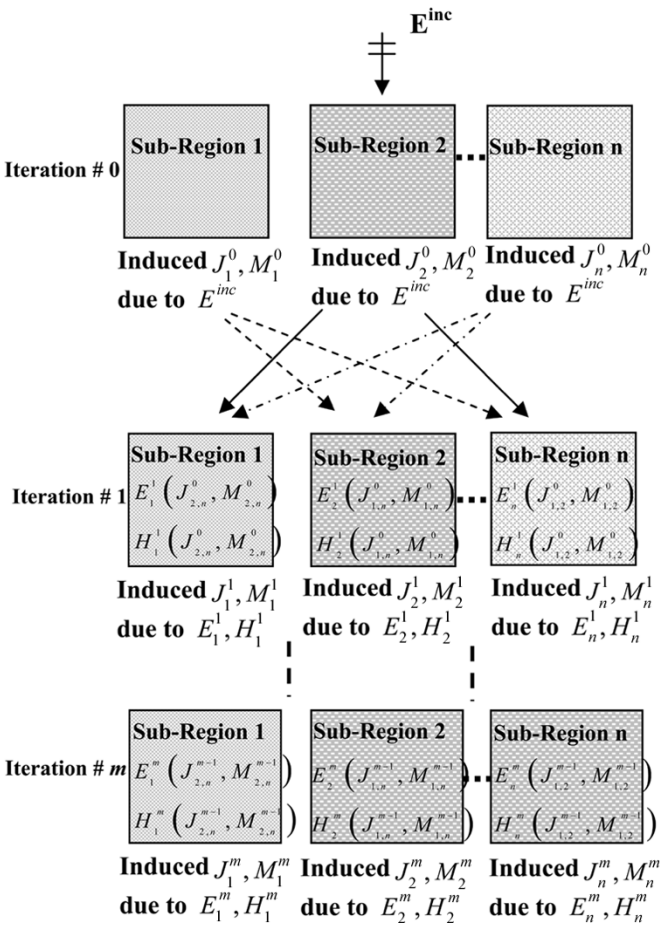

Fig. 2. Scheme for the IMR technique applied by converting the electric and magnetic currents to field components generated on the other regions.

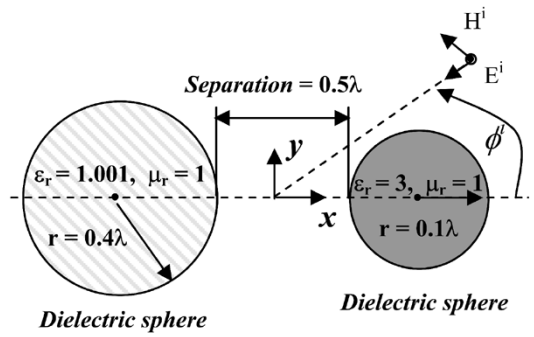

Fig. 3. Geometry of two dielectric spheres.

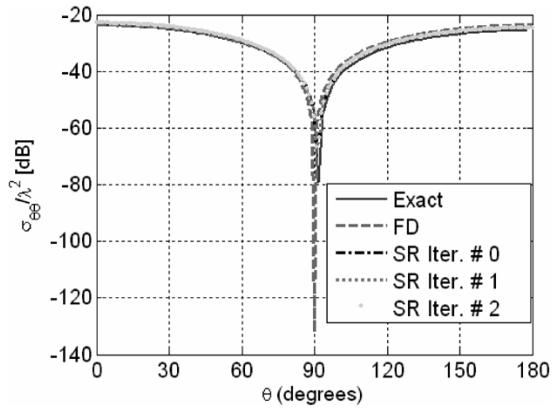

Fig. 4. Bistatic RCS for the configuration defined in Fig. 3.

