Phase angle dependence of sand density observable in hyperspectral reflectance

Charles M. Bachmann [a], William Philpot [c], Andrei Abelev [b], Dan Korwan [a]

[a] Naval Research Laboratory, Remote Sensing Division, 4555 Overlook Ave., SW, Washington D.C. 20375, USA
[b] Marine Geosciences Division, 4555 Overlook Ave., SW, Washington D.C. 20375, USA
[c] Cornell University, School of Civil and Environmental Engineering, 220 Hollister Hall, Ithaca, NY, 14850, USA

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ABSTRACT

This paper describes measurements of the phase angle dependence of sand density observable in hyperspectral reflectance. Bi-directional reflectance distribution measurements in the principal scattering plane were recorded for sand samples prepared near minimum and maximum relative densities. Radiative transfer theory for granular media of a single constituent would predict increased reflectance with increased density. However, sands are usually composite materials, and we observed that reflectance can actually decrease with increasing density when the dominant constituents of the sand are semi-translucent, and a darker fraction with typically smaller grains is also present. We postulate that under these circumstances, as density increases, multiple scattering modes are being suppressed as the darker absorbing fraction occupies more optimally the available pore space.

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1. Introduction

One of the abiding goals of terrestrial remote sensing is to extract physical information about the earth's surface from remote observations. The greater part of this effort has been directed toward understanding the spectral reflectance from different surfaces. For soils, spectral observations are relatively effective for identification of the surface material (Ben-Dor et al., 2009; van der Meer & de Jong, 2001) and are somewhat sensitive as indicators of the physical characteristics of the surface, e.g. texture (Demattê et al., 2010), grain size (Demattê et al., 2010), and density (Demattê et al., 2010; Hapke, 1993, 2012a; Helfenstein & Shepard, 2011). Directional reflectance, specifically the Bidirectional Reflectance Distribution Function (BRDF) holds greater promise for extracting structural details about the soil surface than unidirectional measurements, and the spectral BRDF, though difficult to measure, provides additional information content of potential relevance.

This possibility has been apparent in theoretical treatments of BRDF (Dlugach, Mishchenko, Liu, & Mackowski, 2011; Hapke, 1993, 2008, 2012a; Mishchenko, Dlugach, Yanovitskij, & Zakharova, 1999), although significant differences remain as to the exact nature of the reflectance mechanisms, stemming principally from differences in interpreting the relationship between single grain scattering models and the scattering of media that are aggregates of a very large number of grains. Even among existing models, there is some potential for ambiguity. For example, one of the most frequently cited models, developed by Hapke (2012a), has a large number of free parameters, and it has been observed that it is possible to achieve the same radiometric result by adjusting different terms corresponding to entirely different physical scattering mechanisms (Helfenstein & Shepard, 2011). In addition, a number of empirical and phenomenological models have been developed to exploit the information without the encumbrance of strict physical underpinnings (Cierniewski, Gdala, & Karnieli, 2004; Roujean, Leroy, & Deschamps, 1992). Nonetheless, the connection between details of the BRDF and physical properties of the soil has been documented with measurements in laboratory (Cierniewski & Gulinski, 2010; Coulson, 1966; Hapke, 2012a; Sandmeier & Strahler, 2000) and field settings (Croft, Anderson, & Kuhn, 2012; Irons, Campbell, Norman, Graham, & Kovalick, 1992), as well as with remote sensing observations (Coulson, 1966; Gatebe et al., 2003).

