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

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ARTICLE INFO

Article history:
Received 9 February 2010
Accepted 20 May 2010
Available online 26 May 2010

Keywords:
Lunar surface
Photometry
Albedo
Phase function
Topography
Photoclinometry

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 telescopc 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.

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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 \( \phi \). This is the most important angle variable in planetary photometry. The phase function is a component of the photometric function, which depends only on \( \phi \) (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 \( \phi = 0 \) being locally smooth at other \( \phi \). Therefore, they can be described with a few parameters. The simplest parameters are ratios of phase-function values at different phase angles \( \phi \); 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 \( \phi \) 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...
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 Squire, 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 planetaryology (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 $F(i, e, x)$

$$R(i, e, x) = A_0 F(i, e, x),$$

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 $\gamma$, and the photometric latitude $\beta$. They can be found from the system as (Hapke, 1993)

$$\cos \gamma = \cos e / \cos \beta, \quad \cos \beta = \cos i / \cos (\gamma - x)$$

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

$$F(\alpha, \beta, \gamma) = f(\alpha) D(\alpha, \beta, \gamma),$$

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 disk function suggested by Akimov (1979, 1988a, b)

$$D(\alpha, \beta, \gamma) = \cos(\alpha / 2) \cos \beta)^{0.5} \cos(\gamma - \alpha / 2) \cos(\gamma / 2 - \pi / 2) / \cos \gamma,$$

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

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

$$f(\alpha) = F_{\alpha 0}(\alpha, \beta, \gamma) / D(\alpha, \beta, \gamma).$$

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 $\beta = 0$, $\gamma = \pi / 2$. Then, Eqs. (3) and (4) are significantly simplified

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

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,
the branches of $A_{eq}(x)$ corresponding to $x$ with different signs should be symmetrical. To describe the observed phase dependence $A_{eq}(x)$ of the lunar areas, different model functions may be used. The simplest phase function, which is very appropriate for the phase-angle range 10°–40°, is

$$A_{eq}(x) = A_0 \exp(-\mu x)$$

(7)

where $\mu$ characterizes the slope of the function.

Eq. (1) ignores the resolved lunar topography. To take this into consideration, one needs to use the following formula:

$$f(x) = F_{obs}(x, \beta', \gamma') / D(x, \beta', \gamma'),$$

(8)

where $\gamma' = \gamma + \Delta \gamma$ and $\beta' = \beta + \Delta \beta$ are the photometric coordinates accounting for the topography. The values $\Delta \gamma$ and $\Delta \beta$ can be expressed through the local slopes of the resolved lunar relief.

Let us define the local slope $r$ as the declination of the local surface normal $\mathbf{n}$ from the global one $\mathbf{N}$, i.e., we consider $\mathbf{r} = \mathbf{N} - \mathbf{n}$ where vectors $\mathbf{n}$ and $\mathbf{N}$ are normalized to unity. The local slopes of the surface affect the local illumination/observation geometry and, hence, the photometric coordinates $\gamma$ and $\beta$ of a given point. The slope disturbance of a small surface site (planar element) is linear. Such conditions are well suited for lunar observations at large phase angles, the incident solar rays are nearly co-linear with the lines of selenographic latitude. Hence, for each point of the lunar surface a phase dependence of the equigonal albedo can be plotted. We may numerically minimize the standard deviation of the observed $A_{eq}(x)$ from the model function (7) varying simultaneously the parameters $r_0$, $A_0$, and $\mu$. This automatically provides minimization of brightness variations caused by topographic slopes. For the minimization, we use the Nelder–Mead method (Nelder and Mead, 1965).

The described procedure is possible for the slope component oriented along the illumination direction. For Earth-based observations at large phase angles, the incident solar rays are nearly co-linear with the lines of selenographic latitude. Hence, the reconstructed relief profiles pass along latitude lines, and the coordinates of points on each profile are values of longitude. Therefore, we term this slope component longitudinal, $r_l$. Note, that in geography such a component is named “zonal”.

