A Serial-Parallel FDTD Approach for Modeling the Coupling problem between Two Large Arrays

(*Invited Paper*)

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Abstract–Solution of large problems using a numerically rigorous approach is always challenging because of the heavy burden they impose on the CPU. In this paper we introduce a new serial-parallel FDTD approach to solve large electromagnetic problems, e.g., coupling between two arrays separated by a large distance, that is difficult to handle via a direct application of the FDTD algorithm because of large size. This technique is based on dividing the original problem into relatively small sub-regions, and evaluating the solution that are localized in each of these sub-regions. The excitation of the sub-regions can either be direct sources, as for instance in the aggressor array, or be derived from the fields propagating into domain–from adjacent regions through the interfaces. We show that the results obtained by using the proposed approach compare well with the direct FDTD solution for some test problems, involving coupling between two phased arrays. Of course, the advantage of using the serial-parallel approach is that it can handle very large problems, well beyond the scope of the direct methods.

I. INTRODUCTION

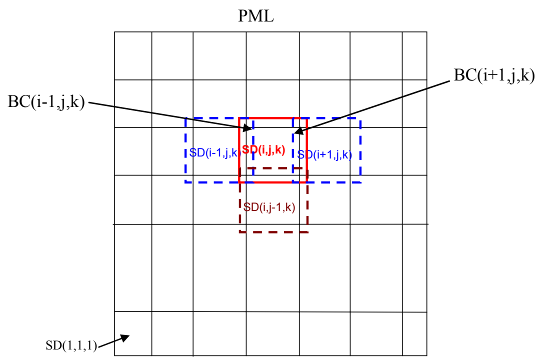
Historically, various asymptotic methods e.g., PO, GTD and PTD have been employed for the solution of electrically large electromagnetic problems. It is well known, however, that asymptotic techniques are not well suited for handling problems that involve inhomogeneous media, complex geometries and multiscale features, *e.g.*, phased arrays, and it is necessary to employ numerically rigorous techniques, such as the Finite Element (FE) method or the Finite Difference Time Domain (FDTD) technique. An obvious limitation of the numerically rigorous techniques, however, is their ability to solve large problems that place a heavy burden on the CPU memory and time. Although numerous attempts have been made by researchers to obviate this problem, it is still difficult, if not impossible, to use numerically rigorous methods to solve large problems with Degrees of Freedom (DOFs) that can fall in the range of 10^8 to 10^{10}, even with a large number of processors.

The domain decomposition method (DDM) is one approach [1, 2] to solving large electromagnetic problems by breaking them up into smaller and more manageable sizes. A DDM has been applied in conjunction with the Finite Difference Frequency Domain (FDFD), by solving the problem [3] in each of the individual subdomains, and then constructs the global solution via an iterative procedure. In [4], the FD method has been applied in conjunction with the PML and the impedance boundary condition for mesh truncation, and has been combined with the overlapping domain decomposition procedure to compute the capacitances of orthogonal interconnect configurations. This technique has been extended to handle interconnect structures that are not necessarily orthogonal, as for instance vias and crossovers oriented at arbitrary angles [5]. The Finite Volume Time Domain (FVTD) and the DDM also has been used to evaluate the current on a cable inside an airplane [6].

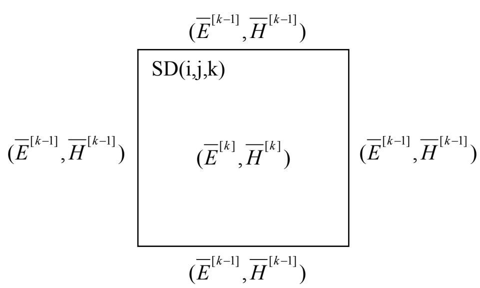
The purpose of this paper is to present a novel time domain approach, referred to herein as the Serial-Parallel FDTD (SPFDTD), for modeling the problem of coupling between two arrays that may be large and may also be separated by a large distance. An example problem is that of phased arrays mounted on masts of a ship, where the intervening space between the arrays may be covered by RAM materials and their separation distance may be large. A preliminary form of this method has been described in [7], in connection with the EMI problem of penetration of EM energy into a large room that present a challenge, because of its size, when one attempts to solve it using the FDTD approach directly. The serial-parallel FDTD method for handling such problems takes a cue from the TDR approach to modeling microwave circuit problems that tracks the propagation of time domain waveforms through a device.

II. THE SERIAL-PARALLEL FDTD METHOD

In the SPFDTD method, we begin by subdividing the computational domain comprising of two arrays, for instance, into moderate-sized subdomains, with overlaps at the interfaces between the domains, as shown in Fig.1.



