Remote Sensing of Environment 193 (2017) 29–37

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Polarized reflectances of urban areas: Analysis and models

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ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 9 February 2017
Accepted 28 February 2017

Keywords:
BPDF
Urban areas
PARASOL
Fresnel equation
NDVI

ABSTRACT

Accurate BPDF (Bidirectional Polarization Distribution Functions) of urban will help to improve the accuracy of inverted aerosol parameters that is very important for the research of urban atmospheric pollution and climate change. With Fresnel formula of polarization as the foundation, this paper studies three important factors that influence the BPDF: shadow, slope distribution and NDVI, and proposes a new BPDF model (named as Xie-Cheng model for convenience in comparison) for urban areas. Because the influence of slope distribution is trivial, only two parameters are needed in the new model, one controlling the shadow and the other for overall scale. An experimental factor is introduced into the model to compensate the influence of NDVI for polarized reflectance more accurately. Experiments prove that new model performs best in both correlation and RMSE for measurements not only with different urban places around the world but also clustered urban data by different NDVIs. Compared with the best current BPDF model, new model can reduce the average RMSE error by about 4.5% for different urban areas. Error distribution in polar coordinates also shows that new model can achieve smallest errors in almost all directions under fixed sun zenith angle.

1. Introduction

Due to the unique advantages of polarization, polarized remote sensing using multiple-viewing-angle polarized measurements has been widely used in the retrieval of aerosol properties (Deuzé et al., 2001; Herman, 2005; Waquet et al., 2009a; Tanré et al., 2011; Dubovik et al., 2011; Cheng et al., 2012; Xie et al., 2013; Kokhanovsky et al., 2015). One of the key factors influencing the precision of aerosol retrieval is polarized reflectance of surface in different directions, which can be modeled by BPDF (bidirectional polarized distribution function). Compared with the surface non-polarized reflectance, surface BPDF is usually considered as spectrally independent (Waquet et al., 2009b) in the visible and infrared regions and described by models based on the assumption of single Fresnel reflection from the surface facets (Roujean et al., 1992; Bréon et al., 1995; Nadal and Bréon, 1999; Maignan et al., 2009; Waquet et al., 2009b; Litvinov et al., 2011, 2012; Xiang et al., 2015, 2016). Although many BPDF models had been developed, none of them was about urban areas, over which the aerosol is crucial for climate change research (Hansen et al., 2005).

Roujean et al. (1992) presented an analysis of polarization measurements acquired over corn and soybean crop canopies and developed a simple physical BPDF model based on the hypothesis that leaves specularly reflect light according to the Fresnel equations. Without considering any attenuation on the incident and outgoing path, Bréon et al. (1995) developed a physically based BPDF for bare soil assuming that the ground is composed of isotropically distributed facets (rough surface). Based on spaceborne POLDER (Polarization and Directionality of Earth's Reflectances) polarization measurements of two months, Nadal and Bréon (1999) proposed a semi-empirical surface BPDF that was adopted by POLDER aerosol product processing line (Deuzé et al., 2001).

Waquet et al. (2009b) compared four BPDF models including scaled Fresnel model, linear combination model developed for bare soil and vegetation (Bréon et al., 1995), Nadal-Bréon model (Nadal and Bréon, 1999), and scaled Fresnel model with shading factor validated by MICROPOL measurements for closely cropped surfaces and forest in the North of France. The results confirmed that the polarization generated by the reflection of vegetated surfaces could be considered as being primarily a specular reflection process. Comparison showed that the linear combination model is not adequate to fit the observed surface polarization angular behavior and Nadal-Bréon model would overestimate the surface polarized reflectance for closely cropped surfaces. Maignan et al. (2009) had performed an extensive comparison of different BPDF models with POLDER satellite data and introduced a new one-parametric model that allowed a similar fit to POLDER data as a previously developed Nadal-Bréon model (Nadal and Bréon, 1999).

Litvinov et al. (2011) proposed a three-parameter BPDF model and tested different models of the BPDF for bare soil and vegetation surfaces using multi-angle, multi-spectral photo polarimetric airborne

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http://dx.doi.org/10.1016/j.rse.2017.02.026
0034-4257/

measurements of the Research Scanning Polarimeter (RSP) which was a prototype for the Aerosol Polarimetry Sensor instrument of the NASA Glory Project (Cairns et al., 1999; Mishchenko et al., 2007). Experiments showed that the new BPDF model was better than the semi-empirical Nadal-Bréon model (Nadal and Bréon, 1999) and the model developed by Maignan et al. (2009). Litvinov et al. (2012) derived physical BPDF model from the general solution of the electromagnetic scattering problems by random media. Multi-angle photo polarimetric airborne measurements of the RSP and satellite POLDER measurements were used to investigate the performance of the presented model.

Compared with the simple land cover types, such as forest, grassland, cropland and desert et al., the combination of urban is very complex, including many buildings, trees and roads. This paper proposes a new semi-empirical BPDF model for urban areas. The multi-angle polarized data contained in PARASOL (Polarization and Anisotropy of Reflectances for Atmospheric science coupled with Observations from a Lidar) BRDF are used to test our new model and achieve good approximation compared with existing models. Only polarized reflectance of 865 nm is used in this paper and the surface-polarized reflectance was considered to be spectrally neutral (Nadal and Bréon, 1999), but in fact many objects in urban areas may be spectrally invariant such as plastics and coated roof, which is beyond the scope of this article and should be a potential issue of urban areas using new instruments with more channels, higher precision and resolution such as 3MI (Marbach and Riedi, 2015) in the future.

