A VSIE Solution for EM Scattering Using the Multilevel Complex Source Beam Method

Z. H. Fan, Y. L. Hu, D. Z. Ding, and R. S. Chen

Department of Communication Engineering
Nanjing University of Science and Technology, Nanjing, 210094, China
eerschen@njust.edu.cn

Abstract **─** Multilevel complex source beam (CSB) method is introduced to accelerate the volume-surface integral equation (VSIE) for the analysis of electromagnetic scattering from the composite structures comprising conductor and dielectric material. The field generated by each basis function or testing function is expressed by use of the equivalent point source defined over the complex sphere. The far interactions between basis functions and testing functions are replaced by the interactions between complex point sources, which can be calculated efficiently by taking advantage of the directionality of the complex point sources. The translation invariance property of Green's function is exploited to further improve efficiency. In numerical examples, the number of CSBs and truncation angle are given for each level, and the computational efficiency of the proposed method is validated by comparison with the conventional VSIE method.

Index Terms **─** Electromagnetic scattering, multilevel complex source beam, volume-surface integral equation.

I. INTRODUCTION

A lot of attention has been paid to the electromagnetic scattering from the composite structures comprising conductor and dielectric material for its wide range of applications. Two kinds of integral equations have been investigated to deal with composite objects. The surface integral equation (SIE) methods, represented by Poggio-Miller-Chang-Harrington-Wu-Tsai (PMCHWT) [1]-[2] integral equation, Müller integral equation [3], electric/magnetic current combined-field integral equation (JMCFIE) [4]-[5] etc., are effective for homogeneous or piecewise homogeneous composite objects, but they are unable to tackle the inhomogeneous materials. Although it requires more number of unknowns than SIE, the volume-surface integral equation (VSIE) method is more powerful since it can handle inhomogeneous dielectric material [6]-[7]. Meanwhile, VSIE uses only the free-space Green's function, which makes programming easier than SIE. This work aims to investigate a novel fast algorithm to speed up the analysis of the VSIE.

When analyzing the integral equation by the method of moments (MoM), the number of unknowns N increases with the electrical size of the scatterers, which prevents directly solving the large structure due to the storage complexity of $O(N^2)$ and the time complexity of $O(N^3)$. During the past several decades, many fast algorithms were proposed to analyze the electrically large scatterers, including the multilevel fast multipole method (MLFMM) [8]-[10], the adaptive integral method (AIM) [11], the adaptive cross approximation (ACA) [12]-[14], etc. Recently, complex source beam (CSB) method and its multilevel version [15]-[18] were proposed to speed up the analysis of perfect electric conductor (PEC) scattering problems. In this method, each basis function is expressed by complex point sources by invoking the extended equivalence theorem [15]. The equivalent point source locates at a complex point, which is obtained by introducing an imaginary spatial displacement to the real position vector. The field generated by complex point source, which is called as complex source beam, has intrinsically the directionality. The directionality of CSB is exploited to accelerate the calculation by replacing the interactions between the basis functions and testing functions belonging to far groups with the interactions between complex point sources. As compared with MLFMM, one advantage of multilevel CSB (MLCSB) is that it requires a lower memory to calculate the interactions between the well separated groups since they are calculated partly with MLCSB rather than globally with MLFMM. The other advantage lies in that MLCSB is free from a particular decomposition of the Green's function. Therefore it is applicable to radiation and scattering problems in inhomogeneous space, for which MLFMM is inconvenient.

In this paper, the solution of VSIE is accelerated by MLCSB for the analysis of the scattering from composite object. The complex point sources are first exploited to express the volume Schaubert-Wilton-Glisson (SWG) basis function [19]. The choices for the number and truncation angle of complex point sources are discussed

Submitted On: July 17, 2015
Accepted On: August 25, 2015

in detail. The computational efficiency is illustrated by comparison with the conventional VSIE.

This paper is organized as follows. In Section II, the basic theory and formulations of VSIE method accelerated by MLCSB are presented. Several numerical results are given to demonstrate the validity of the proposed method in Section III. Conclusions are summarized in Section IV.

II. THEORY AND FORMULATIONS

A. Volume-surface electric field integral equations

We aims to obtain the scattering electric field $\vec{E}^s$ from an arbitrarily shaped composite structure under an incident plane wave $\vec{E}^i$ as shown in Fig. 1. The symbol S denotes the surface of PEC parts of the composite structures, and V denotes the volume of dielectric parts. For dielectric media, the permittivity $\varepsilon(\vec{r})$ is a function of spatial position and the permeability is μ_0. ε_0 and μ_0 denotes the permittivity and permeability of free space.

