

A Parallel Implementation for the Time-Domain Analysis of a Rectangular Reflector Antenna Using OpenMP

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Abstract — This paper presents and evaluates a parallel time domain analysis of a rectangular reflector on multicores machine. Rectangular reflector antennas have motivated the time-domain analysis of electromagnetic scattering problems. The asymptotic time domain physical-optics (TDPO) is applied to the analysis of a rectangular reflector illuminated by a Gaussian-impulse. It is a numerical technique used in computational electrodynamics. The effects of time-delayed mutual coupling between points on the surface will be ignored to avoid the numerical limitations found in other conventional time-domain techniques such as interpolation error, numerical dispersion error, etc. As a result, the scattered signals at the specular reflection point, at the edges, and at the corners can be clearly distinguished. Furthermore, this paper evaluates and compares the performance of the sequential time-domain analysis against the parallel time-domain analysis on multicores machine.

Index Terms — Electromagnetic scattering, parallel computing, rectangular reflector, time domain.

I. INTRODUCTION

Reflector antennas are intensively applied in the radars, communication, and guidance, etc. Nowadays, the problems of electromagnetic (EM) scattering have been widely applied in fields of remote sensing, target identification, radar detection, and so on. The interest in the transient analysis of EM phenomena has been growing in recent years. This is due to the advance of ultra-wide band (UWB) radars and their associated antennas, various antennas have been proposed for UWB application [1], with mobile radio channels by means of their response to pulsed excitation [2]. There are several

methods that are used to analysis the EM scattering that will be explored in next section. They have inherent difficulties with numerical instability, interpolation errors, and need of extensive computer memory and CPU time to solve problems involving large scatterers. It is more efficient to deal with the transient analysis directly in the time domain. The time domain physical-optics (TDPO) [5-6] is an alternative method that requires relatively small amounts of computer memory and CPU time.

Consequently, this paper will focus on implementing the TDPO approximation method on parallel computer system. However, this section will discuss several computational electromagnetic (CEM) numerical methods either implemented in sequential or in parallel as follows.

Physical-optics (PO) approximation is one of these techniques. It has been widely used and considered as a good approximation of the far field electromagnetic scattering [16]. Starting from the Stratton-Chu integral equations, the PO expressions can be obtained for the PO scattered magnetic field in frequency domain [17]. The PO approximation is initially applied in the frequency-domain with the inverse Fourier transform [9] and [10]. Those equations are obtained directly from *Maxwell's equations* by applying *Green's theorem* in its vector form [17-18]. The PO requires integration over the illuminated surface of the scatterer. Due to the complex exponential term, the integrand of the PO integral is a very oscillatory function, especially at high frequencies. Therefore, it is very expensive to compute these kinds of integrals by simple numerical integration techniques such as Levin's integration method [19]. For large scatterer, the PO approximation is an efficient method in the frequency domain [7-8]. To accelerate the computing

of the PO, there are some researches that handle PO in parallel based shared memory [28] and distributed memory [29-30].

Moreover, there exist several analytical and numerical techniques for obtaining the response of scattering problems directly in the time domain, which is the most natural approach to be used, such as the finite-difference time-domain method (FDTD) [3, 11-13]. Recently, the FDTD method is being used to solve a wide variety of practical problems, because it can be competitive with the FEM in terms of versatility and solve time, even on a single PC or laptop computer loaded with a 2 GB memory. However, the main advantage of the FDTD becomes increasingly apparent when it is run either on multi-core processors or MPI protocol with low-cost high speed networks, because it can be parallelized more efficiently than FEM [21-25]. Several works [26-27] present a hybrid FDTD numerical algorithm which has been successfully developed and validated. They employ distributed and shared memory thorough of *MPI* and *OpenMP* [14].

II. THEORY AND FORMULATION

The TDPO integral is evaluated over the illuminated surface of the scatterer with a closed-form expression based on Gaussian-impulse. The formula of the TDPO is derived with the inverse Fourier transform. The scattered field of the TDPO is obtained as follows [20]:

$$\bar{e}^{TDPO}(\bar{r}, t) = -\eta_o \iint_S \frac{1}{4\pi|\bar{r}-\bar{r}'|} \frac{\partial \bar{j}_{st}^{PO}(\bar{r}', \tau(t, \bar{r}'))}{\partial t} ds, \quad (1)$$

where \bar{j}_{st}^{PO} is given as:

$$\bar{j}_{st}^{PO}(\bar{r}', \tau(t, \bar{r}')) = \bar{j}_s^{PO}(\bar{r}', \tau(t, \bar{r}')) - [(\bar{j}_s^{PO}(\bar{r}', \tau(t, \bar{r}')) \cdot \hat{r}') \cdot \hat{r}], \quad (2)$$