(a)



(b)

Fig. 1. Application of the CBFDTD. (a) decomposition of the computational domain; (b) deriving the k-th basis function.

The subdomain sizes are chosen such that they can be handled directly via the FDTD, using the available computer resources. Unlike the conventional domain decomposition approach, where spurious effects arise because of artificial truncation of the individual domains, the primary solutions in the present technique are generated by using PML terminations, which can be made to have a very low reflection. Furthermore, the approach is both physics-based and intuitive, because it is implemented in the time domain. For instance, referring to Fig. 1 (a), if we start with a source located in subdomain SD (1,1,1), the solution in that region would not be affected by the structures in the other subdomains until the signal from the above subdomain has had time to traverse these other subdomains, and has then backtracked into the original subdomain SD (1,1,1) at a later time. These reflections are physical as opposed to being spurious due to truncation effects and are dealt with later in a systematic way. It is also useful to note that all the other subdomains will have no primary excitations because there are no sources located in them.

Let us now turn to the task of generating the field solution in the region on the right (subdomain-2), which stems from the coupling into this region from the source region on the left (subdomain-1). In the example geometry shown in Fig. 2 (a), the field solution in the second region will only be due to the excitation originating from subdomain-1, and until the reflected waves appear in this subdomain from the region to its right at a later time. In addition, if the reflections are relatively small, this coupled field will also be the dominant one in subdomain-2.

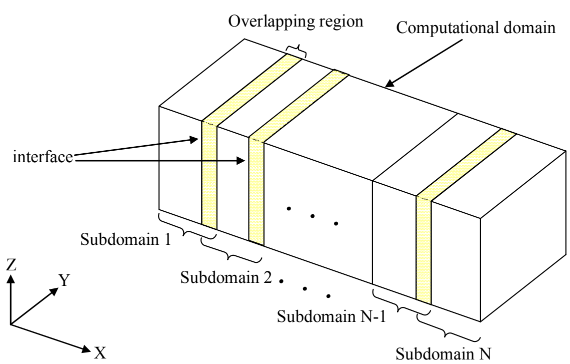
To derive the coupled field in subdomain-2, we first compute and store the fields in the interface plane located in the overlapping region. This field is, of course, obtained from the solution in subdomain-1, with which we have dealt already. We may view these fields as the Huygens' sources that excite the subdomain-2, and, hence, in general, we need to store both the tangential E and H fields in space and time to derive the solution in subdomain-2.

For instance, in the subdomain SD (i,j,k) of Fig. 1 (a), we use the tangential electric field $\overline{E}^{[1]}$ in the plane BC(i-1,j,k) as an excitation, or implicitly as a boundary condition for the subdomain SD(i-1,j,k). Similarly, the fields on BC (i+1,j,k) are used as a boundary condition for the subdomain SD(i+1,j,k) to evaluate the secondary basis. In general, the solution $(\overline{E}^{[k]}, \overline{H}^{[k]})$ in SD (i,j,k) is obtained by applying the FDTD associated with the (k-1)th basis functions which have been derived previously by solving the problem in the adjacent subdomain shown in Fig. 1 (b). Eventually, the field solutions are represented as linear combinations of the basis functions as follows:

$$\overline{E}(x,y,z) = \sum_{k=1}^{M} \overline{E}^{[k]}(x,y,z), \tag{1a}$$

$$\overline{H}(x,y,z) = \sum_{k=1}^{M} \overline{H}^{[k]}(x,y,z). \tag{1b}$$

Assuming a one-dimensional topology as shown in Fig. 2 (a), we update the FDTD equations in each of the subdomains in a sequential manner, starting with the excited one. The primary tangential electric basis field $\overline{E}_t^{[1]}(\bar{r})$, $\bar{r} \in P_1$, is stored where P_1 is the interface plane. This field is then used as a boundary condition to generate the fields coupled into the adjacent subdomains. The tangential electric field is also stored and used as a boundary condition inside the PML layers in the plane P_1 , to ensure that it decays correctly in the transverse directions. Referring to the subdomain (i) in Fig. 2(a), it includes an overlapping region at the interface plane P_i (Fig. 2(b)), and is terminated by PML layers to absorb the outgoing waves. The subdomain (i+1) is bounded by the plane P_i and the stored tangential electric field values in P_i are employed as boundary conditions for the region (i+1).