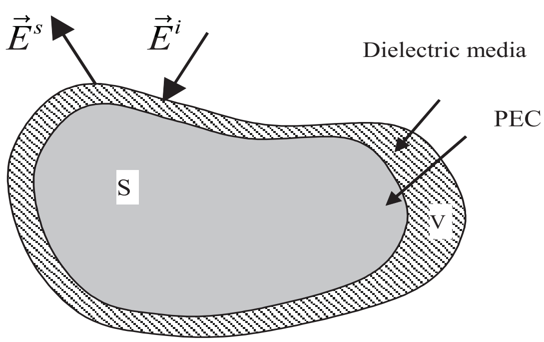


Fig. 1. Geometry of composite structure.

The VSIE [6]-[7] is built by enforcing both the consistency condition of electric field in dielectric V and the boundary condition for the electric field on the PEC surface S:

$$\vec{E}^i = \frac{\vec{D}(\vec{r})}{\varepsilon(\vec{r})} + j\omega\mu_0 \int_V \bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{J}_v(\vec{r}') d\vec{r}' + j\omega\mu_0 \int_S \bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{J}_s(\vec{r}') d\vec{r}' \quad \left(\vec{r} \in V\right), \tag{1}$$

$$\vec{E}^i_{tan} = \left[\begin{array}{l} j\omega\mu_0 \int_V \bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{J}_v(\vec{r}') d\vec{r}' \\ + j\omega\mu_0 \int_S \bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{J}_s(\vec{r}') d\vec{r}' \end{array} \right]_{tan} \quad \left(\vec{r} \in S\right). \tag{2}$$

In equations (1) and (2), j denotes the imaginary unit, $\vec{J}_v$ and $\vec{J}_s$ are the electric current densities in the V and on the S, respectively. $\vec{D}$ is the electric flux density, and $\vec{J}_v(\vec{r}) = j\omega K(\vec{r})\vec{D}(\vec{r})$, $K(\vec{r}) = \left[\varepsilon(\vec{r}) - \varepsilon_0\right] / \varepsilon(\vec{r})$, ω is angular frequency. The subscript tan denotes taking the tangential components of corresponding vector. $\bar{\bar{G}}(\vec{r},\vec{r}\,')$ is the three dimensional dyadic Green's function in free space:

$$\bar{\bar{G}}(\vec{r},\vec{r}') = (\bar{\bar{I}} + \frac{1}{k^2}\nabla\nabla)\frac{e^{-jk|\vec{r}-\vec{r}'|}}{4\pi|\vec{r}-\vec{r}'|}, \tag{3}$$

where $\bar{\bar{I}}$ is the unit dyadic and k is the wavenumber in free space.

In the implementation of method of moments for solving the VSIE, $\vec{D}$ is expanded by the SWG basis functions, and $\vec{J}_s$ is expanded by the Rao-Wilton-Glisson (RWG) [20] basis functions. By use of the Galerkin's testing, equations (1) and (2) can be converted to the following matrix equation:

$$\begin{bmatrix} Z^{DD} & Z^{MD} \\ Z^{DM} & Z^{MM} \end{bmatrix} \begin{bmatrix} D^V \\ I^S \end{bmatrix} = \begin{bmatrix} v^V \\ v^S \end{bmatrix}, \tag{4}$$

where vectors D^V and I^S represent the coefficients of the basis functions which expanding $\vec{D}$ and $\vec{J}_s$, respectively. v^V and v^S relate to incident field for dielectric and PEC parts, respectively.

B. Multilevel complex source beam method

MLCSB method is applied to accelerate the matrix-vector multiplication required by the iterative solver for solving equation (4). To implement the MLCSB scheme, octree grouping is utilized. Based on the extended equivalence theorem introduced in [15], a set of equivalence point sources are constructed for each basis function to generate the same electromagnetic fields in the interesting region. The point sources are distributed at a sphere with complex radius, which are constructed by extending the real coordinates of points on the sphere enclosing the grouping box into complex coordinates. The field generated by the point sources locating at the complex positions, or complex point sources, has directionality, in contrast to the isotropic field generated by real point sources. The directionality depends on the imaginary coordinates of point sources and can be exploited to develop fast algorithms.

The equivalence complex point sources are distributed at the surface of the complex sphere which locating at the angle of [(n-1) $\Delta\theta$, (m-1) $\Delta\varphi_n$] with $n = 1,\cdots,N_\theta + 1$ and $m = 1,\cdots,N_{\varphi n} + 1$, as shown in Fig. 2. Here $\Delta\theta = 180° / N_\theta$ is the angle interval of CSBs along the θ direction. N_θ is the number of CSBs along the θ direction. $\Delta\varphi_n = 360° / N_{\varphi n}$ is the angle interval of CSBs along the φ direction which varying with the θ component of the position vector of points. $N_{\varphi n} = \mathrm{Int}[2(n+1)\sin\left(n-1\right)\Delta\theta]$ is the number of CSBs in the φ direction [18].

