RADIATIVE TRANSFER THEORY FOR POLARIMETRIC REMOTE SENSING OF PINE FOREST

C. C. Hsu, H. C. Han, R. T. Shin, J. A. Kong
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

A. Beaudoin, and T. Le Toan
Centre d'Etude Spatiale des Rayonnements, Toulouse, France

Abstract– In this paper, the radiative transfer theory is applied to interpret polarimetric radar backscatter from pine forest with clustered vegetation structures. To take into account the clustered structures with the radiative transfer theory, the scattering function of each cluster is calculated by incorporating the phase interference of scattered fields from each component. Subsequently, the resulting phase matrix is used in the radiative transfer equations to evaluate the polarimetric backscattering coefficients from random medium layers embedded with vegetation clusters. Upon including the multi-scale structures, namely, trunks, primary and secondary branches, as well as needles, we interpret and simulate the polarimetric radar responses from pine forest for different frequencies and looking angles. The preliminary results are shown to be in good agreement with the measured backscattering coefficients at the Landes maritime pine forest during the MAESTRO-1 experiment.

I. Introduction

In recent years, the application of radar polarimetry for active remote sensing of the earth terrain has inspired extensive interests. A variety of theories have been used for electromagnetic modeling of geophysical terrain, such as snow, ice, and vegetation canopy [1]. Among these studies, the radiative transfer (RT) theory has been commonly used to calculate radar backscattering coefficients from layered geophysical media and to interpret the experimental measurements.

The radiative transfer theory consists of the radiative transfer equations which govern the electromagnetic energy propagation through scattering media. Various models have been developed based on this theory [2–4]. In general, the conventional RT theory ignores the relative phase information associated with structured scatterers, which may play an important role in the overall scattering behavior [5]. In forest, vegetation consists of structures of many different scale length – the trunk, primary branches, secondary branches, and needle leaves, etc. Vegetation elements of each scale are connected to elements of other scales in a fashion statistically described by the unique architecture pertaining to each tree species. For the microwave remote sensing of forest, the vegetation structures not only give rise to the separation of scattering centers for different polarizations, but also provide partially coherent scattering by different scatterers with statistically prescribed relative positions.

In this paper, a four-layer RT model is presented for the modeling of the pine forest in the Landes area, France. We make use of the newly developed branching model for vegetation [7] to account for the scattering properties of structured pine trees. The model thus constructed has a wide validity range in frequency spectrum.

II. Radiative Transfer Theory

Consider an electromagnetic wave incident upon a multilayered random medium with the incident angle θ_o as shown in Fig. 1. The scattering regions 1 to 3 are layers of thickness h_n ($n = 1,2,3$), where discrete scatterers embedded in homogeneous background. The bottom boundary between region 4 and region t can be either a flat surface or a rough surface described by a Gaussian random process.

The vector radiative transfer equation for the specific intensity in each scattering region is of the form

$$\cos\theta \frac{d\overline{I}(\theta,\phi,z)}{dz} = -\overline{\overline{\kappa}}_e(\theta,\phi,z)\cdot\overline{I}(\theta,\phi,z) + \int_{4\pi} d\Omega'\, \overline{\overline{P}}(\theta,\phi;\theta',\phi')\cdot\overline{I}(\theta',\phi',z) \quad (1)$$

where the Stokes vector $\overline{I}$ containing information regarding field intensity and phase relation of the two orthogonal polarizations is defined as

$$\overline{I} = \begin{pmatrix} I_h \\ I_v \\ U \\ V \end{pmatrix} = \frac{1}{\eta}\begin{pmatrix} \langle |E_h|^2\rangle \\ \langle |E_v|^2\rangle \\ 2\,\mathrm{Re}\langle E_v E_h^*\rangle \\ 2\,\mathrm{Im}\langle E_v E_h^*\rangle \end{pmatrix} \quad (2)$$

In (2), the subscripts h and v represent the horizontal and vertical polarizations, respectively. The angular bracket $\langle\,\rangle$ denotes ensemble average over the size and orientation distributions of scatterers; and $\eta = \sqrt{\mu_0/\epsilon_0}$ is the free-space characteristic impedance.

The extinction matrix $\overline{\overline{\kappa}}_e$ represents the attenuation due to both the scattering and absorption, and can be obtained through the optical theorem in terms of forward scattering functions. The phase matrix $\overline{\overline{P}}(\theta,\phi;\theta',\phi')$ characterizes the scattering of the Stokes vector from (θ',ϕ') direction into (θ,ϕ) direction. The phase matrix can be formulated in terms of scattering functions of the randomly distributed discrete scatterers. Along with the boundary conditions, we can solve the radiative transfer equations iteratively for the polarimetric backscattering coefficients [1].