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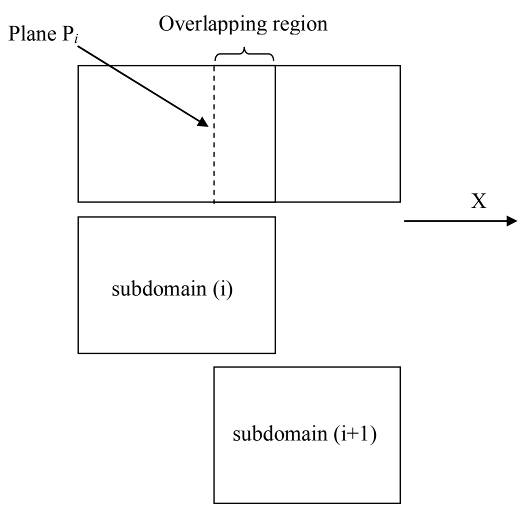


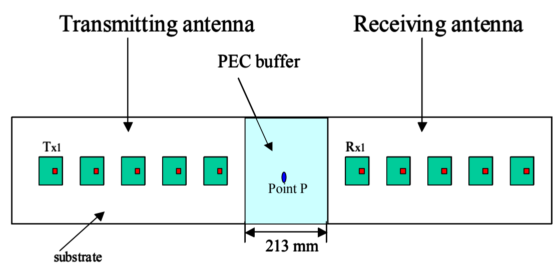
(b)

Fig. 2. Serial application of the SPFDTD with parallel processing along the y-direction. (a) dividing the computational domain into subdomains; (b) schematic diagram for subdomains (i) and (i+1).

III. APPLICATIONS TO THE PROBLEM OF COUPLING BETWEEN TWO ARRAYS

In this section we apply the SPFDTD to the problem of coupling between two patch arrays (see Fig. 3), for which the intervening medium may be inhomogeneous, and we use the total-field FDTD formulation for this problem. We assume that the array on the left is transmitting, while the one on the right is terminated. Our objective is to compute the level of coupling from the transmitter to the receiver, and we also investigate how the coupling is reduced when an absorbing material is introduced between the two arrays.

To analyze large arrays, we can divide the problem into sub-arrays along the longitudinal direction and apply the SPFDTD. In addition, we can also subdivide the intervening geometry into sub-regions with manageable sizes to tackle the coupling problem using the SPFDTD, even when the entire dimension of the problem (arrays + coupling region) is very large.



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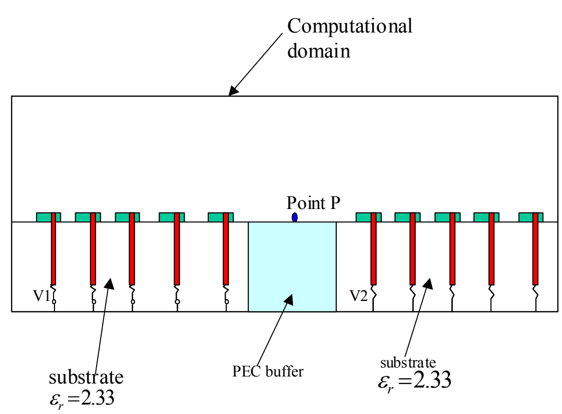
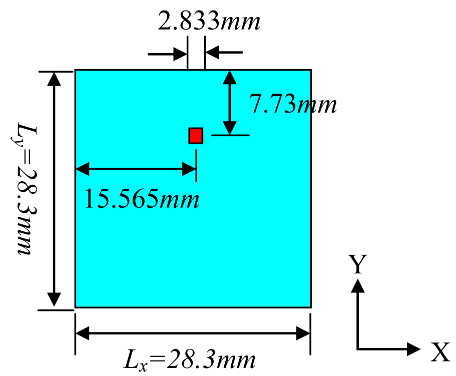


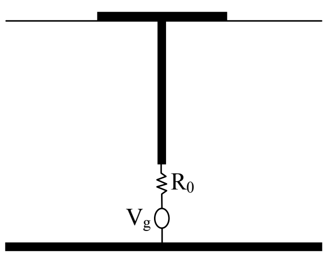
(b)

Fig. 3. Problem of coupling between two 5 x 1 arrays. (a) Top view; (b) Side view.

For the present problem we assume that the two patch arrays are printed on the same substrate, each one has 5 x 1 elements, and that the separation distance between the arrays is $\sim 3\lambda$, (see Fig. 3). The details of the single element in this array are presented in Fig. 4.