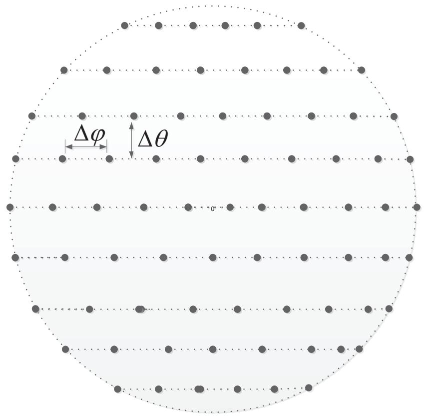


Fig. 2. The distribution of CSBs.

For PEC part, the interactions of observation RWG function $\vec{f}^{\,S}(\vec{r})$ and source RWG function $\vec{f}^{\,S}(\vec{r}')$ are represented by the CSBs as follows [16],[18]:

$$\int_{S_n} \bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{f}_n^{\,S}(\vec{r}')\,\mathrm{d}s' = \sum_{p=1}^{P} \bar{\bar{G}}(\vec{r},\tilde{\vec{r}}'_{np}) \cdot \vec{w}_{np}, \tag{5}$$

$$\begin{aligned}\int_{S_m} \vec{f}_m^{\,S}(\vec{r}) \cdot \sum_{p=1}^{P} \bar{\bar{G}}(\vec{r},\tilde{\vec{r}}'_{np}) \cdot \vec{w}_{np}\,\mathrm{d}s \\ = \sum_{q=1}^{Q} \vec{w}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{w}_{np}.\end{aligned} \tag{6}$$

Similarly, for dielectric part, the interactions of observation SWG function $\vec{f}^{\,V}(\vec{r})$ and source SWG function $\vec{f}^{\,V}(\vec{r}')$ can be represented by the CSBs:

$$\int_{V_n} j\omega K(\vec{r}')\bar{\bar{G}}(\vec{r},\vec{r}') \cdot \vec{f}_n^{\,V}(\vec{r}')\,\mathrm{d}v' = \sum_{p=1}^{P} \bar{\bar{G}}(\vec{r},\tilde{\vec{r}}'_{np}) \cdot \vec{u}_{np}, \tag{7}$$

$$\begin{aligned}\int_{V_m} \vec{f}_m^{\,V}(\vec{r}) \cdot \sum_{p=1}^{P} \bar{\bar{G}}(\vec{r},\tilde{\vec{r}}'_{np}) \cdot \vec{u}_{np}\,\mathrm{d}v \\ = \sum_{q=1}^{Q} \vec{\eta}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{u}_{np},\end{aligned} \tag{8}$$

P and Q are the numbers of CSBs for the basis and testing functions, respectively. They are set to the same value in this work, although they can have different values. $\tilde{\vec{r}}'_{np} = \vec{r}'_{np} - jb_0\hat{r}'_{np}$, $\vec{r}'_{np}$ is the location vector of the p-th CSB for the n-th basis function. $\hat{r}'_{np}$ is a unit vector that from the center of these CSBs to the p-th CSB. b_0 determines the beam waist of the CSB. $\vec{w}_{np}$ is the vector beam weight of the p-th CSB for the n-th RWG function $\vec{f}_n^{\,S}(\vec{r}')$, and $\vec{u}_{np}$ is the vector beam weight of the p-th CSB for the n-thsource SWG function along with its corresponding permittivity $j\omega K(\vec{r}')\vec{f}_n^{\,V}(\vec{r}')$, which distinguishes from the definition of $\vec{w}_{np}$. $\vec{\eta}_{mq}$ is the vector beam weight of the q-th CSB for the m-th observation SWG basis function. In the implementation, the expressions of impedance matrices for far field parts in (4) can be replaced by the interactions between CSBs, and listed as follows:

$$Z_{mn}^{DD} = j\omega\mu_0 \sum_{q=1}^{Q} \vec{\eta}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{u}_{np}, \tag{9}$$

$$Z_{mn}^{DM} = j\omega\mu_0 \sum_{q=1}^{Q} \vec{w}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{u}_{np}, \tag{10}$$

$$Z_{mn}^{MD} = j\omega\mu_0 \sum_{q=1}^{Q} \vec{\eta}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{w}_{np}, \tag{11}$$

$$Z_{mn}^{MM} = j\omega\mu_0 \sum_{q=1}^{Q} \vec{w}_{mq} \cdot \sum_{p=1}^{P} \bar{\bar{G}}\left(\tilde{\vec{r}}_{mq},\tilde{\vec{r}}'_{np}\right) \cdot \vec{w}_{np}. \tag{12}$$