regions. The scattered electromagnetic fields due to an incident wave are calculated separately in each subregion by the FDFD method. Then, fictitious electric and magnetic currents are calculated over imaginary surfaces surrounding the objects in each subregion, based on the equivalence principle. The electromagnetic fields radiated by these currents are calculated at the grid nodes on the TF/SF boundaries of other subregions, using the well-known formulation for the radiation from electric and magnetic surface currents [26] for three-dimensional scatterers. These fields are considered as the new excitation for that region. As an example, for three objects, the fields exciting subregion 1 are a result of the superposition of the fields generated on subregion 1 using the currents calculated from subregions 2 and 3. Then the cycle of calculation of scattered fields, fictitious currents and radiated fields are repeated as a new iteration. The iteration process between regions continues until a convergence criterion is achieved. The sum of all calculated scattered fields through iterations gives the total scattered field, which is equivalent to the scattered field calculated from the solution of the original problem to a certain degree based on the total number of iterations. This iterative procedure is illustrated in Fig. 2.

IV. Numerical Results

Fig. 3 shows the geometry of two spheres, one having relative permittivity $\varepsilon_r = 3$ and relative permeability $\mu_r = 1$, with radius equals to 0.1λ. The other sphere has relative permittivity $\varepsilon_r = 1.001$ and relative permeability $\mu_r = 1$, with radius equals to 0.4λ. The separation between the two spheres is 0.5λ. This configuration was constructed to check the validity of the IMR technique in comparison with that generated using the exact solution of a dielectric sphere having relative permittivity $\varepsilon_r = 3$ and radius equals to 0.1λ; that's why the bigger sphere has relative permittivity almost the same as free space. It is clear from the bistatic radar cross section (RCS) calculated in Fig. 4 for the exact solution, the full-domain solution, and the IMR solution after 2 iterations that the results generated from the IMR procedure converges to the exact solution, with very good agreement.

It was realized that most of the consumed time by the subregion solution relative to the full-domain solution; is in the calculation of the field components at the grid points of the subregions generated due to the electric and magnetic currents from the opposing domain. Thus the TF/SF formulation is introduced to speed up this calculation and thus save around half the time consumed by the full-domain solution. The idea behind the time saving using the TF/SF technique is simply by calculating the fields on just one or two layers in the x, y, and z directions, instead of at each grid point in the whole subregion.

The whole computational domain is divided into two regions separated by a nonphysical virtual surface that is used to connect the fields in each region. The fields generated based on the computed electric and magnetic currents from the opposing subregion are generated on this virtual boundary where they act as an incident field on the same region. The TF/SF technique is used to solve for both the total and the scattered fields, where they are both considered as the unknown fields instead of using

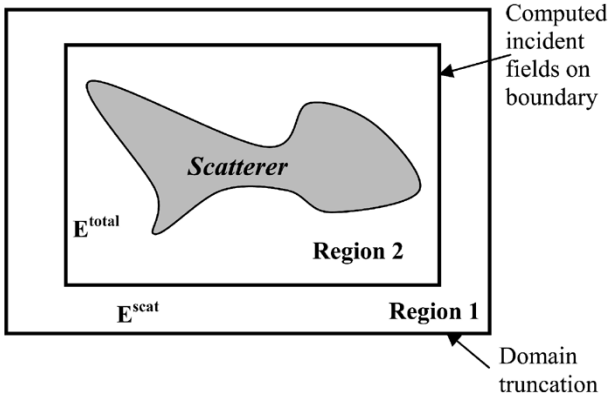

Fig. 5. Total-scattered field zoning connected by a virtual surface.

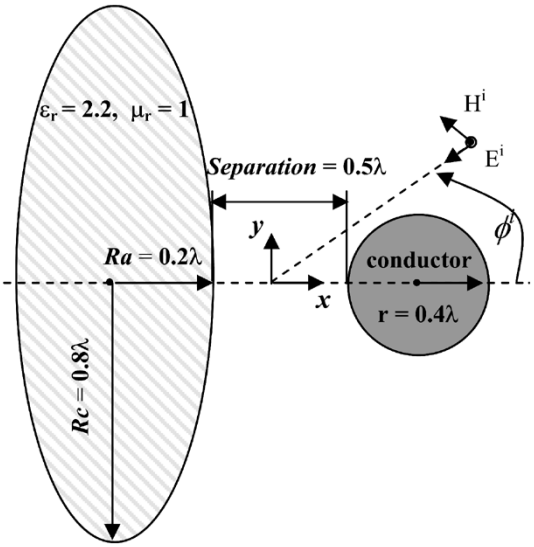

Fig. 6. Geometry of a dielectric spheroid and a conductor sphere.

