Electromagnetic Scattering from Foliage Camouflaged Hard Targets, in VHF-band

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Abstract

A hybrid target-foliage model is developed to investigate the scattering behavior of hard targets embedded inside a forest canopy, in VHF frequency band (20-200 MHz). The proposed model is based on single scattering theory for propagation through and scattering from the forest [1] and an FDTD technique to compute the scattered field from the target [2]. The connection between these two models is accomplished through the application of reciprocity theorem.

I. Introduction

An effective model is developed to characterize the electromagnetic wave interaction between foliage and the target, embedded in the forest canopies. In this model, tree constituents are modeled by dielectric cylinders and disks, whose scattering are analytically derived using high- and low-frequency techniques. A very complex tree structure is generated, using a fractal-based model (known as Lindenmayer systems). Monte Carlo simulation is used to randomly generate the forest trees. The mean field is computed using Foldy's approximation, which accounts for the phase change as well as extinction due to the scattering and absorption of the tree particles. This mean field and its reflected from the ground are the excitation fields for every scatterer. Therefore for each observation point there are 4 scattering contributions. Using an advance forest model [1], in which the observation point can be placed inside the forest possibly in the near field of some scatterers, the model can predict the field behavior accurately. The contribution from all scatterers are coherently added and used as an excitation field for a metallic target. Depending on electric size of the target, appropriate numerical approaches can be chosen to compute the scattering from the target. Since in VHF-band, for a typical hard target (see Fig. 2(a)), the electric size is comparable to the wavelength the FDTD technique is used in order to exactly characterize the scattering from the target. In past, FDTD technique has been widely used for simulation of scattering from buried objects in stratified ground or continuous random media [3], [5]. The reciprocity theorem has also been used in order to transform the near field to far field scattering in FDTD approach earlier [3],[4]. To get the benefit from FDTD accurate analysis, single scattering accurate computation of propagation through and scattering from forest and achieve a fast computational approach we propose hybridization of FDTD with single scattering theory, through using reciprocity theorem. In this paper, first we derive a useful formulation for backscattering from the target above the ground

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plane and also inside the foliage, for general polarization configuration of transmit and receive waves, in terms of the incident fields on the object and near scattered fields from the object, using reciprocity and Huygens' principle. Then using this formulation, and single scattering theory the backscattered field from a camouflaged complex target is calculated .

II. THEORY

Based on reciprocity theorem for two sets of sources and fields denoted by subscripts 1 and 2, we have

$$\int_{V_2} (\overline{E}_1 \cdot \overline{J}_2 - \overline{H}_1 \cdot \overline{M}_2) d\mathbf{r} = \int_{V_1} (\overline{E}_2 \cdot \overline{J}_1 - \overline{H}_2 \cdot \overline{M}_1) d\mathbf{r} \tag{1}$$

Assuming $\overline{M}_1 = 0$ and $\overline{J}_1$ is an elementary current at the radar position, given by

$$\overline{J}_1 = \frac{4\pi}{ik_o Z_o} \frac{r_R}{e^{ik_o r_R}} \, \delta(\overline{r} - \overline{r}_R) \, (-\hat{p}) \tag{2}$$

where k_o and Z_o are the propagation constant and characteristic impedance of free space, respectively. The unit vector $\hat{p}$ can be along principal polarization vectors $\hat{h}_i$ or $\hat{v}_i$. Let us denote $\overline{J}_2$ and $\overline{M}_2$ as the electric and magnetic scattering sources on a fictitious surface enclosing the target. The far-field backscattering from a target, $\overline{E}_2$, can be derived by substituting (2) in (1). Therefore we have

$$\overline{E}_2 \cdot (-\hat{p}) = \frac{ik_o Z_o}{4\pi} \frac{e^{ik_o r_R}}{r_R} \int_{V_2} (\overline{E}_1 \cdot \overline{J}_2 - \overline{H}_1 \cdot \overline{M}_2) \, d\mathbf{r} \tag{3}$$

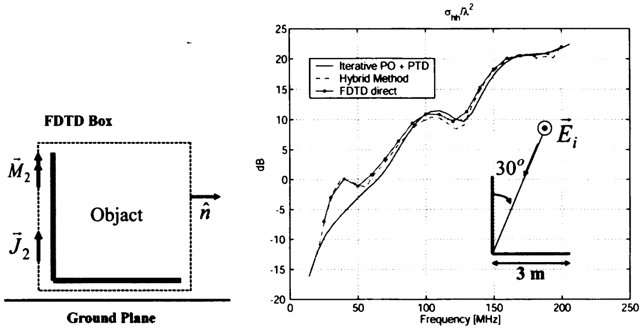
To find the scattering sources $\overline{J}_2$ and $\overline{M}_2$, an FDTD technique is used. First a fictitious box, FDTD box, is considered around the target (see figure 1(a)). Using Huygens' Principle, $\overline{J}_2$ and $\overline{M}_2$ can be computed over the surface in terms of tangential components of near scattered fields $\overline{E}_2$ and $\overline{H}_2$ given by $\overline{J}_2 = \hat{n} \times \overline{H}_2$ and $\overline{M}_2 = -\hat{n} \times \overline{E}_2$. Using these quantities in (3), renders the following expression for the far-field backscattering