Now, the matrix equations can be decomposed into near and far field parts:

$$\left\{\left[Z_{Near}\right] + \begin{bmatrix} \eta Tu & \eta Tw \\ wTu & wTw \end{bmatrix}\right\} \cdot \begin{bmatrix} D \\ I \end{bmatrix} = \begin{bmatrix} v^V \\ v^S \end{bmatrix}, \tag{13}$$

T is the transfer matrix and denotes the interactions between the beams for the well separated groups [16],[18]. To compute the interactions between two well separated groups M and N with acceptable accuracy [18], only the interactions of the CSBs within the truncation angle $\pm\theta_t$ are required due to their radiation directionality, as shown in Fig. 3. The MLCSB method is realized with the octree grouping technique similar to MLFMM [8]. In the finest level, the interactions of self group and near-field groups are computed by the method of moments directly while the interactions of the well separated groups are computed by the CSB method in corresponding levels.

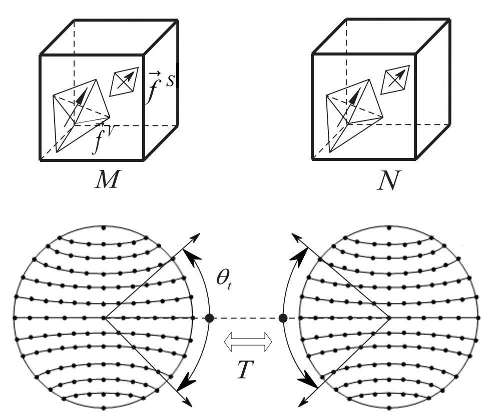


Fig. 3. The interactions between two far field groups by CSBs within $\pm\theta_t$.

The translation invariance property of Green's function is utilized to further improve the efficiency. The number of different interactions between the given group and all its far-field groups at the same level is

7^2-3^2=40 for two-dimension models, and is 7^3-3^3=316 for three-dimension models. Moreover, using the symmetry property of the Green's function, only 12 transfer matrices need to be computed and stored for two-dimension problems as shown in Fig. 4, and 56 transfer matrices for three-dimension problems [18].

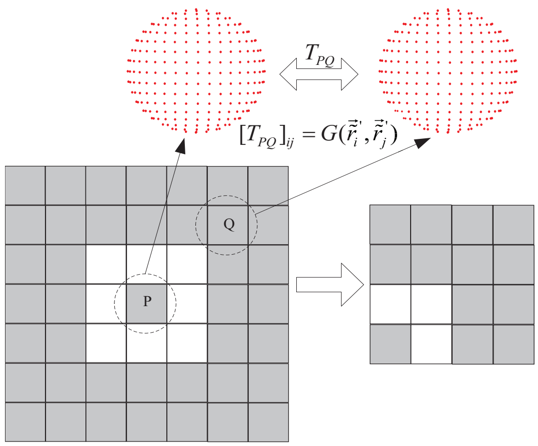


Fig. 4. Interactions between group P and its far field groups.

III. NUMERICAL RESULTS

In this section, two numerical examples are presented to validate the accuracy and efficiency of the proposed MLCSB accelerated VSIE method. All calculations are performed on the personal computer with 2.67 GHz central processing unit (CPU) and 8 GB random access memory (RAM).

Firstly, consider the electromagnetic scattering from a PEC sphere with the radius 0.15 m, coated with a dielectric layer with the thickness 0.03 m and relative permittivity ε_r=2. The incident plane wave operates at the frequency of 1 GHz, and it propagates along z direction with vertical polarization. In our analysis, the number of total unknown is 16905, in which 14491 for dielectric part and 2214 for PEC part. The $\Delta\theta$ value of CSBs is 30°, and the truncation angle θ_t is 160°. The values of bistatic RCS normalized to square wavelength obtained from the MLCSB accelerated VSIE, the Mie series and software FEKO are shown in Fig. 5 and they are in good agreement. The storage requirement and computational time are listed in Table 1. It can be observed that the CSB accelerated VSIE method requires about 62.6% storage and 73.7% time cost less than the conventional VSIE method.

