Remote Sensing of Environment 210 (2018) 325–344

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A modified version of the kernel-driven model for correcting the diffuse light of ground multi-angular measurements

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ARTICLE INFO

Keywords:
Kernel-driven model
BRDF
HDRF
Hemispherical diffuse irradiance
Atmospheric correction
PROSAIL
RAPID
POLDER
CAR

ABSTRACT

When using the kernel-driven bidirectional reflectance distribution function (BRDF) model to process multi-angular measurements, the input multi-angular measurements must be corrected for atmospheric effects. However, in current databases, a significant number of ground-based multi-angular measurements contain either no corrections or only approximate corrections for atmospheric effects. Thus, the blended diffuse light in the total incident irradiance will result in considerable smoothing of the reflectance anisotropy retrieved by the kernel-driven model unless an atmospheric correction process is conducted. In this study, we propose a diffuse-light correction (DLC) form of the kernel-driven model that improves its ability to process multi-angular measurements blended with hemispherical diffuse light. The DLC form of the kernel-driven model can be used to retrieve the intrinsic reflectance anisotropy of the observed target from atmospheric-uncorrected multi-angular measurements. This study used multi-angular data simulated by the PROSAIL and Radiosity Applicable to Porous IndiviDual objects (RAPID) BRDF model, atmospheric-corrected Polarization and Directionality of the Earth's Reflectances (POLDER), Cloud Absorption Radiometer (CAR) multi-angular measurements and their simulated data based on the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) tools to validate the effectiveness of the DLC form of the kernel-driven model. The results indicated that the reflectance factors directly retrieved by the kernel-driven model are considerably smoothed by the blended diffuse light, especially in hotspot regions. Even under clear and cloudless sky conditions, the retrieved hotspot reflectance in the red band is still underestimated by an average of 9.25%, 7.72%, 11.0% and 13.8% for the PROSAIL, RAPID, POLDER and CAR data, respectively. In contrast, the hotspot reflectance retrieved by the DLC form of the kernel-driven model is very close to the intrinsic reflectance anisotropy of the targets; the average relative error of the DLC form of the kernel-driven model is only 1.99%, 1.50%, 4.57% and 3.42%, respectively. Although the reflectance reconstructed by the DLC form of the kernel-driven model in the hotspot region represents a considerable improvement compared with the reflectance retrieved by the original kernel-driven model, its improvement on the root mean square error (RMSE) and the bias of the entire datasets is not very apparent. Using the DLC form of the kernel-driven model can significantly improve the ability of the kernel-driven model to process multi-angular measurements blended with hemispherical diffuse irradiance.

1. Introduction

Ground-based multi-angular reflectance measurements of natural targets are becoming increasingly important in quantitative remote sensing studies. Such measurements can be used (1) to validate the currently available bidirectional reflectance distribution function (BRDF) models (Gao et al., 2001; Hu et al., 1997; Huang, Jiao et al., 2013; Jiao et al., 2016; Lucht et al., 2000; Roujean et al., 1992; Wanner et al., 1995; Wanner et al., 1997), (2) to explore the physical mechanisms of the BRDF effects (Deering et al., 1992; Deering et al., 1994; Irons et al., 1992; Kimes et al., 1986; Kimes et al., 1985), (3) to investigate the relationships between vegetation structure parameters with BRDF effects (Sandmeier, 2000; Sharma et al., 2013), (4) to validate spaceborne multi-angular reflectance measurements (Deschamps

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https://doi.org/10.1016/j.rse.2018.03.030
Received 4 August 2017; Received in revised form 16 March 2018; Accepted 20 March 2018

et al., 1994; Schaaf et al., 2002), (5) to retrieve BRDF archetypal shapes as prior knowledge (Jiao et al., 2015; Jiao et al., 2014; Zhang et al., 2013; Zhang et al., 2015), and (6) to facilitate the development of new BRDF models (Li and Strahler, 1985, 1992; Chen and Leblanc, 1997). However, there are still some issues that need to be addressed if researchers want to process ground-based multi-angular measurements to retrieve the intrinsic BRDF shapes of observed targets.

