

# Angular Aspects of Microwave Single Scattering Albedo from Tapered Vegetation Constituents

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## Abstract

In microwave radiometry of vegetation canopies, the most important contributor to the emission is the long vegetation constituents such as tree trunks and primary branches. Their scattering pattern depends strongly on both shape and orientation. Since they are a dominant contributor to the emission, their scattering pattern must be taken into account properly when solving radiative transfer (RT) equations. A uniform dielectric cylinder model provides a simple model for a tree trunk and primary branches, which are mostly bent, not straight, and not symmetrical with respect to ground in nature. In this paper, the effect of tapering the trunk and branch diameter with height on the single scattering albedo is investigated with numerical simulations of a vertical cone and a vertical cylinder of the same height and volume. The preliminary results show that the single scattering albedo is not symmetric with respect to 90° of incidence angle for those objects such as tapered vegetation components. Its implications on the zero-order RT solutions such as tau-omega model will be also discussed.

## 1. Introduction

Numerous methods for retrieving geophysical parameters from radiometric measurements have been presented in the literature. The inverse solution of the radiative transfer (RT) equations is the most common approach. The RT equations become rather complex when the scattering is important and general analytical solutions do not exist. A number of methods with varying approximations, depending on the application, have been developed such as exact numerical [1], matrix doubling [2, 3], and iterative techniques [4-6]. The complexity of these approaches depends on the assumptions with respect to absorption and scattering within the canopy.

RT models usually consider the vegetation canopy as a layer of discrete scatterers over a random rough lossy ground. Vegetation constituents are usually represented by canonical shapes with random orientation, size, and position statistics. Leaves are modeled as elliptic or circular dielectric disks [7] as shown in Figures 1-a and 1-b while stems (or needles, stalks, branches, trunks) are modeled as finite length dielectric cylinders of commensurate dimensions [8] as shown in Figures 1-c and 1-d. These approximate shapes also have symmetry with respect to ground (xy-plane). On the other hand, actual trunks decrease in diameter from bottom to the top of a tree, and actual branches decrease in diameter from joint points to the tip as shown in Figures 1-e and 1-f [9, 10]. In nature, trunks and branches are mostly bent and they are not straight as shown in Figure 1-g. They usually do not have symmetry with respect to xy-plane. As will be described in this paper, their non-symmetrical shape with respect to ground affects both the scattering pattern and solutions of RT equations.

In the inverse solution of the RT equations, it is usually assumed that downward and upward components of the emitted radiations experience the same amount of attenuation within the vegetation. This assumption is satisfied with the reciprocity property of the particles of arbitrary shapes and azimuthal invariance to the particle rotation statistics. It is also implicitly assumed that scattering and absorption coefficients in upward and downward directions have the same angular dependence when solving RT equations. This is however satisfied only when the vegetation components have symmetric geometric shapes with respect to xy-plane such as cylinders and disks as in Figures 1 a-d. The effect of tapering the trunk and branch diameter with height on single scattering albedo is investigated in this study to demonstrate non-symmetry in single scattering albedo for objects such as a vertical cone. Its effect on inversion based on the zero-order RT solution such as tau-omega model will be also discussed.

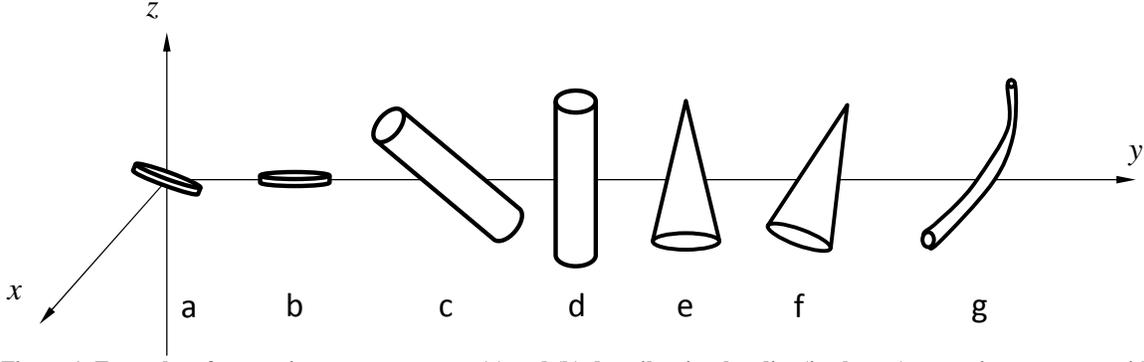


Figure 1. Examples of vegetation scatterer types: (a) and (b) describe circular disc (i.e. leaves) scattering geometry with inclined and vertically orientation, respectively; (c) and (d) describe finitely-long circular cylinder (i.e. branches, trunks) scattering geometry with inclined and vertically orientation, respectively; (e) and (f) describe finitely-long circular cone (i.e. branches, trunks) scattering geometry with inclined and vertically orientation, respectively; and (g) describes finitely-long branch with arbitrary shape and orientation.