$$\bar{j}_s^{PO}(\bar{r}', \tau(t, \bar{r}')) = 2 \hat{n} \times \bar{h}^{inc}(\bar{r}', \tau(t, \bar{r}')), \quad (3)$$

where the vector \bar{r}' locates the integration point on the scatterer surface, \bar{r} is the distance between the observing point P and the origin O as shown in Fig. 1, c is the velocity of the light and is η_o the intrinsic free space impedance, $\bar{j}_s^{PO}(\bar{r}', \tau(t, \bar{r}'))$ is the surface-current distribution in the time domain and $\bar{h}^{inc}(\bar{r}', \tau(t, \bar{r}'))$ is the time-domain magnetic field incident on the surface.

The delay time of the propagation is given by:

$$\tau(t, \bar{r}') = t - \frac{|\bar{r}-\bar{r}'|}{c}. \quad (4)$$

Based on Eq. (1), the surface-current density does not need to be solved. Consequently, minimum computer

memory is required and no interpolation evaluation needs to be carried out because the incident fields are known for all positions and times. This benefit makes this approach suitable for limited computer-memory requirement (e.g., personal computer). Figure 1 shows the geometry of a rectangular reflector illuminated by an incident wave. We assume that incident wave is bandpass Gaussian-pulse transmit from x-polarized small dipole point source, which has the following form:

$$\bar{h}^{inc}(\bar{r}_k, t) = \frac{B}{\sqrt{2\pi} \frac{|\bar{r}_k|}{c} \sigma} \text{Exp}[-((t-\frac{|\bar{r}_k|}{c})/\sigma)^2] [2 \text{Cos}[\omega_o (t-\frac{|\bar{r}_k|}{c})]] \text{Sin}[\theta_x] \hat{\phi}_x. \quad (5)$$

σ is the standard deviation of Gaussian envelope, B is the magnitude parameter of impulse, and ω_o is the angular frequency. From Eq. (5), we can form the time-domain representation $\mathbf{v}(t)$:

$$\mathbf{v}(t) = \text{Exp}[-((t-\frac{|\bar{r}_k|}{c})/\sigma)^2] [\text{Cos}[\omega_o (t-\frac{|\bar{r}_k|}{c})]], \quad (6)$$

as a real signal, we can write $\mathbf{v}(t)$ as:

$$\begin{aligned} \mathbf{v}(t) &= \text{Re}[\text{Exp}[-((t-\frac{|\bar{r}_k|}{c})/\sigma)^2] [\text{Exp}[j\omega_o (t-\frac{|\bar{r}_k|}{c})]]] \\ &= \text{Re}[F(t) \text{Exp}(j\omega_o t)], \end{aligned} \quad (7)$$

where $F(t)$ is analytic low pass input signal:

$$F(t) = I - jQ,$$

where

$$I = \text{Exp}[-((t-\frac{|\bar{r}_k|}{c})/\sigma)^2] \text{Cos}[\omega_o \frac{|\bar{r}_k|}{c}],$$

and

$$Q = \text{Exp}[-((t-\frac{|\bar{r}_k|}{c})/\sigma)^2] \text{Sin}[\omega_o \frac{|\bar{r}_k|}{c}],$$

where I and Q are the *In-phase* and *Quadrate* parts. $F(t)$ corresponds to the complex envelope of $\mathbf{v}(t)$ and is useful to know the intensity of the scattered wave in time domain.

The next step is show how such a bandpass system can be given an equivalent baseband representation at the center frequency, as:

$$U(t) = \frac{1}{2\pi T} \int_{t-\frac{T}{2}}^{t+\frac{T}{2}} u(\tau) \text{Exp}[-j\omega_o \tau] d\tau. \quad (8)$$

The baseband output is the sum over each path, of the delayed replicas of the baseband input. When we get the $U(t)$, it is possible to draw dB plot, as shown in Fig. 3 (b).

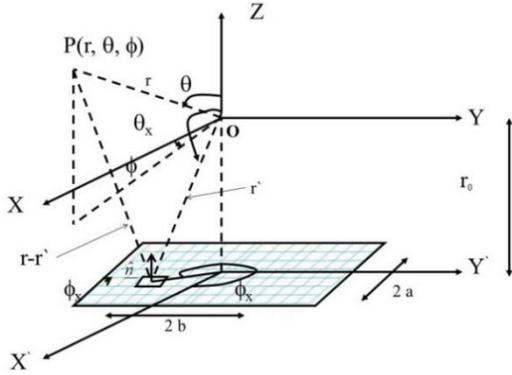


Fig. 1. Geometry of a rectangular reflector.

