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Photopolarimetric properties of leaf and vegetation covers over a wide range of measurement directions

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ABSTRACT

The optical scattering property of the target is the essential signal for passive remote sensing applications. To deepen our understanding of the light reflected from vegetation, we present results of photopolarimetric laboratory measurements from single leaf and two vegetation covers (planophile and erectophile) over a wide range of viewing directions. The bidirectional polarized reflectance factor (BPRF) was used to characterize the polarization property of our samples. We observed positive and negative polarization ($-\mathrm{BPRF}_Q$) of all samples in the forward scattering and backward scattering directions, respectively. Based on the comparison of the BPRF among single leaf, planophile vegetation and erectophile vegetation, our measurements demonstrate that the orientation of the leaf is a key factor in describing the amount of polarization in the forward scattering direction. Our measurements also validated certain model results stating that (1) specular reflection generates a portion of polarization in the forward scattering direction and diffuses scattering of polarized light in all hemisphere directions, (2) BPRF_U is anti-symmetric in the principal plane from a recent study in which the authors simulated the polarized reflectance of vegetation cover using the vector radiative transfer theory. These photopolarimetric measurement results, which can be completely explained by the theoretical results, are useful in remote sensing applications to vegetation.

1. Introduction

Vegetation is a sensitive indicator of many ecosystem properties that influence energy balance, climate, hydrology, and biogeochemical cycling [1]. In the discipline of terrestrial ecology, methods in which leaf- and vegetation cover-level observations are related to landscapes and regions have been the subject of much investigation. Because it is the only means for viewing large portions of the Earth's surface at regular and successive intervals, it is clear that remote sensing offers the opportunity to monitor, quantify and investigate large-scale changes in the response of vegetation to human actions and climate. Therefore, the success of this approach depends on our understanding and interpretation of the optical properties of light reflected by leaves [2,3] and vegetation cover [4,5], and the former fundamentally impacts the latter [6]. Although light can be described in terms of intensity and polarization, most optical remote sensing applications for vegetation primarily address the signal intensity [7] and focus little attention on the polarization measurement result [8]. This phenomenon has shifted after researchers devoted additional effort to improving our understanding and use of the polarization of leaves [9,10] and vegetation covers [11,12] for certain remote sensing sensors that are able to measure polarized radiation.

Without exception, the study of the polarization of vegetation has also experienced a development process ranging from the simple to the complex. First, the polarization measurements began with single leaf [9,10,13] and progressed to vegetation covers [11,14,15]. Researchers concluded that by using polarization measurements, the reflection of a leaf can be separated into two components, i.e., a polarized component from the first surface of the leaf and a non-polarized (or diffuse) component primarily from the internal leaf structure, and suggested that estimates of the specular portion of the reflection from vegetation cover contains information on the leaf surface information independent of that already identified in the light reflected from the interior of the leaves [16]. Additionally, these polarization results also demonstrated the relationship between polarization data and various optical and botanical properties of both leaves and vegetation covers [12].

Second, polarization measurements were performed from ground-based to airborne-based and spaceborne-based platforms.

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Laboratory and field polarization measurements of vegetation are highly important because they can be used to obtain the uninfluenced physical polarization properties. Although several polarization results for vegetation have been measured and analyzed in previous studies [14–23], only a small part of the results [15,19] can be combined with those obtained from airborne and spaceborne polarimetric instruments, such as the Research Scanning Polarimeter (RSP) [24], Micropolarimeter (MICROPOL) [25], Airborne Multi-angle SpectroPolarimetric Imager (Air MSPI) [26], Polarization and Directionality of the Earth's Reflectance (POLDER) [27] and Polarization and Anisotropy of Reflectances for Atmospheric Sciences Coupled with Observations from Lidar (PARASOL) [28], because the airborne and spaceborne measurements were defined as a polarized reflectance factor, whereas the laboratory and field measurements did not address this measure. Consequently, sufficient ground-based polarization measurements of vegetated surfaces should be available for coupling with airborne and spaceborne data in remote sensing applications of vegetation or the atmosphere.

Third, the polarized reflectance of vegetation was simulated using models that were constructed from semi-empirically to physically based ones. Although polarized remote sensing applications focus primarily on atmospheric science, the effect of the polarization of the lower boundary cannot be neglected. Therefore, several researchers proposed polarized reflectance models for interpretation of polarimetric measurements of the earth surface (vegetation is the main contributor) [28–32] and also validated their semi-empirical approaches using polarization measurements obtained over a wide range of viewing directions and several bands using airborne and spaceborne instruments. As mentioned, theoretical and empirical findings indicated that the polarization from vegetation surfaces was primarily generated by specular reflection, which is controlled in part by the Fresnel equation. Recently, researchers applied a vector radiative transfer model to describe the vegetation cover polarized reflectance factor [33], which is more accurate but more complex than the semi-empirical models. However, insufficient polarization measurements of leaf or vegetation cover are available for coupling with the theoretical approach given in [33].