the classical SF approach for the whole computational domain. Fig. 5 illustrates the idea behind the TF/SF technique, where region 1, the inner zone, operates on the total field vector components, whereas the region 2, the outer zone, operates on the scattered field vector components. The TF/SF technique is presented in details in [24].

Fig. 6 shows another configuration that proves the validity of the IMR approach presented in this work for three-dimension structures. As an example a spheroid with $Ra = 0.2\lambda$, $Rb = 0.2\lambda$, and $Rc = 0.8\lambda$ is presented. At a distance of 0.5λ, a conductor sphere is placed to the right of the spheroid with a radius equals to 0.4λ. The spheroid has a relative permittivity $\varepsilon_r = 2.2$ and relative permeability $\mu_r = 1$. This configuration is excited by a theta polarized, plane wave with $\phi^i = 90°$.

Fig. 7 shows the bistatic echo width for the three plane cutes, i.e: xy, xz, and yz plane cuts. It can be seen that, the IMR technique results converge to the full-domain after 3 iterations; with a 24% memory reduction in the storage requirements. The subregion computational time is 48% less than that of the full domain after three iterations. Good agreement, with the full domain solution, is achieved for the three plane cuts after three iterations.

For generality, a more involving configuration is represented in Fig. 8 where three conducting spheres are excited by an incident plane wave with $\phi^i = 90°$. The three spheres are oriented

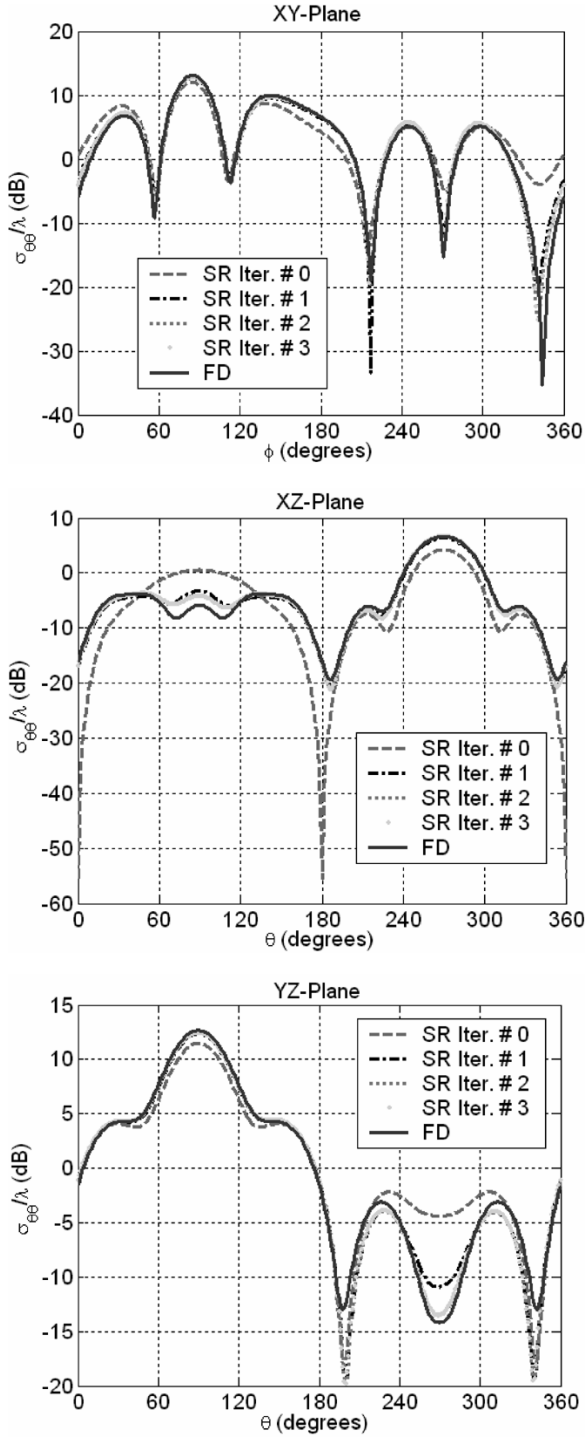

Fig. 7. Bistatic echo width for xy, xz, and yz plane cuts.

