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Retrieving photometric properties of desert surfaces in China using the Hapke model and MISR data

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The retrieval of photometric properties of desert surfaces is an important first step in the parameterization of land surface components of regional dust emission and global radiation models and in Earth system modeling. In this study, the values of Hapke's photometric parameters (ω, h, b, c, $B0$, and $\bar{\theta}$) were retrieved from the Multi-angle Imaging SpectroRadiometer (MISR) instrument at locations in China's deserts. Four pixels represented the typical surface characteristics of the Taklimakan Desert, sand dunes of Kumtag Desert, relatively smooth areas of the Kumtag Desert and the aeolian sandy soil of Loulan. In contrast to earlier studies, we found that the retrieved parameter values were largely affected by the initial value. To combat this problem we used a Monte Carlo method with physical constraints and a conformity indicator to ensure physically meaningful inversion.

The results showed that the angular domain of MISR observations was sufficiently large to determine confidently the values of Hapke's photometric parameters with the exception of the opposition effect width (h). Retrieved values for the single scattering albedo (ω) and macroscopic roughness ($\bar{\theta}$) were consistent with qualitative observations about the structure and composition of the surface material and the nature of the dune forms, respectively. At Loulan, where the surface was smoother than other sites, retrieved values exhibited the strongest backward scattering. These results indicated that at the sensor scale, a rough surface (e.g., dunes) does not necessarily mean more backward scattering than a smooth surface. This finding has significant implications for empirical methods (e.g., using the normalized index of backward-scattered radiance minus forward-scattered radiance as an indicator to indicate surface roughness) which should be used carefully for analyzing surface roughness from remote sensing data. Future research is needed to 1) understand how surface roughness at the sub-pixel scale modifies the angular characteristics of reflectance and to 2) find practical methods for rapid whole image processing for mapping the photometric parameters.

1. Introduction

Formation and evolution of deserts can exert a significant influence on the climate system by altering surface albedo feedback and by supplying to the atmosphere and oceans mineral aerosols that affect the radiative balance of the atmosphere and the global carbon cycle (Ding et al., 2005; Li et al., 1995, 1996). Under an atmosphere largely transparent to solar radiation, desert areas provide a diversity of structure, composition, and spectral reflectance, and thereby affect the amount of solar radiation absorbed or reflected by the surface (Pinty et al., 1989). Removing the influence of illumination and viewing conditions on the reflectance provides photometric parameters such as the single scattering albedo (SSA), roughness and porosity of the surface etc., which provide consistent and repeatable photometric properties that may be diagnostic of the form and functions of deserts and other bare soil surfaces. Field measurements of these properties are sparse or infrequent because of the difficult and sometimes hazardous working conditions in many deserts. The synoptic view of satellite imagery enables researchers to quickly identify the spatial variation of photometric properties of deserts, especially for remote areas of sand seas (ergs). Moreover, repeated imaging of the same area permits the assessment of the dynamic nature of land surfaces with the potential for understanding the specific relationships between dune mobility, climatic variables, and human activity.

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The directional scattering of light is a diagnostic characteristic of surface properties. Surface anisotropy can provide an additional source of information and a better understanding of the geophysical characterization of land surfaces. Anisotropic reflectance has been observed over various bare soil surfaces (Deering et al., 1990; Privette et al., 1995). The anisotropy may be rather complicated for desert areas due to the rising and falling sand ripples at the sub-pixel scales. Shoshany (1993) found with an empirical method that desert stone pavements produce anisotropic reflection with a clear backscattering regime. Karnieli and Cierniewski (2001) inferred the roughness of desert rocky surfaces from bidirectional reflectance data using a geometrical reflectance model. Cooper and Smith (1985) used a Monte Carlo soil reflectance model to study the effect of macroscopic surface irregularities. Although these studies described the Bidirectional Reflectance Factor (BRF) of soils well, the physical mechanisms responsible for the directional behavior of soils were not clear with these methods.

The bidirectional reflectance model derived by Hapke (1981, 1984, 1993, 2002) relates the radiance field emerging from a surface to physically meaningful parameters such as the SSA, the macroscopic roughness, and the porosity of the surface. Many studies have used the Hapke model for exploring planetary regolith, but relatively few attempts have been made to retrieve photometric properties of the Earth's surface (Chappell et al., 2006, 2007; Jacquemoud et al., 1992; Pinty et al., 1989; Privette et al., 1995). Bidirectional reflectance over arid surfaces is mainly influenced by the intrinsic spectral optical properties of the soil and by the presence of roughness elements (Escadafal, 1989). The generalized Hapke equation (1993, p. 346) with a roughness correction factor can be used to calculate the effects of macroscopic roughness on light scattered by a surface with an arbitrary diffuse reflectance function. Unfortunately, there have been no published studies of this type of Hapke model applied to Earth's surface despite numerous examples applied to the planetary regolith.