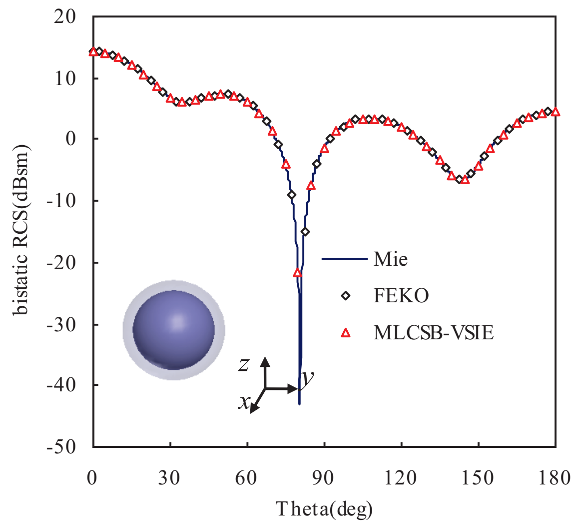


Fig. 5. The bistatic RCS of coated sphere (phi=0), obtained from proposed method, Mie series and software FEKO.

Table 1: Computational efficiency comparison (number of unknowns: 16905)

	CPU Time (s)	Memory (GB)
VSIE	1495	2.3
MLCSB-VSIE	392	0.86

In order to investigate the choices of $\Delta\theta$ and θ_t for each level of MLCSB, the scattering from coated cuboids with four different sizes are computed as the second example. The size of the grouping box at the finest level is kept to 0.18 wavelength. The number of unknowns and the adopted number of level increase as the size of the structure increases. The structures are all illuminated by a vertical polarization plane wave along z direction and the frequency is 300 MHz. Some structural and computational parameters are listed in Table 2. All the structures are coated by a dielectric layer with relative permittivity of ε_r=2 and thickness of 0.05 m.

Table 2: Parameters of the coated cuboids

	Dimension of PEC Part (unit: m)	Number of Unknowns	Number of Levels
Model 1	0.6*0.3*0.3	8794	1
Model 2	1.2*0.3*0.3	15128	2
Model 3	2.4*0.3*0.3	27913	3
Model 4	4.8*0.3*0.3	53454	4

Here, the relative root mean square (RRMS) error is exploited to compare the accuracy of the methods, and which is defined as:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left|a_i-b_i\right|^2\Big/\left|b_i\right|^2}, \tag{14}$$

where a_i and b_i are the bistatic RCS values (unit: m^2) of the proposed method and conventional VSIE method, respectively, and n denotes the number of observation points. To determine the appropriate values of $\Delta\theta$ and θ_t for each level, we first fix θ_t as 180° to prevent the truncating error and check the RCS accuracy with different $\Delta\theta$. When analyzing the proper $\Delta\theta$ for a higher level, the values of $\Delta\theta$ for the lower levels are chosen as the maximum $\Delta\theta$ value satisfying the RRMS error less than 0.01 for the corresponding low level models. The RRMS error curves for different $\Delta\theta$ at different levels are shown in Fig. 6. From Fig. 6, we can find that the $\Delta\theta$ values can be chosen as 30°, 22.5°, 20°, 15° from level 1 to level 4 to ensure the RRMS error less than 0.01. Then we fix $\Delta\theta$ to the values for corresponding levels, and check the RCS accuracy with different θ_t for each level. The RRMS error curves for different θ_t are shown in Fig. 7, and it can be concluded that the θ_t values can be chosen as 160°, 140°, 100° and 80° from level 1 to 4, respectively, to ensure the RRMS error less than 0.01. The bistatic RCS curves of model 3 calculated with the above $\Delta\theta$ and θ_t are shown in Fig. 8. Good agreement is observed between MLCSB accelerated VSIE method and the conventional method. The memory requirement and total CPU time for two methods are given in Fig. 9. It can be observed that the MLCSB accelerated VSIE method requires about much less storage and time less than the conventional VSIE does.

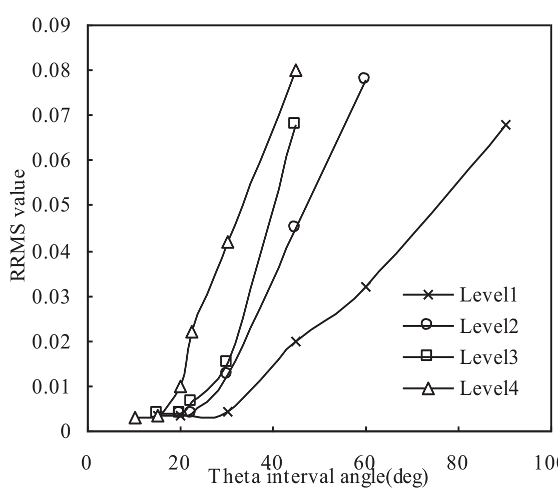


Fig. 6. The RRMS values of bistatic RCS for different theta angle interval with different levels.