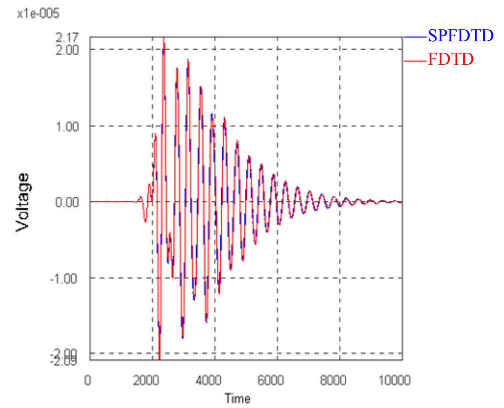
(a)



(b)

Fig. 4. (a) Top view of the single element patch, (b) Modeling of coaxial feeding line using a voltage source with internal resistor inside a feeding gap.

The resonant frequency of this patch antenna is 3.25 GHZ. All of the elements of the transmit array are excited with a voltage source whose internal resistance is 50 Ω, and all the receiver elements are also terminated by using 50 Ω resistors. The computational domain for this problem has the dimensions of 99mm x 803 mm x 237 mm, and we use the cell sizes of $\Delta x = \Delta y$ = 2.83 mm and Δz = 0.285 mm. We employ the SPFDTD after dividing the original problem region into two subdomains and using two processors along the horizontal direction. The dimensions of the first subdomain are 99 mm × 505 mm × 237 mm, while it is 99 mm × 494 mm × 237 mm for the second, with an overlapping length of 196mm. Figure 5 plots the voltage at the terminals of R_{x1}, and the field E_z at the point P (see Fig. 3), located on the receive array. Figure 6 shows the ratio of the voltage at R_{x1} to the voltage at T_{x1} in the frequency domain. The comparisons, presented in Figs. 5 and 6, show very good agreements between the SPFDTD results and those derived via a direct application of the FDTD.



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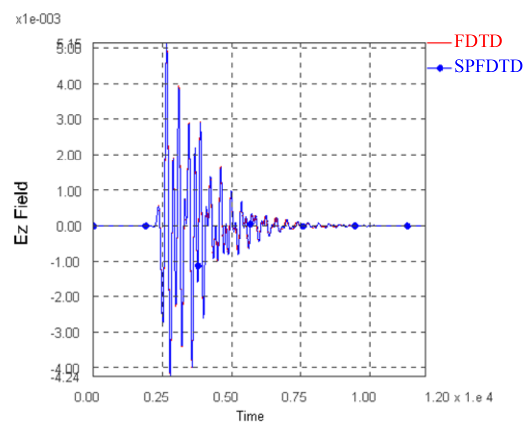


(b)

Fig. 5. Comparison of the results of the CBFDTD and the direct application of the FDTD: (a) Voltage V2(t) at Rx1; (b) electric field Ez (t) at the point P of Fig. 3.

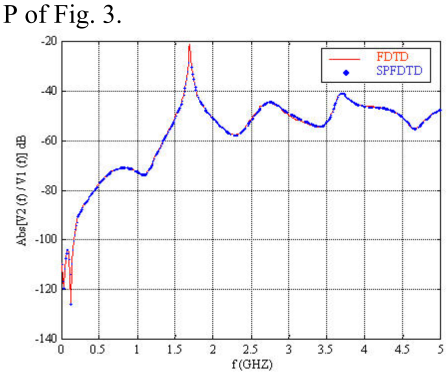
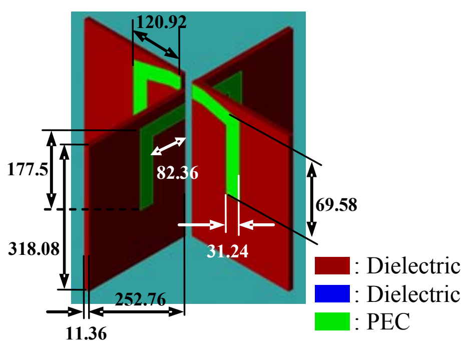


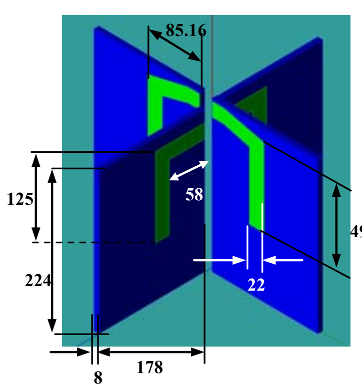
Fig. 6. Comparison of the results of the CBFDTD and the direct application of the FDTD for V2(f)/V1(f), where V2 is the voltage at Rx1, V1 is the voltage at T x 1.

For the second example we consider a larger and more complex problem, which is representative of antennas used for shipboard applications. It is comprised of two arrays of folded dipoles, arranged in a spiral fashion, one of which is designed for the X-band while the other for the Ku-band. The elements are shown in Fig. 7 and the entire coupled system appears in Fig. 8. The relevant dimensions of the array are: Ku band array $8.64\lambda_0 \times 8.16\lambda_0$; X-band array $11.52\lambda_0 \times 11.04\lambda_0$; separation between these two arrays is $40\lambda_0$, where λ_0 is the free space wavelength at 14.2 GHz.

