Numerical studies of scattering properties of leaves and leaf moisture influences on the scattering at microwave wavelengths

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Abstract

This study uses 3-dimensional finite difference time domain method to accurately calculate single-scattering properties of randomly orientated leaves and evaluate the influences of vegetation water content (VWC) on these properties at 19 and 37 GHz frequencies. The studied leaves are assumed to be thin elliptic disks with two different sizes and have various VWC values. Although the leaf moisture produces considerable absorption during scattering processes, the effective efficiencies of extinction and scattering of leaves still near-linearly increase with VWC. Calculated asymmetry factors and phase functions indicate that there are significant amounts of scattering at large scattering angles in microwave wavelengths, which provides good opportunities for off-nadir microwave remote sensing of forests. This study lays a basic foundation in future quantifications of the relations between satellite measurements and physical properties of vegetation canopies.

1. Introduction

Forests modulate land surface and planetary boundary layer energy and hydrological budgets on local, regional, and continental scales, primarily through turbulent, especially evapotranspiration, processes. Scattering properties of forest leaves are essential in understanding the evapotranspiration processes. Min and Lin[1, 2] have shown that the satellite estimated emissivity difference vegetation index (EDVI) at microwave wavelengths is sensitive to evapotranspiration fractions of forests and, along with incoming solar radiative energy, statistically significantly correlated to evapotranspiration fluxes. The errors in estimated evapotranspiration fluxes are much less than those from other operational satellite techniques. This index is also an excellent empirical indicator of spring onset and growing season duration of forests due to its inherited relationship with the leaf physiology of vegetation canopy. The EDVI values are qualitatively decided by physical and biological properties of vegetation canopy[1]. More specifically, these microwave index values are directly related to the vegetation water content (VWC, also called gravimetric moisture, defined as the ratio of the weight of vegetation moisture to the total weight of vegetation) of the upper layer of vegetation canopy[1]. However, quantitative relationship between EDVI and VWC is still unknown owing to the difficulties in the calculations of both single and multiple scattering properties of tree leaves and vegetation canopies. For irregular shaped vegetation materials, such as forest leaves and small branches, there are no general analytical solutions for their single scattering properties (e.g., scattering phase function, extinction and scattering cross-sections, single scattering albedo, and asymmetry factor). While these vegetation materials, especially the tree leaves, are the most important contributors to the scattering and absorption at microwave wavelengths for the upper layer of vegetation canopies[1]. Numerical calculations of broad leaves of deciduous trees at microwave wavelengths are mostly based on approximate solutions for disk shaped particles as shown by Koh and Sarabandi[3] and other works[4, 5]. Accurate solutions for leaf scattering at microwave spectra are needed for forest remote sensing and vegetation canopy monitoring.

This study tries to use 3-dimensional finite difference time domain (3D FDTD) method to numerically obtain the exact solutions of single scattering properties of randomly orientated leaves. The influences of leaf moisture on the scattering are among the most important focus areas considered in this study. The 3D FDTD method is an accurate approach that directly solves the Maxwell's equations of electromagnetic fields with arbitrary shaped dielectric bodies imbedded in uniform media, and has been used by authors in various single-scattering calculations at visible and near infrared wavelengths for both absorbing and non-absorbing irregularly shaped dielectric materials[6-8]. This study extends the 3D-FDTD applications to microwave spectra. Specifically, the frequencies considered here are the same as those used in EDVI calculations[1, 2] for the Special Sensor Microwave Imager (SSMI) measurements, i.e., 19.35 and 37.0 GHz (hereafter 19 and 37 GHz respectively). The scattering calculations at the SSMI wavelengths support forest studies using satellite remote sensing techniques. Section 2 discusses basic vegetation properties and the FDTD method for leaf scattering calculations. The results of the scattering calculations are presented in Section 3. We summarize this study in Section 4.

2. Analysis techniques

Totally dehydrated leaves of deciduous trees are generally light in weight. Their density is only around 0.33 g/cm^3, and much less variable than those under normal conditions[9, 10]. The vegetation water content of fresh leaves varies from dry (4%) to very wet (~70%) conditions.

