Scattering of Waves by Rough Surfaces and Vegetation Based on Three Dimensional Numerical Simulations

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ABSTRACT

The scattering of rough surface and vegetation structure are studied with the 3-dimensional numerical simulations. For the rough surface scattering, the study is focused on the angular, frequency, and polarimetric dependence of the scattering. The simulation results are compared well with the experimental measurements from real-life soil surface at L and C frequency bands with the fixed surface roughness parameters. For the scattering from vegetation, a computational electromagnetic model for modeling the foliage clutter is developed. An efficient numerical algorithm is used to solve the matrix equations. The algorithm is applied to calculate scattering from various simulated trees with up to 1000 branches.

INTRDUCTION

Scattering of rough surface and vegetation structures has been an interested topic because of its broad applications in the remote sensing and target detection. The backscattering coefficients from wet soils are measured to evaluate the soil moisture [1]. To detect stationary targets hidden under the foliage, the echoes from the targets are similar in strength to comparable clutter returns from trees, which cause a false alarm rate too high for robust detection of targets. As a consequence, a clear understanding of the fundamental scattering properties of rough surface, a single tree, or a small group of trees is important for reliably extracting the informations of soil moisture and target.

In this paper, we report the results of scattering of waves by random rough surfaces and vegetation structures based on 3-dimensional Monte Carlo simulations of the solutions of Maxwell equations. Numerical simulations are used to calculate the scattering coefficients of soil surfaces at microwave frequencies. The sparse matrix canonical grid method (SMCG) [1] combined with the physics-based two-grid method (PBTG) [2] is used to facilitate the matrix solution and to solve large-scale rough surface scattering problem. The computer code has also been implemented for parallel computation on low cost Beowulf PC clusters [3]. Simulations are focusing on determining the frequency dependence and polarimetric dependence of scattering of soil surface using the same physical roughness parameters for a variety of soil moisture and roughness conditions.

For the scattering of vegetation structure, the focus is on a computaitonal electromagnetic model for the foliage clutter. A structure with dielectric cylinder models is being used to simulate trees with bare branches. The method of moment is applied to calculate tree scattering signatures by discretizing the volume integral equation of the electric field and transforms it into matrix equations. An efficient numerical algorithm based on the sparse matrix iterative approach (SMIA) is used to solve the matrix equations by decomposing them into a sparse matrix for the near (strong) interactions, and a complementary matrix for the far (weak) interactions among the cylindrical sub-cells of the tree structures. Using a direct sparse solver to estimate the strong interaction part, we iteratively included the weak interaction contribution to update the solution. The key feature of this approach is that very little iteration is required to obtain convergent solutions. We have applied the numerical tree scattering model based on SMIA to calculate scattering from various simulated trees with up to 1000 branches. Solutions based on the SMIA method agree very well with the exact matrix inversion.

FORMULATION FOR ROUGH SURFACE SCATTERING

Assume an electromagnetic wave from the medium 1 impinging on the rough interface of media 1 and 2, which is governed by a random height profile $z = f(x, y)$. Based on the Maxwell's equations, the fields on the surface should satisfy the surface integral equations.

$$\overline{E}_l(\overline{r})/2 + (-1)^l \int \hat{n}' \times \overline{H}_l(\overline{r}') i\omega\mu G_l dS' \\ + (-1)^l P\int [(\hat{n}' \times \overline{E}_l(\overline{r}')) \times \nabla' G_l + \hat{n}' \cdot \overline{E}_l(\overline{r}') \nabla' G_l] dS' = \delta_{1l} \overline{E}^{inc}(\overline{r}) \tag{1}$$

$$\overline{H}_l(\overline{r})/2 + (-1)^{l-1} \int \hat{n}' \times \overline{E}_l(\overline{r}') i\omega\varepsilon_l G_l dS' \\ + (-1)^l P\int [(\hat{n}' \times \overline{H}_l(\overline{r}')) \times \nabla' G_l + \hat{n}' \cdot \overline{H}_l(\overline{r}') \nabla' G_l] dS' = \delta_{1l} \overline{H}^{inc}(\overline{r}) \tag{2}$$