## 2. Scattering, Absorption, and Extinction

The volume extinction coefficient  $\kappa_{ep}(\hat{\mathbf{t}}^\pm)$ , is determined by the forward scattering amplitudes, averaged over all particle size and angle orientations according to the forward scattering theorem (also known as the optical theorem) [1, 2]. The superscripts “-” and “+” here indicate propagation with a  $z$ -component toward the ground, and propagation with an upward  $z$ -component, respectively, as shown in Figure 2. In the figure, unit vectors  $\hat{\mathbf{t}}^\pm$  and  $\hat{\mathbf{o}}^\pm$  represents incoming and outgoing radiation, respectively. Since the forward scattering amplitude of an arbitrary moist particle is a complex quantity, then the homogenous vegetation medium will attenuate the mean wave. This attenuation is related to the absorption and scattering of the average wave by the scatterers as the wave travels within the canopy. The volume extinction coefficient can be written as sum of volume scattering and absorption coefficients of the layer:

$$\kappa_{ep}(\hat{\mathbf{t}}^\pm) = \kappa_{ap}(\hat{\mathbf{t}}^\pm) + \kappa_{sp}(\hat{\mathbf{t}}^\pm) \quad (1)$$

where the quantities  $\kappa_{ap}(\hat{\mathbf{t}}^\pm)$  and  $\kappa_{sp}(\hat{\mathbf{t}}^\pm)$  are absorption and scattering coefficients with polarization  $p \in \{h, v\}$ , respectively. Horizontal and vertical polarization is denoted by  $h$  and  $v$ , respectively.

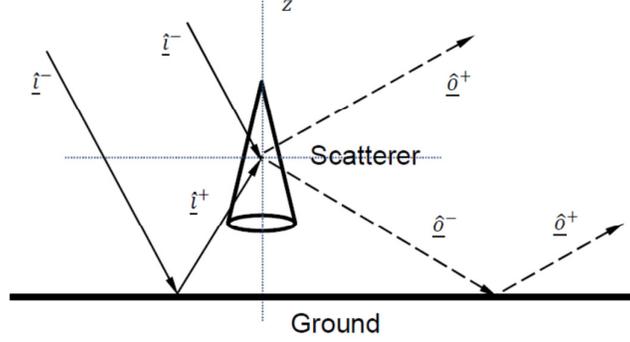
The emitted radiations experience the same amount of attenuation within the vegetation irrespective of whether the waves travel in the  $\hat{\mathbf{t}}^-$  ( $-\hat{\mathbf{t}}^+$ ) direction (downward) or the  $-\hat{\mathbf{t}}^-$  ( $\hat{\mathbf{t}}^+$ ) direction (upward), i.e.  $\kappa_{ep}(\hat{\mathbf{t}}^\pm) = \kappa_{ep}(-\hat{\mathbf{t}}^\pm)$  due to the reciprocity property of the particles. In addition,  $\kappa_{ep}(\hat{\mathbf{t}}^\pm)$  is equal to  $\kappa_{ep}(\hat{\mathbf{t}}^\mp)$  due to azimuthal invariance to the particle rotation statistics [1].

The portion of total extinction within the vegetation that is due to scattering is given by:

$$\kappa_{sp}(\hat{\mathbf{t}}^\pm) = \int_{2\pi} d\Omega' \sum_{q=h,v} F_{qp}(\hat{\mathbf{o}}^\pm; \hat{\mathbf{t}}^\pm) + \int_{2\pi} d\Omega' \sum_{q=h,v} F_{qp}(\hat{\mathbf{o}}^\mp; \hat{\mathbf{t}}^\pm) \quad (2.a)$$

where the integrations are performed over  $2\pi$  and  $d\Omega'$  is the unit volume over angles. The integration volume limit is divided into sum of two hemispheres to separate the radiation into upward and downward directions. The summation over  $q$  accounts for the possible polarization contribution of the scattered waves. This coefficient describes the amount of total  $q$ -polarized scattered power due to a unit amplitude  $p$ -polarized incident wave in the direction of  $\hat{\mathbf{t}}^\pm$ . Here, the collective phase function per unit volume is given by:

$$F_{qp}(\hat{\mathbf{o}}^\pm; \hat{\mathbf{t}}^\pm) = \sum_{\alpha} \langle |f_{qp}^{(\alpha)}(\hat{\mathbf{o}}^\pm; \hat{\mathbf{t}}^\pm)|^2 \rangle \quad (2.b)$$