III. PARALLEL IMPLEMENTATIONS OF THE TDPO

In this paper, the *OpenMP* [14] programming interface was employed to parallelize the computations of the EM based on the TDPO method. It was developed on the multicore central processing unit (CPU) in multiple precisions arithmetic. *OpenMP* has been used to parallelize the code and memory-hierarchy-based optimization techniques to reduce the computer time of the code. Using these techniques, the computer time can be reduced in a factor close to the number of cores of the CPU [33]. While acceleration of the computational electromagnetic methods on graphics processing units (GPUs) has recently become a hot topic of investigations, multicore CPU still remains a source of significant computational power comparable to the GPU throughput for specific algorithms [15]. To the best of our knowledge, accurate computation of scattered field of the TDPO over rectangular reflector illuminated by a Gaussian-impulse for rectangular requires the multiple precision arithmetic, which has not been implemented as a library on GPUs yet. Therefore, it can be anticipated, that the proposed parallel CPU implementation will open the door to the implementation of the TDPO method on heterogeneous computing systems simultaneously deploying the computational power of multicore CPUs and GPUs for the tasks best suited for each.

In this paper, the authors implemented their computing solution on parallel using *OpenMP* as follows. It begins with a single thread of control, called the *master thread*, which exists for the duration of the program. The set of variables available to any particular thread is called the *thread's execution context*. During execution, the master thread may encounter parallel regions, at which the master thread will fork new threads, each with its own stack and execution context. At the end of the parallel region, the forked threads will terminate, and the master thread continues execution.

The master thread performs the following steps to

compute scattered field of the TDPO:

- The geometry parameters of the rectangular reflector antennas are input to master thread. In addition, it initializes the constant values using Eq. (5) that calculates the incident wave $\vec{h}^{inc}(\vec{r}_k, t)$.
- Calculate the scattered field of the TDPO equation $\vec{e}^{TDPO}(\vec{r}, t)$ by transforming the integral in equation 1 into sum of scatter fields over $M \times N$ small rectangular reflectors. The master thread creates NTHREADS worker threads where each one calculates the sum over a small rectangle reflector.

The computing of the scattered field of the TDPO over rectangular reflector is obtained by Eq. 1. The rectangular reflector can be divided into $M \times N$ small rectangular reflectors as shown in Fig. 1, where $M=2a/0.1\lambda$, $N=2b/0.1\lambda$, and λ denotes the wavelength. Consequently, the integration in Eq. 1 can be expressed as the summation of scattered fields over these $M \times N$ small rectangular reflectors. Therefore, it is time-consuming calculations that are needed to be performed in parallel. At this time, the code has been parallelized by distributing the M vectors of rectangular reflectors into NTHREADS threads. Each thread calculates the sum of the scattered field over N rectangular reflectors. The total sum of all the scatter fields by $M \times N$ small rectangular reflectors constitutes the scattered field by the target as follows:

```
#pragma omp parallel shared () private () {
    #pragma omp for schedule (static)
    for (i=-M; i<=M; i++)
        for (j=-N; j<=N; j++)
            sum = sum + Compute_ScatteredField (i, j);
}
```

The main problem that appears in using *OpenMP* is the order of the loops. If the directions of the observation points are used as outer loop, then each core can compute the scattered field created by all the rectangular in one direction, and at the end, it should store the result in a position of the output vector. But if the index of the rectangular reflector is used as the outer loop, then each core must compute the scatter field over this small rectangular and then use the reduction method to add all the results. Unfortunately, the reduction method is not well implemented for vectors in *OpenMP*, and each core must wait for the others to write their results.

IV. NUMERICAL RESULTS AND DISCUSSION

To explore the effectiveness of the used parallel technique, this paper implemented and carried out sequential and parallel experiments to examine the processing time needed to compute of the scattered field of the TDPO over rectangular reflector.