This paper is organized as follows. Section 2 describes the data and definitions for our experiments. Section 3 compares the state-of-art BPDF models and proposes our new model for urban areas. The comparisons of different BPDF models in terms of correlation and RMSE are discussed in Section 4. Finally, conclusions are given in Section 5.

2. Data and definitions

The urban data used in this paper are from BRDF databases generated from POLDER instrument onboard the PARASOL satellite. Although the database was named by BRDF and mainly concerned the directional signatures of the reflectance, it was also extended to provide the polarized reflectance at 865 nm (near infrared) which is much less affected by the highly polarized molecular and aerosol scattering than the shorter wavelength channels, such as 490 nm and 670 nm measured by POLDER instrument. In-flight calibration of polarized channels was carried out using the sun's glitter and the expected accuracy is about 0.5% in the near-infrared channel 865 nm and about 2% in the visible channels, in terms of percent polarization (Toubbe et al., 1999). The LSCE, one of the POSTEL Expertise Centre, defined a new method to select the BRDFs from PARASOL data acquired from November 2005 to October 2006 in order to build four BRDF databases: two monthly databases gathering the best quality BRDFs for each month independently, two yearly databases designed to monitor the annual cycle of surface reflectance and its directional signature whose selection of high quality pixels was based on the full year. The monthly and yearly BRDF databases were organized based on the IGBP classification and the GLC2000 land cover map. In this paper, we use the urban type (IGBP class: 13) data from BRDF database classified by IGBP land cover map which can be downloaded freely from POSTEL website (http://postel.mediasfrance.org).

In the BRDF database, the multi-angle reflectances of 6 bands (490, 565, 670, 765, 865, 1020 nm) and polarized reflectance of 865 nm, along with the geometrical angles of each measurement direction (sun zenith, view zenith, and relative azimuth) of one month for each site were saved into a file. Only linear polarization was considered in the BRDF database, so the polarized reflectance R_p can be defined as:

$$R_p = \frac{\pi\sqrt{Q^2 + U^2}}{E_0 \cos(\theta_s)} \tag{1}$$

where Q and U are the components of Stokes vector, θ_s is the sun zenith, E_0 is the irradiance at the top of atmosphere. All files were firstly divided into different directories according to the classification and then organized by NDVI, which is an important parameter to distinguish different surface cover types. The average NDVI of one month was calculated and saved into the file.

3. BPDF model for urban type

Several BPDF models were proposed up to now, which can be divided into two categories: physical and semi-empirical. But none of them was developed and validated for urban type specially. Table 1 lists all the previous BPDF models (see Appendix B) and compares their differences in several aspects: type, number of parameters, surface types and device.

Based on the principle of polarized reflectance and characteristics of urban areas, we propose a new BPDF model for urban type

$$R_p = \mathrm{A} \times F_p(N, \gamma) \times f_{sh}(\gamma) \times \exp(-w \times \mathrm{NDVI}) \tag{2}$$

$$f_{sh}(\gamma) = \left(\frac{1 + \cos k_\gamma(\pi - \gamma)}{2}\right)^3 \tag{3}$$

where $w = 0.7$ and two parameters are included in new model: A and k_γ. $F_p(N, \gamma)$ is the polarized Fresnel function to describe the polarized specular reflectance (see Appendix A). The shadowing function $f_{sh}(\gamma)$ was used in the Litvinov model and k_γ controls the shadowing. In order to compensate for the influence of NDVI to polarized reflectance better, we add an experimental parameter w. The physical model (Rondeaux and Herman, 1991) is not adopted as the foundation of our new model like Nadal-Bréon, Maignan and Litvinov model, whereas we use the polarized Fresnel function directly. The reason is that a large amount of vegetation and bare soil are contained in the urban areas, so the physical model designed for vegetation is not suitable for the urban type. Our new model considers the influence of shadow and NDVI, whereas we do not introduce the slope function.

3.1. Shadow

According to the real measurements, the polarized reflectance decreases with the scattering angle. The simulated polarized reflectances of two physical models coincide with the measurements well when the scattering angle is large, but overestimate the measurements as the scattering angle is smaller than some threshold. This phenomenon can be explained by shadowing effect. When seen from the backward scattering direction (scattering angle = 180°), there are no places

Table 1
Comparison of previous BPDF models.

Authors	Year	Type	Num. of parameters	Surface types	Device
Rondeaux et al.	1991	Physical	0	Crop canopies	Polarimeter from LOA
Bréon et al.	1995	Physical	0	Bare soils, vegetaion	REFPOL
Nadal & Bréon	1999	Semi-empirical	2	Forest, shrublands, low vegetation, desert	POLDER
Waquet et al.	2009	Semi-empirical	2	Forest, closely cropped surfaces	MICROPOL
Maignan et al.	2009	Semi-empirical	1	14 IGBP classes except for urban	PARASOL
Litvinov et al.	2011	Semi-empirical	3	Soil, vegetation	RSP