EM Scattering Computation of Electric-large Lossy Dielectric Target Based on Ray Tracing

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Abstract— The high frequency (HF) PO/GO computation based on ray tracing approach is presented to fast compute the EM scattering from arbitrary dielectric target with electric-large size. For lossy medium, the generalized Snell-Descartes and Fresnel laws are introduced to determine the propagation direction of equi-phase and equi-amplitude plane of reflection and refraction wave, which is the main difference from the classical ray tracing approach. The GO reflection and refraction rays are traced according to the propagation direction of equi-phase surface step by step. Accompany with the wave propagation, the phase delay is computed along the normal direction of equi-phase, and the energy attenuation is computed along the normal direction of equi-amplitude. On the exiting surface, the PO integration of surface field is considered for outgoing field computation. For lossy dielectric surface, the PO surface field is inhomogeneous, and this paper derives an analytical integral formula for arbitrary triangular patch to avoid the numerical integral on the dense meshing of 1/8 wavelength. In numerical simulation, the target is constructed with triangular dielectric patches according to its geometry CAD model, not need to mesh according to the electric wavelength. Several models, such as multi-layer dielectric plate, dielectric coating plate, lossy dielectric cubic, et al., are used for validation and comparison with FEKO software, taking the requirements of memory and CPU time into consideration. The numerical simulation indicates that the new HF method is valid and efficient for electric-large target with arbitrary dielectric medium.

1. INTRODUCTION

MoM and FDTD [2] are both numerical methods which are widely used for RCS calculation of radar objectives. However, they're not suitable for electric-large complex objects for the large requirement in both computer storages and computing time. Much more effective approaches are high-frequency methods, especially for PO [3] and GO [4]. Xu and Jin [5] put forward a novel method called bi-directional analytic ray tracing (BART). In BART, objects are composed of many triangle facets based on its CAD model and they are traced by rays which are expressed as triangular beams through triangle operations. The consumption of storages and time only depends on the ray tracing orders and shapes of objects without the influences of frequencies. However, the BART has not been applied to lossy dielectric materials [6]. When the BART is applied to lossy materials, the properties of lossy materials should be considered. When electromagnetic wave impinges on lossy interfaces, complex refracted angles are yielded by the complex Snell Descartes [7, 8] law, which means the equal-phase surface and the equal-amplitude surface won't coincide.

In this paper, the BART [5] is extended for electric-large lossy object. The complex Snell-Descartes law is used for determining the transmitting direction of both equal-phase plane and equal-amplitude plane and a novel computing method is deduced. Some examples such as lossy object or multiple layered plates are also computed and E-BART is compared with numerical method.

2. E-BART FOR DIELECTRIC LOSSY TARGET

BART was originally proposed for RCS calculation of electric-large PEC object. The core conception of this method is to trace two rays from forward direction in transmitter and backward direction in receiver based on Fresnel law step by step. If two rays impinge on a same facet, then a scattering path is formed. The whole scattering contribution is calculated by 1-order PO and multi-order GO. To extend it to lossy dielectric objects, complex Snell-Descartes laws [7, 8] and novel computing method are introduced in E-BART.

2.1. PO/GO

When an EM wave $\mathbf{E}_i(\mathbf{r}) = \hat{\mathbf{e}}_i E_0 e^{i\mathbf{k}_i\cdot\mathbf{r}}$ impinges on the surface of a lossy media, the equal-phase surface and equal-amplitude surface won't coincide. The wave vector can be decomposed of transmitting vector of equal-phase $\hat{\mathbf{o}}$ and the attenuation vector of equal-amplitude $\hat{\mathbf{f}}$. The wave vector $\mathbf{k}$ is expressed as $\mathbf{k} = k_0(N\hat{\mathbf{o}} + iK\hat{\mathbf{f}})$.

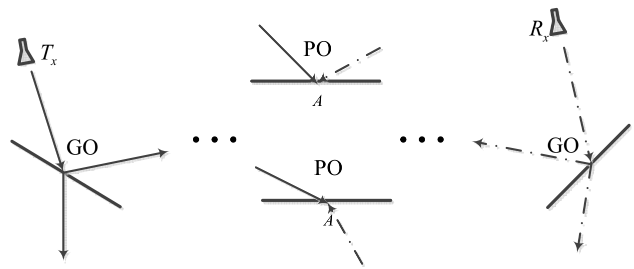

Figure 1: Ray tracing paths of E-BART.