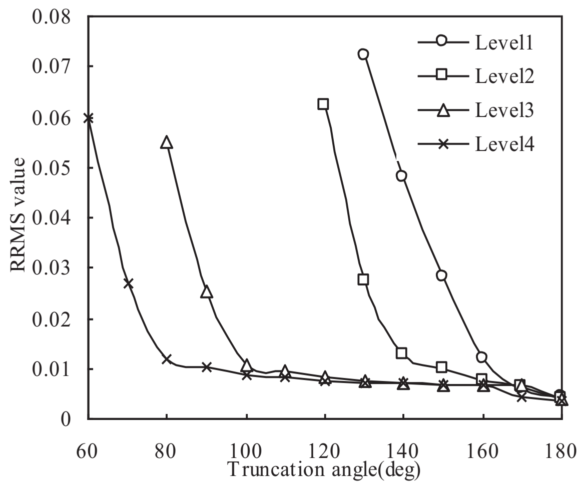


Fig. 7. The RRMS values of bistatic RCS for different truncation angle with different levels.

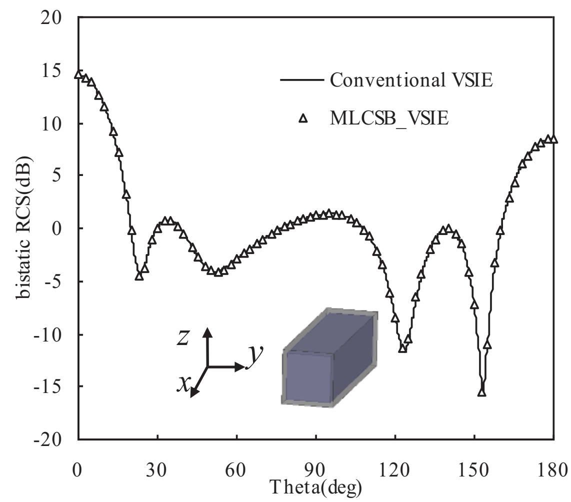
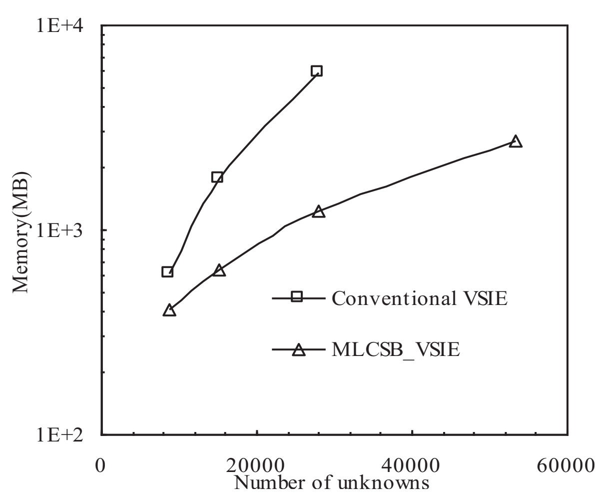
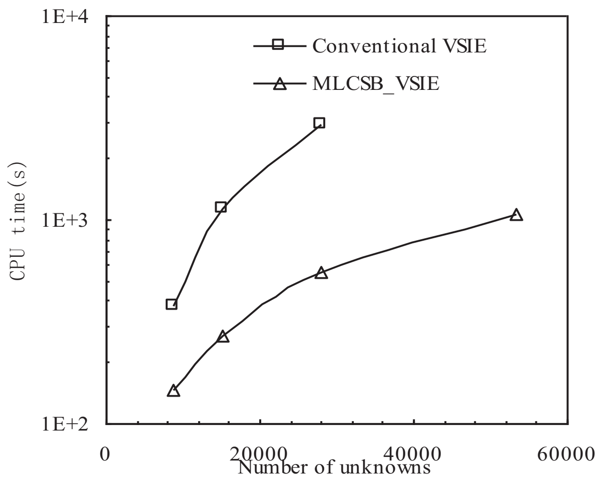


Fig. 8. The bistatic RCS of model 3 (phi=0).



(a)



(b)

Fig. 9. The comparisons of consumption for different models with different number of unknowns: (a) memory and (b) CPU time.