A direct solution of this large array coupling problem requires the solution of a problem involving 6.97×10^9 unknowns, and represents a formidable challenge. Typically, a CPU equipped with 2 GB of memory can handle a problem requiring up to about 8.3×10^7 unknowns. The direct FDTD simulation for the two-array coupling problem with ~7 billion unknowns requires at least 85 CPUs on a distributed processor, with 170 GB of memory, which is obviously quite burdensome. The number of DOFs is so large for this problem because the smallest cell size in the x-, and y-directions is on the order of $\lambda_0/208$ and the size is approximately double that in the z-direction. We should mention that such a fine discretization is needed to accurately represent the geometry in the feed region, and that we use a non-uniform mesh and gradually increase the cell size to $\sim \lambda_0/20$ in the region between the two arrays.



(a) X band array element



(b) Ku band array element

Fig. 7. Folded dipole elements of the Ku- and the X-band spiral arrays. The dimensions are in mils.

However, the use of the SPFDTD approach eases the system resource requirements mentioned above, renders the problem manageable, and yields the desired estimate of the signal coupled into the array in the right, when one on the left is transmitting. To handle this problem with the SPFDTD method, the above problem is divided into two sub-domains, shown in Fig. 9, and the number of unknown involved in each region is 3.6×10^9 and 3.81×10^9, respectively.

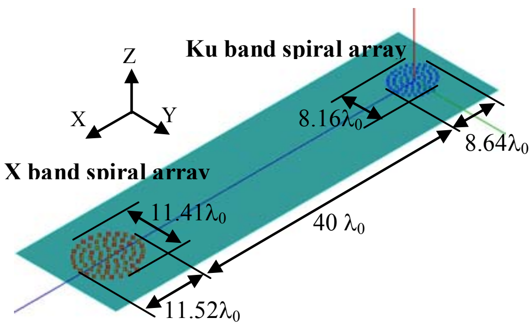


Fig. 8. Layout of the Ku- and the X- band spiral arrays.

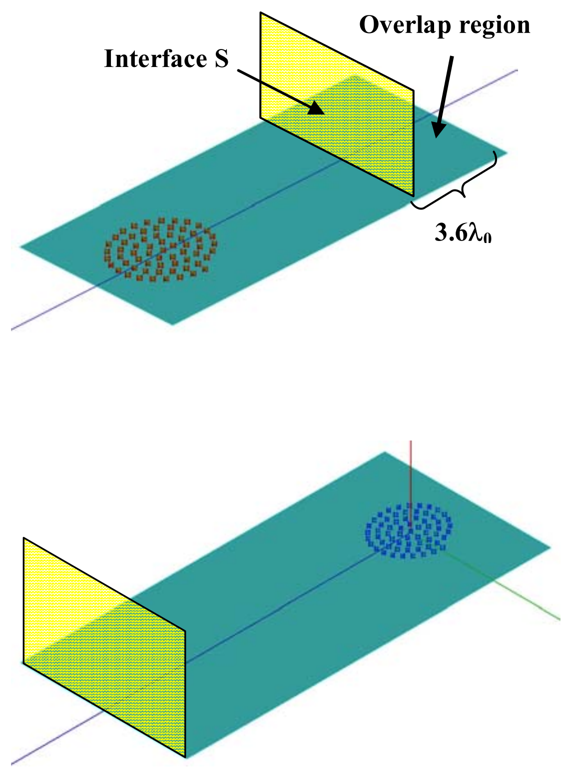


Fig. 9. Set-up for serial-parallel FDTD simulation.

Following the lines of the previous example, we again compute the tangential fields on the interface plane directly in the time domain, downsample it in the time domain by approximately a factor of 10, and store these fields in external files that are to serve as excitations for the following stage. Downsampling is employed because the time step associated with the FDTD, which is dictated by the Courant condition, typically results in over-sampling and, hence, redundancy. This is because according to the Nyquist criterion, a sampling rate in the time domain that equals twice the highest frequency component in the incident pulse is sufficient to recover the original signal from the sampled data. Additionally, we employ the downsampling because it reduces the hard drive space required to store the tangential fields on the interface, needed for the computation step that follows, namely the field computation in the adjacent domain situated on the right of the interface.

