Simulation of Radar Scattering from Electrically Large Objects under Tree Canopies

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Abstract

In this paper, a model is developed to investigate the scattering behavior of hard targets embedded inside a forest canopy, at high frequencies. Wave penetration through and scattering from a forest canopy is calculated, using a coherent scattering model which makes use of realistic tree structures [3]. Physical optics (PO) approximation is used to estimate the equivalent current on an electrically large, perfectly electric conducting (PEC) object, located above a ground plane and under a tree canopy. In this model, reciprocity theorem is used effectively in order to derive the backscattering from the target above the ground plane and also to calculate the interaction of the target scattered field with the foliage.

1 Introduction

Detection and identification of hard targets inside vegetation canopies have long been challenging problems. To develop an effective method to detect foliage camouflaged targets using radars, the phenomenology of electromagnetic wave interaction with foliage and the target, embedded in forest canopies must be thoroughly understood. Electromagnetic (EM) scattering from vegetation canopies can be simplified to finding scattering from individual dielectric cylinders and thin dielectric disks, arranged in a semi-deterministic fashion, and their interaction with half space dielectric representing the ground. Dielectric cylinders are used to model needles, branches and trunks, and thin dielectric disks are used to model the broad leaves. The formulations for calculating scattering and attenuation caused by vegetation particles are derived analytically, using high- and low-frequency techniques [1]. To estimate the scattering properties from a target inside a canopy, fields' behavior should be predicted in a very accurate fashion which should include the interaction of scattered fields from vegetation with the target and vice versa. This is in addition to the direct scattering from the target for a mean field illumination that gets through the vegetation layer. Most existing models treat foliage by an absorbing layer above the target. But for more precise prediction of the fields' behavior, EM wave propagation through a forest canopy must be treated by realistic models for trees, such as fractal-based models (Lindenmayer systems), and field computation must be carried out coherently, using single scattering or multiple scattering models. Such a model is implemented in [2], where the scattering from each tree component, when illuminated by the mean field, is calculated and the total scattering is expressed as the coherent summation of all the scattering contributions. The mean field, formulated by the aid of Foldy's approximation, accounts for the phase change as well as extinction due to the scattering and absorption of the tree particles. However, in this model the observation point is in the far-field, outside the forest. Recently, a more advance model was proposed [3], in which the observation point can be placed inside the forest, possibly in the near field of some scatterers. Scattering formulations for individual scatterers were modified to be uniformly valid from near-field to far-field regions. In general, a hard target has a very complex geometry and material property. Scattering from these electrically large objects may be treated by PO approximation in order to achieve some level of accuracy and maintain computational efficiency. At very low frequencies, scattering from the forest itself may be rather small, and scattering behavior from the hard target is not much different from that of the target without the forest. At high frequencies, however, the forest attenuates and distorts the incident wave phase front significantly. Therefore, in order to calculate the scattered field from the target embedded in

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a highly scattering environment, an accurate hybrid method is required. As mentioned before, using the reciprocity theorem, the back scattered field, from the induced currents on the target can be computed from the forward field calculation. Basically, the field components at a point on the target for elementary current elements at the transmitter point are first computed to find the induced current on the target. Then, using reciprocity, the scattered field in the back scatter direction is calculated. This way interaction of vegetation and target as well as target and vegetation is taken into account. As such, multiple scattering between target and vegetation is ignored.

2 Formulation

PO approximation is widely used to predict scattering from large scatterers [4]. To treat an irregularly shaped object with PO approximation, the object is first decomposed into many flat elementary patches, which have a simple geometry such as rectangular or triangular. Then, using tangent plane approximation, the current on the lit region of the scatterer is approximated as [5],

$$\vec{J} \approx 2\ \hat{n}\times\vec{H} = -2i\frac{Y_o}{k_o}\hat{n}\times(\nabla\times\vec{E}) \tag{1}$$