Where the equations with index of $l = 1$ and 2 are the surface integral equations in the media 1 and 2, respectively. The integral $P\int$ denotes a Cauchy principal integral and G_1 and G_2 are the 3-dimensional Green's functions of free space and the lower dielectric medium, respectively. The unit normal vector $\hat{n}'$ refers to primed coordinate and points away from the second medium. The function of δ_{1l} is zero if $l = 2$ and one if $l = 1$. The incident wave of $\overline{E}_i(\overline{r})$ and $\overline{H}_i(\overline{r})$ is tapered so that the illuminated rough surface can be confined to the surface area $L_x \times L_y$. The method of moments (MoM) is used to discretize the integral equations into the matrix equation. However due to the large number of surface unknowns, it is impossible to solve the matrix equation with a traditional solver such as matrix inversion or Gaussian elimination method for large-scale rough surface simulation. Instead, the iterative technique is used in the paper with the sparse-matrix canonical grid method [1] to facilitate the matrix-vector multiplication and reduce the memory requirement. Furthermore, for the wave scattering from the lossy dielectric rough surfaces with large permittivity, we use a dense grid to sample the rough surface profile to increase the accuracy and to include fine-small structures of natural surfaces. The increased CPU time for the dense sampling is reimbursed by employing the physics-based two-grid method [1-2]. The SMCG and PBTG are used together to reduce the total CPU time and memory requirement. The computational complexity is O($N \log N$), where N is the number of grid points on the coarse grid. Parallel implementation is done using low cost Beowull cluster [3]. The solved surface fields are used to calculate the bistatic scattering coefficients and backscattering coefficients.

FORMULATION AND SPARSE MATRIX ITERATIVE APPROACH FOR VEGETATION SCATTERING

The discrete dipole approximation (DDA) has been applied to calculate electromagnetic waves scattering from trees, where tree trunks and branches have been modeled as thin dielectric circular cylinders [1,5,6]. The volume integral equation for an electric field is given as

$$\overline{E}(\overline{r}) = \overline{E}^{inc}(\overline{r}) + \frac{k_0^2}{\varepsilon_0} \int_V \overline{\overline{G}}_0(\overline{r}, \overline{r}') \cdot [\varepsilon_p(\overline{r}') - \varepsilon_0] \overline{E}(\overline{r}') d\overline{r}' \tag{3}$$

where $\overline{E}^{inc}(\overline{r})$ is the incident wave, $\varepsilon_p(\overline{r})$ is the permittivity distribution within region V, and k_0, ε_0, and $\overline{\overline{G}}_0(\overline{r}, \overline{r}')$ are the wavenumber, permittivity, and dyadic Green's function of free-space, respectively. If we subdivide the volume into small elemental volumes ΔV_i centered at $\overline{r}_i$, $i = 1,2,\ldots,N$, then (3) can be rearranged as the DDA matrix equation.

$$\overline{\overline{Z}} \cdot \overline{X} = \overline{C} \tag{4}$$

where the vector $\overline{C}$ corresponds to the known incident field and $\overline{X}$ is the unknown polarization vector and is to be solved numerically. Elements of the impedance matrix $\overline{\overline{Z}}$ are determined by the Green's dyad function. In the sparse matrix iterative approach (SMIA), the matrix equation (4) is solved iteratively by decomposing the impedance matrix $\overline{\overline{Z}}$ into two parts as follows,

$$\overline{\overline{Z}} = \overline{\overline{Z}}^{(s)} + \overline{\overline{Z}}^{(w)} \tag{5}$$

where $\overline{\overline{Z}}^{(s)}$, which is a sparse matrix, includes the near (strong) interactions among the cylindrical sub-cells, and $\overline{\overline{Z}}^{(w)}$ is a complementary matrix for the far (weak) interactions containing the remaining elements of the impedance matrix. The numerical procedure is using a sparse solver to estimate the first order solution,

$$\overline{\overline{Z}}^{(s)} \cdot \overline{X}^{(1)} = \overline{C} \tag{6}$$

and iteratively include the weak interaction contribution to update the higher order solution,

$$\overline{\overline{Z}}^{(s)} \cdot \overline{X}^{(n+1)} = \overline{C} - \overline{\overline{Z}}^{(w)} \cdot \overline{X}^{(n)} \tag{7}$$

