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Scattering Model for Hard Target Embedded inside Forest Using Physics-based Channel Model Based on Fractal Trees

프랙탈 나무 모델을 이용한 숲 속에 숨어 있는 타겟의 산란모델

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Abstract

In this paper, a hybrid model is developed, which can estimate scattering properties of a target embedded inside a forest. The model uses a physic-based channel model for a forest to accurately calculate the penetrated field through a forest canopy. The channel model is based on a fractal tree geometry and single scattering theory. To calculate scattering from the target, physical optics(PO) is used to compute an induced current on the target surface since the dimension of the target is generally very large and the shape is very complicated. Then using reciprocity theorem, scattering generated by the PO current is calculated without an extra computational complexity.

요 약

이 논문에서는 숲 속에 숨어있는 타겟의 산란 특성을 계산할 수 있는 효율적인 모델을 계발한다. 이 산란 모델은 숲의 산란 특성을 계산하기 위해 프랙탈 기하학과 single scattering 이론을 사용하는 channel model과 타겟 자체의 산란 특성을 계산하기 위해 physical optic(PO) 근사법을 사용하는 hybrid 모델이다. 그리고 전체 모델의 계산량을 줄이기 위해 가역정리를 사용하여 간단하게 타겟과 숲 사이의 상호 작용을 계산한다.

Key words : Wave Penetration Into Canopy, Scattering, Target Inside a Forest

Ⅰ. Introduction

Detection and identification of targets in a strong clutter background, for example a target over a rough terrain, or embedded in a random medium such as a forest canopy, have long been a subject of intensive investigation. Whereas significant progress have been made towards the development of detection and identification algorithms for targets over a clutter background, through the application of multi-sensor systems such as optical, thermal radar systems, detection of foliage-covered targets with the required probability of detection and false alarm rate still remains at large an unsolved problem.

To develop an effective model to detect foliage camouflaged targets, the phenomenology of electromagnetic wave interaction with foliage and the target inside a forest must be thoroughly understood. Many models for monitoring vegetation or wave penetration into canopies which are based on electromagnetic theory or experiments have been proposed, but many of them focus on estimating backscattering from vegetation, or mean-field inside a canopy using simple techniques such as Foldy's approximation[1]. However, to estimate scattering properties from a target inside a canopy, accurate field behavior should be required at observa-

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tion points inside a forest, which should include the complete effects of the vegetation. Recently a model[2] was proposed based on single scattering theory and a fractal model for trees(Lindenmayer system), which can accurately predict scattered field from many tree constituents such as tree trunks, branches etc. In this model, scattered field from individual tree constituents modeled by circular cylinder and dielectric disks is calculated by uniform formulations which are valid in the near-field to far-field regions of the scatterers.

In general, a target itself has a very complex geometry, electrically large dimension, and material properties. Hence it is very hard and inefficient to exactly compute scattering from the complicated target by using any numerical method such as method of moment(MoM). Scattering from these electrically large objects, however may be very accurately estimated by high frequency techniques such as PO approximation to maintain computational efficiency. To further reduce the overall complexity of the scattering model, reciprocity theorem can be used to estimate the effect of the canopies on the scattered field from the embedded target at an observation point outside the forest. Simply explaining the proposed procedure for the scattering model, first using the channel model the incident fields at many points on the target surface are computed which include the effect of vegetation. Then from the calculated fields the induced current on the target body can be calculated by using PO approximation. Based on the PO current reciprocity theorem is used to estimate the scattered field from the target at the original source point or radar point. Using the reciprocity theorem the interaction between vegetation and target is naturally taken into account up to first order. Hence, in the developed model, multiple scattering between target and vegetation can not be considered.

Ⅱ. Forest Model

From electromagnetic scattering point of view, a tree can be considered as a complex object composed of a group of various scatterers structured in a semi- deterministic fashion with electrical characteristics very much dependent on their moisture content. At UHF frequencies and higher, dimensions of tree trunk, the primary and secondary branches, or even leaves and twigs can be much larger than or comparable to the wavelength. Noting that a relatively large cluster of trees around an observation point significantly contribute to the total field at the receiver, field calculations based on brute force numerical techniques are not possible at microwave frequencies or higher. However, if the multiple scattering among branches and leaves is ignored, a single scattering model can be constructed. To a high degree of accuracy this model can predict the first order statistics of the total field within a forest. This is because through the averaging process the dominant portion of the total field(coherent effect) can survive, and the multiple interactions are minimized. In modeling the forest, one approach is to distribute the vegetation particles(leaves and branches) uniformly[3], however, it is found that for frequencies up to about 3 GHz it is important to preserve the structural information of tree canopies for accurate prediction of radar backscatter[4]. This effect can be expected to be even more important when the observation point is within the forest. Basically, not only the coherence of the scattered fields from the vegetation structure must be preserved, but also the near-field effects of lower branches and tree trunks near the observation point must be accounted for

