□特輯 I /전자파 응용기술□

이방성 물질의 마이크로파대역 열 발산 모델

(A Thermal Microwave Emission Model for Row-Structured Vegetation)

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ABSTRACT

A simple emission model applicable for low scattering (scattering ≪ absorption) anisotropic layer is developed and applied to the interpretation of measurements of microwave emission from row crops. The vegetation layer of row crops is modeled as a random slab embedded with small spheroid with major axis aligend paralel to the crop-row direction. The total emission is given in a simple algebraic form based on the zero-order radiative transfer theory. The single scattering albedo for spheroid and its polarimetric phase function are presented. The effects of layer azimuthal dependence on emission are accounted for by using an anisotropic albedo in the zero-order transfer theory. The developed emission theory favorably compares with the brightness temperature measured over soybeans canopy.

요 약

약산란 이방성 물질의 마이크로파 열 발산을 예측하는 모델을 개발하였다. 이방성 물질은 조그마한 열입자가 어떤 특정한 방향으로 놓여있는 것으로 모델화하였다. 간단한 열전달 방정식을 사용하여서 모델을 단순화하였다. 이 모델은, 실제 C대축 이하에 농작물 발산측정 실험치와 비교하여 본 결과 측정치와 이론치가 잘 맞음을 보여준다.

I. Introduction

In the passive sensing of vegetation and forests from satellite platforms, microwave sensing techniques play an important role in characterizing the condition and types of vegetative terrain. A series of experiments dealing with radiometric emission from vegtation canopy have been performed using ground-based radiometer at the fields of soybeans, corn, and

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wheat, etc. As the recent meausrements(1,2) indicate, the emission from row crops strongly depends upon the direction of the vegetation row structures relative to the polarization of radiometer receiving antenna.

The purpose of this paper is to develop an emission model to explain the existing emission data of row crop canopy and to aid in understanding the emitting process for a row-strucgtured vegetation layer such as often encountered in agricultural scenes.

In the past, a number of emission theories have been developed and applied to interpret the vegetative and nonvegetative terrain emission data(3,6). However, it should be noted that none of aforementioned theories are directly applicable to the row crop emission problems due to their theoretical assumption of azimuthal isotropy of the emitting layer. This causes the existing theories to be less useful in the interpretation of row crop microwave emission data. hence, it is essential to develop an emission theory which can account for the effects of the row direction of canopy with respect to radiometer polarization and nadir andgles. For the sake of simplicity, the vegetation canopy is assumed to be a tenuous medium at the microwave frequencies; hence, it is possible to use the radiative transfer theory in emission model development. We model a vegetation canopy as a random scattering layer embedded with small dielectric spheroids with the major axis aprallel to the crop row direction. The effects of geometric row structure of vegetation layer can be accounted for by assuming that each scattering center such as leaf is aligned to a certain preferred direction. In the following section, an emission model is developed in the context of zero order transfer theory and its theoretical behavior and comparison with measurements are presented. A concluding remark and further recommendations are given in conclusions.

Ⅱ. Emission Model Development

Consider a small spheroid situated at the origin shown in Fig.1. The semi axes of the spheroid along x, y and z directions are a, b, and b, respectively (a>b). The incident and scattered polar and azimuthal angles are θ, θ', ϕ, and ϕ', respectively. In the low frequency approximation (ka <0.1, k; wave number in free space), the solutions for the scattered field due to an electromagnetic incident wave impinging upon a small spheroid are available in(7). From the scattered field expressions, it is possible to construct the phase function which, by definition, relates incident and scattered Stokes vectors(8). The first two-by-two elements of the phase function are found to be

$$P=\begin{bmatrix} P_{vv} & P_{vh} \\ P_{hv} & P_{hh} \end{bmatrix} \tag{1}$$

where

$$P_{vh}=\delta^2[-(\sin\phi\ \cos\theta'\ \cos\phi')/\alpha+(\cos\phi\cos\theta'\ \sin\phi')/\beta]^2$$

$$P_{hh}=\delta^2[(\sin\phi\sin\phi')/\alpha+(\cos\phi\cos\phi')/\beta]^2$$

$$P_{vv}=\delta^2[(\cos\phi'\ \cos\theta\cos\phi\ \cos\theta')/\alpha+(\sin\phi'\ \cos\theta\sin\phi\cos\theta'+\sin\theta\sin\theta')/\beta]^2$$

$$P_{hv}=\delta^2[-(\sin\phi\cos\theta\cos\phi)/\alpha+(\cos\phi'\cos\theta\ \sin\phi')/\beta]^2$$

