Transient Analysis of Electromagnetic Scattering using Marching-on-in-Order Time-Domain Integral Equation Method with Curvilinear RWG Basis Functions

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Abstract ─ In this paper, a modified marching-on-in-order time-domain integral equation method is utilized to analyze transient electromagnetic scattering from arbitrarily shaped objects. The spatial and temporal testing procedures are separate, and both of them are performed with the Galerkin's method. The curvilinear RWG basis functions are used as spatial basis functions with curved triangular patch modeling. It gives a remarkable reduction to the number of unknowns, also the memory requirement and CPU time, without sacrificing the accuracy. The use of the weighted Laguerre polynomials as temporal basis functions ensures an absolutely stable solution even in late time. Several numerical results, including the single ogive and NASA almond, are given to demonstrate the accuracy and efficiency of the proposed method.

Index Terms ─ Curvilinear RWG basis functions, Laguerre polynomials, marching-on-in-order time-domain integral equation, transient scattering.

I. INTRODUCTION

Accurate and efficient transient simulation has drawn great interest in the past decades for its important applications in the ultra wide band (UWB) technology, electromagnetic compatibility (EMC), radar imaging, etc. Numerical techniques in time domain falls mainly within the scope of the finite difference time-domain (FDTD) [1], the time-domain finite element method (TD-FEM) [2], and the time-domain integral equation (TDIE) [3], which can overcome the drawbacks encountered in the partial differential equation (PDE) methods. The most popular method to solve TDIE is the marching-on-in-time (MOT) procedure [4], but it may suffer from late-time oscillation and inaccuracy. Some progresses seem to eliminate the drawback [5, 6].

In the realm of the integral equation method, the RWG basis function defined over the planar triangular patches was proposed to model the behavior of the induced surface current [7, 8]. Afterwards, the curvilinear counterpart with curved triangular patch modeling was developed, and much less unknowns are required without a loss of accuracy [9, 10].

References [11-13] used the curvilinear RWG (CRWG) basis functions and other techniques to analyze transient scattering based on the time-domain magnetic field integral equation (TD-MFIE) with MOT procedure. For closed bodies, because using the time-domain electric field integral equation (TD-EFIE) or TD-MFIE alone would lead to wrong results near the resonant frequencies, the time-domain combined field integral equation (TD-CFIE) is preferred [14].

Recently, the marching-on-in-order (MOO) TDIE solver with weighted Laguerre polynomials as temporal basis functions was introduced, which can obtain unconditionally stable solution [15-18]. In this scheme, accurate results near the resonant frequencies can be ensured with only TD-EFIE or TD-MFIE [18]. However, the conventional MOO TDIE method is not efficient in terms of RAM and CPU time. To circumvent the bottleneck, in this paper CRWG basis functions are utilized with MOO TD-EFIE to analyze the electromagnetic scattering from conducting objects.

This paper is organized as follows. Section II presents the formulation of MOO TD-EFIE and the CRWG basis functions. This is followed, in Section III, by giving several numerical results to demonstrate the accuracy and efficiency of the proposed method. The conclusion is drawn in Section IV.

II. FORMULATION

A. MOO TD-EFIE

With the boundary condition on the surface of the conducting scatterers, the time-domain electric field equation (TD-EFIE) is

$$\mathbf{E}^i(\mathbf{r},t)|_{\tan} = \frac{1}{4\pi}\left[\mu_0\int\frac{\dot{\mathbf{J}}(\mathbf{r}',t-\Delta t_R)}{R}dS' - \frac{\nabla}{\varepsilon_0}\int_0^{t-\Delta t_R}\int\frac{\nabla'\cdot\mathbf{J}(\mathbf{r}',\tau)}{R}d\tau dS'\right]|_{\tan}, \quad (1)$$

where $\mathbf{E}^i(\mathbf{r},t)$ is the incident electric field, $R=|\mathbf{r}-\mathbf{r}'|$ is the distance between the observation point $\mathbf{r}$ and source point $\mathbf{r}'$, $\Delta t_R = R/c$, $\dot{\mathbf{J}}$ is the first derivative of the electric surface current density $\mathbf{J}$ with respect to time t, c, μ_0, and ε_0 are light speed, permeability, and permittivity in free space, respectively.