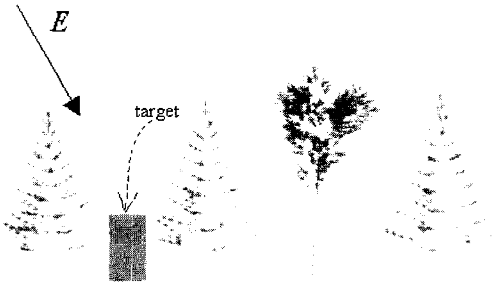


Fig. 1. Problem geometry: radar and target outside and inside a forest, respectively.

very accurately.

Fig. 1 shows the problem geometry where a field is incident from outside a forest on a target embedded inside the forest. As the signal passes through the foliage, it experiences attenuation and scattering which depend on signal parameters such as frequency, polarization, and incidence angle as well as vegetation attributes such as tree type, density, and height. As mentioned earlier, to model the interaction of electromagnetic waves with vegetation accurately, tree structures must be modeled rather accurately. Considering the number of branches and leaves on a tree and the variability in their sizes and orientations, generating a tree structure can be a very difficult task. This can be done efficiently by approximating tree structures by fractal geometries. Here we use a statistical Lindenmayer system[2],[4] in conjunction with botanical properties pertinent to specified tree specie. In this model, the geometry of vegetation particles is also approximated by canonical geometries such as dielectric disks, needles, and layered dielectric cylinders. Each particle in the medium is assumed to be illuminated by the incident wave, attenuated by the foliage along the ray between the particle and the canopy top. The attenuation through the foliage is calculated using Foldy's approximation[1] and single scattering theory is invoked to compute the field scattered from all vegetation particles and their images in the ground plane in the vicinity of the observation point. The total field is then obtained by adding all scattered field components coherently.

Ⅲ. High Frequency Scattering Model for Hard Target

PO approximation is widely used to predict scattering from large scatterers[5],[6]. 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 rectangle or triangle. Then, using tangent plane approximation, the current on the lit region of the scatterer is approximated as [5],

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

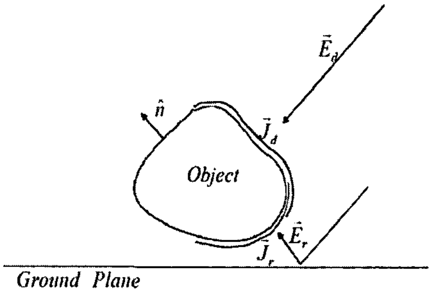


Fig. 2. Electric currents induced on the object due to the direct and reflected electric fields.

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. 2.

According to Fig. 2, when an object is above the ground plane, the PO current should be estimated with two incident waves, direct wave and reflected wave from the ground plane. It is very difficult to consider the ground plane effect in an exact manner due to the complexity of Green's function. For simplicity, in this paper the four-ray geometric optics(GO) model is used, which is simple to apply and accurate if scatterers are located sufficiently high above the ground plane. The incident field on the target is composed of the superposition of mean field through the tree canopy and scattered fields from all tree constituents. Also individual incident field can be decomposed into two components such as a direct wave and a reflected wave 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,

$$\vec{E}_1 = (\vec{E}_d + \vec{E}_r)_{direct} + \sum_{scatterers} (\vec{E}_d + \vec{E}_r)$$

$$\vec{J}_1 = \frac{4\pi}{ik_o\eta} \frac{r_R}{e^{ik_o r_R}} \delta(\vec{r} - \vec{r}_R)\hat{p}$$

$$\vec{E}_2 = \vec{E}^s$$

$$\vec{J}_2 = (\vec{J}_d + \vec{J}_r)_{direct} + \sum_{scatterers} (\vec{J}_d + \vec{J}_r) \tag{3}$$

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 the direct and reflected fields, respectively. According to Fig. 2, for each wave, GO approximation is adopted to determine the lit and shadow areas on the target surface for the individual incident field. The equivalent current $\vec{J}_2$ is a surface current, estimated by (1). Therefore, the backscattered field can be expressed as a 2-D integral.