91-72810/92$03.00 © IEEE 1992

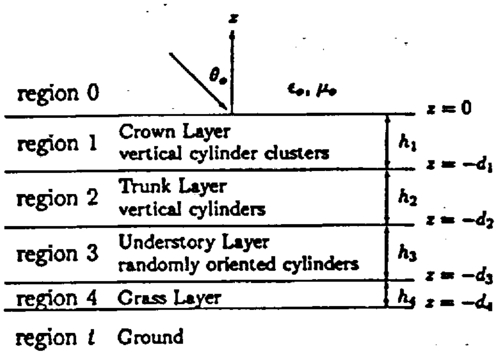

Figure 1. Configuration

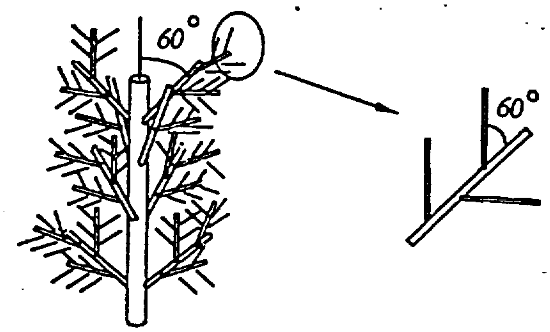

Figure 2. Cylinder Cluster

III. Scattering Function for Clustered Structure

In order to take into account the partially coherent effect due to clustered vegetation structures, we formulate the phase matrix based on the branching model for vegetation. In pine forest, most of the scatterers are of cylindrical shapes. Hence in this study, the main subject is cylinder clusters. For the cylinder cluster that has one center cylinder and N branching cylinders, the total backscattering function $f_{\alpha\beta}$ is

$$f_{\alpha\beta} = f_{0\alpha\beta} + \sum_{n=1}^{N} f_{n\alpha\beta}\, e^{i\phi_n} \tag{3}$$

where $f_{0\alpha\beta}$ is the $\alpha\beta$-th element of the scattering matrix for the center cylinder, and $f_{n\alpha\beta}$ is $\alpha\beta$-th element of the scattering matrix for the n-th branching cylinder. $\alpha, \beta, \gamma, \delta$ represent horizontal or vertical polarization.

Assuming all the branching cylinders are identical and independent of each other, the correlation of f is

$$\begin{aligned}\langle f_{\alpha\beta} f^*_{\gamma\delta}\rangle &= \langle f_{0\alpha\beta} f^*_{0\gamma\delta}\rangle + N\,\langle f_{n\alpha\beta} f^*_{n\gamma\delta}\rangle \\ &+ 2N\,\mathrm{Re}\left[\langle f_{0\alpha\beta}\rangle\langle f^*_{n\gamma\delta}\rangle\langle e^{-i\phi_n}\rangle\right] \\ &+ N(N-1)\langle f_{m\alpha\beta}\rangle\langle f^*_{n\gamma\delta}\rangle \\ &\cdot \langle e^{i\phi_m}\rangle\langle e^{-i\phi_n}\rangle \end{aligned} \tag{4}$$

The relative phase of the n-th branch with respect to the center cylinder is defined as

$$\phi_n = (\overline{k}_i - \overline{k}_s)\cdot \overline{r}_n$$

where $\overline{k}_i$ and $\overline{k}_s$ are the incident and scattered wave vectors, respectively. $\overline{r}_n$ is the location of the n-th branching cylinder relative to the center cylinder.

In (4), the third and fourth terms are the coherent terms. It can be seen that the incoherent approximation is valid when the average of the random phase factor $\langle e^{i\phi_j}\rangle$ is so small that the coherent terms are negligible as compared with the incoherent terms. However, this is not true for vegetation structure with scale length comparable with wavelength.

For the calculation of scattered fields of different cluster elements, dielectric cylinders can be used to model trunks, branches and coniferous leaves [6,7]. Leaves of deciduous tree can be modelled as disks [6,8]. The truncated infinite cylinder approximation [9] is employed in this study to calculate scattered fields from cylinders.

IV. Comparison with Experimental Data

The experiment is conducted by the Centre d'Etude Spatiale des Rayonnements (CESR) at the Landes forest, in southwest France, using the NASA/JPL Synthetic Aperture Radar (SAR) during the MAESTRO-1 campaign in August 1989. A strong correlation between P-band backscattering coefficients and pine forest parameters has been observed in the measurement data [10].

To model the pine forest, the RT model described in previous sections is adopted as depicted in Fig. 1. The top layer (region 1) consists of vertically orientated three-scale dielectric cylinder clusters charactering the trunks and the attached smaller scale branching clusters. These smaller scale branching clusters include primary and secondary branches, as well as needles. However, at P-band, only the primary and secondary branches are important. In the three-scale model, all the smaller scale cylinders are uniformly distributed along a larger scale center cylinder with 60° angle relative to the orientation of the center cylinder, as show in Fig. 2. Region 2 contains vertically oriented dielectric cylinders representing tree trunks. In region 3, vertical cylinders and randomly oriented thin cylinders coexist characterizing a mixture of the tree trunks and the short vegetation in the forest understory. The underlying grass/ground consists of the attenuating grass layer and the ground.

