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An assessment of the bidirectional reflectance models basing on laboratory experiment of natural particulate surfaces

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A B S T R A C T

The bidirectional reflectance model is commonly used to study surface structure and composition of atmosphereless celestial bodies basing on photometric measurements. We conducted a test of two bidirectional reflectance models, which are theoretically similar but with different form, to assess their ability for calculating the bidirectional reflectance of particulate surfaces and if the parameters could be confidently linked to the surface's property. Two types of natural particulate surfaces with controlled particle sizes vary from 300 μm to 900 μm have been measured in the visible and near-infrared wavelength with the NENULGS (Northeast Normal University Laboratory Goniospectrometer System), we only used these measurement results at 560 nm and 670 nm which are regarded to the evaluation standard of models. In this range of particle size, the bidirectional reflectance models were well match to the experimental data as the results shown in previous publications. Although some parameters of the models can be used to simulate the reflectance of particulate surface, they contain no reliable information on the physical property of our samples. Furthermore, the influence of the number of viewing angles on the precision of modeling results has been tested in this paper. It is clear that an increase of the number of viewing angles and the range of azimuth angles could allow us to improve precision on the estimation of parameters. Comparing with the best fitted model reflectance, we also found that if we used the parameters, which derived from measurements in the principal plane for individual incident zenith angle, to model the bidirectional reflectance may overestimate the computed results in the backward scattering direction and underestimate the computed results in the forward scattering direction. The difference between modeled results and measurements can reach up to 20% in the backward direction when using the parameters inverted in the principal plane. However, if we used the parameters, which derived from the combined measurements in the principal plane for two incident zenith angles, to model the bidirectional reflectance, the maximum difference reaches up to 50% in the backward direction. In the context of experimental measurement study, we suggest that there must be enough measured results at different viewing and azimuth angles when using the bidirectional reflectance models, which are considered as semi-empirical at best, to describe the scattering property or surface structure of particulate system as shown in this study.

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1. Introduction

One of the abiding goals of terrestrial remote sensing is to extract physical property about the earth surfaces from aircraft and spacecraft observations. The greater part of this effort has been directed toward understanding the bidirectional reflectance function and the spectral reflectance from different surfaces, both of them are of particular importance for the applications of remote sensing in geophysics and planetary astrophysics in the Solar System [1]. For particulate surfaces, such as soil or sand, spectral reflectance is somewhat sensitive as an indicator of the surface physical characteristics, e.g. grain size [2] and texture [3].

Moreover, the Bidirectional Reflectance Distribution Function (BRDF) holds greater promise for extracting structural details about the particulate surface than the traditional unidirectional measurements, and the spectral BRDF provides additional information content of effective relevance. For these scientific reasons, the theoretical reflectance model is necessary so that the characterization data of particulate surface may be derived from predictive simulations provided by the model.

The possibility mentioned above has been executed in theoretical treatments of optical characteristics relating to the appearance of particulate media [1,4–16], at the same time, the computer light scattering models that are located between theoretical and experimental studies also gain great attention from researchers and are valuable for understanding the scattering properties of particulate media [67–70], however, there are significant differences remain as to the exact nature of the reflectance mechanisms, coming principally from different perspective in interpreting the relationship between single particle scattering models and the scattering of particulate media that are aggregates of a large number of particles. For example, among different photometric model used in geophysics and planetology, one of the most frequently cited model, developed by Hapke [10–14], may be possible to characterize a material from reflectance data acquired with various angular and illumination conditions by adjusting different free parameters. At the same time, there were some attempts to modify the model and to suggest alternatives by other scientific workers [17–19] because of the shortcomings of the model. But the Hapke model is still widely used in the interpretation of photometric data obtained from natural and planetary surfaces and it is also an active research area for remote sensing applications [20–25].

To determine the parameters of Hapke model, photometric observations of particulate surfaces are needed for a wide range of incidence and emission angles. It is difficult to achieve these observations from Earth-based telescopes and orbital data for planetary studies, and even though remote sensing techniques have been greatly improved over recent years [26–29], most part of aircraft and spaceborne data of natural particulate surfaces still appear to lack enough observational diversity. As laboratory measurements on controlled materials with multi-angular ranges as wide as possible are mandatory to provide ground truth and benchmarks, these information will be used to interpret remotely observed signals. So far, a number of experiments have been undertaken on the connection between details of the bidirectional reflectance and physical properties of particulate surfaces in laboratory [22,24,25,30–34,71]. The primary objective of the present study is to assess the bidirectional reflectance models from an experimental opinion basing on the laboratory measurements, which are performed using the NENULGS (Northeast Normal University Laboratory Goniospectrometer System) [35]. The relationship between the parameters of models and the particulate surfaces' property is the main study content. In addition, we are also interested in the influence of the number of viewing angles on the precision of modeling results, which gains less attention from scientists. We have to highlight that we do not discuss the theory of the models in this paper.

The remainder of this paper is organized as follows. Brief background information about the models is given in the next section. In Section 3, samples and measurements progress are outlined. The measurements, assessment and analysis results are shown in Section 4. In Section 5, we present the conclusions of this study.

2. Models description

For this work, one of the models (M-1, hereafter) for computing the bidirectional reflectance is the Hapke model version [36] with the update for the anisotropic multiple-scattering approximation and the coherent-backscattering enhancement [13,14]. This model uses specific parameter, whose number may vary from 4 to 9 depending on the photometric effects, to characterize a particulate material from reflectance data acquired under various incidence and illumination conditions [24,25]. We adopt an abbreviated form of Hapke's equations whose detailed patterns are presented by Shkuratov [37]:

$$R=\frac{\omega}{4}\frac{\mu_0}{\mu_0+\mu}B_{CB}(\alpha,B_{0cb},h_{cb})\times(B_{SH}(\alpha,B_{0sh},h_{sh})p(\alpha,b,c)+M(\mu_0,\mu,\omega,b,c))S(\mu_0,\mu,\varphi,\bar{\theta}) \quad (1)$$

The equation relies on eight parameters: ω is the single-scattering albedo; B_{0sh} is the amplitude and h_{sh} is the width of shadow-hiding opposition effect (SHOE); the amplitude and width of the effect of coherent backscattering opposition enhancement (CBOE) are B_{0cb} and h_{cb}; $\bar{\theta}$ is the macroscopic roughness correction factor which is the mean topographic slope angle of surface roughness; b and c are the parameters of the phase function; μ_0 and μ are the effective cos(i) and cos(e), respectively, and i is the incident angle, e is the emergent angle; φ is the azimuth angle (between the planes of incidence and emergence direction), α is the phase angle (between the incoming and outgoing light directions); $M(\mu_0,\mu,\omega,b,c)$ which is the function to model the effects of multiple scattering from anisotropic scatters[13] and $S(\mu_0,\mu,\varphi,\bar{\theta})$ is the function for macroscopic roughness. We did not consider the factor B_{CB} in the following assessment part, because 8° is the smallest phase-angle that we could provide when performing the measurement using the apparatus in this paper. To