$$\mathbf{S}_{pq} = \pm \frac{ik_o Z_o}{4\pi} \int_{\mathbf{S}} [\overline{H}_{2q} \times \overline{E}_{1p} + \overline{E}_{2q} \times \overline{H}_{1p}] \cdot \hat{n} \, ds \tag{4}$$

where p and q can be h or v polarizations. The first and second subscripts of scattering element denote the receive and transmit polarizations, respectively. The minus sign in (4) is chosen when receive polarization is vertical. For our problem, the incident fields on the target $\overline{E}_1$ and $\overline{H}_1$ are composed of scattered fields from all tree constituents such as branches, trunks, and leaves, and the direct field attenuated by the foliage, mean field. Each of these field components are decomposed into a direct and a reflected field from the ground plane. Therefore, we have

$$\begin{aligned} \overline{E}_1 &= (\overline{E}_d + \overline{E}_r)_{mean} + \sum_{Scatterers} (\overline{E}_d + \overline{E}_r) \\ \overline{H}_1 &= (\overline{H}_d + \overline{H}_r)_{mean} + \sum_{Scatterers} (\overline{H}_d + \overline{H}_r) \end{aligned} \tag{5}$$

Since scattering from and propagation through foliage is a linear system in time, the expressions of $\overline{E}_1$ and $\overline{H}_1$ in (5), computed in frequency domain are simply the Fourier transform of the electric and magnetic fields in time domain. Therefore, by taking an inverse Fourier transform, the time domain expressions of fields are



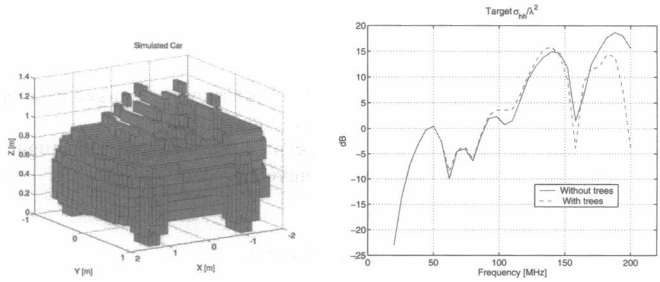
(a) (b)

Fig. 1. (a) Geometry of the problem. Surface S, containing an object above the ground plane. (b) Comparison of backscattering RCS from a dihedral corner reflector in free space, calculated by direct FDTD, the reciprocity approach (4), and physical optics approximation for an H-polarized incident plane wave propagating along $\theta_i = 30^o$ and $\phi_i = 180^o$.

computed and used as an excitation sources for the FDTD technique. Likewise, the resulting scattered fields from FDTD are transformed to frequency domain, using Fourier transform. The resulting near-field scattering $\overline{E}_2$ and $\overline{H}_2$, and the incident fields $\overline{E}_1$ and $\overline{H}_1$ are finally used in (4) to compute the backscattered field. For calculation of reflected field from ground plane we should note that due to the presence of object there will be ground shadowing by the object itself. For our problem, where the object is sitting on or very close to the ground plane, an absorber layer is considered just below the FDTD box. This way the ground reflection from the area directly underneath the target can be eliminated. The process is validated, first by considering a $3m \times 3m \times 3m$, metallic dihedral corner reflector, in free space. The time span is about 200 *nsec*, and simulation is performed over frequency range of $14 - 206$ MHz. The cell size in FDTD code is set to 12 *cm*. Figure 1(b) shows the backscatter RCS of the dihedral, using direct FDTD, the reciprocity approach given by (4), and physical optics approximation as a function of frequency, for an H-polarized incident plane wave, propagating along $\theta_i = 30^o$ and $\phi_i = 180^o$. A very good agreement is shown.

III. Simulation Results

A complete simulation is considered. A metallic car (see Fig.2 (a)) is placed above a lossy ground plane, with relative permittivity of $\epsilon_r = 5.62 + i\ 0.94$. Eight pine trees, generated by statistical L-system, having average height of 15 *m*, crown radius of 3 *m*, crown height of 10 *m*, trunk radius of 10 *cm*, and more than 5000 branches per tree, are closely arranged around the target. The FDTD box, with size of $5m \times 5m \times 5m$, and cell size of 10 *cm* is considered. This box renders 62,424 surface points inside the forest, whose fields must be determined. To make the code faster and at the same time observe accurate results, only scattering effect of tree particles which have radius of more than 0.01λ has been captured. The time span is about 180 *nsec*, and simulation is performed over frequency range of



(a) (b)

Fig. 2. Comparison of backscattering RCS from a metallic car, above a dielectric ground plane with $\epsilon_r = 5.62 + i\,0.94$, inside and outside of the forest for horizontal polarizations of incident plane wave propagating along $\theta_i = 30^o$ and $\phi_i = 180^o$. (a) Simulated car in FDTD code (b) σ_{hh}/λ^2.

$14 - 206\ MHz$. Figure 2 (b) compares the backscatter RCS from target, inside and outside of the forest. As shown, at lower frequencies the effect of forest on modifying the backscattered response of the target is negligible. However at higher frequencies, the forest reduces and distorts the RCS pattern. The computation time is estimated about 3 days, using two AMD Athlon processors, with 2 GHz CPU and 1 GB RAM.

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