$\mathbf{J}$ can be expanded using N spatial basis functions and M temporal basis functions as

$$\mathbf{J}(\mathbf{r},t) = \sum_{n=1}^{N}\left(\sum_{j=0}^{M-1}J_{n,j}\varphi_j(\bar{t})\right)\mathbf{f_n}(\mathbf{r}), \quad (2)$$

and $\mathbf{f_n}(\mathbf{r})$ is the spatial basis function and specifically the CRWG in this paper. $\varphi_j(\bar{t})$ is the temporal basis function, i.e. the weighted Laguerre polynomial, defined as

$$\varphi_j(\bar{t}) \triangleq e^{-st/2}L_j(st), \quad (3)$$

where s is a temporal scaling factor and L_j is the j-th order Laguerre polynomial with the form

$$L_j(t) = \frac{e^t}{j!}\frac{d^j}{dt^j}\left(t^j e^{-t}\right),\ 0\le t<\infty. \quad (4)$$

The temporal derivative and integration terms in (1) are given as [17]

$$\dot{J}_n(t) = s\sum_{j=0}^{\infty}\left(0.5J_{n,j}+\sum_{k=0}^{j-1}J_{n,k}\right)\varphi_j(\bar{t}) \triangleq s\sum_{j=0}^{\infty}J^D_{n,j}\varphi_j(\bar{t}), \quad (5)$$

$$\int_0^t J_n(\tau)d\tau = \frac{2}{s}\sum_{j=0}^{\infty}\left(J_{n,j}+2\sum_{k=0}^{j-1}J_{n,k}(-1)^{j+k}\right)\varphi_j(\bar{t}) \triangleq \frac{2}{s}\sum_{j=0}^{\infty}J^I_{n,j}\varphi_j(\bar{t}), \quad (6)$$

After the spatial and temporal testing procedure with the Galerkin's method, for the i-th order case we obtain

$$\left(sA_{mn}0.5J_{n,i}+\frac{2}{s}\Psi_{mn}J_{n,i}\right)e^{\frac{-s\Delta t_R}{2}} = \int_0^{\infty}V_m(t)\varphi_i(\bar{t})dt - \sum_{j=0}^{i-1}\left\{sA_{mn}J^D_{n,j}+\frac{2}{s}\Psi_{mn}J^I_{n,j}\right\}\varphi_{i,j}(s\Delta t_R) - \left[sA_{mn}\sum_{k=0}^{i-1}J_{n,k}+\frac{2}{s}\Psi_{mn}\cdot 2\sum_{k=0}^{i-1}J_{n,k}(-1)^{k+i}\right]e^{\frac{-s\Delta t_R}{2}}, \quad (7)$$

where

$$\varphi_{i,j}(s\Delta t_R) = \varphi_{i-j}(s\Delta t_R) - \varphi_{i-j-1}(s\Delta t_R), \quad (8)$$

$$A_{mn} = \frac{\mu_0}{4\pi}\int\mathbf{f_m}(\mathbf{r})\cdot\int\frac{\mathbf{f_n}(\mathbf{r}')}{R}dS'dS, \quad (9)$$

$$\Psi_{mn} = \frac{1}{4\pi\varepsilon_0}\int\nabla\cdot\mathbf{f_m}(\mathbf{r})\int\frac{\nabla'\cdot\mathbf{f_n}(\mathbf{r}')}{R}dS'dS, \quad (10)$$

$$V_m(t) = \int\mathbf{f_m}(\mathbf{r})\cdot\mathbf{E}^i(\mathbf{r},t)dS. \quad (11)$$

Rewrite (7) into a matrix equation

$$\left[\mathbf{Z}^E{}_{mn}\right]\left[\mathbf{J}_{n,i}\right] = \left[\mathbf{V}^E{}_{m,i}\right] - \left[\mathbf{V}'^E{}_{m,i}\right], \quad (12)$$

where

$$\mathbf{Z}^E{}_{mn} = \left(sA_{mn}0.5+\frac{2}{s}\Psi_{mn}\right)e^{\frac{-s\Delta t_R}{2}}, \quad (13)$$

$$\mathbf{V}^E{}_{m,i} = \int_0^{\infty}V_m(t)\varphi_i(\bar{t})dt, \quad (14)$$

$$\mathbf{V}'^E{}_{m,i} = \sum_{j=0}^{i-1}\left\{sA_{mn}J^D_{n,j}+\frac{2}{s}\Psi_{mn}J^I_{n,j}\right\}\varphi_{i,j}(s\Delta t_R) + \left[sA_{mn}\sum_{k=0}^{i-1}J_{n,k}+\frac{2}{s}\Psi_{mn}\cdot 2\sum_{k=0}^{i-1}J_{n,k}(-1)^{k+i}\right]e^{\frac{-s\Delta t_R}{2}}. \quad (15)$$

We can solve the matrix equation recursively to get the temporal coefficients order by order. Then the surface current density can be obtained from (2).