To validate the SPFDTD approach for this problem, we initially downsize it to a smaller version that is more manageable for direct solution, *viz.,* the coupling between a Ku band and an X band spiral array of folded dipoles, both of which have 8-elements. The sizes of the Ku band and X band arrays are $2.27\lambda_0 \times 2.41\lambda_0$ and $3.17\lambda_0 \times 3.43\lambda_0$, respectively, and the separation distance between them is $11.52\lambda_0$, where λ_0 is the free space wavelength at 14.2 GHz. The size of the computational domain for the entire problem is $21.6\lambda_0 \times 6.96\lambda_0 \times 3.72\lambda_0$. For the serial parallel FDTD simulation, the problem domain is divided into 2 subdomains, whose dimensions are $11.4\lambda_0$ and $12.12\lambda_0$, along the x-direction, and there is an overlap of $1.92\lambda_0$ shared by the two regions. The number of unknowns involved in the entire problem is 6.33×10^8, while the corresponding number for two stages of the first the serial-parallel processes are 3.02×10^8 and 3.53×10^8, respectively. Both the direct and serial-parallel processes were simulated on a 16 CPU cluster, equipped with dual AMD Opteron CPUs and 8 GB of memory on each node. The total CPU time needed to run 8000 FDTD time steps were: 4:37 h for the direct, 2:02 h for the first stage and 2:35 h for the second. Figure 10 shows the comparison of the time domain signals (E-field components) generated from the direct FDTD as well as the SPFDTD at an observation point P located at $1.92\lambda_0$ from the left end of the computational domain boundary in the second region, which is also shown in this figure.

The agreement between these results is seen to be excellent. Fig. 11 shows the voltage and current measurements at the terminals of a folded dipole element AE (see Fig. 11) in the receiving array. Again, the agreement between the direct simulation result and that of the SPFDTD is seen to be very good. This example validates the application of the SPFDTD method to the problem of coupling between arrays that can be far apart.

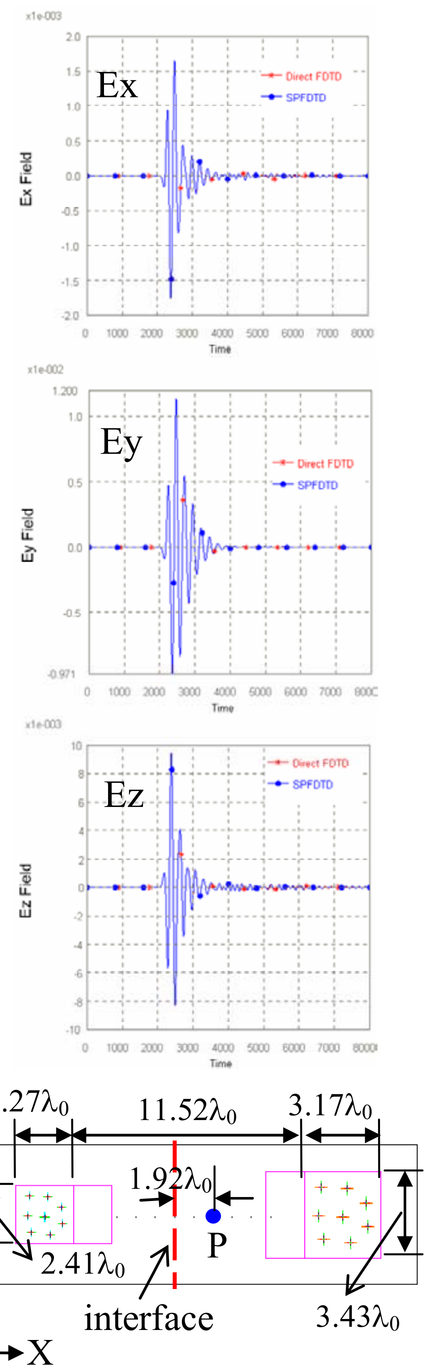


Fig. 10. E-field signals at an observation point P in the time domain.

Following this validation exercise, we return to the original problem of coupling between Ku and X band arrays shown in Fig. 8. Of course, the problem can be divided into more than two subdomains, if desired, so that the solution in each of these individual regions can be handled with fewer CPUs because of the reduction in the problem size in these sub-regions. For the present