Note that P_{pq} refers to the phase function elements corresponding to p-polarized scattered wave resulting from q-polarized incidence wave (v:vertical polarization and h:horizontal polarization). Horizontal (vertical) polaization is when the direction of electric field is perpendicular(parallel) to the plane of incidence.

where $\delta=\frac{2}{3}k^2(\epsilon-1)$; ϵ is the spheroid dielectric constant

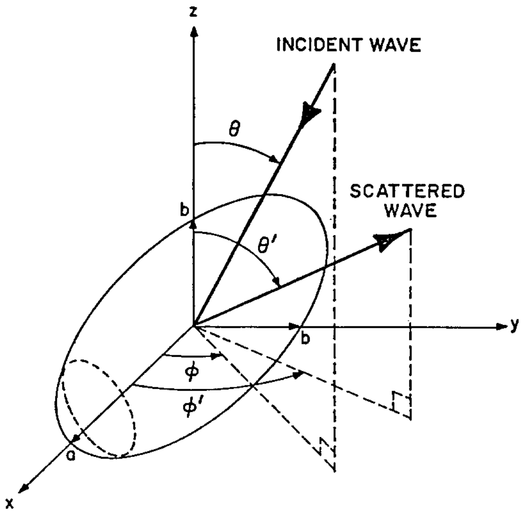

Fig. 1 Geometry of Emission Problem

$$\alpha=(\epsilon-1)I_a+2/ab^2$$

$$\beta=(\epsilon-1)I_b+2/ab^2$$

$$I_a=\int_0^{\infty}\frac{dx}{(a^2+x)^2\,(b^2+x)^{0.5}}$$

$$I_b=\int_0^{\infty}\frac{dx}{(b^2+x)^2\,(a^2+x)^{0.5}}$$

In addition to the phase function, the radiative transfer formulation calls for the expression for single scattering albedo associated with a spheroid. The single scattering albedo is defined as a ratio of total scattered power to incident power. Hence, the scattering albedo ω_h

for horizotally-polarized incidence is obtained by integrating P_{vh} and P_{hh} over the 4π solid angle with respect to scattered angles.

$$\omega_h=\int_0^{2\pi}\int_0^{\pi}(P_{hh}+P_{vh})\sin\theta'\,d\theta'\,d\phi'$$
$$=\omega_o(\sin^2\phi+\frac{\alpha^2}{\beta^2}\cos^2\phi),\ \text{where } \omega_0=\frac{8\pi\delta^2}{3\alpha^2} \quad (2)$$

Similarly, the albedo for vertically polarized incidence is

$$\omega_v=\int_0^{2\pi}\int_0^{\pi}(P_{vv}+P_{hv})\sin\theta'\,d\theta'\,d\phi'$$
$$=\omega_0[\cos^2\theta(\cos^2\phi+\frac{\alpha^2}{\beta^2}\sin^2\phi)+\frac{\alpha^2}{\beta^2}\sin^2\theta] \quad (3)$$

Consider a random scattering layer sparsely containing small spheroids. Utilizing the matrix doubling formulation(3) or its equivalent radiative transfer approaches (4-6), one can compute the total emission from the scattering layer above the half-space (ground). It is known that total emission from a scattering layer above the ground consists of three contributions such as semission T_1 from the ground, upwelling emission T_2 from the scattering layer, and downwelling emission T_3 from the layer reflected by the ground(6). In case the single scattering albedo is much less than unity such as considered here in vegetation passive sensing problem, the total emission T_p is approximately given as (6-9)

$$T_p=T_1+T_2+T_3$$
$$T_1=(1-R_p^2)\exp(-\tau/\mu)T_g$$
$$T_2=(1-\omega_p)[1-\exp(-\tau/\mu)]T_m \quad (4)$$
$$T_3=(1-\omega_p)R_p^2\ \exp(-\tau/\mu)[1-\exp(-\tau/\mu)]\ T_m$$

where p=v or h

where ω_p and τ are albedo and optical depth of the scattering layer. $\mu=\cos\theta$, R_p : p-polarized Fresnel ground reflection coefficient. T_m and T_g are the layer and ground physical temperatures, respectively.