Owing to the advances in multi-angular imaging technology, space-borne multi-angle sensors such as Polarization and Directionality of the Earth Reflectances (POLDER) and Multi-angle Imaging Spectro-Radiometer (MISR) provide the opportunities to acquire quickly off-nadir viewing data from space to assess the anisotropy of the surface components, and to improve the quantification of the structure of land surfaces. Most work with multi-angle sensors focus on vegetation rather than soils (e.g., Chen et al., 2003, 2005; Chopping et al., 2007; Pinty et al., 2002). Research on non-vegetated areas used the POLDER bidirectional reflectance product to develop an empirical relationship with aerodynamic roughness length which was mapped across desert surfaces (Laurent et al., 2005; Marticorena et al., 2004). Nolin and Payne (2007) extracted surface roughness of glacier ice from MISR data using an empirical relationship with the Normalized Difference Angular Index (NDAI). The advantages of the above empirical methods are that they provide quick and intuitively reasonable results but their physical meaning is unclear. For example, at the sensor scale, do rough surfaces produce more backward scattering of light than smooth surfaces?

There appear to be no published examples of retrieved photometric properties of the Earth's deserts from space-borne multi-angular data using Hapke's physical model. The MISR data and Hapke's macroscopic function (Hapke, 1993, p. 346) provide an opportunity to retrieve values of the photometric function and to derive physically meaningful parameters of the Earth deserts. Thus, the objective of this research is to investigate the utility of space-borne multi-angular MISR observations combined with the Hapke model to retrieve photometric properties of deserts in China.

Properties of sand dunes in the research area have been investigated by many workers (e.g., Liu et al., 2006; Wang et al., 2002; Wei et al., 2007). Additional information on soil types and properties was available in the 1:1,000,000 Soil Property Database of China. We also used the 1:2,000,000 Desert Distribution Map of China and 1:100,000 Desert Database of China to assist our research. Moreover, several Chinese scientists familiar with the research area provided additional valuable information. Although high-resolution aerial photography or field observations were not available, our results allow some preliminary conclusions to be drawn on the geophysical properties of the desert area, by means of a direct comparison with previous research results.

2. Methodology

2.1. Remotely sensed data

We used multi-angle remotely sensed data from MISR onboard NASA's Earth Observing System (EOS) Terra satellite launched in December 1999. The MISR instrument consists of nine cameras arranged with different view angles relative to the Earth's surface, and the along-track angles are 0° (nadir) for the An camera, and 26.1°, 45.6°, 60.0° and 70.5° forward and backward of nadir for the Af/Aa, Bf/Ba, Cf/Ca, and Df/Da cameras, respectively. Each of the nine cameras obtains images at four wavelengths in blue, green, red, and near-infrared that are centered at 446, 558, 672 and 866 nm, respectively. Over a 7-min interval, a particular location within the instrument swath is sequentially viewed by each of the nine MISR cameras. Thus, for an overpass each pixel is viewed at essentially the same solar geometry but nine different viewing angles. MISR Level 2 products (MIL2ASLS) obtained on 31 August 2007 were used in this study when the sky was clear of clouds. MISR Level 2 Surface products are 1100 m resolution and are screened for contamination from sources such as clouds, cloud shadows, sun glitter over water, topographically complex terrain, and topographically shadowed regions (Bothwell et al., 2002). A detailed description of the instrument can be found in Diner et al. (1998).

2.2. Study area

The study area coincides with MISR Path 140, Orbit number 40962, and Blocks 58–59 (Fig. 1). We chose this path because it contains two deserts: Taklimakan and Kumtag Desert which were historically separate but which now are almost contiguous to one another. The study of this area, therefore, is of great importance in understanding the wind activities and the dynamics of dune formation. The per pixel inversion of a physical model over an entire image is computationally expensive and often the model may not converge to a unique solution. To avoid this difficulty, representative locations were selected for careful analysis of the inversion procedure. The results were then compared with ancillary information about the surface characteristics. Three groups of pixels were chosen to represent three kinds of land surface in the research area (Fig. 1).

The first group (Group I: points A, D, and G) is in the Taklimakan Desert; the largest active desert in China and the second largest in the world (Wang et al., 2002). Group I represents the eastern portion of Taklimakan Desert. It is dominated by small 'simple' linear dunes with a N–S directional trend, an average height of <10 m and wide interdunes (ca. 300–1200 m wide) composed of aeolian sandy soils. Group II (points B, E, H, J, and K) is in the central-west area of Kumtag Desert. Dunes in this region are predominantly of the 'compound' linear type. The dunes are on average 10–50 m high, 50–100 m wide and 10–20 km long. Points B, H, and J represent the sand dune area of the Kumtag Desert, and points E and K represent the relatively smooth and level area of the Kumtag Desert, which is regarded as peripheral to the Gobi Desert (pseudo-Gobi) by some scientists. Group III (points C, F, and I) is about 42 km to the east of the ancient city of Loulan (now not evident) and which we named Loulan in the analysis. Group III is not regarded as desert now but it has an aeolian sandy soil type.

The black and white images from China–Brazil Earth Resources Satellite (CBERS, spatial resolution is 19.5 m) for points A, B, E, and C are shown in Fig. 2a, b, c, and d, respectively. The images show that the land surface is the smoothest for Loulan (Fig. 2d) while the roughest for the sand dunes (Fig. 2a and b). The angular information of the 9 cameras