Thus, we fit the parameters $r_l$, $A_0$, and $\mu$, using a set of observations of the Moon carried out at various phase angles before and after full-moon. We map simultaneously the topographic slopes, albedo $A_0$, and the parameters of phase function compensating for the influence of the resolved topography.

3. Mapping the topography slopes and parameters of phase function

For the mapping we used data of absolute photometry of the Moon carried out in 2006 at the Maidanak Observatory (Uzbekistan) with a 15-cm refractor at red light 610 nm (Velikodsky et al., 2010). The data set of 12 maps of absolute albedo at $x = 12.81°$, 14.73°, 16.21°, 17.78°, 18.74°, and 21.02° before full-moon and at $x = 12.33°$, 13.42°, 14.19°, 15.07°, 16.19°, and 21.79° after full-moon were used in our analysis. The observation data were selected to have maximally symmetric values of phase angles before and after full-moon. The range of phase angles approximately from 12° to 22° allows us to use a relatively simple (one exponent) model phase function (7). The maximal phase angle 22° allows us to map almost the full visible disk in contrast to our previous work (Korokhin and Akimov, 1997). The resolution element of our data is approximately 3.2 × 3.2 km² in the lunar disk center. This is the minimal base of roughness.

Before calculations all images have been additionally co-registered using an algorithm of soft co-registration (Kaydash et al., 2009a) to compensate for the influence of Earth’s atmospheric turbulence that deforms the lunar images. Fig. 1 presents a map of $A_0$, i.e., the albedo distribution that is not influenced by topography. We note that this is
a result of albedo extrapolation defined with formula (7) to \( \alpha = 0 \) using 12 images obtained at phase angles 12–22°. The distribution of \( A_0 \) is similar to that of the equigonal albedo \( A_{eq}(\alpha) \) at any moderate phase angle and characterizes the reflection properties of the lunar surface materials. It should be emphasized that the albedo map in Fig. 1 does present real brightness distribution at \( \alpha = 0 \), as it ignores variations of opposition-effect amplitudes that are not described by formula (7). The opposition spike has components of shadow-hiding and coherent backscattering effects (e.g., Hapke, 1993; Shkuratov et al., 2004). To include these in the analysis, a more complicated approximation of the phase function is needed (Velikodsky et al., 2010).

Fig. 2 shows a distribution of the longitudinal component \( r_1 \) of the topographic slope calculated on a 3.2 km base. The distribution in Fig. 3 shows realistic values of slope up to 8°. This is in agreement with our assumption that topographic slopes on bases provided by Earth-based telescope observations are small. Some sites demonstrate slopes reaching 20°. The maximal value of slope we obtained in this analysis is 22°, observed at the selenographic coordinates \( l = 0.2°, b = 21.6° \) in Montes Apenninus. This new map of longitudinal slopes coincides well with our previous results (Korokhin and Akimov, 1997).

Shown in Fig. 4 is a map of the parameter \( \mu \) of function (7) determined in the range of phase angles 12–22°. The distribution describes the steepness of the phase dependence of the lunar surface brightness. The parameter \( \mu \) can be determined using many calibrated images; whereas, a phase-angle-ratio image includes only two components. In any case, the images of the phase ratio and of the parameter \( \mu \) calculated for the same phase angle range should be very similar. As one can see, the parameter \( \mu \) demonstrates an inverse correlation with albedo: the higher the steepness \( \mu \), the lower the albedo. This is in agreement with our previous results (Shkuratov et al., 1994; Korokhin and Akimov, 1997; Kreslavsky et al., 2000; Kreslavsky and Shkuratov, 2003; Kaydash et al., 2009b).