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

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

$$\sigma^s_{pq} = 4\pi\, r_R^2 \left|\bar{E}^s_{pq}\right|^2 \tag{5}$$

When the aforementioned procedure is applied to a case where a scatterer is above a ground plane, the following equation for scattered field from the scatterer at an original source point can be obtained.

$$\int_v \vec{E}_1 \cdot \vec{J}_2 dv = \int_v \vec{E}_2 \cdot \vec{J}_1 dv \approx -2\int_s \hat{n} \cdot \left(\vec{E}_1 \times \vec{H}_1\right) ds$$

Since the field consists of two components, direct and reflected waves, $\vec{E}_1 \times \vec{H}_1$ in the above equation can be expanded as

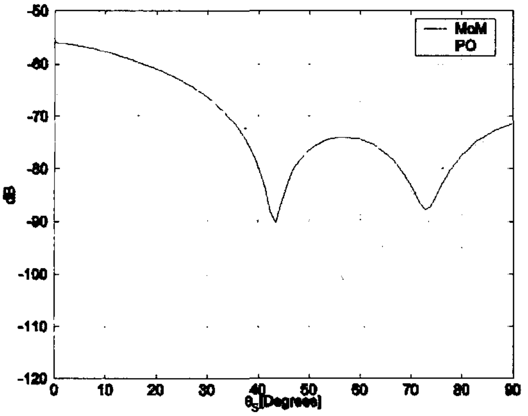
$$\begin{aligned} \vec{E}_1 \times \vec{H}_1 &= \left(\vec{E}_1^i + \vec{E}_1^r\right) \times \left(\vec{H}_1^i + \vec{H}_1^r\right) \\ &= \vec{E}_1^i \times \vec{H}_1^i + \vec{E}_1^i \times \vec{H}_1^r + \vec{E}_1^r \times \vec{H}_1^i + \vec{E}_1^r \times \vec{H} \end{aligned} \tag{6}$$

where the superscript, r indicates the reflected waves from the ground plane and i the direct waves. The first and second terms in (6) are the direct scattered fields due to the direct and reflected incident waves on the target, respectively. The third and final terms are the reflected scattered field from the ground plane due to the direct and reflected incident waves on the target, respectively. Hence (6) expressed the famous four-rays model to deal with a ground plane approximately. Therefore the proposed procedure based on the reciprocity theorem may be accurate and exact up to first order.

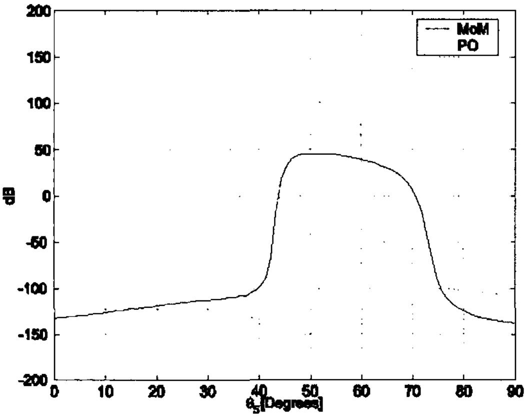
Ⅳ. Simulation Results

PO approximation is widely used for scattering calculation for a large object and/or at high frequencies, but the accuracy of the approximation may be doubtful especially if the shape of a scatterer is very complicated since higher order interactions are ignored. However, inside a random media, field is incident on a target in every direction due to scattering from many particles, and so the dominant scattered field at an observation point from the target may be scattered fields in the specular direction from some particles of the random media. Since specular scattering is the strongest among all scattered field components, and PO approximation can estimate the specular scattered field very accurately, the accuracy of PO approximation may be sufficient for scattering from an object inside a random media. To verify this observation, scattering from two circular disks is considered. The two disks are identical, whose radius and dielectric constant are 2 cm and 26.6+i11.56, respectively. Frequency is set at 10 GHz. One disk is located on x-y plane, and the other is aligned at θ= 31.22° and φ= 258.8°. First one incident plane wave is considered, whose orientation is 0.27 $\hat{x}$+0.078 $\hat{y}$ +0.36 $\hat{z}$.