where $\vec{E}$ and $\vec{H}$ are the incident electric and magnetic fields on the object, respectively, and $\hat{n}$ is a normal unit vector, as shown in Fig. 1. According to Fig. 1., when an object is above the ground plane, the PO current should be estimated with two incident waves, directed and reflected waves from the ground plane. It is very difficult to consider the ground plane effect in an exact fashion. For simplicity, in this paper the four-ray geometric optics (GO) model is used, which is accurate if scatterers are located sufficiently high above the ground plane. The incident field on the target is composed of the superposition of scattered fields from all tree constituents such as branches, trunks, and leaves and each can be decomposed into a direct and a reflected field from the ground plane. The scattered field from the target for each incident field can be easily calculated using reciprocity. Since the system is linear, we can express the reciprocity theorem for two sets of sources and fields, denoted by 1 and 2, as [5],

$$\langle 1\ ,\ 2\rangle = \langle 2\ ,\ 1\rangle \tag{2}$$

where, we define,

$$\begin{aligned}
\vec{E}_1 &= (\vec{E}_d+\vec{E}_r)_{direct} + \sum_{scatterers}(\vec{E}_d+\vec{E}_r)\\
\vec{J}_1 &= \frac{4\pi}{ik_o\eta}\frac{r_R}{e^{ik_o r_R}}\delta(\vec{r}-\vec{r}_R)\hat{p}\\
\vec{E}_2 &= \vec{E}^s\\
\vec{J}_2 &= (\vec{J}_d+\vec{J}_r)_{direct} + \sum_{scatterers}(\vec{J}_d+\vec{J}_r)
\end{aligned} \tag{3}$$

The point source $\vec{J}_1$ which is placed at the radar location $\vec{r}_R$, generates the horizontal or vertical polarization of $\hat{p}\,(\hat{h}/\hat{v})$, and $\vec{E}_1$ is a total summation of direct and reflected fields, including both the scatterings from all the tree components and the direct incident field (mean-field) indicated by the subscript *direct*. The electric currents of $\vec{J}_d$ and $\vec{J}_r$ are generated by direct and reflected fields respectively. According to Fig. 1., for each wave, GO approximation is considered for determining the lit and shadow areas. The equivalent current $\vec{J}_2$ is a surface current, estimated by (1). Therefore, the back-scattered field can be expressed as a 2D integral.

$$\vec{E}^s_{pq} \approx \pm \frac{ik_o\eta}{4\pi}\frac{e^{ik_o r_R}}{r_R}\iint_{surface}\vec{E}_{1q}\cdot\vec{J}_{2p}ds \qquad (4)$$

where p and q are h or v. The minus sign is chosen when p is vertical polarization. Numerically, the surface integral of (4) is calculated by a summation of all the contributions of the elementary patches. Finally, the RCS can be calculated from,

$$\sigma^s_{pq} = 4\pi\ r_R^2\left|\vec{E}^s_{pq}\right|^2 \qquad (5)$$

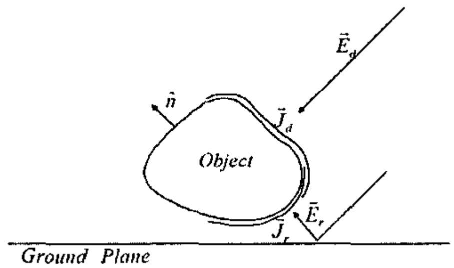

Figure 1. Electric currents induced on the object due to the direct and reflected electric fields.