The iterations are carried out until the error norm criterion

$$\frac{\left\| \overline{\overline{Z}} \cdot \overline{X}^{(n)} - \overline{C} \right\|}{\left\| \overline{C} \right\|} \le \delta \tag{8}$$

is satisfied. δ has been set equal to 1×10^{-4} for the numerical computations presented in the next section.

SIMULATION RESULTS FOR SURFACE SCATTERING

Fig. 1 and 2 show the backscattering coefficients obtained from the Monte Carlo simulations as a function of incident angles and the comparisons with the experimental measurements. The experimental results are from [4] and were taken from the same soil surface fields at two conditions of wet and dry soil moistures. The rms height and correlation length of the measured soil surface are 1.12cm and 8.4 cm, respectively. In the numerical simulation, we use these physical surface roughness parameters and soil moistures (relative permittivity) provided by [4] for both L and C band simulations. The rough surfaces are generated with the spectrum of the exponential correlation function that is also close to the description reported by the reference. The Fig. 1 is simulated from the wet condition of soil and Fig. 2 is from dry condition. The Fig. 1a and 2a is for L band and Fig. 1b and 2b is for C band. The Fig. 2a gives the best match between the simulations and measurements. And other figures also show the fairly good agreements between the simulations and the measurements.

SIMULATION RESULTS FOR VEGETATION SCATTERING

Fig. 3 shows a tree generated from Lindenmayer system. The tree height is 6.27*m*, and the total number of branches, including the trunk, is 1023. The total number of cylindrical cells is 2593 and it leads to the total number of unknowns of 7779. We use the matrix inversion, conjugate gradient method (CGM), and the proposed method of SMIA to solve the same problem for the bistatic scattering coefficients of the simulated tree, respectively. The permittivity of tree is chosen to be $\varepsilon_p = 11 + i4$. The radio wavelength is $\lambda = 1m$ and the incidence angle is $\theta_i = 45^\circ$. The simulation results are shown in Fig. 4. Solutions based on the SMIA method agree very well with the exact matrix inversion and CGM. However, the number of iteration for the SMIA is only 14 while the CGM takes 1143 iterations. The total CPU is 1539 seconds for the SMIA and 27937 seconds for the CGM. Thus the SMIA provides a very fast solution while keeps accuracy of the tree scattering problem.

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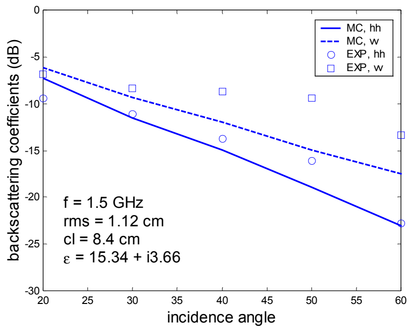