Among soil physical variables, various modeling and experimental studies have shown that reflectance is highly dependent on porosity (or packing density) (Demattê et al., 2010; Hapke, 2008, 2012a; Shepard & Helfenstein, 2011). Most models predict that for a single material, the reflectance increases as the density increases (or porosity decreases). This is an explicit outcome of the Hapke (Demattê et al., 2010; Hapke, 2008, 2012a; Shepard & Helfenstein, 2011) model which predicts an increase in reflectance as the filling factor increases for all but the very highest albedos ($\omega > 0.99$). This has been consistently observed in laboratory studies whether the increase in density is due to a decrease in particle size (Capaccioni, Cerroni, Barucci, & Fulchignoni,

1990; Georgiev, Gatebe, Butler, & King, 2009; Kaasalainen, 2003) or to an increase in the packing density of the same material (Capaccioni et al., 1990; Demattê et al., 2010; Naranen et al., 2004; Shepard & Helfenstein, 2007).

Consideration of spectral variations associated with the phase function has generally been secondary to the overall scattering problem. Nonetheless, a link has been established between the size and packing density of ice particles and a change in the depth of absorption bands with phase angle (Kolokolova, Liu, Buratti, & Mishchenko, 2011). There is also model-based evidence for a link between particle size and bidirectional reflectance via the single scattering albedo (Xie, Yang, Gao, Kattawar, & Mishchenko, 2006), with reflectance increasing as the particle size decreases, especially for particles smaller than 200 μm. The predicted increase is minimal in the visible but becomes stronger at longer wavelengths in the infrared. When spectral measurements have been reported, the measurements typically have shown few significant differences in the shape of the phase function at different wavelengths (Gatebe et al., 2003), or the shape of the reflectance spectrum at different densities (Georgiev et al., 2009).

The expectation is that, as the density of a soil increases (and porosity decreases), the reflectance increases. However, the directional reflectance changes that we have observed (and report below) contradict this expectation. As will be seen, for the particular sand examples which we observed using a hyperspectral laboratory goniometer, reflectance decreased as the density increased. Furthermore, there are clearly spectral variations in the shape of the phase function. We will first review the major existing theories, emphasizing the underlying assumptions, describe our experimental apparatus, and present the results. Following that is a discussion of what is unique about these measurements and some hypotheses concerning the possible reasons for the unexpected results.

2. BRDF and density effects

2.1. BRDF: theoretical background

There are currently two rather distinct approaches to modeling the BRDF of natural surfaces. One, developed by Hapke (2012a) over the past 30 years, is grounded in the phenomenological physics of radiative transfer, but has been modified empirically to address practical issues; the other approach, espoused by Mishchenko et al. (Mishchenko et al., 1999; Mishchenko, Travis, & Lacis, 2006) and others (Dlugach et al., 2011; Tishkovets, Petrova, & Mishchenko, 2011), follows directly from Maxwell's equations and is based rigorously on coherent backscattering (CB) theory. Though the solutions are strictly applicable only when individual particles are sufficiently separated for a far-field assumption to be valid, the Mishchenko model has been applied to dense media with impressive results indicating that the theory is, in fact, applicable to dense media (Tishkovets et al., 2011). Due largely to computational limitations, several important restrictions remain, however, including a limit on the size of the particles to be considered and a requirement that the particles be either non-absorbing or only weakly absorbing. As a result, this model has as yet produced few predictions relevant to the particle sizes or absorption characteristics that are of concern here. Thus, we will rely largely on predictions from the Hapke model. In interpreting the results of our present study, we recognize that for our BRDF measurements of sand samples in this paper, we are in the regime where the sample must be considered a densely packed, random particle medium. In this regime, both the Hapke model (Hapke, 2012a) and the coherent backscattering theory of Mishchenko (Dlugach et al., 2011) describe a distinct change in the shape of the scattering phase function, which becomes more peaked in the opposition direction and flatter away from opposition as the packing density increases. This is also consistent with laboratory measurements that have shown similar results when comparing single particle scattering with "agglutinate" spherical particles (McGuire & Hapke, 1995). In the same study, similar

effects occurred when the density of internal scatterers was increased in single grain scattering experiments. As the density of internal scatterers was progressively increased, the phase function changed from highly forward scattering to a diminished forward scattering regime with more scattering at intermediate phase angles and an increased back-scattering lobe, and finally at the highest densities to a predominantly backscattering phase function. They generally observed that other types of induced particle irregularities tended to produce similar changes to the phase function.