Fig. 3 shows a comparison of the magnitude and phase of the scattered field as a function of elevation angles of observation points. As seen in the figure the

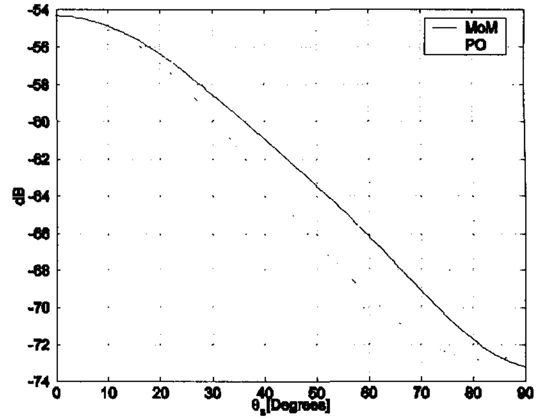


(a) Magnitude

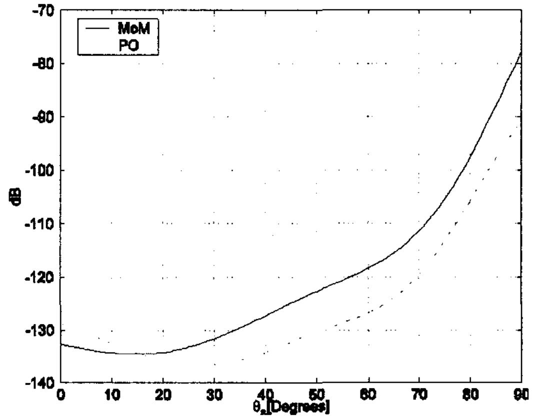


(b) Phase

Fig. 3. Comparison of scattered field from two circular disks calculated by two methods, moment method and PO. One plane wave is incident on the disks.



(a) Magnitude

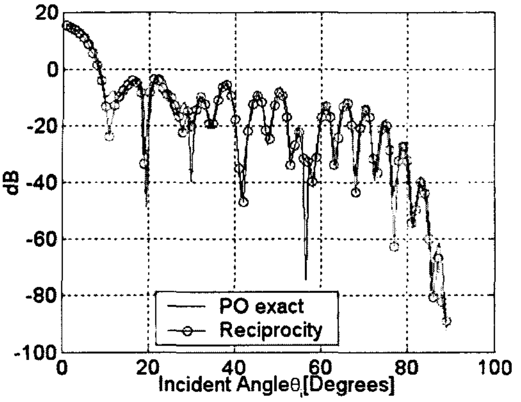


(b) Phase

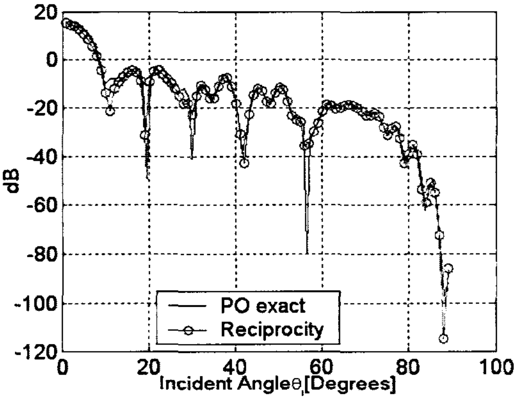
Fig. 4. Comparison of scattered field from two circular disks calculated by two methods, moment method and PO. 2000 plane waves are incident on the disks, whose magnitude and phase are randomly distributed.

results of PO approximation has a very large discrepancy (>10 dB) compared with the results of MoM. Next to simulate an effect of a random media, it is assumed that 2000 plane waves are incident on the same scatterers whose orientations and magnitudes are randomly distributed. Fig. 4 shows the same plots, but these comparisons show the accuracy of PO approximation is improved drastically for both magnitude and phase over the whole comparison region.