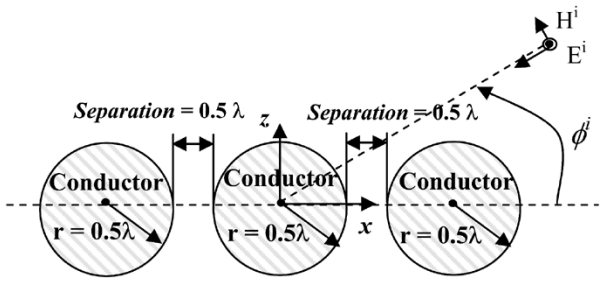

Fig. 8. Geometry of three identical conducting spheres oriented along the x-axis.

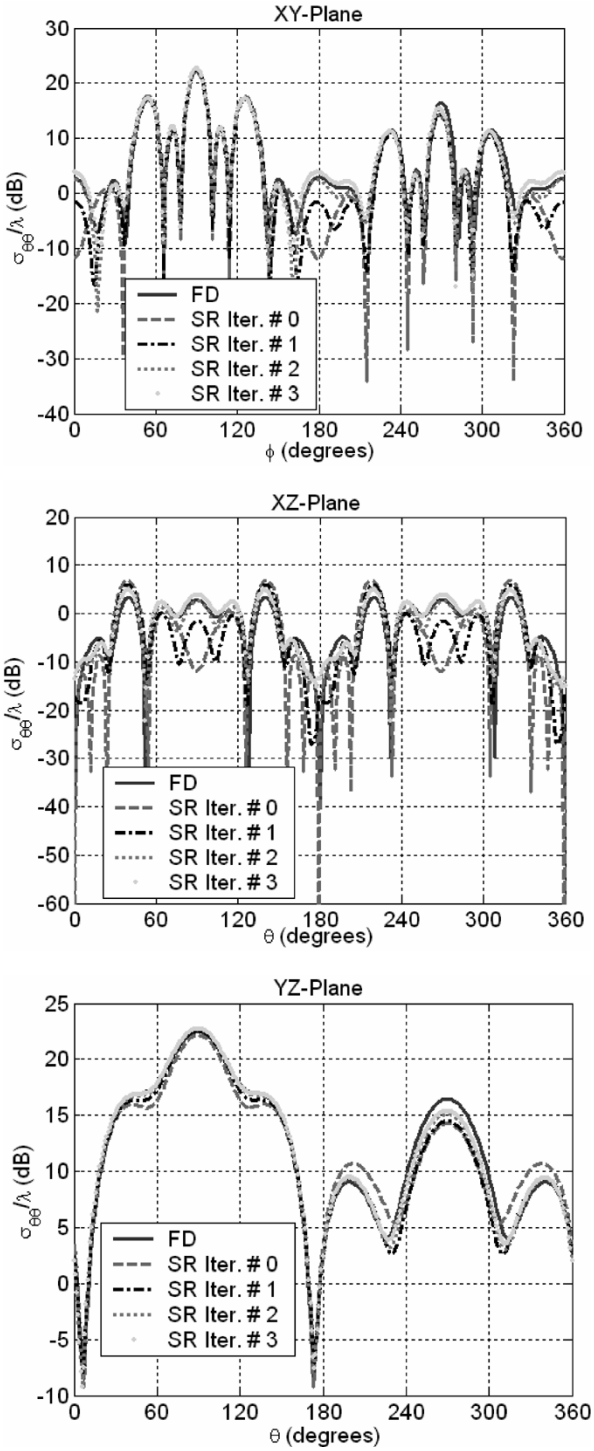

Fig. 9. Bistatic echo width for $\boldsymbol{xy}$, $\boldsymbol{xz}$, and $\boldsymbol{yz}$ plane cuts.