Define $\hat{\mathbf{n}}$ as the normal vector of interface of two different materials. θ demonstrates the included angle between $\hat{\mathbf{n}}$ and $\hat{\mathbf{o}}$, γ demonstrates the included angle between $\hat{\mathbf{n}}$ and $\hat{\mathbf{f}}$.

Define $n = \sqrt{\varepsilon_r} = n' + in''$, complex cosine $\cos\tilde{\alpha}$ and complex sine $\sin\tilde{\alpha}$ can be expressed as follows:

$$\cos\tilde{\alpha} = \frac{N\cos\theta + iK\cos\gamma}{n' + in''} \sin\tilde{\alpha} = \frac{N\sin\theta + iK\sin\gamma}{n' + in''} \tag{1}$$

Then the Fresnel reflection and refraction coefficients are as follows:

$$\begin{aligned} R_h &= \frac{\eta_2\cos\tilde{\alpha}_1 - \eta_1\cos\tilde{\alpha}_2}{\eta_2\cos\tilde{\alpha}_1 + \eta_1\cos\tilde{\alpha}_2}, \quad T_h = \frac{2\eta_2\cos\tilde{\alpha}_1}{\eta_2\cos\tilde{\alpha}_1 + \eta_1\cos\tilde{\alpha}_2} \\ R_v &= \frac{\eta_1\cos\tilde{\alpha}_1 - \eta_2\cos\tilde{\alpha}_2}{\eta_1\cos\tilde{\alpha}_1 + \eta_2\cos\tilde{\alpha}_2}, \quad T_v = \frac{2\eta_2\cos\tilde{\alpha}_1}{\eta_1\cos\tilde{\alpha}_1 + \eta_2\cos\tilde{\alpha}_2} \end{aligned} \tag{2}$$

Then the PO matrix can be expressed according to [5–9]. When $k \to \infty$, GO matrix is deduced as follows, $\hat{\mathbf{q}}$ and $\hat{\mathbf{p}}$ are vectors of vertical and horizontal polarizations.

$$\begin{aligned} \tilde{\mathbf{R}} &= \begin{bmatrix} \left(\hat{\mathbf{q}}_i \times \hat{\mathbf{k}}_r\right)\cdot\hat{\mathbf{e}}_{sv} & \hat{\mathbf{q}}_i\cdot\hat{\mathbf{e}}_{sv} \\ \left(\hat{\mathbf{q}}_i \times \hat{\mathbf{k}}_r\right)\cdot\hat{\mathbf{e}}_{sh} & \hat{\mathbf{q}}_i\cdot\hat{\mathbf{e}}_{sh} \end{bmatrix} \begin{bmatrix} R_v & 0 \\ 0 & R_h \end{bmatrix} \begin{bmatrix} \hat{\mathbf{e}}_{iv}\cdot\hat{\mathbf{p}}_i & \hat{\mathbf{e}}_{ih}\cdot\hat{\mathbf{p}}_i \\ \hat{\mathbf{e}}_{iv}\cdot\hat{\mathbf{q}}_i & \hat{\mathbf{e}}_{ih}\cdot\hat{\mathbf{q}}_i \end{bmatrix} \\ \tilde{\mathbf{T}} &= \begin{bmatrix} \left(\hat{\mathbf{q}}_i \times \hat{\mathbf{k}}_t\right)\cdot\hat{\mathbf{e}}_{sv} & \hat{\mathbf{q}}_i\cdot\hat{\mathbf{e}}_{sv} \\ \left(\hat{\mathbf{q}}_i \times \hat{\mathbf{k}}_t\right)\cdot\hat{\mathbf{e}}_{sh} & \hat{\mathbf{q}}_i\cdot\hat{\mathbf{e}}_{sh} \end{bmatrix} \begin{bmatrix} T_v & 0 \\ 0 & T_h \end{bmatrix} \begin{bmatrix} \hat{\mathbf{e}}_{iv}\cdot\hat{\mathbf{p}}_i & \hat{\mathbf{e}}_{ih}\cdot\hat{\mathbf{p}}_i \\ \hat{\mathbf{e}}_{iv}\cdot\hat{\mathbf{q}}_i & \hat{\mathbf{e}}_{ih}\cdot\hat{\mathbf{q}}_i \end{bmatrix} \end{aligned} \tag{3}$$