The albedo \( A_0 \) and steepness \( \mu \) maps calculated using the described algorithm are almost free from the influence of the lunar topography (see Figs. 1 and 4). Figs. 5 and 6 show the case, if we ignore the compensation for the topography, i.e., when the phase-function parameters (7) \( A_0 \) and \( \mu \) are calculated without accounting for the lunar relief. The difference, especially between the steepness distributions (see Figs. 4 and 6), seems to be dramatic. In the case of Figs. 1 and 4 some traces of relief are observed near the limb and the polar regions. This probably is caused by neglecting the latitudinal component of local slopes and the presence of areas on the source images with too large emergence and incidence angles.

Errors in using the approximation with the function (7) are shown in Fig. 7. Typical values of the error (the standard deviation divided by \( A_0 \) in percents) are 0.35–0.5% for maria, 0.4–1.0% for highlands, and up to 4% for bright craters. Areas near the limb have maximal values of errors (up to 20%). Small errors are observed in maria, because their surface is relatively flat. Moreover, the function (7) works for maria better than for highlands and bright craters. Thus, higher errors for highlands and bright craters are caused by more complicated topography in addition to the simplified function with one exponent (7) being not representative of the phase curves of highlands. High errors near the limb appear due to the presence of real shadows in addition to poor image co-registration caused by neglecting real heights of the lunar sites in the compensation for libration. In spite of some shortcomings of the technique, the approximation of phase function without accounting for the influence of the lunar relief gives much larger errors.

4. Comparison with LALT data

As has been noted, recent altimetric data have been obtained with the LALT (laser altimeter) aboard the spacecraft Kaguya (Araki et al., 2009). The LALT was able to obtain a range of data on a global scale along the satellite’s trajectory including the high latitude region above 75° that has never been measured by an
Although the data set is somewhat raw yet (Korokhin et al., 2010), we used the global LALT topography for comparison with our photoclinometric data in order to compensate for the topographic effect for the phase-angle-ratio maps.

Before the comparison we processed the LALT data. We transformed the data array to put the point with zero selenographic coordinates in the center of the image. Then, we re-sampled the LALT map to the resolution of our ground-based observations. The next step was calculating the longitudinal component of the surface slopes from the height distribution. Then, we transformed the LALT map from a cylindrical onto an orthographic projection. Finally, the image was smoothed by a Gaussian filter with $\sigma = 0.8$ pix to make the resolution of the LALT and our maps similar. We computed the map of longitudinal topographic slopes determined on a 3.2 km base (see Fig. 8) from the LALT distribution of heights. Both the maps show a very similar distribution of the longitudinal slopes over the lunar disk (cf. Figs. 2 and 8), including the maximal value of the slope $22^\circ$ at the point with the selenographic coordinates $l = 0.2^\circ$, $b = 21.6^\circ$.

However, more detailed analysis reveals differences. For instance, our map demonstrates a weak residual influence from albedo (see the Copernicus ray system) and worsening resolution to the limb. The LALT map exhibits many small topographic artifacts. Fig. 9a and b show maps of longitudinal slopes for the central portion of the lunar disk ($\sim 50^\circ \times 50^\circ$) in a cylindrical projection: the upper panel correspond to LALT data and the lower one to our map. The most typical artifacts are displaying some craters as hummocks (see, e.g., marks 1–3, 7–9 in Fig. 9a, b) or disappearance of craters (marks 4–6). Sometimes, the LALT map reveals nonexistent peaks (see marks 10 and 11). The most probable reasons for these artifacts are errors of interpolation at mosaicing. We also note the presence of longitudinal modulation...
5. Topography correction of photometric data

Although we have mapped the longitudinal component only, this allows for correction of Earth-based photometric observations, because illumination of the lunar surface varies mainly due to changing selenographic longitude of the Sun. For the correction of maps of albedo, it is necessary to apply the following correcting coefficient for each point of the lunar disk

$$k = \frac{D(\alpha, \beta, \gamma)}{D(\alpha_0, \beta_0, \gamma_0)},$$

where $D(\alpha, \beta, \gamma)$ and $D(\alpha_0, \beta_0, \gamma_0)$ are the disk functions, respectively, without and with taking into account topography slopes. In the numerator of Eq. (20), photometric coordinates $\gamma$ and $\beta$ of the point are calculated using its current selenographic coordinates $l$ and $b$. In the denominator of Eq. (20), $l_0$ and $b_0$ are calculated using the obvious formula $l_0 = l + r_l \cos b$.