This moisture contributes strongly to the microwave absorption and scattering within vegetation materials. There are generally no specific models to calculate vegetation dielectric properties at frequencies higher than 20 GHz. Studies[9-11] show that the dual-dispersion model[10] results in very good agreements with experimental measurements for sampled leaves, especially at X-band. This study expands the dual-dispersion model to the SSMI wavelengths (19 and 37 GHz) in the calculations of leaf dielectric properties. The room temperature is assumed for the analyzed leaves. Although there are some variations in leaf dielectric properties with temperatures, the changes are generally small[9-11], especially in the conditions well above the frozen point. To analyze single scattering characteristics of broad leaves, the shape of leaves is assumed to be elliptic disks. The basic sizes of the elliptic leaves considered are chosen to be normal leaves with 2.5 cm long semi-axis, 1.25 cm short semi-axis, and 0.1 cm thickness. We have also computed scattering features of leaves with a half of the long and short semi-axes without changes in the thickness. For simplicity, hereafter we refer these two kinds of leaves as full size (FS) and half size (HS) ones, respectively. Since the sizes of these assumed FS and HS leaves are comparable to the SSMI wavelengths, especially at 37 GHz, calculations using either geometric optics or Rayleigh-Gens approximations would produce significant errors in calculated phase functions and other scattering properties. Accurate solution techniques, such as FDTD, are critical for the computations of the scattering electromagnetic fields.

The FDTD technique with the uniaxial perfectly matched layer (UPML) absorbing boundary conditions (ABC)[12, 13] is used to calculate the near-electromagnetic fields scattered and transmitted by leaves in the time domain. The time series at each grid point in the computational domain is calculated through updating the electromagnetic field components using the correspondence of the Maxwell's equations at the finite spatial-temporal grid. The scattering and absorption quantities are calculated at the end of computation.

Figure 1 illustrates the basic geometry of light scattering by a leaf that sits on x-y plane with bottom of the leaf at z = 0. Also shown in this figure are the coordinate system used in the derivation of the light-scattering formulae and the incident (i) and scattered (s) intensities (I) of the electromagnetic fields. We assume that at beginning the incident electromagnetic waves are normal to the leaf surface and propagate along the z direction. Each spatial cell in our calculation is assigned to be 1/N of the wavelength of the incident light, where N equals to 20 times of the real parts of leaf refractive indices and varies from ~40 to ~90 depending on frequency and VWC. The large N or small cell size used here is to account for quick changes of electromagnetic fields in spatial domains due to large leaf refraction at the SSMI frequencies. The time step is set to be one half of the time that the light can travel through a single cell. In the incident and all side directions, the computational domain is truncated by the UPML ABC[12, 13]. The perfectly matched boundary layer absorbs all electromagnetic waves propagated to these boundaries, making no further interference of scattered and incident lights. In order to obtain differential values of electromagnetic fields, magnetic and electric field components are evaluated alternatively at different temporal and spatial grid points with half time-step and half cell-size differences, respectively.

After finishing the leaf scattering calculation of the normal light incidence, we rotate incident lights in both zenith (θ) and azimuth (ϕ) angles and, then, re-compute the scattering electromagnetic fields. In order to simulate the scattering effect of the random orientation of natural leaves, our final scattering characteristics are the results of all calculations weighted by the spatial weights of zenith and azimuth angles. Since satellite microwave sensors, such as

SSMI, generally provide vertically (V) and/or horizontally (H) polarized radiation measurements, we transfer the I and Q components of incident and scattered Stokes vectors into V and H components of the Stokes parameters in this study. The four elements in the Mueller matrix (or phase functions) directly related to these I and Q components are also changed correspondingly, and named as P_{VV}, P_{VH}, P_{HV}, and P_{HH}, respectively, as shown in next sections. The P_{VV} and P_{HH} elements represent leaf co-polarization effects of incident and scattered lights, while the other two elements describe those for cross-polarization. Because there are almost no measurements of full Stokes vectors from satellite microwave instruments, we only discuss these four phase function elements in the following sections. The other phase function elements in the Mueller matrix are left for future studies.

3. Results

Scattering characteristics are usually described by bi-directional distributions of incident and scattered lights and the extinction and scattering of scattering objects (note: the absorption is the difference between extinction and scattering). The bi-directional distributions are measured by the phase functions mentioned in the last section. For the extinction and scattering, we use effective efficiencies of extinction and scattering to quantify these physical properties, which are defined as the ratio of the extinction or scattering cross-section to the elliptic area of leaves as shown in Fig. 1. This definition of effective efficiencies can be easily used in microwave remote sensing applications for leaf extinction and scattering calculations.

Figure 2 shows the variations of effective efficiencies of extinction and scattering with VWC for FS and HS leaves at frequencies of 19 (left) and 37 (right) GHz. In normal VWC dynamic ranges as calculated in this study, these efficiencies near-linearly vary with VWC.