B. CRWG basis function

The CRWG basis functions are defined over curved triangular patches. Compared with planar triangular patches, the curved ones give a significant reduction to the mesh density, and hence the number of spatial unknowns, without a loss of the accuracy of the geometry modeling and the numerical solution.

As shown in Fig. 1, a curved triangular patch is defined by six nodes, and a position in the (ξ_1,ξ_2) parameter space is described by

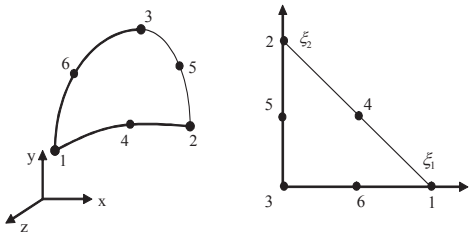
$$r(\xi_1,\xi_2)=\sum_{j=1}^{6}\varphi_j(\xi_1,\xi_2)\, r_j\,, \tag{16}$$

where r_j is the Cartesian coordinate, $\varphi_j(\xi_1,\xi_2)$ is the shape function with the form

$$\varphi_j(\xi_1,\xi_2)=\begin{cases}2\xi_j(\xi_j-1/2), & j=1,2,3\\ 4\xi_{j-3}\xi_{j-5}, & j=4,5,6\end{cases}, \tag{17}$$

and

$$\xi_1+\xi_2+\xi_3=1\,. \tag{18}$$



(a) **(b)**

Fig. 1. (a) A curved triangular patch with six nodes in the Cartesian coordinate system, (b) The triangular patch in the (ξ_1,ξ_2) parametric space.

The CRWG basis function is defined as

$$\begin{cases}\mathbf{f}_1(\mathbf{r})=\dfrac{\pm1}{J}[\xi_2\mathbf{I}_3-(1-\xi_1-\xi_2)\mathbf{I}_2]\\ \mathbf{f}_2(\mathbf{r})=\dfrac{\pm1}{J}\left((1-\xi_1-\xi_2)\mathbf{I}_1-\xi_1\mathbf{I}_3\right),\\ \mathbf{f}_3(\mathbf{r})=\dfrac{\pm1}{J}\left(\xi_1\mathbf{I}_2-\xi_2\mathbf{I}_1\right)\end{cases} \tag{19}$$

where

$$\mathbf{I}_1=-\frac{\partial\mathbf{r}}{\partial\xi_2},\ \mathbf{I}_2=\frac{\partial\mathbf{r}}{\partial\xi_1},\ \mathbf{I}_3=\frac{\partial\mathbf{r}}{\partial\xi_2}-\frac{\partial\mathbf{r}}{\partial\xi_1}, \tag{20}$$

and J is the Jacobi factor

$$J(\xi_1,\xi_2)=\left|\frac{\partial\mathbf{r}}{\partial\xi_1}\times\frac{\partial\mathbf{r}}{\partial\xi_2}\right|. \tag{21}$$

The surface divergence of the CRWG basis function is

$$\nabla_s\bullet\mathbf{f}_\beta(\mathbf{r})=\frac{\pm2}{\sqrt{J}}\quad(\beta=1,2,3)\,. \tag{22}$$

The differential tangent vector and normal surface element are given below, respectively,

$$d\mathbf{r}=\frac{\partial\mathbf{r}}{\partial\xi_1}d\xi_1+\frac{\partial\mathbf{r}}{\partial\xi_2}d\xi_2\,, \tag{23}$$

$$d\mathbf{S}=\frac{\partial\mathbf{r}}{\partial\xi_1}\times\frac{\partial\mathbf{r}}{\partial\xi_2}d\xi_1d\xi_2\,. \tag{24}$$

The surface normal unit vector is

$$\hat{\boldsymbol{n}}(\xi_1,\xi_2)=\frac{1}{\sqrt{g}}\frac{\partial\mathbf{r}}{\partial\xi_1}\times\frac{\partial\mathbf{r}}{\partial\xi_2}, \tag{25}$$

where

$$g=g_{11}g_{22}-g^2{}_{12}\,, \tag{26}$$

$$g_{ij}=\frac{\partial\mathbf{r}}{\partial\xi_1}\cdot\frac{\partial\mathbf{r}}{\partial\xi_2}. \tag{27}$$

III. NUMERICAL EXAMPLES

This section gives several numerical results obtained using an implementation described above to validate the proposed method. All CPU times are taken on a 3.0GHz processor.