IV. CONCLUSION

In this paper, the MLCSB accelerated VSIE method is utilized to efficiently analyze the electromagnetic scattering from composite structures comprising PEC and dielectric material. The parameter values of MLCSB method are discussed in detail. The comparisons of memory consumption and CPU time with conventional VSIE are given. From the numerical results, the accuracy and efficiency of the proposed scheme are demonstrated.

REFERENCES

[1] P. L. Huddleston, L. N. Medgyesi-Mitschang, and J. M. Putnam, "Combined field integral equation formulation for scattering by dielectrically coated conducting bodies," *IEEE Trans. Antennas Propag*., vol. 34, no. 4, pp. 510-520, Apr. 1986.

[2] K. C. Donepudi, J-M. Jin, and W. C. Chew, "A higher order multilevel fast multipole algorithm for scattering from mixed conducting/dielectric bodies," *IEEE Trans. Antennas Propag*., vol. 51, no. 10, pp. 2814-2821, Oct. 2003.

[3] P. Yla-Oijala and M. Taskinen, "Well-conditioned Muller formulation for electromagnetic scattering by dielectric objects," *IEEE Trans. Antennas Propag*., vol. 53, no. 10, pp. 3316-3323, 2005.

[4] P. Yla-Oijala and M. Taskinen, "Application of combined field integral equation for electromagnetic scattering by dielectric and composite objects," *IEEE Trans. Antennas Propag*., vol. 53, no. 3, pp. 1168-1173, 2005.

[5] P. Ylä-Oijala, M. Taskinen, and J Sarvas, "Multilayered media Green's functions for MPIE with general electric and magnetic sources by the Hertz potential approach," *Progress In Electromagnetics Research*, vol. 33, pp. 141-165, 2001.

[6] C. C. Lu and W. C. Chew, "A coupled surface-volume integral equation approach for the calculation of electromagnetic scattering from composite metallic and material targets," *IEEE Trans. Antennas Propagat.*, vol. 48, pp. 1866-1868, 2000.

[7] C. Luo and C. C. Lu, "Electromagnetic scattering computation using a hybrid surface and volume integral equation formulation," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 22, no. 3, pp. 340-349, 2007.

[8] J. M. Song and W. C. Chew, "Fast multipole method solution using parametric geometry," *Microwave and Optical Technology Letters*, vol. 7, no. 16, pp. 760-765, 1994.

[9] J. M. Song, C. C. Lu, and W. C. Chew, "Multilevel fast multipole algorithm for electromagnetic scattering by large complex objects," *IEEE Trans. Antennas Propag.*, vol. 45, pp. 1488-1493, 1997.

[10] D. Z. Ding, S. F. Tao, and R. S. Chen, "Fast analysis of finite and curved frequency-selective surfaces using the VSIE with MLFMA," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 24, no. 5, pp. 425-436, 2011.

[11] E. Bleszynski, M. Bleszynski, and T. Jaroszewicz, "AIM: adaptive integral method for solving large-scale electromagnetic scattering and radiation problems," *Radio Sci.*, vol. 31, pp. 1225-1251, 1996.

[12] K. Zhao, M. N. Vouvakis, and J. F. Lee, "The adaptive cross approximation algorithm for accelerated method of moments computations of EMC problems," *IEEE Transactions on Electromagnetic Compatibility*, vol. 47, no. 4, pp. 763-773, 2005.

[13] J. M. Tamayo, A. Heldring, and J. M. Rius, "Multilevel adaptive cross approximation (MLACA)," *IEEE Trans. Antennas Propag*., vol. 59, no. 12, pp. 4600-4608, Feb. 2004.

[14] Z. N. Jiang, R. S. Chen, Z. H. Fan, Y. Y. An, M. M. Zhu, and K. W. Leung, "Modified adaptive cross approximation algorithm for analysis of electromagnetic problems," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 26, no. 2, pp. 160-169, 2011.

[15] K. Tap, *Complex Source Point Beam Expansions for Some Electromagnetic Radiation and Scattering Problems*, Ph.D. dissertation, Ohio State Univ., Columbus, OH, USA, 2007.

[16] K. Tap, P. H. Pathak, and R. J. Burkholder, "Complex source beam-moment method procedure for accelerating numerical integral equation solutions of radiation and scattering problems," *IEEE Trans. Antennas Propagat.*, vol. 62, pp.

2052-2062, 2014.

[17] D. Z. Ding, Z. H. Fan, S. F. Tao, and R. S. Chen, "Complex source beam method for EM scattering from PEC objects," *Antennas and Wireless Propagation Letters*, vol. 14, pp. 346-349, 2015.