Although the leaf moisture produces considerable absorption during leaf scattering processes, the higher the VWC, the stronger the extinction and scattering. The reason of the increases of effective efficiencies of extinction and scattering of tree leaves with VWC is that both real and imaginary parts of refractive indices of leaves increase with VWC. There are about a factor of 5-10 variations in these efficiencies. This large variability of extinction and scattering of tree leaves generates a great complicity in satellite remote sensing of vegetation canopies and makes estimations of VWC and vegetation-atmosphere interaction very hard empirically when emission signals from the canopies are used. From this figure we can also find that effective efficiencies, especially the effective scattering efficiencies, at a given frequency are similar for both FS and HS leaves, i.e., for a unit area, large and small leaves have almost the same scattering effects when these leaves are randomly orientated. Because of the cross-sections of extinction and scattering of tree leaves are the products of their corresponding effective efficiencies and the leaf areas, the actually extinction and scattering of FS leaves are much higher than those of HS leaves. This scattering feature of less size dependence is similar to those of absorbing sphere particles[14] when size parameter, $x = 2\pi a/\lambda$, is larger than 2. Here a is the radius of sphere particles, and λ is the wavelength of incident light. For our 19 and 37 GHz cases, when the long semi-axes of FS and HS leaves are denoted as a, the values of the size parameter $2\pi a/\lambda$ are all above 2 and vary from about 5 to 20. Compared to those at 37 GHz, the effective efficiencies of scattering at 19 GHz are generally smaller owing to the combined effects of the differences in size parameter and refractive index. The changes of effective efficiencies of extinction with VWC at both 19 and 37 GHz are faster than those for scattering because the absorption of leaves increases with increasing vegetation moisture. The single scattering albedos and asymmetry factors (not shown) have much less variability than those effective efficiencies of extinction and scattering, and vary mostly from 0.55 to 0.8 and to 0.76, respectively. The calculated moderate values of asymmetry factor for elliptic disks are generally smaller than those of non-absorbing large sphere particles, and comparable to those of large absorbing spheres[8]. These moderate values of asymmetry factors indicates that leaves may have fair strong side- and back-scattering (see also Figs. 3-5 below), which provides good opportunities for monitoring vegetation canopies using off-nadir microwave satellite remote sensing techniques such as SSMI or synthetic aperture radar.

The phase functions of leaf scattering for low VWC (4%) FS leaves are shown in Figure 3, along with calculated values for some important parameters, such as effective extinction (ext) and scattering (sca) efficiencies, single scattering albedo (alb), and asymmetry factor (asy). As expected, cross-polarization values are much smaller than those of co-polarization at all scattering angles and for both 19 (left) and 37 (right) GHz cases. The overlap of P_{VH} and P_{HV} curves in the figure reflects the symmetry of the two quantities and the accurate calculations of the FDTD model. Due to this weak scattering property and much less calculations and measurements for cross-polarization than those for co-polarization [e.g., 3, 15], this study will not discuss cross-polarization features further and only be focused on co-polarization components. The P_{HH} components of the phase functions are basically bigger than P_{VV} components, which has been observed by satellite measurements on vegetated land surface emissivity, $e = 1 - r$, where r is reflectivity. The observed emissivity values at V polarization are higher than those at H polarization[1, 16] due to weaker reflectivity at this polarization as shown here in its phase functions. At large scattering angle directions, both P_{HH} and P_{VV} components at 19 GHz have noticeable oscillations with scattering angles. These oscillations are even significant at 37 GHz. When leaf moisture is increased to a high (68%) VWC value (i.e., in stronger absorption case), this oscillation feature still shows up in the calculated results (Fig. 4). Similar P_{HH} and P_{VV} variations with scattering angles were also found by a study[3] of an idealized square vegetation disk at 10 GHz. Thus, this oscillation feature, as that of large sphere particles, may be a general character of large scattering disks at microwave wavelengths. Since the distributions of electromagnetic fields are basically decided by the interaction of incident and scattered lights, size parameters of both large and small dimensions of irregular-shaped scattering particles have significant influences on scattering phase functions. Although FS leaves are generally thin for the SSMI frequencies, size parameters for both long and short semi-axes are large. Thus, the scattering effect for large size parameter in our FS leaf cases shows up in the calculated results.