2.2. Field Computation of a Single Tracing Path

According to BART, the total RCS contribution of a certain path can be expressed as

$$\mathbf{E}_s = \frac{e^{ik_0 r}}{r}\left\{\prod_{b=m}^{1}\overline{\mathbf{G}}_b e^{i\mathbf{k}_b\cdot\mathbf{r}_b}\cdot\overline{\mathbf{P}}\cdot\prod_{f=1}^{n}\overline{\mathbf{G}}_f e^{i\mathbf{k}_f\cdot\mathbf{r}_f}\right\}\cdot\mathbf{E}_i \tag{4}$$

$\overline{\mathbf{G}}$ is the GO matrix of a certain dielectric interface. $\overline{\mathbf{P}}$ is the PO matrix of the facet A. This computation formula is applied to PEC objects, but it is not suitable for lossy dielectric objects.

As the scattering field is contributed by the induced electric and magnetic surface currents exposed to the outer free space, the integrated PO facet should not be inside the tracing object and the PO position should be replaced by the last hitting facet, which is exposed to the free space. The contribution of original PO facet is expressed as a transformed GO matrix and the contribution of last hitting facet is expressed as a transformed PO matrix.

The transformed GO matrix relies on the PO integration I_0. When the geometrical reflection or geometrical refraction occurs, I_0 reaches the maximum value A_0, which is the intersected area of facet A. Then the transformed GO matrix $\overline{\mathbf{G'}}_P$ can be approximately derived as $\overline{\mathbf{G'}}_P = (I_0/A_0)\overline{\mathbf{G}}_0$. The matrix $\mathbf{G}_0$ shares the same formula of Eq. (3). The transformed PO matrix $\overline{\mathbf{P'}}_G$ is demonstrated according to [5–9]. Substituting $\mathbf{k} = k_0(N\hat{\mathbf{o}} + iK\hat{\mathbf{f}})$, $\mathbf{r} = \hat{\mathbf{o}}l$, $\overline{\mathbf{G'}}_P$ and $\overline{\mathbf{P'}}_G$ into Eq. (4), we can get

$$\mathbf{E}_s = \frac{e^{ik_0 r}}{r}\frac{I_0}{A_0}\left\{\overline{\mathbf{P'}}_G\cdot\prod_{b=m}^{2}\overline{\mathbf{G}}_b e^{ik_0 N_b l_b} e^{-k_0 K_b\left(\hat{\mathbf{f}}_b\cdot\hat{\mathbf{o}}_b\right)l_b}\cdot\overline{\mathbf{G}}_0\cdot\prod_{f=1}^{n}\overline{\mathbf{G}}_f e^{ik_0 N_f l_f} e^{-k_0 K_f\left(\hat{\mathbf{f}}_f\cdot\hat{\mathbf{o}}_f\right)l_f}\right\}\mathbf{E}_i \tag{5}$$

3. NUMERICAL SIMULATION

In this section, some numerical examples are presented for E-BART validation. Firstly a two-layer plate's presented here. The dielectric constant of upper layer and lower layer is $\varepsilon_{r1} = 3 + i3$ and $\varepsilon_{r2} = 4 + i4$, respectively. The sizes of the two layers are both $1\,\mathrm{m} \times 1\,\mathrm{m} \times 0.01\,\mathrm{m}$. Assuming electromagnetic wave ($\theta_i = 30°$, $\varphi_i = 0$, $f = 1.26\,\mathrm{GHz}$) impinges on the plates. From Figure 2, we can see that E-BART matches with FEKO well, except at some low grazing angles. In FEKO, about 2.45 GBytes and 15 mins are needed, while only about 50 Mbytes and 25 s are needed in E-BART.