Semi-empirical kernel-driven BRDF models have been widely used for many aspects of remote sensing (Dong et al., 2016; Jiao et al., 2016), such as the accumulation and application of prior knowledge of BRDF archetypal shapes (Jiao et al., 2015; Jiao et al., 2014; Zhang et al., 2016; Zhang et al., 2015) and the estimation of vegetation structure parameters (Chopping et al., 2008; Gao et al., 2003; He et al., 2012; Hill et al., 2011; Jiao et al., 2018; Pisek et al., 2011; Wang et al., 2011; Wei and Fang, 2016; Zhu et al., 2012). When using kernel-driven models to process multi-angular measurements, the input multi-angular measurements are required to be corrected for atmospheric effects (Lucht et al., 2000). However, a significant amount of the ground-based multi-angular reflectance measurements in the currently accumulated databases still include only approximate or no corrections for atmospheric effects (Lyapustin and Privette, 1999). Several studies have indicated that the BRDF shapes of the observed target are considerably distorted by the presence of blended diffuse light in the total incident irradiance (Asrar and Myneni, 1993; Huang et al., 2017; Lewis and Barnsley, 1994; Lyapustin and Privette, 1999; Martonchik, 1994; Schaepman-Strub et al., 2006). The accuracy of the retrieved reflectance factors will degrade when uncorrected ground-based multi-angular measurements are processed directly by the kernel-driven model. Accordingly, the accuracy of the accumulated BRDF archetypal shapes and the estimated vegetation structure parameters based on kernel-driven models will also be influenced.

To correct the atmospheric effects, Martonchik (1994) developed an accurate bidirectional reflectance retrieval algorithm based on radiative transfer solutions. The method requires that the observed multi-angular reflectance measurements contain a representative number of solar zenith angles. To reduce the requirement for solar zenith angles, Lyapustin and Privette (1999) developed a new algorithm that can retrieve the bidirectional reflectance using only one solar zenith angle. The semi-empirical Rahman-Pinty-Verstraete (RPV) BRDF model (Rahman et al., 1993) was used to provide prior information concerning the general BRDF shapes. However, the iterative approach used by this method affects its efficiency when processing large amounts of data. In addition, both of the abovementioned methods are aimed at correcting the blended diffuse light in multi-angular measurements; thus, they do not directly improve the ability of the kernel-driven model to process multi-angular measurements blended with diffuse light.

In this study, a diffuse-light correction (DLC) form of the kernel-driven model is developed to improve its ability in processing the multi-angular measurements blended with hemispherical diffuse irradiance. The DLC form of the kernel-driven model considers conditions in which hemispherical diffuse irradiance is blended into the total incident irradiance. It assumes that the simulated reflectance factors by the kernel-driven model fit well with the inherent reflectance anisotropy of the observed target when no diffuse irradiance is blended in the multi-angular measurements, and the ratio of diffuse-to-total incident irradiance can be observed during the measurement. Then, the intrinsic reflectance anisotropy of the observed target can be retrieved from the multi-angular measurements blended with the diffuse light using the DLC form of the kernel-driven model.

The bidirectional reflectance factors (BRF) and hemispherical-directional reflectance factor (HDRF) data simulated by the PROSAIL and Radiosity Applicable to Porous IndiviDual objects (RAPID) BRDF model, atmospheric-corrected Polarization and Directionality of the Earth's Reflectances (POLDER), Cloud Absorption Radiometer (CAR) BRF measurements and their simulated HDRF data based on the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) tools are utilized to evaluate the effectiveness of the DLC form of the kernel-driven model. The reflectance factors retrieved by the original and the DLC form of the kernel-driven model from the HDRF data are compared with the BRF data. Finally, the reflectance factors under various ratios of diffuse-to-total incident irradiance are simulated by the DLC form of the kernel-driven model to explore its usage in the application of quantitative remote sensing.