A. Sphere

As the first example, we consider a metallic sphere centered at the origin with a radius of 0.5 meter. The problem is discretized into 219 CRWG basis functions and 50 temporal basis functions (i.e., the weighted Laguerre polynomials). The incident Gaussian pulse is with the form of

$$\mathbf{E}^i(\mathbf{r},t)=\hat{\boldsymbol{x}}\frac{4}{\sqrt{\pi}T}\boldsymbol{e}^{-\gamma^2}, \tag{28}$$

$$\gamma=\frac{4}{T}\left(t-t_0-\mathbf{r}\cdot\hat{\boldsymbol{k}}/c\right), \tag{29}$$

where $\hat{\boldsymbol{k}}$ is the unit vector in the direction of the wave propagation and is along $-\hat{z}$ direction in this example. t_0 = 12 lm represents a time delay of the pulse peak from the time origin, and T = 8 lm is the pulse width. In this work, we use lm as time unit, which is the short form of light meter. One light meter is the time taken by the electromagnetic wave to travel one meter in free space. This pulse has a frequency spectrum of 125 MHz. The scaling factor s is with the value of 1.0×10^9.

The θ component of the backward far field response ($\theta = 0°$, $\phi = 0°$) from the sphere is shown in Fig. 2 (labeled C 219). For the sake of comparison, results obtained in Reference [18] (labeled Ref) and that via 795 conventional planar RWG (PRWG) basis functions (labeled P 795) are also shown. Good agreement can be observed.

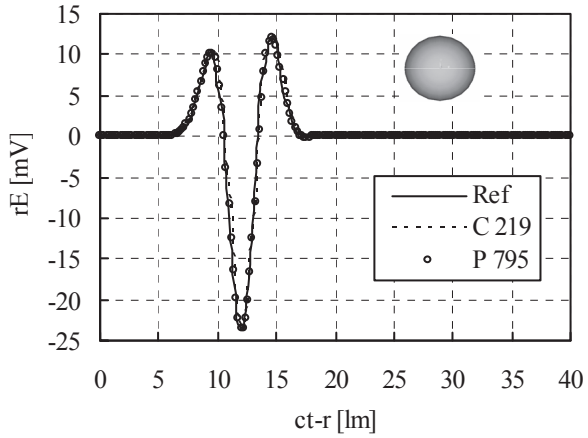


Fig. 2. θ component of transient backward far field response from a sphere.

B. Single ogive

Another example is a metallic single ogive. The analytical expression for this target is as follows:

for –1.27 m < x < 1.27 m and –π < φ < π, define

$$f(x) = \sqrt{1-(\frac{x}{5})^2 \sin^2 22.62^\circ} - \cos 22.62^\circ$$

$$y = \frac{f(x)\cos\varphi}{1-\cos 22.62^\circ} \quad . \quad (30)$$

$$z = \frac{f(x)\sin\varphi}{1-\cos 22.62^\circ}$$

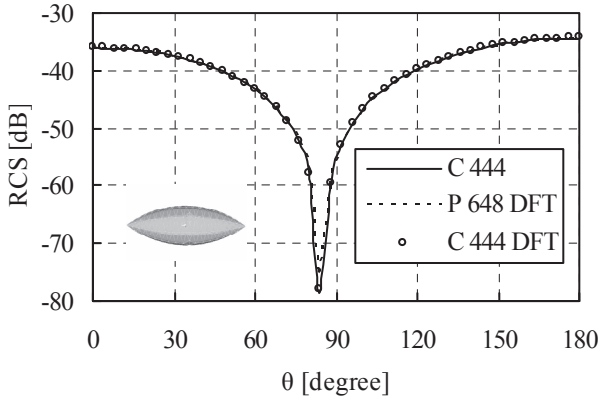
The incident wave used in this example is a modulated Gaussian pulse given by

$$\mathbf{E}^i(\mathbf{r},t) = \hat{\boldsymbol{x}}\cos(2\pi f_0 \tau)\exp\left(-\frac{(\tau - t_p)^2}{2\sigma^2}\right), \quad (31)$$