In Fig. 10a, b we present, respectively, topographically corrected and uncorrected maps of the phase ratio $2/21^\circ$. It can be seen that the topography in Fig. 10a is significantly suppressed. Despite the phase angle ranges $10^\circ$–$20^\circ$ and $2^\circ$–$20^\circ$ being somewhat different, the resemblance the phase-ratio map and the map of the parameter $\mu$ is clearly seen (cf. Figs. 4 and 10a). As can be anticipated, the phase-ratio images reveal a correlation with albedo. Low albedo areas (dark mantle deposits) in Mare Tranquillitatis, Mare Vaporum, and Sinus Aestuum (see also Taurus Littrow and Sulpicius Gallus) reveal the most steep phase function, while bright craters and their rays (e.g., Tycho, Copernicus, and Proclus) have the smallest slope of the function. This is somewhat unexpected result as the craters are rather bright and, hence, at small phase angles ($< 5^\circ$), the coherent backscattering effect should prominently manifest itself (e.g., Hapke, 1993). This result could be explained by the small width of the opposition spike from the effect of coherent backscattering. However, the phase ratio image $1/5^\circ$ (it will be published) demonstrates the same behavior: bright craters and their rays have small phase-ratio slope.
We also note that there is very noticeable difference between Mare Serenitatis and Mare Tranquillitatis. We note that differences were observed for color ratio in the visible spectral range (e.g., Pieters and McCord, 1976; Shkuratov et al., 1999).

Detailed comparison of the phase ratio map \( \frac{21}{21^2} \) with albedo shows that there are many anomalous regions that do not exactly coincide with the albedo boundary. For instance, the Aristarchus Plateau and Marius Hills (pyroclastic formations) clearly show up on the phase-ratio images. We note that the topographic correction helps in visualizing these anomalies. Corrected photometric data allow us to study the phase dependence of the lunar surface brightness not only for flat mare regions, but for highlands and other areas with rough resolved topography. For instance, relatively small swirls in the region of the central nearside highlands (Blewett et al., 2007) are more apparent if the topographic effect is removed.

6. Conclusion

1. We have studied two approaches to remove the resolved topography effect from images of phase-function parameters of the Moon using altimetry measurements carried out with the Kaguya (JAXA) LALT instrument and new photoclinometry data obtained with Earth-based telescopic observations. Using these techniques, we have mapped the longitude component of the lunar topography slopes with a resolution of 3.2 km/pix. Overall, we have found good correlation when comparing our map with the corresponding data obtained from Kaguya altimetry.

2. Our approach to retrieve information about the topography, albedo, and the parameters of phase function from photometric images requires using a robust set of absolutely calibrated images obtained for the same scene at different phase angles. We numerically minimized the standard deviation of the observed \( A_{eq}(\alpha) \) from the model function (7) varying...
the parameters $\eta$, $\alpha$, and $\mu$ (see designations above). This procedure minimizes the effect of topographic slopes. In applying this technique, we used new data of absolute photometry of the Moon obtained at the Maidanak Observatory (Uzbekistan).

3. Although the LALT and photoclinometry maps show good correlation, more detailed analysis reveals differences. In particular, the photoclinometric map demonstrates a weak residual influence from albedo. The LALT map exhibits many small topographic artifacts, displaying some craters as hummocks. Thus, our map would be proposed for an independent control of the LALT data.

4. Corrected photometric data allow one to study phase dependence of the lunar surface brightness not only for flat mare regions, but for highlands and other areas with expressed topography. This is useful, for example, in studying the swirlls in the region of the central nearside highlands (Blewett et al., 2007).

Acknowledgment

This study was supported by CRDF Grant UKP2-2897-KK-07.

References