Next to verify the proposed procedure based on the reciprocity theorem for the calculation of backscattering from a target, scattering from a perfect electrical conductor(PEC) is considered where the size of the PEC plate is $3\lambda \times 3\lambda$ horizontally placed 1 m above a lossy ground plane. For this simulation the relative permittivity of the ground plane is set to be $\varepsilon_r = 5.6 + i\,0.8$ and the frequency is chosen as 2 GHz. To calculate the integral in (4), the plate is meshed into 144 segments of $\lambda/4 \times \lambda/4$ square elementary patches. On each patch, the electric field and the electric current are considered constant and equal to the value at the center point of that patch. Fig. 5 shows the comparison between the exact PO calculation[6] and approximation of (4), as a function of the incident angle. As can be seen in the figure, the proposed procedure generates very accurate



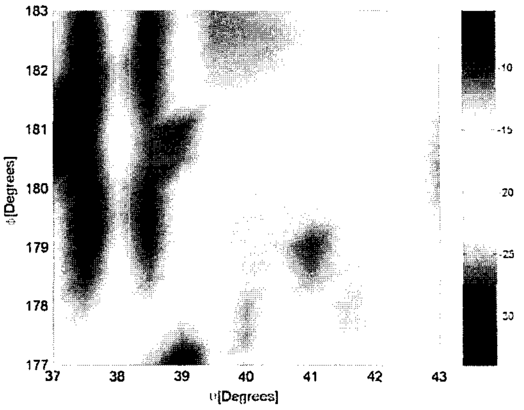
(a) σ_{hh}



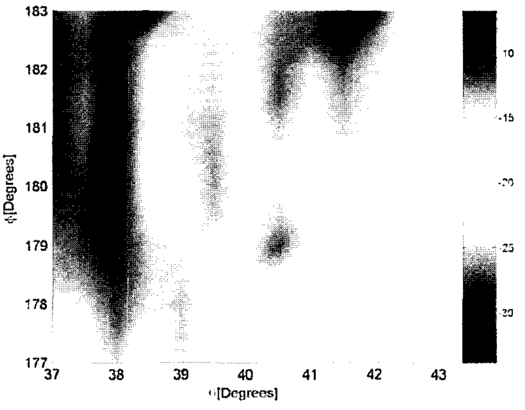
(b) σ_{vv}

Fig. 5. RCS of a $3\lambda \times 3\lambda$ PEC square plate, horizontally placed 1 m above a lossy half space, as a function of the incident angle θ, for $\phi = 0°$. Comparison between the exact PO calculation and approximation of (4).

results which are in excellent agreement with the results of the exact PO calculation.



(a) σ_{hh}

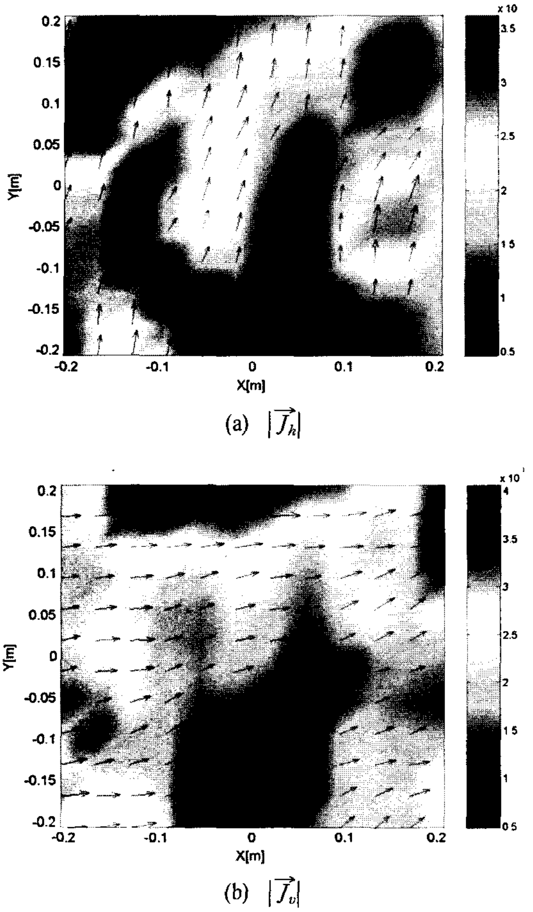


(b) σ_{vv}

Fig. 6. Estimated RCS of a $3\lambda \times 3\lambda$ PEC sqaure 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.

For a complete simulation, 10 pine trees were randomly located around the plate, with density of 0.05 trees/m^2 whose height is 15 m. Fig. 6 shows the plot of RCS of the plate inside the pine 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. 7 shows the calculated PO current distribution on the plate for a case of θ_i=37.5° and ϕ_i= 177°. As can be seen, the electric current is almost aligned in $\hat{y}$ and $\hat{x}$ directions for h- and v-polarization, respectively since the mean field is very high, but the current fluctuates very much.