In case the ground is covered with perfectly metallic surface ($R_p=1$), then total emission from the scattering layer is given as

$$T_p=(1-\omega_p)\ [1-\exp(-2\tau/\mu)]T_m \quad (5)$$

It is interesting to note from Eq. (2), (3) and (5) that the difference between T_v and T_h at nadir is determined by both α^2/β^2 (degree of spheroidal elongation) and ϕ (incidence azimuthal angle of radiometer). In the next section, we shall investigate the theoretical behavior of Eq.(5) and fit soybeans canopy emission data given in [1]

Ⅲ. Analysis

Fig.2 shows the theoretical emission behavior of the layer containing small spheroids when the shape of spheroid varies. The underlying ground is assumed to be covered with a perfectly conducting material. The nadir angle is 0 degree and the optical depth and

chosen to be 1 and 0.12, respectively. Since the incidence azimuth angle ϕ is chosen as 0, the direction of horizontally polarized incident E-field (electric field) vector is perpendicular to the major semi-axis (a) of the spheroid, whereas the direction of the vertically-polarized is paralled to the major semi-axis(a). The brightness temperatures at nadir are plotted as a function spheroidal shape parameters α^2/β^2 in Fig. 2. Note that the smaller the anisotropic parameter α^2/β^2 is, the more needle-like the slope of spheroid becomes. It is seen that when the direction of the incidence electric field is parallel to the longer dimension (a) of an ellipsoid, emission remains unaffected. This is because in the low frequency approximations considered in this study, the scattered field from the small dipole-like spheroid remains constant with the incidence angle when the major axis is parallel to the direction of the incident E-field. When the incident E-field is horizontally polarized (perpendicular to longer dimension a) the emission decreases as the shape becomes more spherical ($\alpha^2/\beta^2 \rightarrow 1$). This occurs because an increase in α^2/β^2 results in an increase in effective scattering albedo, thus decreasing the emission from the spheroidal particles.

Fig.3 shows the theoretical emission behavior of the scattering layer at nadir as radiometer rotates azimuthally 90 degrees. As expected from Fig. 2, maximum emission occurs whenever the radiometer E-field direction is perpendicular to the majoraxis of ellipsoid since this is when minimum scattering occurs from a dipole-like spheroid, In view of the theoretical behavior