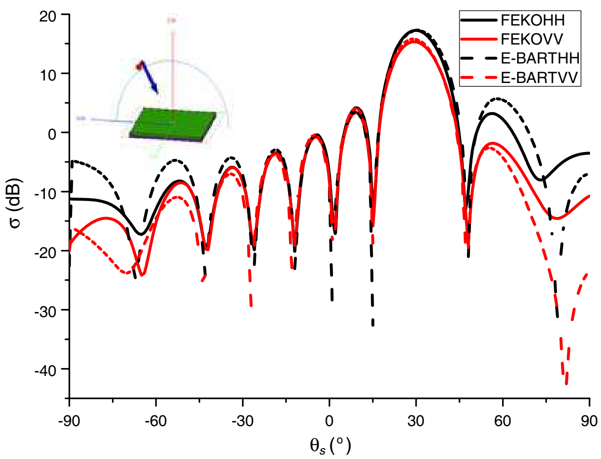

Figure 2: Comparisons of E-BART and FEKO.

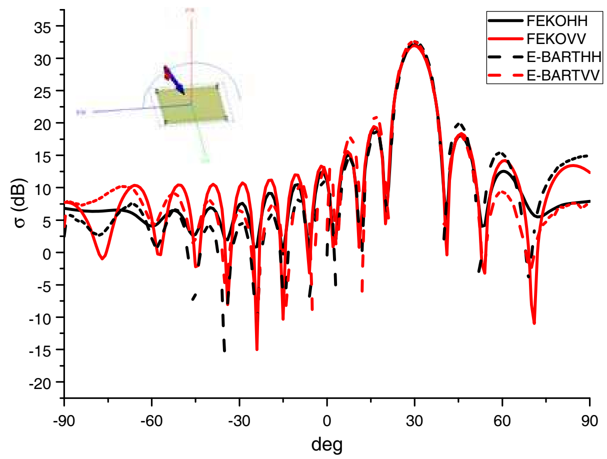

Figure 3: RCS of a coated PEC plate.

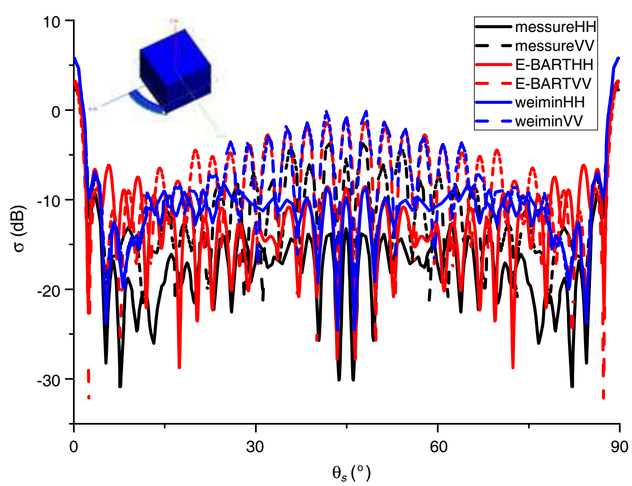

Figure 4: Comparison of different methods for PVC-cube RCS.

Now consider a coated plate consisted of an interior PEC plate ($2\,\mathrm{m} \times 2\,\mathrm{m} \times 0.1\,\mathrm{m}$) and an exterior lossy dielectric plate ($2.1\,\mathrm{m} \times 2.1\,\mathrm{m} \times 0.12\,\mathrm{m}$, $\varepsilon_r = 2 - 0.02i$). The electromagnetic wave ($f = 1\,\mathrm{GHz}$) propagates from $\theta_i = 30°$, $\varphi_i = 0$ and the RCS in $\theta_s = -90° \sim 90°$, $\varphi_s = 180°$ is computed. It can be seen that E-BART also matches well with coated PEC objects, except at some low grazing angles. In FEKO, about 4.5 GBytes is needed and about 1 h will be cost. While in E-BART, only 40 Mbytes and 1min are consumed.

Another example of lossy PVC-cube is tested here to validate E-BART. The side length of the cube is $sl = 12\,\mathrm{cm}$ and dielectric constant is $\varepsilon_r = 2.7 + i0.01$. The following figure compares E-BART with the method of Weinmann. It's proved that within $\theta_s \in (20° \sim 45°)$, E-BART yield a better result. But the result still deviates from the measured results especially for HH polarization because of the non-edge diffraction in the extended E-BART.

4. CONCLUSION

The E-BART method utilizes the complex Snell-Descartes laws to determine the propagation paths and the novel analytical computing method to get the RCS of complex lossy objects. According to the comparisons of numerical methods, E-BART is effectively for the RCS of complex lossy objects.

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