along the x-axis, each having a radius of 0.5λ with a 0.5λ separation. This configuration proofs the validity of the presented technique for multiple objects, as it has been constructed, where more interaction processes are required between the objects. In Fig. 9 the bistatic echo width for the three plane cutes, i.e: xy, xz, and yz plane cuts is presented. It is clear from the results that the numerical results generated using the IMR technique is converging to the full-domain results after three iterations with a very good resemblance, and 49% time saving.

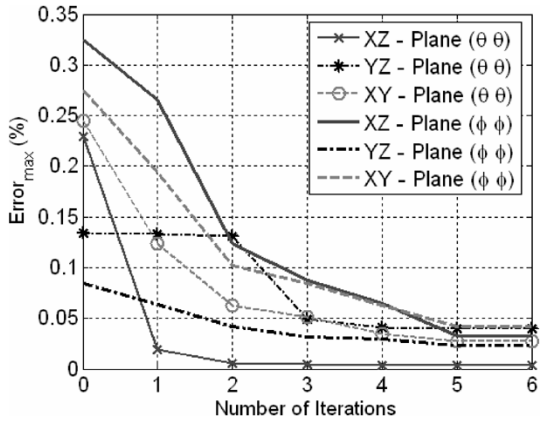

Fig. 10. Maximum relative error for the problem illustrated in Fig. 6, for both $(\theta\theta)$ and $(\phi\phi)$ polarizations.

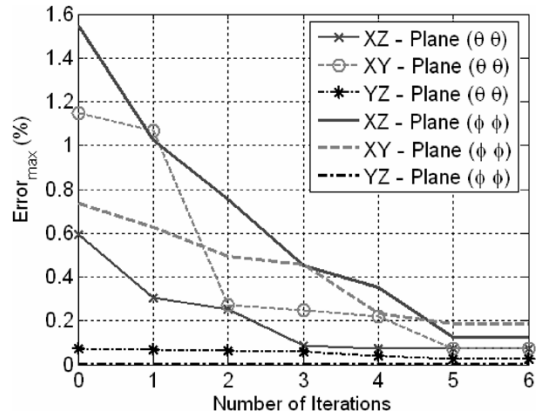

Fig. 11. Maximum relative error for the problem illustrated in Fig. 8, for both $(\theta\theta)$ and $(\phi\phi)$ polarizations.

To prove the convergence of the solution for the problems illustrated in Figs. 6 and 8, for both $(\theta\theta)$ and $(\phi\phi)$ polarizations; a maximum relative error defined at each iteration as

$$|Error|_{\max} = \max \left| \frac{\sigma - \sigma_{FD}}{\sigma_{FD}} \right| \times 100\%,$$

is plotted in Figs. 10, and 11, respectively.

Convergence of the numerical results to correct solutions with regard to the minimum distance between the objects is examined through several experiments. No exact criteria were established to determine the minimum distance between the scatterers that provides accurate solutions relative to those based on the full domain solution. However, these experiments, for 2-D and 3-D scattering problems, have shown that when the object's separation distance is in the order of 0.5λ; convergence is always guaranteed to the correct solution. For separation distances less than 0.5λ, the proposed IMR technique converges but not necessary to the correct solution. This proposed IMR technique is developed for problems that include separated scatterers in order to save memory. However, if the distance between some objects is less than 0.5λ, these objects should be combined in one region by itself. There are no restrictions imposed by this IMR technique on having multiple objects in one region.

V. Conclusion

In this paper an iterative multiregion technique is proposed to solve large-scale electromagnetic problems that can be decomposed into separated subregions using the FDFD method. This new approach is found to be efficient in producing accurate results with good saving in the computer memory usage and computational time for three-dimensional problems relative to those of the full-domain problem.

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