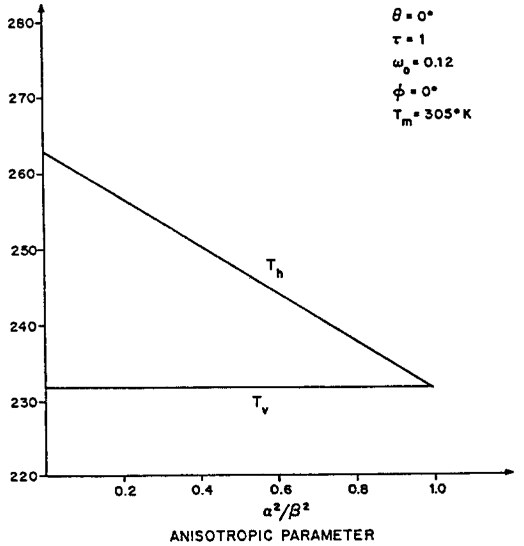

Fig.2 Brightness Temperature from Scattering Layer of Spheroids versus α^2/β^2

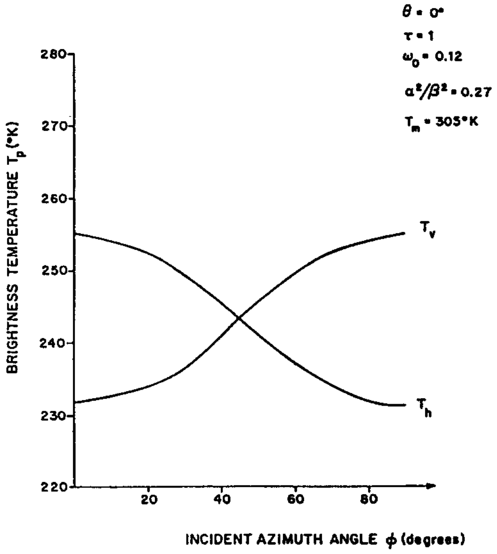

Fig.3 Azimuthal Angular Behavior of Brightness Temperature from Scattering Layer of Spheroids

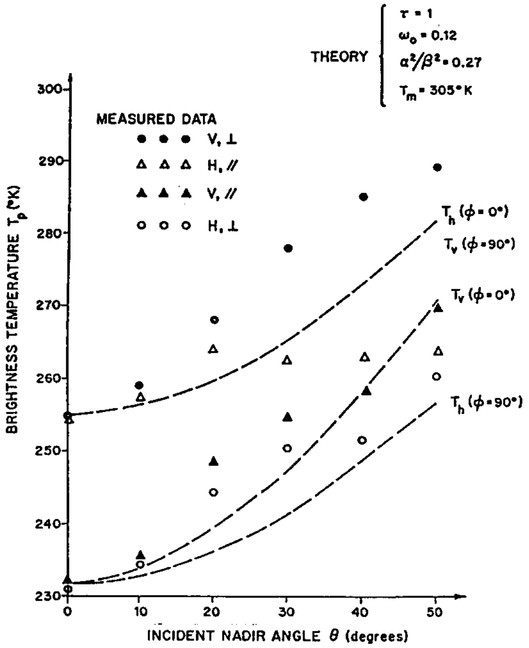

Fig.4 Comparison of Measured Brightness Temperature with Theory

shown in Fig. (2), (3), and the measurement data in Fig. (4), we model the soybeans canopy as a layer of spheroidal collections where a longer dimension (a) of spheroids are aligned with a row direction of the canopy.

Figure 4 shows the comparison with the brightness temperatures at 2.7 Ghz measured over lush soybeans canopy by Brunfeldt and Ulaby⁽¹⁾. The measurement was performed in such a way that the emission from the underlying ground is effectively suppressed by covering the ground with a metallic sheet within a radiometer footprint. Angular measurements at four different configurartions are shown with different symbols. For instance, the symbols v, ⊥ refers to the measured data when the verticallypolarized radiometer scans across the row of the canopy. (Note this case corresponds to $T_v(\phi=90°)$ in theoretical fit). We model the row-structured soybean canopy as a random layer embedded with small spheroids aligned along a row direction. AT first glance, this modeling approach may appear inadequate in that each soybean leaf is more likely to be independent of azimuthal orientation (ϕ). Even though each leaf, may have no such preferred azimuthal orientation, the soybean canopy as a whole can be regarded as such due to the geometric row structure of the field. As seen in Fig. 4, despite the inadequacy of its assumption, the theory fits reasonably the data in some cases. Theoretical fits to the data are shown, using Eq.(5). To realize the best fit. ω_0 and otpical depth are arbitrarily chosen as 0.12, 1 and $\alpha^2/\beta^2=0.27$. Even though the theory is developed based on the crude single scattering approximation of the zeroorder transfer theory, the general angular trends of the emission theory favorably compare with the measured data. This suggests that the effects of multiple scattering may not be important in microwave passive sensing problems below C-band.

Ⅳ. Conclusions

A simple expression is derived to estimate the microwave brightness temperature from the vegetation scattering layer with a row structure. The theoretical expressions fairly well explain the measurement behavior observed over soybean canopy. The developed simple estimation formula is useful in quickly estimating the brightness temperatures from row crops.

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