In this paper, our goal is improved coupling of the photopolarimetric measurements with the vector radiative transfer model results of vegetation for the purpose of deepening our understanding of the optical properties of light reflected from vegetation. To achieve this goal, we (1) perform photopolarimetric measurements on leaves and two types of vegetation cover over a wide range of viewing directions; (2) define the polarized radiance of a leaf and vegetation covers in terms of a bidirectional polarized reflectance factor (BPRF), which is the same as the model results; and (3) demonstrate the theoretical model in [33] from the experimental point of view.

The reminder of this paper is organized as follows. The definitions are given in Section 2. Section 3 describes the details of the investigated samples and the measurement procedures. Section 4 presents the photopolarimetric measurements of leaves and two types of vegetation cover. A comparison of measurements and model results is covered in Section 5. Finally, Section 6 summarizes our conclusions.

2. Definition

In practical measurements, without considering the polarization of the light reflected from the sample surface, the bidirectional reflectance factor (BRF) of each sample (defined as the ratio of the reflected radiant flux (dL_{sample}) from the sample surface area (dA) to the reflected radiant flux (dL) from an ideal and diffuse surface of the same area (dA) in the identical viewing geometry under single-direction illumination) was used in the laboratory and can be defined as follows [34,35]:

$$BRF(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v) = \frac{dL_{sample}(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v)}{dL(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v)}\rho_\lambda \tag{1}$$

Where θ_{s} is the incident zenith angle, θ_{v} is the viewing zenith angle, φ is the relative azimuth angle, φ_{s} is the incident azimuth angle, and φ_{v} is the viewing azimuth angle. Strictly speaking, our measurements should be referred to as the bi-conical reflectance factor (BCRF), as shown in [34,35]. However, to maintain a definition of the reflectance factor that is identical to that used in previous studies [15,36,37], we assume that the BRF is approximately equal to the BCRF.

In polarimetric measurements, the polarization state of light reflected by a target surface can be described by the four Stokes parameters (I, Q, U and V), whereas V is usually negligible after reflection [8]:

$$I = (L_{0^\circ} + L_{45^\circ} + L_{90^\circ} + L_{135^\circ})/2 \tag{2}$$

$$Q = L_{0^\circ} - L_{90^\circ} \tag{3}$$

$$U = L_{45^\circ} - L_{135^\circ} \tag{4}$$

$$I_p = \sqrt{Q^2 + U^2} \tag{5}$$

$$Dolp = \frac{\sqrt{Q^2 + U^2}}{I} \quad or \quad Dolp = -\frac{Q}{I} \tag{6}$$

where L_x is the polarized reflected radiance from a surface at different polarizer directions, the reference plane for the four polarizer directions (0°, 45°, 90° and 135°) is taken to be the meridional plane of the instrument, I_{p} is the polarized reflected radiance from a surface, and *Dolp* is the degree of linear polarization, the second definition of *Dolp* is an approximation, which has been used to determine the sign of *Dolp*. The bidirectional polarized reflectance factor (BPRF) has been used to quantify the polarized reflected radiance [28–31,38,39]:

$$BPRF(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v) = \frac{\pi I_p}{E\cos(\theta_s)} \tag{7}$$

where E is the top-of-atmosphere solar irradiance. A common method for obtaining an estimate for the total spectral irradiance ($E\cos(\theta_{\mathrm{s}})$) is to measure the spectral radiance L from a horizontal reference panel of known hemispherical spectral reflectance (ρ_λ) and assumed Lambertian properties [40]:

$$E\cos(\theta_s) = \frac{\pi L}{\rho_\lambda} \tag{8}$$

Thus, the BPRF is defined as the ratio of the polarized reflected radiance (dI_{p}) from the surface area (dA) to the reflected radiance (dL) from an ideal and diffuse surface of the same area (dA) under identical viewing geometry and illumination direction in the laboratory measurements [41]:

$$BPRF(\lambda, \theta_s, \theta_v, \varphi_s, \varphi_v) = \frac{dI_p(\lambda, \theta_s; \theta_v, \varphi_s, \varphi_v)}{dL(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v)}\rho_\lambda \tag{9}$$

The Spectralon panel, which was supplied by the manufacture, was used as a perfect Lambertian panel in this study. Moreover, the following BPRFs of the Stokes parameters (Q and U) are defined:

$$BPRF_Q(\lambda, \theta_s, \theta_v, \varphi_s, \varphi_v) = \frac{dQ(\lambda, \theta_s; \theta_v, \varphi_s, \varphi_v)}{dL(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v)}\rho_\lambda \tag{10}$$

$$BPRF_U(\lambda, \theta_s, \theta_v, \varphi_s, \varphi_v) = \frac{dU(\lambda, \theta_s; \theta_v, \varphi_s, \varphi_v)}{dL(\lambda, \theta_s, \theta_v; \varphi_s, \varphi_v)}\rho_\lambda \tag{11}$$