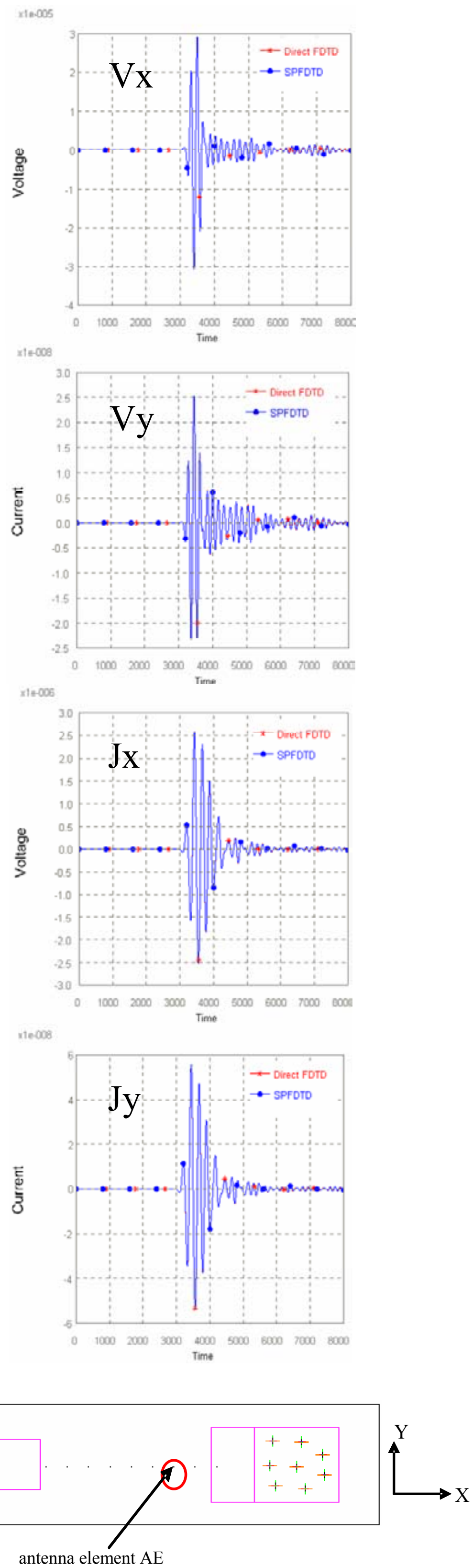
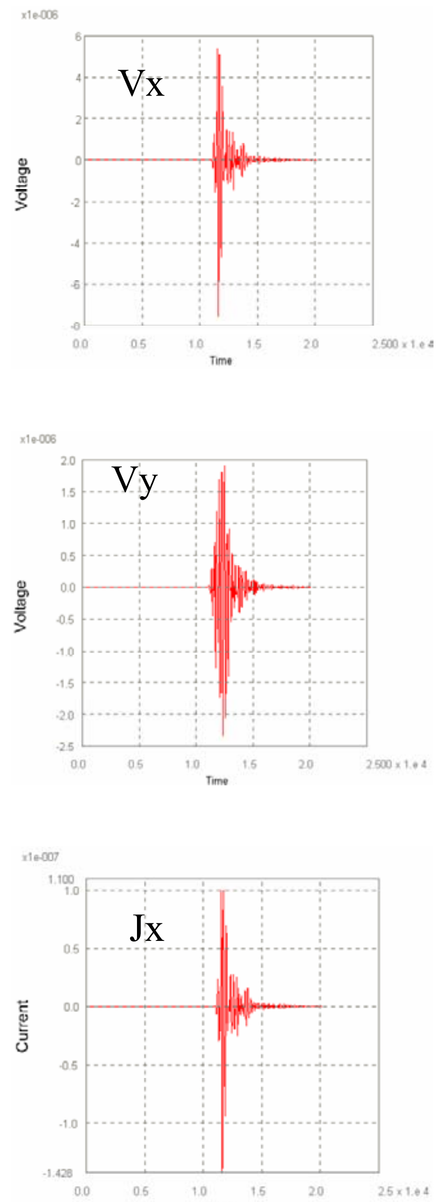
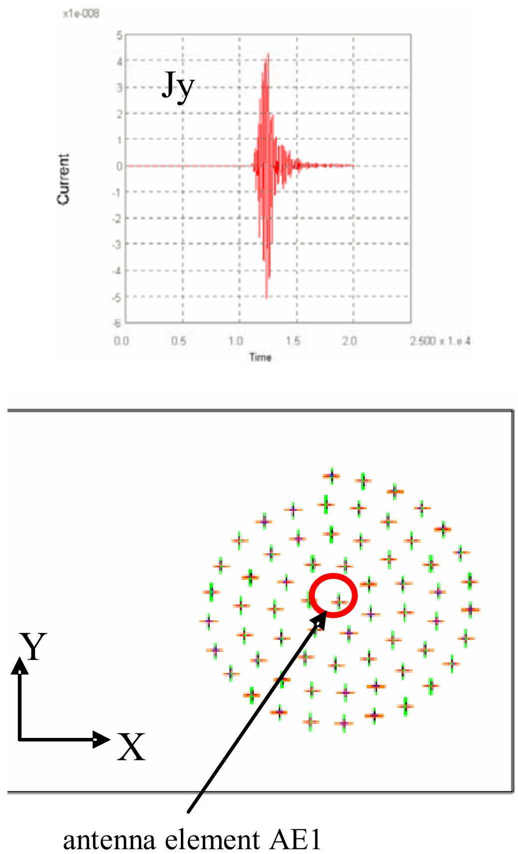


