

Remote Sensing of Vegetation/Forests Based on Fast Hybrid Multiple Scattering Theory Method for Large-Scale Full-Wave Simulations

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We present full-wave simulations of microwave propagation in vegetation and forests and the results are used in microwave remote sensing of soil moisture. Microwave remote sensing include the SMAP mission (the Soil Moisture Active Passive at 1.4 GHz) which provides the global mapping of soil moisture; NASA-ISRO SAR Mission; and the reflectometry missions CYGSS and HydroGNSS. Previously, the Vegetation Water Content (VWC) threshold was set at 5 kg/m² based on radiative transfer equation (RTE) model, excluding forests with VWC greater than 15 kg/m². The RTE is a heuristic approach with several ad hoc assumptions—(a) uniform and random distributions of scatterers such as disks and cylinders (b) branches, stems, and trunks are calculated, separated, and added incoherently. In RTE, the attenuation rate per unit distance is not well-defined, particularly for non-uniform distribution and for layered vegetation as the stalks/trunks, unlike leaves and branches extend from bottom to top. For these reasons, the need for the full-wave simulations emerged to solve the 3D-Maxwell's equations using exact shapes and positions of plants and trees. Accurate physical and electromagnetic models enable us to analyze gaps among trees and plants. Full-wave simulations are used to model non-uniform distributions and the plant or tree as a single object with T-matrix instead of incoherent additions of cross sections of branches and stalks.

Full-wave simulations of vegetation fields or forested areas are challenging because they are large-scale problems with hundreds of plants and trees in the simulation domain. Conventional full-wave solvers based on FEM and MoM are not feasible due to excessive CPU time and memory requirements. Commercial software such as FEM or MoM are limited to small sample areas and small number of plants. To address these issues, the Fast Hybrid Multiple Scattering Theory Method (FHMSTM) was proposed. The FHMSTM consists of three steps. The first step involves extracting the T-matrix representing scattering characteristics of a single plant or tree, allowing electromagnetic solutions outside an enclosing cylinder. The second step formulates the Foldy-Lax equation using vector cylindrical waves, which accounts for electromagnetic wave interactions between plants/trees. In this formulation, T-matrices and translation addition theorems are used to calculate these interactions. In vegetation fields/forests, there are hundreds of corn plants or trees. This requires the Foldy-Lax equation to sum order of 10,000 waves for a single wave number, leading to an increase of CPU time and memory usage. To efficiently and quickly sum the waves, the third step applies a triple Fast Fourier Transform (Triple-FFT) to the Foldy-Lax equation, minimizing CPU time and memory usage while including many plants or trees in the microwave simulations. In this paper we simulate domain with a large number of different plants and trees of 19 meters height, such as 300 in number. The domain area is 60 m by 60m for forests, and 8 meters by 8 meters for crops.

Many findings are obtained from the application of the FHMST to large-scale corn fields and forests. The first one is the validation of gap effects in the forested environment. The gaps among the trees allow for higher transmission. The FHMST based on the full-wave solver accurately characterizes the gap effects. Our method is also applied to the corn fields. From full-wave simulations of 36 by 13 corn plants with a row structure, we find out that the transmissivity dependence on the azimuthal angles. Finally, we implement the validation of the FHMST to support reliability of our results. In SMAPVEX19-22, GPS received signals were measured under the forest canopy with clear features of spatial distributions of received electric fields in Massachusetts. The FHMSTM simulation of 300 trees in Massachusetts forest takes only 2 hours and 80 GB of memory. We compare the results obtained from the FHMSTM with these measured GPS electric field intensity. The results show good agreement between the FHMSTM and the GPS signals.