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Photometric modelling for laboratory measurements of dark volcanic sand

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ABSTRACT

We have performed laboratory measurements of the bidirectional reflectance factor (BRF) of a sample of dark volcanic sand. The measurements were carried out with three different treatments of the sample to produce different porosity and roughness characteristics. We model the measured BRF with a semi-numerical scattering model for particulate media, meant especially for dark planetary regoliths. We compare the BRF in two different spectral bands, 500–600 nm and 800–900 nm. The particulate medium (PM) scattering model is found to fit the measured data well, with a phase function representing the differences between the spectral bands. The interpretation of the physical parameters of the PM model is qualitatively sound, but remains somewhat uncertain due in part to the difficulty of characterizing the measured sample.

1. Introduction

For most of the bodies in the Solar System, the only sources of data available to us are photometry, spectrometry, and polarimetry. For the great majority, these properties can be observed only as disk-integrated quantities as the bodies are too small to resolve with our telescopes. In a few cases, images taken by spacecraft show a disk-resolved view of the surface and only a handful of objects have been actually studied up close by a variety of scientific instruments.

A good understanding of the spectral reflection properties of these objects is necessary in order to make most of the observed data. Disk-integrated spectrometry allows, e.g., for asteroid classification by spectral type, which indicates the mineral composition [4], and photometric lightcurves allow the determination of an asteroid's rotation state and shape [12]. A good reflectance model is also necessary for the photometric correction of imaging data of planetary surfaces taken by spacecraft [6]. Images taken in different illumination geometries can be compared and analysed together only after the effects of the geometry have been taken into account.

Due to the Apollo missions, the lunar regolith is the best understood of the planetary surface materials and serves as a prototype for the regoliths of other atmosphereless bodies such as the asteroids. It is formed from basaltic and anorthositic lunar rocks broken up by micrometeorites, thermal stress and solar radiation [15]. Volcanic basalt on Earth is used to produce regolith analogs, which approximate the chemical and physical properties of the samples returned from the Moon [16].

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Many models for the reflectance of regolith-covered Solar System bodies have been developed, such as those of Lumme and Bowell [14], Hapke [10] and Shkuratov [24]. Li et al. [13] provide an up-to-date review on models applied to asteroid photometry.

Many laboratory studies of various regolith analogues exist in the literature, usually focused on one particular detail, such as the opposition effect features [25,3], the effects of packing density [18,9], estimating the parameters of a particular model or family of models [5,23], or comparing different models. Johnson et al. [11] study several different lunar and martian regolith analogues as well as real lunar regolith samples.

The purpose of this study is to test a model presented by Wilkman et al. [27], which describes the reflectance of a particulate surface through a combination of the scattering properties of individual grains and a correction for the particulate packing. We apply the model to a sample of dark volcanic sand to demonstrate its applicability in modelling surfaces such as the lunar regolith.

In Section 2, we review the theory of bidirectional reflectance. In Section 3, we describe the experimental setup and the sample we have measured. In Section 4, the numerical reflectance model we use is described. Section 5 presents the results of the measurements and modelling and Section 6 describes our conclusions.

2. Theory

The reflectance behaviour of a surface is described by its bidirectional reflectance factor (BRF). In general, the BRF is a function of four angles: θ_i and ϕ_0 are the zenith and azimuth angles of incidence, θ_e and ϕ are the zenith and azimuth angles of emergence. Additionally, the phase angle α, the complement of the scattering angle is used. The BRF is also a function of the wavelength of light. The cosines of the zenith angles $\mu_0 = \cos\theta_i$ and $\mu = \cos\theta_e$ are widely used for convenience.

If the target is horizontally and azimuthally isotropic, the functional dependence is reduced to three variables, as the only azimuthal variable is the difference $\phi - \phi_0$. In the present study, this is assumed to be the case, and we set $\phi_0 = 0^\circ$. The geometric definitions of the angles are given in Fig. 1. When $\phi = 0$, the incident and emergent directions are on the same side of the zenith.

The BRF is defined as a ratio of the reflected light intensity of a given target to an ideal Lambertian reflector with a spherical albedo of unity under same incident irradiation:

$$\mathrm{BRF}(\mu, \mu_0, \phi, \phi_0) = \frac{I(\mu, \phi)}{\mu_0 I_0(\mu_0, \phi_0)} \tag{1}$$

where I_0 is the incident collimated flux, $I_0(\Omega) = \pi F_0 \delta(\Omega - \Omega_0)$, and $I(\mu, \phi)$ is reflected radiance. This definition makes the BRF equal to the reflection coefficient R of the surface, which relates the incident flux πF_0 to the reflected intensity,

$$I(\mu, \mu_0, \phi, \phi_0) = \mu_0 R(\mu, \mu_0, \phi, \phi_0) F_0, \tag{2}$$

because the reflection coefficient for a Lambertian surface is unity, $R_L = 1$.

BRFs of typical remote sensing targets vary greatly. Some targets are forward scattering, some are backward scattering, some have a strong specular reflection, some reflect highly to low zenith angles [19–22,29]. Each target has its unique BRF that depends on all of its geometrical and physical properties. Thus the BRF information can be a valuable tool in target classification and quantification.

The *plane albedo* $A_p(\mu_0)$ is the fraction of the incident flux scattered by a planar surface into the whole sky hemisphere. The plane albedo is a property of the surface and a function of the incident light direction,

$$A_P(\mu_0, \lambda) = \frac{1}{\pi} \int \int \mu R(\mu_0, \mu, \phi, \lambda) \mathrm{d}\mu \mathrm{d}\phi, \tag{3}$$

where λ is the wavelength of the light. In principle, the integrations in Eq. (3) run over full hemispheres and wavelength range, but in many practical applications the observational range may be limited to a smaller wavelength range, e.g., only visual light, and the field of view of the instrument is also often limited; typical albedometers see zenith angle ranges of $\pm 70^\circ$ to $\pm 80^\circ$.

3. Laboratory measurements

3.1. The measurement apparatus

The BRF measurements have been taken using the Finnish Geodetic Institute Field Goniospectrometer FIGIFIGO, an automated portable instrument for multi-angular reflectance measurements. The FIGIFIGO system consists of a motor-driven moving arm that tilts up to $\pm 90^\circ$ from the vertical, optics at the end of the arm, and an ASD FieldSpec Pro FR 350–2500 nm spectroradiometer. The active optics system at the top of the measurement arm has been built using lenses and Thorlabs lens tube system components. The signal from the sample comes to the optics through a servo-driven mirror. The turnable mirror allows the control computer to stabilize spectrometer field-of-view at the sample within accuracy of 1 cm from all zenith directions even if the sample is not positioned exactly at the center of rotation. The length of the telescopic measurement arm is adjustable from 1.55 to 2.65 m and it houses an inclinometer to provide the control computer with the measured zenith angle. A detailed description of the instrument can be found in [8,22].

Typically, the detector footprint diameter is about 10 cm, elongating at larger sensor zenith angles as $1/\cos\theta$, and wandering around a few centimeters due to material flexing and with azimuthal movements.

The illumination scheme in the laboratory is presented in Fig. 2. In the laboratory experiments, a halogen lamp is used as a light source. The lamp light is collimated by a parabolic mirror and directed to the target by a plane mirror. The illuminated area of the sample is large enough to contain the footprint in all of the viewing geometries used.

The instrument has been calibrated by taking a nadir measurement from a Labsphere Spectralon 25×25 cm white reference plate before and after each measurement