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Frequency Dependence of Scattering by Dense Media of Small Particles Based on Monte Carlo Simulation of Maxwell's Equations

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Abstract The frequency dependence of scattering by geophysical media at microwave frequencies is an important issue because multi-frequency measurements are useful for remote sensing applications. Classically, the independent scattering theory states that if the particles are small, scattering is proportional to the fourth power in 3-D scattering and the third power in 2-D scattering. In this paper, we study rigorously the frequency dependence of scattering by dense media by Monte Carlo simulations of the solutions of both 2- and 3-dimensional Maxwell's equations. The particle positions are generated by deposition and bonding techniques. The Sparse-Matrix Canonical-Grid method has been applied to speed up the simulation of scattering by 2D small particles. Numerical solutions of Maxwell's equations indicate that the frequency dependence of densely packed sticky small particles is much weaker than that of independent scattering. The results are illustrated using parameters of snow in microwave remote sensing.

I Introduction

Wave propagation and scattering in the densely packed media are important issues in the volume scattering problem of geophysical media [1][2]. The frequency dependence of emission and scattering of snow at microwave remote sensing frequencies (e.g. 19GHz, and 37GHz) is a quantity that must be studied rigorously because multi-frequency measurements are useful for remote sensing applications. When the particles are much smaller than a wavelength, the frequency dependence is to the fourth power for 3-D particles and the third power for the 2-D particles, based on the conventional independent scattering model. Physically, in densely packed media, the particles can adhere to form aggregates. The correlation between particles has to be taken into account. To better understand such a scattering property, we study the frequency dependence of scattering by sticky and non-sticky particles rigorously. In this rigorous approach, we generate the positions of particles rigorously using bonding technique; and then solve the Maxwell's equations that include all the multiple scattering based on Monte Carlo simulation. For the sticky particles, the frequency variation is dependent on a "sticky" parameter representing the degree of adhesiveness of the cylinders. The extinction, scattering and absorption properties of dense media are calculated for dense media of sticky and non-sticky particles. The T-matrix method is used. It has been shown that the internal field formulation of Foldy-Lax equations have much better condition numbers for the matrix equations [2]. Thus the use of internal field formulation is advantageous for iterative solution of the Foldy-Lax matrix equation. Various numerical parameters are tested to show that the results are accurate. Convergence tests are performed for these numerical parameters. A sufficient number of realizations of the Monte Carlo simulations is performed to ensure the convergence. Up to 50 realizations are used in this paper. For most of the cases, the results converge within 20 to 30 realizations. The number of particles used in this study is between 100 and 2000 depending on the fractional volume and frequency.

IV Simulation Results and Discussions

We use the internal field formulation and conjugate gradient (CG) method in computing the numerical results. In the following, we present results for dielectric cylinders with ε_p=3.2 based on Monte Carlo simulations for non-sticky and sticky cylinders (2D problem) and spherical particles (3D problem). In Table 1, we tabulate the results of normalized scattering coefficients κ_s/k for the 2-D scattering problem.

For 3D scattering problem, we tabulate the frequency dependence of scattering rates in Table II. The scattering rate at 18 GHz is used as reference. Assuming the scattering rates and frequencies has the relationship of

$$\frac{\kappa_s(at\ f_2)}{\kappa_s(at\ f_1)} = \left(\frac{f_2}{f_1}\right)^n \qquad (9)$$

where f_1 and f_2 are the frequencies, κ_s is the scattering rate at a specific frequency, and n is the index of frequency dependence.