Changing tree locations and tree shapes, backscattering is calculated from a $\lambda \times \lambda$ PEC plane inside the same pine forest. 4 realizations are done. Fig. 8 shows the mean and simulation range of the predicted scattering by the target. As expected, the mean of scattering is reduced compared with that without the forest, and the computed RCS fluctuates very much due to the effect of the forest. Since tree trunk is the largest scatterer, σ_{vv} is smaller than σ_{hh}. As seen in the figure, it is observed that scattering from a forest is larger than that from the target since the plane is much smaller than trees.



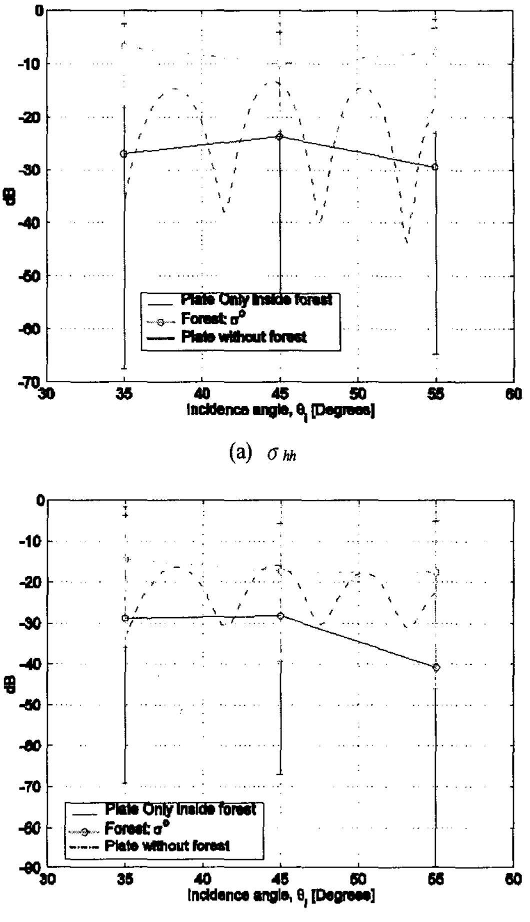
(a) $|\vec{J}_h|$

(b) $|\vec{J}_v|$

Fig. 7. Current distribution on the plate for θ_i=37.5° and ϕ_i=177°.

V. Conclusions

In this paper, a hybrid model is developed based on the known physics-based channel model for a forest and PO approximation to estimate a scattering characteristics of a target embedded inside a forest. The forest channel model generates an artificial forest based on fractal tree geometry and calculates scattered fields at a point inside a forest from tree constituents such as trunks, branches, and leaves in a uniform manner. Using the channel model, fields on a target body is accurately estimated, and converted to current distribution through the standard PO procedure. Based on the estimated PO current, backscattering can be easily calculated using reciprocity theorem. In this paper, the proposed procedure is verified, and the backscattering is calculated from a large PEC plate inside a pine forest.



(a) σ_{hh}

(b) σ_{vv}

Fig. 8. Monte Carlo simulation of RCS of a $\lambda\times\lambda$ PEC plane inside a pine forest as a function of elevation angles. 4 realizations are considered.

References

[1] L. L. Foldy, "The Multiple Scattering of Waves", *Phys. Rev.*, vol. 67, no. 3, pp. 107-119, Feb. 1945.

[2] I. Koh, K. Sarabandi, "Polarimetric channel characterization of foliage for performance assessment of GPS receiver under tree canopies", *IEEE Trans. on Antennas Propagat.*, vol. 50, no. 5, pp. 713-726, May 2002.

[3] K. Sarabandi, *Electromagnetic Scattering from Ve-*

getation canopies, Ph. D. dissertation, University of Michigan, Ann Arbor, MI, 1989.

[4] Y. C. Lin, K. Sarabandi, "Monte Carlo coherent scattering model for forest canopies using fractal-generated trees", *IEEE Trans. on Geoscience and Remote Sensing*, vol. 37, no. 1, pp. 440-451, Jan. 1999.

[5] Roger F. Harington, *Time-Harmonic Electromagnetic Fields*, John Wiley & Sons, NY, 2001.

[6] Hristos. T. Anastassiu, "Radar cross section of a perfectly conducting, flat, polygonal plate over a dielectric, lossy half space: a closed form, physical optics expression", *IEEE Proc. on Mathematical Methods in Electromagnetic Theory*, *MMET'02*, vol. 2, pp. 505-507, Sep. 2002.

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