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Canopy polarized BRDF simulation based on non-stationary Monte Carlo 3-D vector RT modeling

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ABSTRACT

Vector radiative transfer (VRT) has been largely used to simulate polarized reflectance of atmosphere and ocean. However it is still not properly used to describe vegetation cover polarized reflectance. In this study, we try to propose a 3-D VRT model based on a modified Monte Carlo (MC) forward ray tracing simulation to analyze vegetation canopy reflectance. Two kinds of leaf scattering are taken into account: (i) Lambertian diffuse reflectance and transmittance and (ii) specular reflection. A new method to estimate the condition on leaf orientation to produce reflection is proposed, and its probability to occur, $P_{l,\max}$, is computed. It is then shown that $P_{l,\max}$ is low, but when reflection happens, the corresponding radiance Stokes vector, $\boldsymbol{I}_o$, is very high. Such a phenomenon dramatically increases the MC variance and yields to an irregular reflectance distribution function. For better regularization, we propose a non-stationary MC approach that simulates reflection for each sunny leaf assuming that its orientation is randomly chosen according to its angular distribution. It is shown in this case that the average canopy reflection is proportional to $P_{l,\max}\cdot\boldsymbol{I}_o$ which produces a smooth distribution. Two experiments are conducted: (i) assuming leaf light polarization is only due to the Fresnel reflection and (ii) the general polarization case. In the former experiment, our results confirm that in the forward direction, canopy polarizes horizontally light. In addition, they show that in inclined forward direction, diagonal polarization can be observed. In the latter experiment, polarization is produced in all orientations. It is particularly pointed out that specular polarization explains just a part of the forward polarization. Diffuse scattering polarizes light horizontally and vertically in forward and backward directions, respectively. Weak circular polarization signal is also observed near the backscattering direction. Finally, validation of the non-polarized reflectance using the ROMC tool is done, and our model shows good agreement with the ROMC reference.

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1. Introduction

In order to analyze remote sensing observations, a physical model linking the observed surface radiometric properties to the measured radiances is needed. In the particular case of vegetation canopy, radiative transfer (RT) modeling is used to simulate and understand the different radiative phenomena within the media such as scattering, extinction, absorption and emission [1]. The RT theory was first proposed by Chandrasekhar [2] to study radiation scattering in conventional (i.e. rotationally invariant) media. Since the latter are assumed turbid (null scatterer size), this theory could not be directly used to model radiation transport in discrete medium like leaves and shoots in the vegetation case [3]. To overcome such a limitation, 3-D radiative transfer models based on iterative discrete ordinate approach [1] or Monte Carlo (MC) ray tracing techniques [4,5] have been proposed.

Classical radiative transfer model deals with radiance (scalar value) variation within the vegetation cover without taking into account the light polarization. Particularly, such a modeling neglects light Fresnel reflection by the interface between air and the cuticle wax layer, although it is known that, the amount of specularly reflected light by plants such as corn and grass is large in forward scattering direction. For such a configuration, canopy appears bright and almost white instead of green [6]. Starting from scalar RT, Nilson and Kuusk [7], Vanderbilt and Ustin [8] tried to simulate reflection produced by the first scattering by leaves. Particularly, they model the degree of linear polarization, however such an approach does not takes into account the leaf inclination in the estimation of the exiting light polarization which cannot explain the diagonal and negative polarizations for inclined-forward observation directions. Such a phenomenon has been already observed on ocean using PARASOL polarimetric

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measurements [9]. It was particularly shown that radiance reflected on the ruffled ocean polarization depends on the speed and direction of wind, indeed the latter modulates the roughness and the orientation of ocean waves which reflect polarized light. In vegetation canopy, the wave surface orientation can be replaced by the leaf normal orientation and the same effect can be produced. Unfortunately, such effect is still not observed since spaceborne sensor observation is affected by the atmosphere polarization and their current resolution (kilometric) is not enough to analyze vegetation canopy signal. Nevertheless, unmanned aerial systems (UAS) have revolutionized the remote sensing observation techniques allowing us to do low altitude and high resolution measurements. Particularly, accurate polarimetric sensors are currently under development by different space agencies such as CNES in France.

To simulate properly polarization phenomena, vector RT model should be used [10]. It deals with the light Stokes vector (four dimension) that represents the light intensity and the different polarization states (horizontal–vertical, diagonal and circular) as well as the four-by-four Stokes scattering (Mueller) matrix that describes the way a given medium diffuses polarized light Stokes vector. This theory has been firstly proposed by Chandrasekhar [2] based on phenomenological approach. More recently, Mishchenko et al. [10] have proposed a microphysical interpretation of this theory starting from the electromagnetic theory, approximating scattered light composition and doing some assumptions about medium components. In comparison with the extension of the scalar RT theory [7,8,11], VRT can deal with any polarization effect. Particularly, diagonal and circular polarization cannot be handled using the scalar theory. The polarization amplification and canceling due to the presence of leaves of similar and different orientations as well as multiple scattering is far from to be taken into account using the latter theory.