2. Method and data

2.1. Kernel-driven model

The equation for the kernel-driven model can be expressed as (Lucht et al., 2000; Roujean et al., 1992; Wanner et al., 1995):

$$R(\theta, \vartheta, \phi, \Lambda) = f_{iso}(\Lambda) + f_{vol}(\Lambda)K_{vol}(\theta, \vartheta, \phi) + f_{geo}(\Lambda)K_{geo}(\theta, \vartheta, \phi) \tag{1}$$

where $R(\theta,\vartheta,\phi,\Lambda)$ are the BRF in band Λ. $f_{iso}(\Lambda)$, $f_{vol}(\Lambda)$ and $f_{geo}(\Lambda)$ are the three parameters of the kernel-driven model. $K_{vol}(\theta,\vartheta,\phi)$ and $K_{geo}(\theta,\vartheta,\phi)$ are the volumetric scattering kernels and geometric-optical surface scattering kernels, which are a function of the solar zenith angle (θ), view zenith angle (ϑ) and relative azimuth angle (ϕ). The volume-scattering kernels are based on the radiative transfer theory presented by Ross (1981). The kernels include the Rossthick (Roujean et al., 1992), Rossthin (Wanner et al., 1995), RossthickMaignan (Maignan et al., 2004), and RossthickChen kernels (Jiao et al., 2016). Moreover, the geometric-optical kernels include the Roujean kernel (Roujean et al., 1992), LiSparse and LiDense kernel (Wanner et al., 1995), Li-Transit kernel (Li et al., 1999) and reciprocal versions of the Li kernels (Lucht et al., 2000).

If atmospherically corrected reflectance measurements $\rho(\Lambda)$ made at angles (θ,ϑ,ϕ) are given, the optimal three model parameters $f_{iso}(\Lambda)$, $f_{vol}(\Lambda)$ and $f_{geo}(\Lambda)$ can be retrieved using the least square method (Lucht et al., 2000). Then, the reflectance factors in any illumination and view direction can be simulated using the three parameters. However, if the input multi-angular reflectance measurements are blended with the hemispherical diffuse irradiance, the three parameters should not be directly inversed from the multi-angular data using Eq. (1). Otherwise, the retrieved reflectance factors will be considerably smoothed compared with the inherent reflectance anisotropy of the observed target.

In the following section, we derive the DLC form of the kernel-driven model, which can directly retrieve the three model parameters from the multi-angular reflectance measurements blended with diffuse light. Thus, the reflectance factors without the influence of diffuse light can be simulated using the three parameters.

2.2. The DLC form of the kernel-driven model

The radiance received by the sensors (L) consists of three components (Lee and Kaufman, 1986; Schaepman-Strub et al., 2006):

$$L = L_{atm} + L_{dir} + L_{diff} \tag{2}$$

where L_{atm} is the radiance of light scattered by the atmosphere without being reflected by the target (usually termed atmospheric path radiance, Fig. 1(a)). L_{dir} is the radiance of sunlight directly incident the target, then reflected by the target, and then transmitted directly from the target to the sensor through the atmosphere (Fig 1(b)). L_{dir} is a useful signal that provides the total information concerning the reflectance anisotropy of the observed target (Lee and Kaufman, 1986; Schaepman-Strub et al., 2006; Tanre et al., 1983). L_{diff} represents the diffuse radiance. It also consists of three components:

$$L_{diff} = L_{diff1} + L_{diff2} + L_{diff3} \tag{3}$$

where L_{diff1} is the radiance of light scattered by the atmosphere before reaching the surface, reflected by the target and then directly transmitted to the sensor (Fig. 1(c)). L_{diff2} is the radiance of light transmitted directly through the atmosphere, reflected by the target, and then