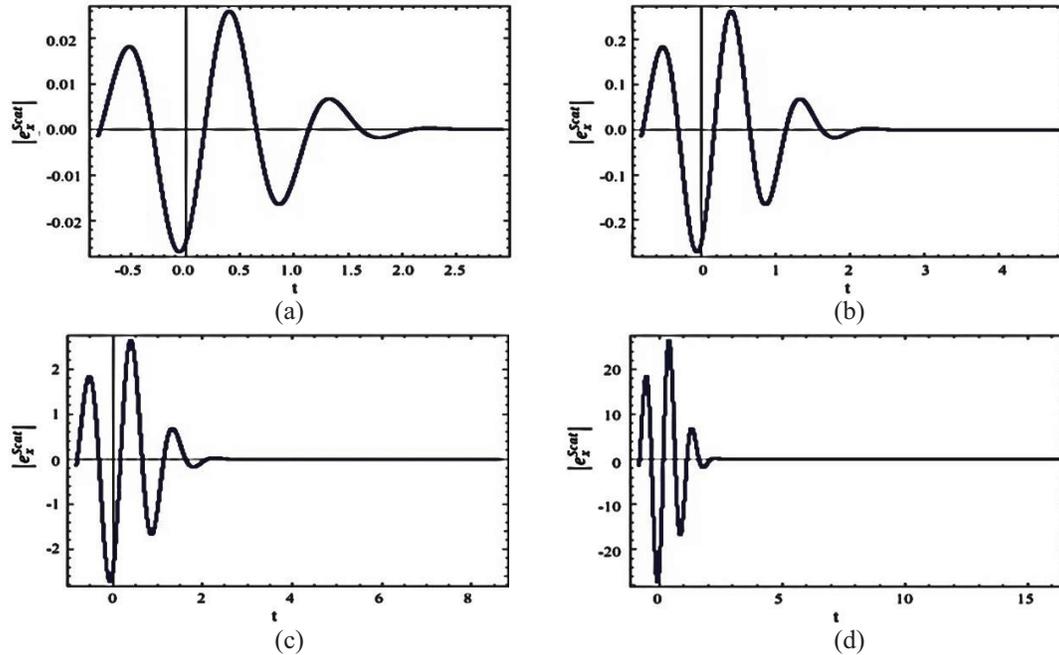


Fig. 2. (a-d). Scattered field rectangular reflector with Gaussian-impulse excitation TDPO with reflector diameters, d , $2d$, $4d$ and $8d$, respectively.

A. Setup

These computing algorithms were implemented by C++ programming language using *Microsoft Visual Studio Professional 2012* on a *HP server (ProLiant ML350p Gen8)* with two *Intel Xeon (R) processors (E5-2620 @ 2.00 GHz)*, each processor has 6 cores and 32 GB RAM. The total number of physical cores is 12. Hence, it is capable of running 12 threads simultaneously. The multicore CPU implementation was performed using the *OpenMP* programming model as in [14,31]. For the purpose of comparison, we have used *Mathematica* version 9.0.

B. Numerical results

Numerical results were obtained for a variety of configurations. As a target, we use a PEC rectangular plate as shown in Fig. 1, where λ is the wave length, σ is the standard deviation of Gaussian-impulse and $\tau = \frac{t-t_0}{\sigma}$ and $d = c\sigma$ is the reflector diameter.

Figure 2 (a)-(d) shows the numerical solution of the scattered field of the TDPO. The three scattering components shall be distinct, i.e., specular reflection at the center of rectangle, edge diffraction at the center of the edge, and corner diffraction at the corners were shown in Fig. 2 (a)-(d), respectively. In Fig. 2 (a)-(d), the reflectors diameters are d , $2d$, $4d$ and $8d$, respectively. The scattered field TDPO increases as a result of increasing the reflectors diameter d by factors 2, 4, and 8. The results appear to be more accurate and stable

faster than those obtained by frequency domain physical optics [20]. For greater reflector size, the time domain solution requires considerably more computing power consequently we implemented it in parallel. Figure 3 (a) shows that the observation point is very close to the reflector shadow boundary associated with upper diffraction point and Gaussian-impulse excitation with coordinates $r = 100$ m, $\theta = 65^\circ$, $\phi = 0^\circ$. Radiation pattern for Gaussian-impulse excitation, based in the peak response at the three scattering components is plotted in Fig. 3 (b). To compute the scattered field of the TDPO over rectangular reflector with diameter $10d$ the single-threaded code requires 177.422 seconds. While the multi-threaded code with 12 threads requires 19.73 seconds. The merits of the parallel computing are speedup S_l and efficiency E_l using l parallel threads that can be computed as follows [32]: $S_l = T_{\text{sequential}}/T_l$ and $E_l = T_{\text{sequential}}/(l \cdot T_l)$, where $T_{\text{sequential}}$ is the computing time in sequential, T_l is the computing time using l threads and $1 \leq S_l \leq l$. However, the computing overhead is determined as follows: $O(l) = T_l(1 - E_l) = T_l - (T_{\text{sequential}}/l)$. This experiment shows that with 12 threads the computing is speedup by 8.99x and efficiency is 75%. Figure 4 (a) shows the plot that presents the speedup as a function of reflector diameters (d , $2d$, $4d$, $6d$ and $8d$ respectively). Moreover, it verifies that *Mathematica* runs between 1.65 and 1.72 times slower than *OpenMP C++* implementation. The multi-thread code achieves an excellent speedup when executed on multiple cores. Figure 4 (b) demonstrates the required computing time