Fig. 1a

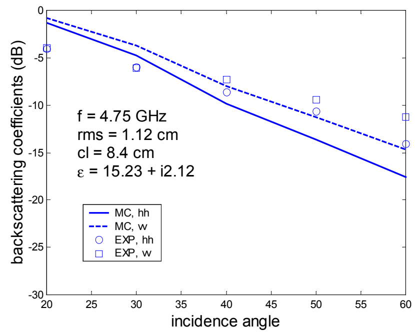


Fig. 1b

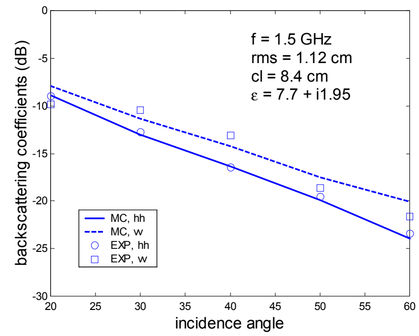


Fig. 2a

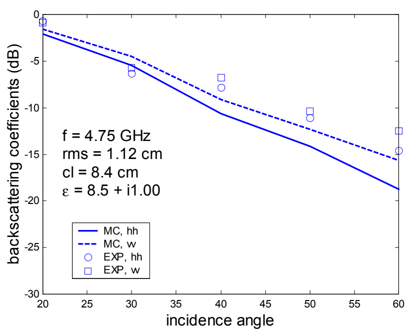
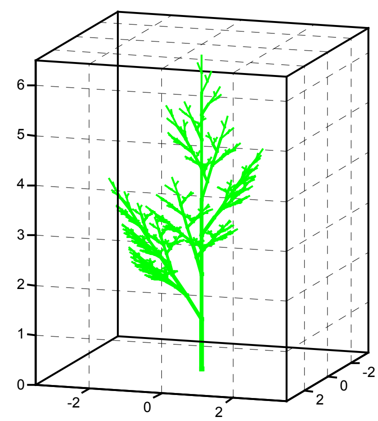


Fig. 2b

Fig. 3



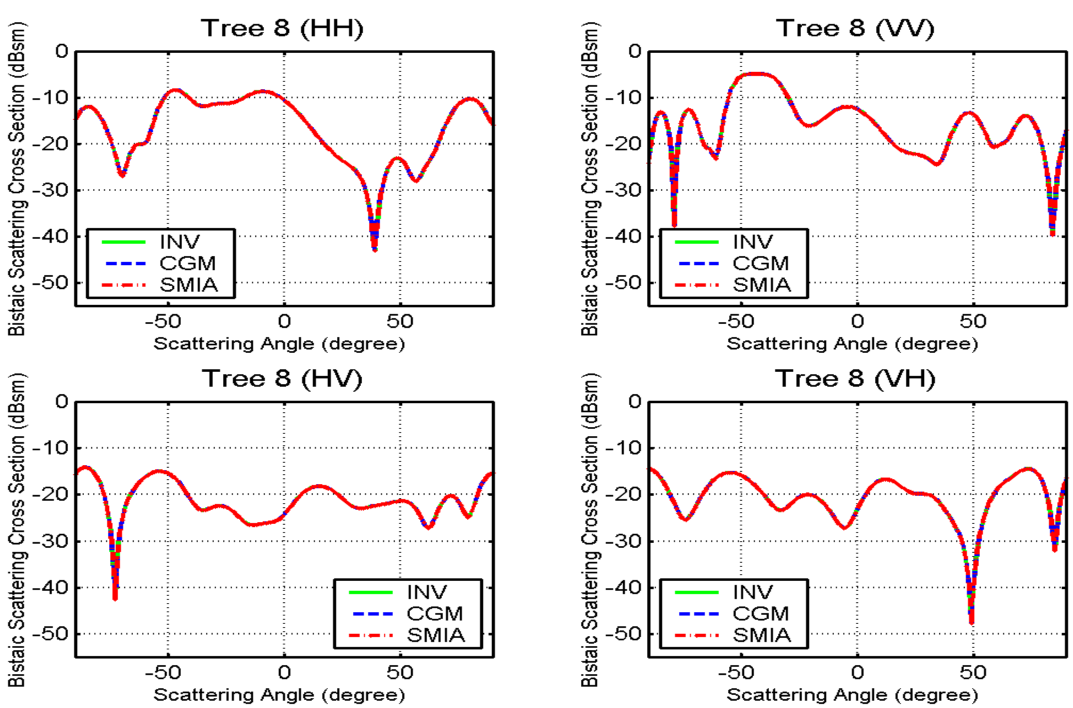


Fig. 4 Comparison of the bistatic scattering cross sections of the simulated tree calculated by the full matrix inversion (INV), conjugate gradient method (CGM), and sparse matrix iterative approach (SMIA).