3 Simulation

To verify the procedure which uses the reciprocity theorem for calculation of back scattering, a simple example is considered where a $3\lambda \times 3\lambda$, PEC plate is horizontally placed 1m above a lossy ground plane. For this simulation relative permittivity of the ground plane is set to $\varepsilon_r = 5.6 + i\ 0.8$ and the frequency is chosen to be $f = 2GHz$. For calculating the integral in (4), the plate is meshed into 144 segments of $\lambda/4 \times \lambda/4$ square elementary patches. In this approximation, for each elementary patch, the electric field and the electric current are considered constant and equal to their values at the center point of that elementary patch. Fig. 2. shows the comparison between the exact PO calculation and approximation of (4), as a function of the incident angle. As can be seen, the procedure generates very accurate results with respect to exact PO calculation. For complete simulation, 10 pine trees were randomly located around the plate, with density of $.05\ trees/m^2$. Fig. 3. shows the plot of RCS of the plate inside the forest, as a function of azimuthal and elevation incident angles with spacing of 0.5° for each angle. As expected, more fluctuation is observed along the elevation angle than the azimuthal angle. Fig. 4. shows the current distribution on the plate for one realization of $\theta_i = 37.5^\circ$ and $\phi_i = 177^\circ$. As can be seen, the electric current is almost aligned in $\hat{y}$ and $\hat{x}$ directions for h- and v- polarization, respectively.

4 References

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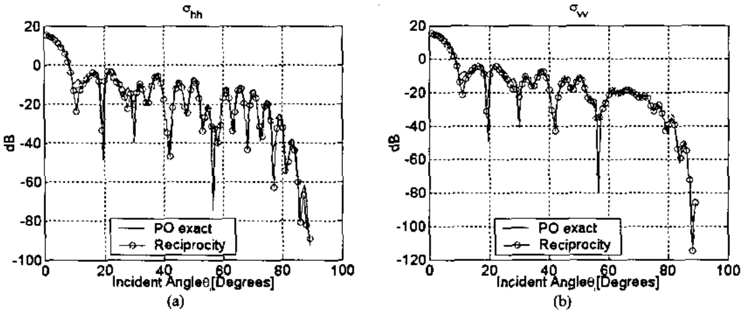

Figure 2. RCS of a flat $3\lambda \times 3\lambda$ square, PEC plate, horizontally placed 1 m above a lossy half space, as a function of the incident angle θ, for $\phi = 0^{\circ}$. Comparison between the exact PO calculation and approximation of (4), for (a) σ_{hh} and (b) σ_{vv}.

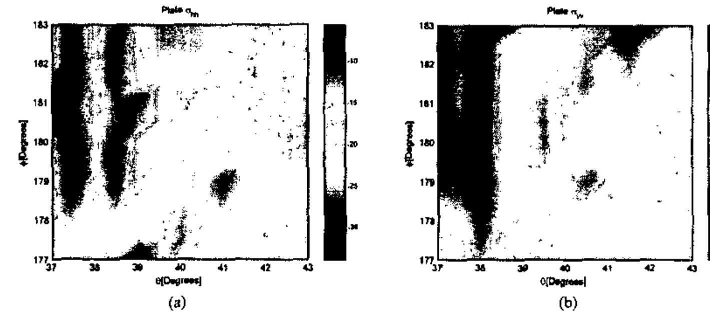

Figure 3. Estimated RCS of a $3\lambda \times 3\lambda$ flat PEC plate, over a lossy half space and below a forest canopy of pine trees as a function of elevation and azimuthal angles of θ and ϕ, (a) σ_{hh} and (b) σ_{vv}.

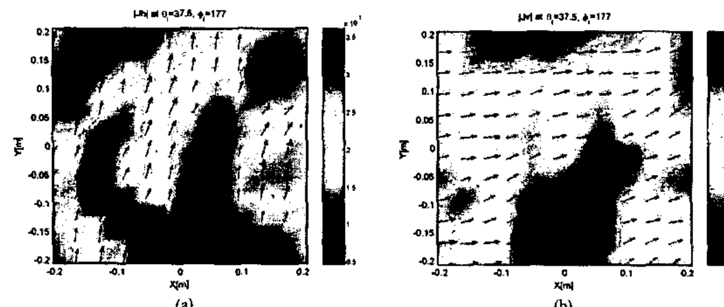

Figure 4. Current distribution on the plate for $\theta_i = 37.5^{\circ}$ and $\phi_i = 177^{\circ}$, (a) $|\vec{J}_h|$ and (b) $|\vec{J}_v|$.