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Removal of topographic effects from lunar images using Kaguya (LALT) and Earth-based observations

Viktor V. Korokhin [a,*], Yuriy I. Velikodsky [a], Yuriy G. Shkuratov [a], Vadym G. Kaydash [a], Sergey Y. Gerasimenko [a], Nikolai V. Opanasenko [a], Gorden Videen [b], Carle Pieters [c]

[a] *Institute of Astronomy, Kharkiv V.N. Karazin National University, 35 Sumskaya Street, Kharkiv 61022, Ukraine*
[b] *Space Science Institute, 4750 Walnut Street, Suite 205, Boulder, CO 80301, USA*
[c] *Department of Geological Sciences, Brown University, Providence, RI 02912, USA*

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ABSTRACT

Lunar images acquired at non-zero phase angles show brightness variations caused by both albedo heterogeneities and local topographic slopes of the surface. To distinguish between these two factors, altimetry measurements or photoclinometry data can be used. The distinction is especially important for imagery of phase-function parameters of the Moon. The imagery is a new tool that can be used to study structural anomalies of the lunar surface. To illustrate the removal of the topographic effects from photometric images, we used Earth-based telescopic observations, altimetry measurements carried out with the Kaguya (JAXA) LALT instrument, and a new photoclinometry technique that includes analysis of several images of the same scenes acquired at different phase angles. Using this technique we have mapped the longitudinal component of lunar topography slopes (the component measured along the lines of constant latitude). We have found good correlations when comparing our map with the corresponding data from Kaguya altimetry. The removal of the topographic surface properties allows for the study of the phase-function parameters of the lunar surface, not only for flat mare regions, but for highlands as well.

1. Introduction

An important goal of photometric studies of planetary images is to identify the physical properties of the material covering the surface of planetary bodies. One approach to this problem is to determine the photometric function, i.e., the function of how the intensity of light reflected from planetary areas varies with illumination and observation angles. The angle between vectors from the observed point to the light source and to the observer is the phase angle α. This is the most important angle variable in planetary photometry. The phase function is a component of the photometric function, which depends only on α (Hapke, 1993). The phase functions are determined by the complexity of the structure of the surface. Usually these phase functions have a single sharp maximum at $\alpha=0$ being locally smooth at other α. Therefore, they can be described with a few parameters. The simplest parameters are ratios of phase-function values at different phase angles α; these characterize the slopes of phase curves. The slope also may be characterized with parameters of an analytical curve used for fitting to brightness measurements (see below). Imagery of the Moon can be made in terms of phase-angle ratios for different pairs of α using original well calibrated brightness images. Such imagery is a relatively new and effective tool that can be used to study structural anomalies of the lunar surface (e.g., Shkuratov et al., 1994; Korokhin and Akimov, 1997; Kreslavsky and Shkuratov, 2003; Kreslavsky et al., 2003; Kaydash et al., 2009a, b). For instance, using photometric images acquired with Earth-based telescopes, weak swirls were found in the southern portion of Oceanus Procellarum (Shkuratov et al., 2010). The phase-angle-ratio images allow one to estimate spatial variations of the complexity of unresolved surface roughness and microtopography. However, the resolved topography spoils the images hampering their interpretation.

Brightness variations on images of the lunar surface depend on the spatial distributions of local topographic slopes, albedo (that is, a characteristic of the surface material composition), and the global illumination/observation geometry. The lunar resolved topography influences brightness spatial variations, since the local surface slopes, or height gradients, change the local incident i and emergent e angles. This effect can be especially significant at large phase angles. Removing the influence of the resolved topography requires data on local slopes. Suitable global lunar height distributions have been obtained recently with the Laser Altimeter (LALT) aboard the spacecraft Kaguya (JAXA) (Araki et al., 2009), which we use in our analysis. Photogrammetry, photoclinometry (shape-from-shading) or their combination are techniques that allow one to retrieve

* Corresponding author. Tel.: +38 057 707 5064.
E-mail address: dslpp@astron.kharkov.ua (V.V. Korokhin).

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information about the relief and albedo distributions directly from photometric images.

Photogrammetry is based on the use of mutual parallaxes of surface details observed at two different angles. It can only be used if stereo images are available. For instance, photogrammetry cannot be practically applied to telescopic images of the Moon acquired from Earth, as the viewing geometry weakly varies for the Moon. However, this method has been used to retrieve the topographic information on different planets from images obtained during space missions (e.g., Connors, 1995; Oberst et al., 1999; Cook and Robinson, 2000; Herrick and Sharpton, 2000). Attempts have been made to recover the albedo distribution on a surface from images using the photometric stereo approach (e.g., Chen et al., 2002). Recently Clementine and Hubble Space Telescope images of the Apollo-17 landing area were used to map heights using the photogrammetric technique (Opanasenko et al., 2007). The Clementine and HST images have almost the same resolution, similar phase angles, and effective wavelength; however, the viewing angles are different. An automatic procedure to find the parallaxes, based on the determination of mutual shifts of the same lunar surface details by finding the maximum of the cross-correlation function of small portions of both images in a "running window," was used.

When photogrammetry is not applicable, photoclinometry has been exploited. This technique takes advantage of the fact that surface facets with orientations more nearly perpendicular to the illumination direction appear brighter than those facets facing away from the Sun. There are many different varieties of photoclinometry. In the simplest approach, a single image is used. By integrating slopes along a line parallel to the illumination direction, one can assemble a topographic profile. This approach ignores albedo and illumination/observation geometry variations over a surface. If the geometry can be taken into account, the albedo is unknown and may produce ambiguities. Thus, the albedo distribution should be estimated together with the determination of topography. When there are many images of the same scene at a fixed angle of view and different phase angles, one can find not only albedo and topography, but also the phase function for each point of the studied surface.