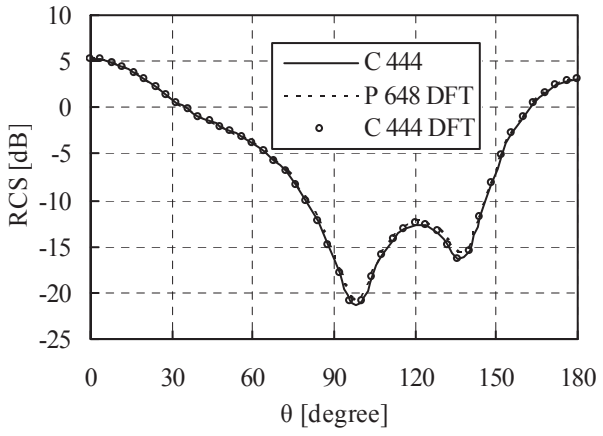
where the central frequency f_0 is 160 MHz, $\tau = t - \mathbf{r}\cdot\hat{\boldsymbol{k}}/c$, $\hat{\boldsymbol{k}}$ is along $-\hat{z}$ direction, $\sigma = 6/(2\pi f_{bw})$, $t_p = 4.5\sigma$, the bandwidth f_{bw} of the signal is 320MHz.

The problem is discretized into 444 CRWG basis functions and 100 temporal basis functions. The scaling factor s is with the value of 1.5×10^9.

After the solution procedure in time domain, the far-field signals are Fourier transformed into the frequency domain and then the bistatic radar cross section (RCS) in $\varphi = 0^\circ$ plane at several representative frequencies are calculated. These frequencies are chosen near the lowest, the middle and the highest frequency of the frequency band, and in this example they are 20 MHz, 160 MHz and 300 MHz. The results (labeled CRWG 444 DFT) are compared with those obtained via frequency domain MoM using 444 CRWGs (labeled C 444) and TD-EFIE using 648 PRWGs (labeled P 648 DFT) in Fig. 3. The results are in good agreement with each other. It's worth mentioning that 648 is the minimum number of PRWGs through exhaustive numerical experiments with increasing spatial unknowns.



(a)



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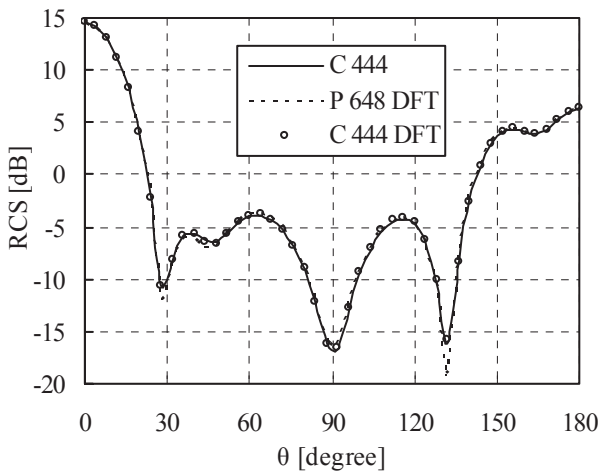


(c)

Fig. 3. Bistatic RCS of the single ogive: (a) 20 MHz, (b) 160 MHz, and (c) 300 MHz.

C. NASA almond

A metallic NASA almond is referred to as the last structure. The mathematical description used for this target is as follows:

for $-0.41667 < l < 0$ and $-\pi < \varphi < \pi$, define

$$x = dl \text{ m}$$

$$y = 0.193333d\sqrt{1-\left(\frac{l}{0.416667}\right)^2}\cos\varphi, \quad (32)$$

$$z = 0.064444d\sqrt{1-\left(\frac{l}{0.416667}\right)^2}\sin\varphi$$

for $0 < l < 0.58333$ and $-\pi < \varphi < \pi$

$$x = dl \text{ m}$$

$$y = 4.83345d\left[\sqrt{1-\left(\frac{l}{2.08335}\right)^2}-0.96\right]\cos\varphi \quad (33)$$