With this model, we calculate backscattering coefficients for six pine stands of different ages. The ages of the forest under investigation are 6, 14, 20, 30, 38, and 46 years old. It is observed that as forest becomes aged, the average radius of tree trunk grows bigger and the average tree height also becomes taller. The primary and secondary branches grow bigger as well. In general, the above-ground biomass increases despite the decrease in the number of trees per unit area as forest ages. Since the ground truth indicates that the surface is very smooth for observation at P-band, we model the ground as a planar surface. The grass layer above the ground is considered as an homogeneous attenuating layer of 0.2 m height and characterized by a dielectric constant $(1.05 + i0.5)$. The calculated results for P-band are shown in Fig. 3. The discrete points are the data collected by SAR; the curves are the theoretical results. It is found from the simulations, the main contribution for HH backscattering coefficient is from trunk–ground interaction and scattering from branches. As for the VV and HV, the branches are the dominate scatterers.

V. Conclusions

Radiative transfer theory is applied to the modeling of polarimetric radar backscatter for vegetation canopy. The phase matrix is derived with the coherent effects due to the clustered structures. With this model, we simulate multi-frequency and multi-angular backscattering coefficients at different radar polarizations. Theoretical results are in good agreement with the measurement data collected by NASA/JPL SAR. This paper presents the comparison performed at P-Band frequency.

Acknowledgments

This work was supported by the NASA Grant No. NAGW-1617, the NASA Contract No. 958461, the ESA Contract No. AO/1-2413/90/NL/PB, and the ONR Contract No. N00014-89-J-1107.

References

[1] Tsang, L., J. A. Kong, and R. T. Shin, *Theory of Microwave Remote Sensing*, Wiley-Interscience, New York, 1985.

[2] Han, H. C., S. V. Nghiem, and J. A. Kong, "Analytical solution of vector radiative transfer equation with rough surface boundary condition," *Progress in Electromagnetics Research Symposium*, Cambridge, Massachusetts, 1991.

[3] Shin, R. T., and J. A. Kong, "Radiative transfer theory for active remote sensing of two-layer random medium," *Progress in Electromagnetic Research*, Vol. 1, Chapter 4, ed. by J. A. Kong, Elsevier, New York, 1989.

[4] Tsang, L., J. A. Kong, and R. T. Shin, "Radiative transfer theory for active remote sensing of a layer of nonspherical particles," *Radio Science*, Vol. 19, 629–642, 1984.

[5] Yueh, S. H., J. A. Kong, J. K. Jao, R. T. Shin, and T. Le Toan, "Branching model for vegetation," *IEEE Trans. Geosci. Remote Sensing*, Vol. GE-30, No. 2, 1992.

[6] Karam, M. A., A. K. Fung, and Y. M. M. Antar, "Electromagnetic wave scattering from some vegetation samples," *IEEE Trans. Geosci. Remote Sensing*, Vol. GE-26, No. 6, 799–808, 1988.

[7] Durden, S. L., J. J. van Zyl, and H. A. Zebker, "Modeling and observation of the radar polarization signature of forested areas," *IEEE Trans. Geosci. Remote Sensing*, Vol. GE-27, No. 3, 290–301, 1989.

[8] Lang, R. H., and H. A. Saleh, "Microwave inversion of leaf area and inclination angle distribution from backscattered data," *IEEE Trans. Geosci. Remote Sensing*, Vol. GE-23, No. 5, 685–694, 1985.

[9] van de Hulst, H. C., *Light Scattering by Small Particles*, Dover, New York, 1981.

[10] Le Toan, T., A. Beaudoin, J. Riom, and D. Guyon "Relating forest biomass to SAR data," *IEEE Trans. Geosci. Remote Sensing*, Vol. GE-30, No. 2, 1992.

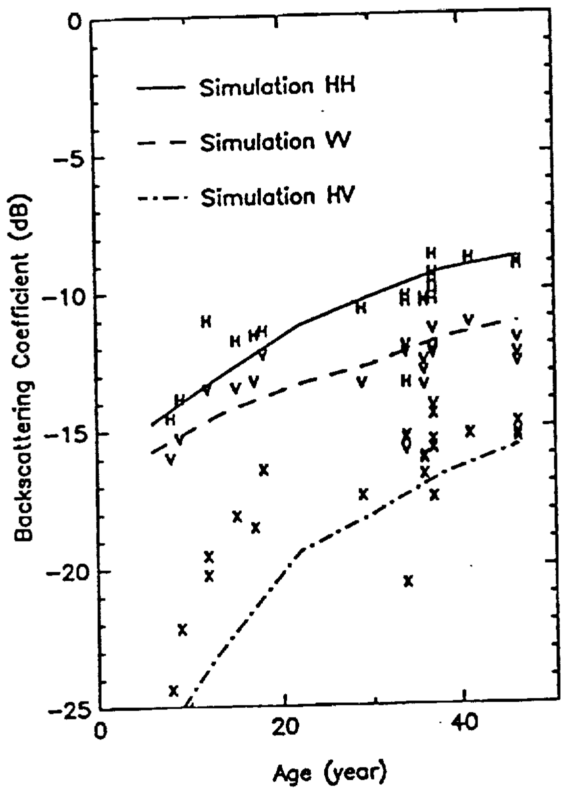

Figure 3. Backscattering for P-band