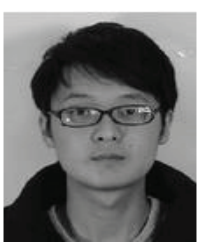
[18] Z. H. Fan, X. Hu, and R. S. Chen, "Multilevel complex source beam method for electromagnetic scattering problems," *Antennas and Wireless Propagation Letters*, vol. 14, pp. 843-846, 2015.

[19] D. H Schaubert, D. R. Wilton, and A. W. Glisson, "A tetrahedral modeling method for electromagnetic scattering by arbitrarily shaped inhomogeneous dielectric bodies," *IEEE Trans. Antennas Propag.*, vol. 32, pp. 77-85, 1984.

[20] S. M. Rao, D. R. Wilton, and A. W. Glisson, "Electromagnetic scattering by surfaces of arbitrary shape," *IEEE Trans. Antennas Propag.*, vol. 30, no. 3, pp. 409-418, 1982.

Zhenhong Fan was born in Jiangsu, China, in 1978. He received the M.Sc. and Ph.D. degrees in Electromagnetic Field and Microwave Technique from Nanjing University of Science and Technology (NJUST), Nanjing, China, in 2003 and 2007, respectively.

During 2006, he was with the Center of Wireless Communication in the City University of Hong Kong, Kowloon, as a Research Assistant. He is currently an Associate Professor with the Electronic Engineering of NJUST. He is the author or co-author of over 20 technical papers. His current research interests include computational electromagnetics, electromagnetic scattering and radiation.



Yanlong Hu received the B.Sc. degree in Information and Computing Sciences from Nanjing University of Information Science & Technology, Nanjing, China, in 2011. He is currently working towards the Ph.D. degree in Electromagnetic Fields and Microwave Technology at the School of Electrical Engineering and Optical Technique, Nanjing University of Science and Technology.

His current research interests include computational electromagnetics, antennas, electromagnetic scattering and propagation.

Dazhi Ding was born in Jiangsu, China, in 1979. He received the B.S. and Ph.D. degrees in Electromagnetic Field and Microwave Technique from Nanjing University of Science and Technology (NUST), Nanjing, China, in 2002 and 2007, respectively.

During 2005, he was with the Center of Wireless Communication in the City University of Hong Kong, Kowloon, as a Research Assistant. He is currently an Associate Professor with the Electronic Engineering of NJUST. He is the author or co-author of over 30 technical papers. His current research interests include computational electromagnetics, electromagnetic scattering, and radiation.

Rushan Chen (M'01) was born in Jiangsu, China. He received the B.Sc. and M.Sc. degrees from the Department of Radio Engineering, Southeast University, China, in 1987 and 1990, respectively, and the Ph.D. degree from the Department of Electronic Engineering, City University of Hong Kong, in 2001.

He joined the Department of Electrical Engineering, Nanjing University of Science and Technology (NJUST), China, where he became a Teaching Assistant in 1990 and a Lecturer in 1992. Since September 1996, he has been a Visiting Scholar with the Department of Electronic Engineering, City University of Hong Kong, first as Research Associate, then as a Senior Research Associate in July 1997, a Research Fellow in April 1998, and a Senior Research Fellow in 1999. From June to September 1999, he was also a Visiting Scholar at Montreal University, Canada. In September 1999, he was promoted to Full Professor and Associate Director of the Microwave and Communication Research Center in NJUST, and in 2007, he was appointed Head of the Department of Communication Engineering, NJUST. He was appointed as the Dean in the School of Communication and Information Engineering, Nanjing Post and Communications University in 2009. And in 2011, he was appointed as Vice Dean of the School of Electrical Engineering and Optical Technique, Nanjing University of Science and Technology. His research interests mainly include microwave millimeter-wave systems, measurements, antenna, RF-integrated circuits, and computational electromagnetics. He has authored or co-authored more than 200 papers, including over 140 papers in international journals.

Chen received the Science and Technology Advance Prize several times given by the National Military

Industry Department of China, the National Education Committee of China, and Jiangsu Province. He is the recipient of the Foundation for China Distinguished Young Investigators presented by the National Science Foundation (NSF) of China in 2003. In 2008, he became a Chang-Jiang Professor under the Cheung Kong Scholar Program awarded by the Ministry of Education, China. Besides, he was selected as a Member of Electronic Science and Technology Group by Academic Degree Commission of the State Council in 2009. Chen is a Fellow of the Chinese Institute of Electronics (CIE), Vice-Presidents of Microwave Society of CIE and IEEE MTT/APS/EMC Nanjing Chapter. He serves as the Reviewer for many technical journals such as IEEE Trans. on AP and MTT, Chinese Physics etc., and now serves as an Associate Editor for the International Journal of Electronics.