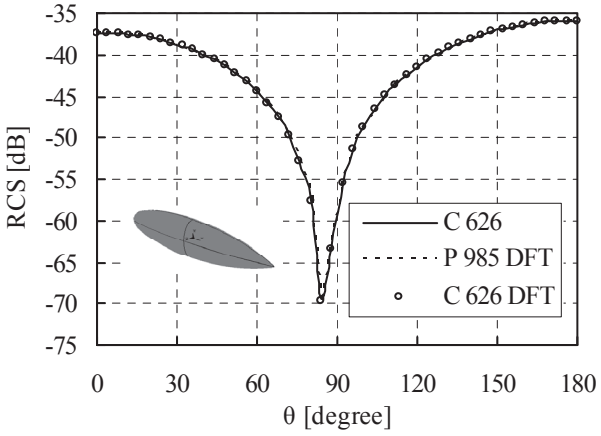
$$z = 1.61115d\left[\sqrt{1-\left(\frac{l}{2.08335}\right)^2}-0.96\right]\sin\varphi$$

where d=2.52374 m.

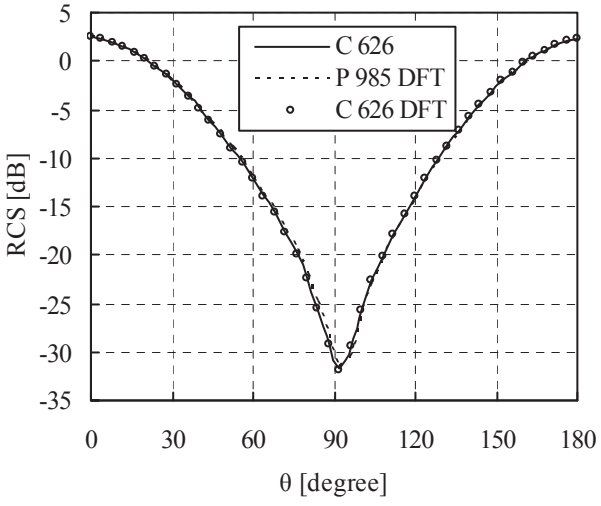
The incident wave used in this example is a modulated Gaussian pulse with the form of (31). The problem is discretized into 626 CRWG basis functions and 100 temporal basis functions. The central frequency of the incident modulated Gaussian pulse is 110 MHz and the frequency bandwidth is 220 MHz. The scaling factor s is with the value of 1.5×10^9. After a Fourier transform, the bistatic RCS in $\varphi = 0^\circ$ plane at 20 MHz, 110 MHz and 200 MHz are given.

The result (labeled C 626 DFT) is compared with those obtained via frequency domain MoM using 626 CRWGs (labeled C 626) and TD-EFIE using 985 PRWGs (labeled P 985 DFT) in Fig. 4. 985 is found to be the minimum number of PRWGs for an almost indistinguishable result, which are more than that of the CRWGs.

The efficiency of the proposed method is further compared in Table 1. Considerable reduction to both memory requirement and total CPU time are achieved.



(a)



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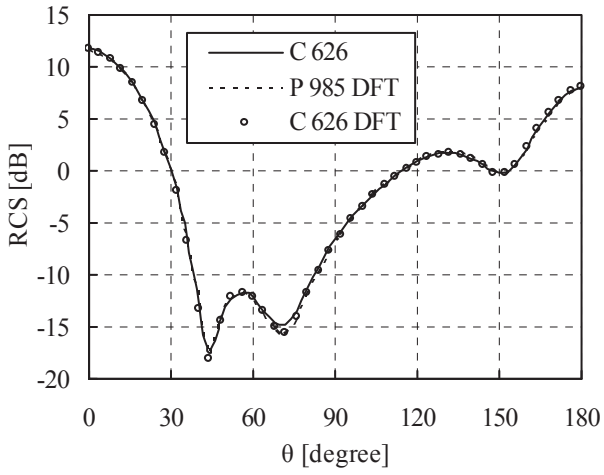

(c)

Fig. 4. Bistatic RCS of the NASA almond: (a) 20 MHz, (b) 110 MHz, and (c) 200 MHz.

Table 1: Comparison of memory requirement and total CPU time

		Geometries		
		Sphere	**Ogive**	**Almond**
Matrix Size	**PRWG**	795	648	985
	CRWG	219	444	626
RAM (MB)	**PRWG**	244	321	744
	CRWG	18	151	300
Total Time (s)	**PRWG**	275	754	1896
	CRWG	14	298	734

VI. CONCLUSION

In this paper, the marching-on-in-order time-domain integral equation method with curvilinear RWG spatial basis functions is presented to analyze transient electromagnetic scattering from arbitrarily shaped objects. Stable solutions can be ensured, and the memory requirement and CPU time are reduced without sacrificing the accuracy.

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