The MC methods are used to solve problems relying on repeated random sampling until convergence to an ‘acceptable’ numerical solution. Generally, such methods are useful when an analytic solution is not possible. Monte Carlo ray tracing in the optical domain has been widely used to solve the radiative transfer or electromagnetic problem within matters such as cosmic atmospheric dust particles, aerosol particles, clouds, soil and vegetation canopy [12]. Generally, these methods construct 3-D complex scenes composed by trees, soil, etc. using a large number of primitives such as triangles. For instance, a tree can be composed by three kinds of triangles corresponding to leaves, branches and trunk. Then, the radiative transfer is simulated by tracking the paths of a huge number of rays within the scene until they are absorbed or exit the scene. As initialization, the rays representing sun and atmosphere radiation reach the top of scene at random positions. Rays continue their propagation in straight-line until hitting the scene components, then the corresponding photons are absorbed or scattered according to the radiative features of the components. The bidirectional reflectance is estimated as the ratio between the photon reaching the sensor and those reaching the scene [12]. Due to the need of a large number of photons, the running time is a problematic point for MC. In order to reduce it and increase the precision for small number of photons, Thompson and Goel [13] propose a MC variance reduction technique called ‘photon spreading’. At each scattering event, a secondary ray is sent toward the sensor possibly with a non-null field of view (FOV). This approach has been implemented in the Rayspread model [14]. The drawback of this theory is that it cannot sample rare events as they produce discontinuous peaks in the solution space. Specular reflection is an example of such an event since scattering by a smooth surface occurs only in a narrow solid angle, which makes it difficult to simulate.

In this paper, we propose a new 3-D vector RT model to simulate properly the different polarization effects (e.g. coherent backscattering, circular polarization, etc.) that are induced by leaves within a vegetation cover. This 3-D vector radiative transfer model treats separately leaf diffuse scattering and leaf specular polarized reflection. Both of them are simulated using forward MC ray-tracing. Nevertheless, as the specular effect generates irregular polarized reflectance, a non-stationary MC approach assuming that leaf orientations are randomly distributed according to the leaf normal angular distribution proposed. In addition, in order to increase the model accuracy, the probability that a leaf produces specular reflectance is revisited and new formulas taking into account leaf orientations are given.

This paper is organized as follows. Section 2 provides an overview about the state of art on vegetation light polarization. Section 3 recalls the theoretical background. Then, Section 4 outlines our approach. After that, Section 5 shows our experimental results. Finally, Section 5 summarizes our conclusions and perspectives.

2. State of the art on vegetation polarized reflectance

Most remote sensing sensors do not measure polarized radiation. This is mainly due to the fact that unpolarized radiation is usually much larger than polarized radiation. In addition, measuring polarization requires more complex sensors. Nevertheless, more and more laboratory [15–17], field [18,19] airborne [20] and spaceborne [21] polarimetric sensors are being developed. Indeed, studies on light polarization by vegetation have shown the efficiency of polarimetry to retrieve canopy structural and biophysical properties [22], and to differentiate several kinds of leaves [15], etc.

Several sensors with resolutions varying from leaf scale [17] to kilometric pixel size [23] have been used to study vegetation polarized reflectance. The objectives depended on the sensor spatial resolution and also on its capacity to measure polarizations. Indeed, a simple measure of the degree of linear polarization can be enough to highlight the specular reflection [24] whereas it is necessary to measure several scattering coefficients of the Mueller matrix to identify for instance biomarker [16].

Laboratory laser instruments, spectropolarimeters, are the most accurate sensors for measuring leaf biophysical properties. Most basic measurements have dealt with the degree of polarization [25]. Testing the bidirectional reflectance of a number of leaves, Xie et al. [26] showed that the degree of linear polarization increases as a function of the incident and observation angles. Grant et al. [27] have studied the reflectance at the Brewster angle (the angle that maximizes the degree of polarization). They concluded that specular reflection is produced at the leaf surface whereas the diffuse scattering is generated in the interior of the leaf. More in depth, the polarized part of the specular reflectance is due to the mid-size particles (Mie scattering), whereas the unpolarized reflectance is due to small-size (Rayleigh scattering) ones. The comparison between adaxial and abaxial leaf surfaces shows that the former contains clusters of small wax flakes, whereas mid-size wax filaments compose the latter. This difference explains why the abaxial surface reflects more polarized lights. Rondeaux and Guyot [28] came to the same conclusions. Furthermore they explain the presence of polarized light far from the reflection direction by the Mie scattering which has an effect equivalent to a rough surface. Moreover, to take into account the roughness of the leaf surface, Brakke [29] proposed to multiply the original Fresnel reflection relationship by a spectrally independent correction term that depends on the leaf roughness, the leaf refraction index and on the incidence angle.

More precise leaf polarimetric measurements have also been

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