The scattering characteristics for HS leaves are generally similar to those of FS leaves, especially for 37 GHz cases, except the magnitude of oscillations in large scattering angles are much smaller. Figure 5 plots phase functions of leaves with intermediate VWC (48%), in which case about half of the leaf weight is from water. The smooth feature at large scattering angles of the phase functions at 19GHz is similar to those for small spheres, and likely the results of smaller size parameters, especially for short semi-axis dimensions, of the ellipse at the wavelength compared to FS cases. At forward scattering directions, the scattering phase functions at 37 GHz are considerably larger than those at 19 GHz, a clear scattering phenomenon for different particle size parameters.

4. Summary

Single scattering properties, such as effective efficiencies of extinction and scattering, single-scattering albedo, asymmetry factor, and phases function, of tree leaves are critical parameters for satellite quantitative observations of land surface vegetation-atmosphere interactions. However, currently there is very limited knowledge about these scattering properties. This study uses 3D-FDTD method to numerically calculate accurate solutions of single scattering properties of randomly orientated leaves and evaluate the influences of vegetation water content on these scattering properties at 19 and 37 GHz SSMI wavelengths. The studied leaves are assumed to be thin elliptic disks with two different sizes and have various VWC values. The effective efficiencies of extinction and scattering defined and calculated in this study may be useful in future microwave remote sensing of forest canopies. We find that although the leaf moisture produces considerable absorption during scattering processes of tree leaves, the effective efficiencies of extinction and scattering still near-linearly increase with VWC with a factor of 5 ~ 10 variations at the considered wavelengths. Calculated asymmetry factors and phase functions indicate that the scattering at large scattering angle directions of broad leaves of deciduous trees could be strong, especially at some special angles for certain sized leaves and wavelengths. Our calculated single scattering properties, especially the phase functions of tree leaves, lay a basic foundation for multiple scattering calculations of forest radiation transfer, and provides a great potential to quantify the relations between satellite measurements and physical properties of vegetation canopies. To realize the potential, further studies on the scattering of different types of leaves and branches and evaluations of microwave radiative transfer processes within canopy layers are needed.

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Figures

Fig. 1. The coordinate system and leaf position used in this study. The incident (i) and scattered (s) intensities (I) of the electromagnetic fields are also illustrated. At beginning, the incident light is normal to the leaf surface and along the *z* direction, then, changes in zenith θ and azimuth ϕ directions for the final scattering properties of randomly orientated leaves.

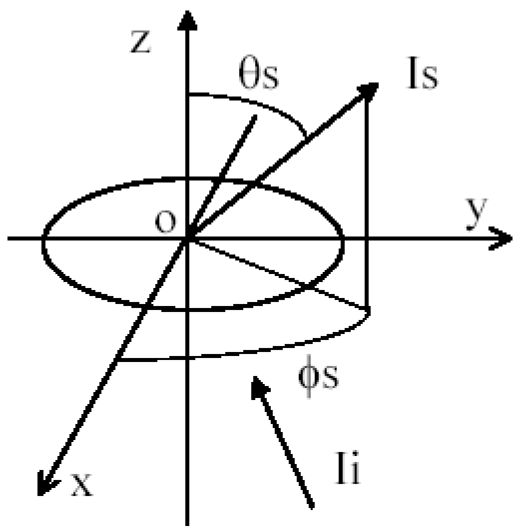

Fig. 2. Variations of effective efficiencies of extinction (ext) and scattering (sca) with vegetation water content (VWC) for FS and HS leaves at frequencies of 19 (left) and 37 (right) GHz.