**Figure 2. The direct and reflected components of the mean field are shown. The incoming and outgoing radiations are indicated as solid and dashed vectors, respectively.**

where the bistatic scattering amplitude of the  $\alpha$ th group of scatterers is given by the quantity  $f_{qp}^{(\alpha)}(\hat{o}^\pm; \hat{i}^\pm)$ . As seen in Eq. (2.a), the calculation of the scattering coefficient involves an integration of vegetation scatterers phase functions over all directions for the possible polarization combinations. The scattering coefficient is in general dependent on sensor parameters such as polarization and incidence angle, and vegetation properties such as plant architecture and vegetation water content. The fractional power scattered within the vegetation layer with respect to total extinction is denoted by the single-scattering albedo, which is given by:

$$\omega_p(\hat{i}^\pm) = \kappa_{sp}(\hat{i}^\pm)/\kappa_{ep}(\hat{i}^\pm) \quad (3)$$

This paper aims to show that the single scattering albedos (or scattering coefficient) in the upwelling and downwelling directions do not have the same symmetric angular dependence as the extinction coefficient does. In addition to reciprocity and the rotational particle statistics that are invariant in the azimuthal coordinates, geometrical symmetry with respect to ground-plane is required for the single scattering albedo to follow the same angular dependence as the extinction does. To demonstrate this symmetry requirement, the single scattering albedos of a cylinder and a cone with the same height and volume will be compared. Table 1 provides the characteristics of the scatterers. To make the problem easier, both cylinder and cone are assumed to be vertically oriented. However, one can easily extend these results to the cases where scatterers are not vertically oriented but azimuthally symmetric.

In Fig. 3, the single scattering albedos of vertical cone and cylinder are plotted as a function of incidence angle for every  $2^\circ$  over  $0^\circ$  to  $180^\circ$ . The results are given in both polarization states. The cylinder albedo is calculated by a dielectric cylinder of finite length approximation [8] while the cone albedo is calculated with exact numerical techniques [11]. In the figure, incidence angles below  $90^\circ$  represent the upward radiation while those smaller than  $90^\circ$  represent the downward radiation. As can be seen from the figure, the single scattering albedo of the finite dielectric cylinder (the red curve with a circle marker) is symmetric with respect to  $90^\circ$  whereas that of the cone (the blue curve with a square marker) is not. This non-symmetry in the cone single scattering albedo can also affect the form of radiative transfer solutions. This difference could be important at L-band since the branches and trunks are the most important contributors to emission and scattering.

### 3. Conclusion

In microwave radiometry of vegetation canopies, it is usually assumed that the emitted radiations experience the same amount of attenuation within the vegetation irrespective of whether they travel in the downward direction or the upward direction. This is due to the reciprocity property of the particles and azimuthal invariance to the particle rotation statistics. It is also implicitly assumed that scattering and absorption coefficients follow similar angular trend as the extinction coefficients. This assumption however requires that the shapes of vegetation particles are symmetric with respect to the ground. The former is satisfied in most natural vegetation that exhibits uniform distribution in azimuth, whereas the latter is rarely the case. This study presents angular aspects of microwave single scattering albedo from tapered vegetation constituents as compared to that of uniform dielectric cylinder models. The focus will be particularly placed on the effects of the lack of symmetry in the albedo on the solution of RT equations and inversion by the zero-order RT model such as tau-omega model. Preliminary results indicate that non-symmetry in single scattering albedo could be substantial, particularly at near vertical incidence angles.

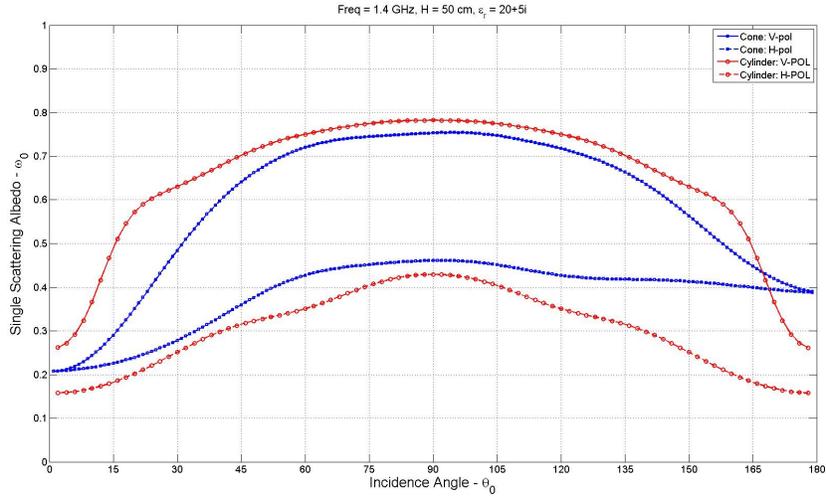


Figure 3. Single scattering albedo as a function of incidence angle.

Table 1 Properties of vegetation constituents considered in this study.

Type	Size		Relative Dielectric	Orientation	Frequency
	Radius	Length			
Circular Cylinder	0.01155 m	0.50 m	20 + 5i	Vertical	1.4 GHz
Circular Cone	0.02 m	0.50 m	20 + 5i	Vertical	1.4 GHz

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