The photoclinometric technique and its applications have a long history. Recovering lunar topography using photoclinometry was proposed by van Diggelen (1951). Later a series of studies devoted to lunar and planetary surface photoclinometry using Earth-based and space mission observations was carried out (e.g., Lambiotte and Taylor, 1967; Watson, 1968; Tyler et al., 1971; Bonner and Schmall, 1973; Parusimov and Kornienko, 1973; Howard et al., 1982; Muinonen et al., 1989; Wildey, 1973, 1975; McEwen, 1991; Jankowski and Squyres, 1991; Watters and Robinson, 1997; Kirk et al., 2003; Lohse et al., 2006). The shape-from-shading method also has been developed in research unrelated directly to planetology (e.g., Ramachandran, 1988; Horn, 1989; Leclerc and Bobick, 1991; Vega and Yang, 1993; Tsai and Shah, 1994; Zhang et al., 1999; Wohler and Hafezi, 2005). Parusimov and Kornienko (1973) and later Davis and Soderblom (1984) pointed out that the topography determination should be carried out simultaneously with the determination of surface albedo using several different images.

One of the main sources of photoclinometry errors is random noise of images. To provide an optimal filtration of the noise, Parusimov and Kornienko (1973), Hung et al. (1988), Kornienko et al. (1994), and Dulova et al. (2008) proposed the Bayesian approach to determine topography and optical characteristics of a planetary surface from photometric imagery. This technique uses a statistical approach and makes it possible to formulate a well posed mathematical problem in the presence of measurement noise. Note that the algorithm by Parusimov and Kornienko (1973) uses the fact that the height distribution must be a gradient field; whereas, the noise component may be a gradient or rotor field. Thus, canceling the rotor component of the resulting signal can noticeably suppress the noise.

In this manuscript, we present results of a new photoclinometry technique that includes analysis of many calibrated images of the same scenes acquired at different phase angles. We demonstrate the capability of the method using high-quality absolute photometric imagery of the Moon obtained with the Kharkiv 15-cm refractor at Maidanak Observatory (Uzbekistan) (Velikodsky et al., 2010). An earlier implementation of the method (Korokhin and Akimov, 1997) used a linear approach that implies that the slopes are small. As we deal with many high-quality images that provide low noise, the methods of optimal filtration (e.g., Dulova et al., 2008) were not used. In addition, we present results of removing the topographic effects from lunar images of the photometric-function parameters. We use altimetry measurements carried out with the Kaguya (JAXA) LALT and results of our photoclinometry technique.

2. New technique in lunar photoclinometry

The reflectance R of a planetary surface can be expressed through the photometric function $F(i, e, \alpha)$

$$R(i,e,\alpha) = A_0 F(i,e,\alpha), \tag{1}$$

where i and e are the incident and emergent angles, respectively. The value A_0 is the reflectance (albedo) at a standard illumination/observation geometry. In lunar photometry another suite of angles is often used: the photometric longitude γ, and the photometric latitude β. They can be found from the system as (Hapke, 1993)

$$\cos\gamma = \cos e/\cos\beta, \quad \cos\beta = \cos i/\cos(\gamma-\alpha) \tag{2}$$

The values β and γ are functions of the lunar surface coordinates. As has been noted, the photometric function $F(\alpha, \beta, \gamma)$ can be presented as (Hapke, 1993)

$$F(\alpha,\beta,\gamma) = f(\alpha)D(\alpha,\beta,\gamma), \tag{3}$$

where $f(\alpha)$ is the phase function and $D(\alpha, \beta, \gamma)$ is the disk function. The latter describes the global brightness distribution over the lunar disk, e.g., the brightness trend from the limb to terminator. We here use the lunar disk function suggested by Akimov (1979, 1988a, b)

$$D(\alpha,\beta,\gamma) = \cos(\alpha/2)(\cos\beta)^{\nu\alpha/(\pi-\alpha)}\cos((\gamma-\alpha/2)\pi/(\pi-\alpha))/\cos\gamma, \tag{4}$$

where α is measured in radians and ν is the roughness coefficient (Akimov et al., 1999, 2000); $\nu=0.34$ for maria and $\nu=0.52$ for highlands, and we used below the average value $\nu=0.43$. This function ((4)) describes the scattering by the lunar surface more precisely than the Lommel–Zeeliger and Minnaert scattering laws (Akimov, 1988b; Kreslavsky et al., 2000).

To find the phase function from reflectance, one needs to calculate

$$f(\alpha) = F_{obs}(\alpha,\beta,\gamma)/D(\alpha,\beta,\gamma). \tag{5}$$

Using formulas (3) and (4), photometric data for each lunar point can be transformed to the same photometric conditions. In particular, the data can be brought to the so-called mirror illumination/observation geometry at the photometric equator, i.e., when $\beta=0$, $\gamma=\alpha/2$. Then, Eqs. (3) and (4) are significantly simplified

$$A_{eq}(\alpha) \equiv R(\alpha/2, \alpha/2, \alpha) = A_0 f(\alpha). \tag{6}$$

The value $A_{eq}(\alpha)$ is termed the equigonal albedo, which can be found for each point of the lunar disk, allowing a photometric comparison between all the points (Korokhin et al., 2007). Evidently,