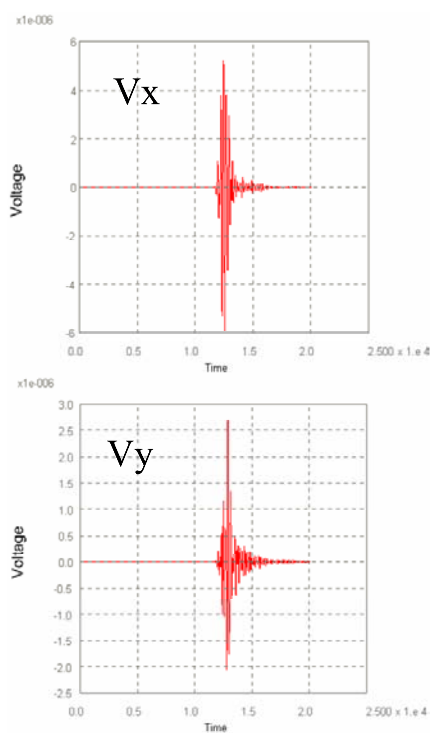
Fig. 11. Voltage and current signals at an antenna element AE in the time domain.

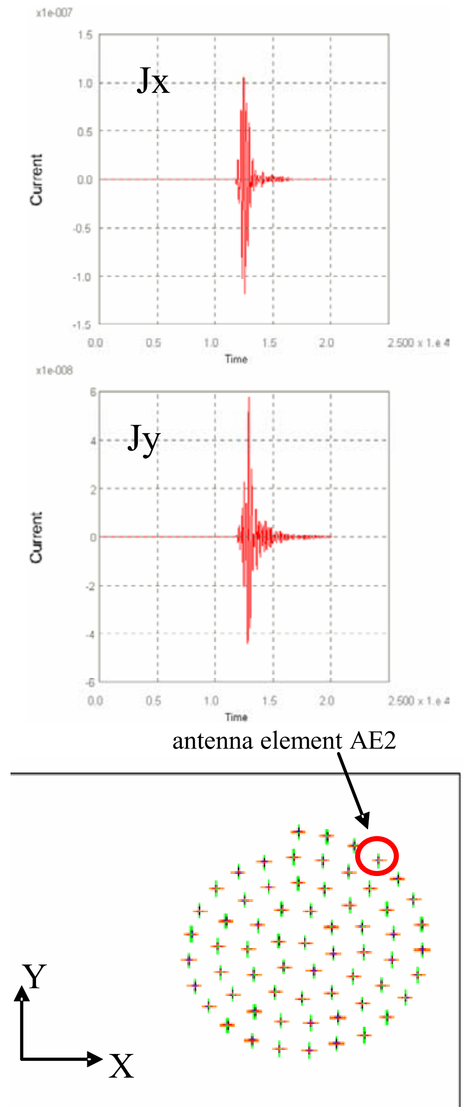
case, where we use two subdomains, we simulate them with 56 CPUs on a PC cluster, where each node is equipped with dual Intel Xeon 3.06 or 3.2 GHz CPUs and 4 GB of memory. The CPU time consumed are 33 hour 24 minutes for 22000 time steps associated with the first stage simulation, and 96 hours for 20000 time steps in the latter one. The extra CPU time consumed in the second stage accounts for the interpolation process used to recover the tangential field information on the interface at time steps where the tangential field information is not recorded during the first stage of the simulation. The simulation results are shown in Fig.12 for the induced current and voltage measurements at the antenna elements (AE1 and AE2) in the receiving array.





(a) Voltage and current signals at antenna element AE1.





(b) Voltage and current signals at antenna element AE2.

Fig. 12. Voltage and current signals at antenna elements in time domain.

IV. CONCLUSIONS

In this paper we have developed a novel FDTD technique, referred to herein as the SPFDTD, designed to solve large electromagnetic radiation and scattering problems. The SPFDTD approach is capable of handling very large problems ($>10^9$ DOFs) that may not be amenable to analysis using a direct approach.

By following the same procedure as employed for the forward-going waves, this technique has also been extended [7] to the case where there are reflections from discontinuities in the second domain that introduce waves traveling in the reverse direction, whether we are solving scattering or antenna coupling problems.

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