according to different reflector diameters along with increasing the number of parallel threads. This figure shows that for small wavelength the effect of parallel has less significant, however it shows significant impact as the reflector diameter is increasing. Moreover, we extend our experiments to reflector diameter $25d$ and then we are able to calculate the scatter field in sequential within 12 hours and 14 minutes however it take one hour and 35 minutes and 20 seconds with carrying out 12 threads per 12 cores. This experiment shows that with 12 threads the computing is speedup by 8.02x and efficiency around 65%.

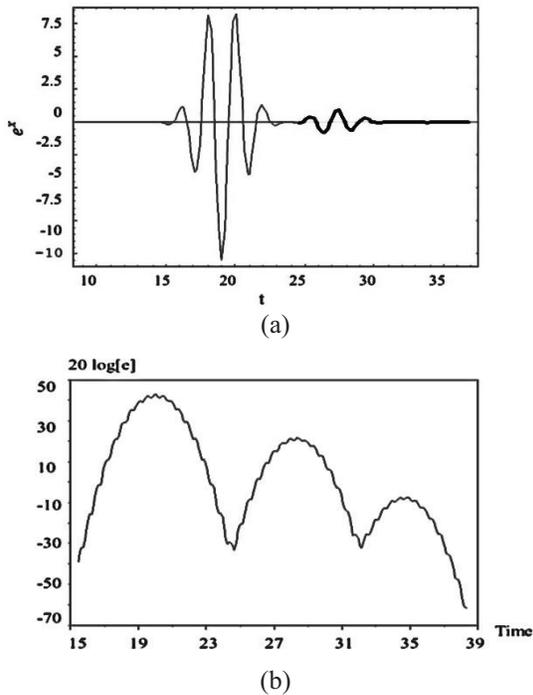


Fig. 3. (a) Scattered field of a rectangular reflector with Gaussian-impulse excitation at $r = 100$ m, $\theta = 65^\circ$, $\phi = 0^\circ$, and (b) radiation pattern for Gaussian-impulse excitation.

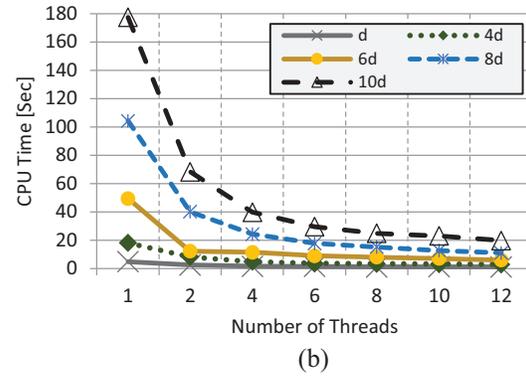
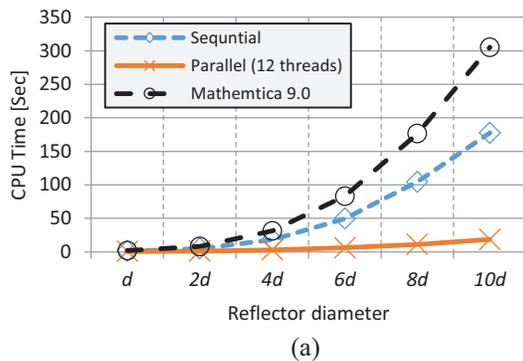


Fig. 4. Speeding up the computing of the scattered field of the TDPO over rectangular reflector.

IV. CONCLUSION

To determine the analysis of a rectangular reflector illuminated by a Gaussian-impulse considering the UWB radar application, this work extends the concept of the frequency-domain physical optics approximation to time-domain. The scattered field of the TDPO is obtained by performing the inverse Fourier transform over the frequency-domain scattered field that is obtained by calculating the integral over the illuminated surface using the free space *Green's* function.

The numerical results show the applicability of TDPO, as the scattered signals at the specular reflection point, edge diffraction and corner diffraction. Figure 2 (a)-(d) shows comparisons of the TDPO results based on a frequency domain physical optics. The frequency domain physical optics solution requires considerably more computer time and becomes inherently unstable. Moreover, the TDPO can reduce CPU time drastically. The parallel implementation of the TDPO is developed over multicores using *OpenMP*. The parallel performance of the parallel TDPO program is measured. Finally, the results show that the speed up ratio is approximately equal to 8.99x with 12 threads.

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