Hapke's radiative transfer model (Hapke, 2012a) provides several terms to describe the scattering of light from granular materials. These terms include contributions from single scattering, multiple scattering, the shadow hiding opposition effect (SHOE), and the coherent backscatter opposition effect (CBOE) in the expression for the bidirectional reflectance, $r(\theta_i, \theta_e)$:

$$r(\theta_i, \theta_e) = K \frac{w}{4\pi} \frac{\mu_i}{\mu_i + \mu_e} \left\{ p(g)[1 + B_{S0} B_S(g)] + \left[H\left(\frac{\mu_i}{K}\right) H\left(\frac{\mu_e}{K}\right) - 1 \right] \right\} \times [1 + B_{C0} B_C(g)]$$

(1)

where K is the porosity coefficient, w is the single scattering albedo, $\mu_i = \cos(\theta_i)$ and θ_i is the angle of incidence of the light source, $\mu_e = \cos(\theta_e)$ is the observation angle of scattered light, $g = \theta_e - \theta_i$ is the phase angle, $p(g)$ is the phase function, $B_S(g)$ is a function describing the angular dependence of the SHOE and B_{S0} an associated scaling constant, $B_C(g)$ is a function describing the angular dependence of the CBOE and B_{C0} an associated scaling constant, and $H\left(\frac{\mu_i}{K}\right)$ is the Chandresekar H-function, which describes multiple scattering contributions. The SHOE and CBOE contributions affect primarily smaller phase angles, so that both $B_S(g)$ and $B_C(g)$ decrease monotonically with increasing phase angle g. A recent empirical study (Souchon et al., 2011) evaluating Hapke's model concludes that among previously published results using Hapke's model, the SHOE should provide the larger contribution except below very small angles <3°. The angular width of the opposition effect is dependent on the grain size distribution of the medium and appears in the expressions for $B_S(g)$ and $B_C(g)$ which both depend on this distribution (Hapke, 2012a).

Although the model has been applied in a broad range of applications from simple, well-characterized powders to complex soils, much of the theoretical work has been based on the assumption of narrow size distributions of spherical particles composed of uniform materials. There are convincing arguments as to why Hapke's model may be valid for realistic materials, and his model has proven quite successful in explaining characteristics of BRDF measurements in specific cases (Hapke, 1984, 1986; Hapke & Wells, 1981). However, it has been somewhat less reliable when inverted to extract information about the physical properties of unknown targets from reflectance measurements (Shepard & Helfenstein, 2011). Difficulties arise from a relatively recent modification of the model (Hapke, 2008, 2012a) designed specifically to address the relationship of reflectance to porosity outside of the opposition effect.

Porosity affects Hapke's model of predicted BRDF in two specific ways. Firstly, it appears as a functional dependence in an overall multiplicative factor (Eq. 1), the porosity coefficient, K, that depends nonlinearly on the filling factor, where $\phi = 1 - \rho$, and ρ is the porosity. For equant particles, Hapke (2012a) finds:

$$K = \frac{-\ln\left(1 - 1.209\phi^{2/3}\right)}{1.209\phi^{2/3}}$$

(2)

which increases monotonically with increasing filling factor up to $\phi = \left(\frac{1}{1.209}\right)^{3/2} \cong 0.75$. Secondly, the porosity factor appears as a scale factor in the Chandresekar H-functions that comprise the multiple scattering term in Hapke's model (Eq. 1). This term is proportional to: $H\left(\frac{\mu_i}{K}\right) H\left(\frac{\mu_e}{K}\right) - 1$, where $\mu_i = \cos(\theta_i)$ and $\mu_e = \cos(\theta_e)$ are respectively the cosines of the incident and scattered directions. Although the product of the H-functions decreases weakly with increasing filling factor $\hat{\upsilon} \phi$