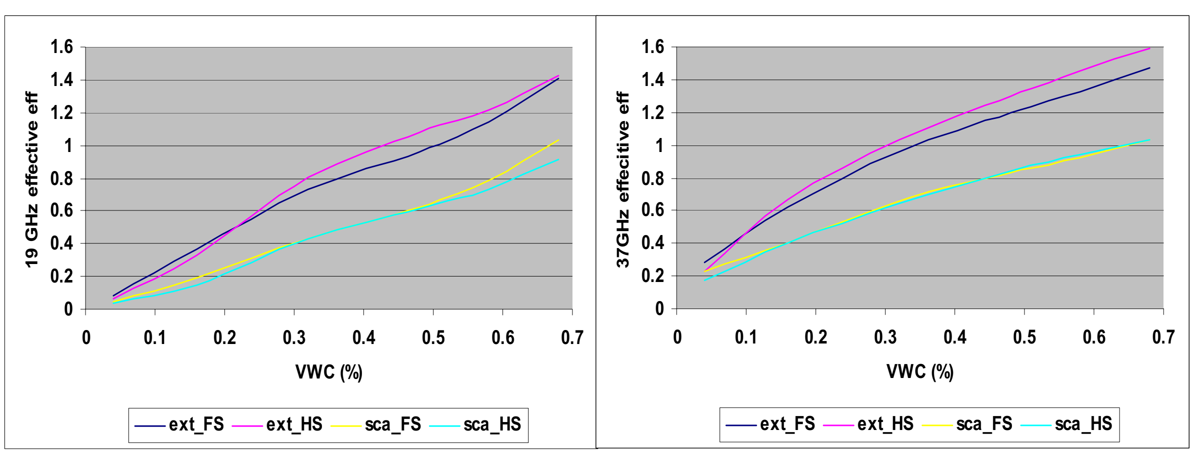

Fig. 3 Phase functions of leaf scattering for FS low VWC (4%) leaves at both 19 and 37GHz. Effective efficiencies of extinction and scattering, albedo (alb) and asymmetry factor (asy), are listed.

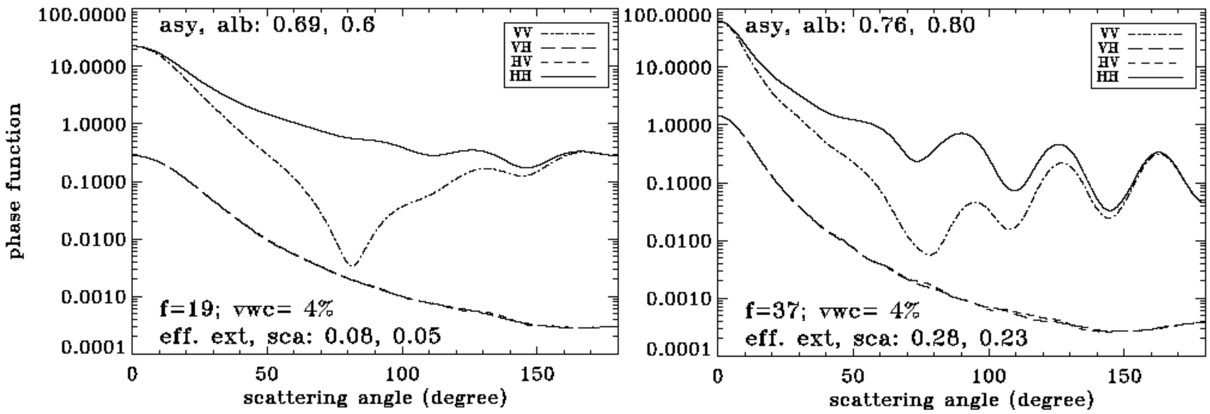

Fig. 4 Phase functions of co-polarizations for FS 68% VWC leaves.

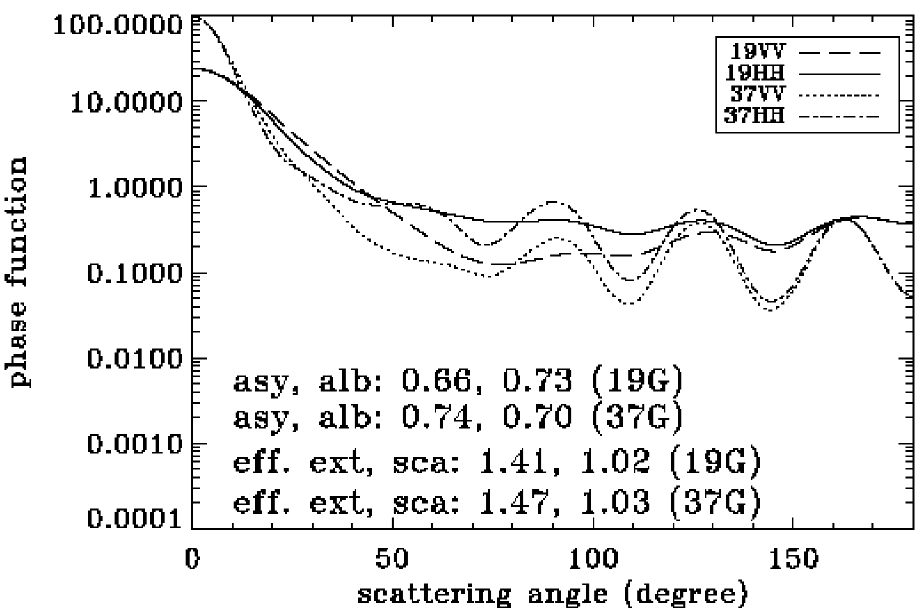

Fig. 5 The same as Fig. 4, except for HS leaves with 48% VWC.