PHOTOMETRIC ANALYSIS OF LUNAR SURFACES WITH COMPLEX TOPOGRAPHY

Introduction: All earth based observations of the moon have been performed at small phase angles and at controlled incidence i and emergence e geometry. For this scenario the phase angle $\alpha$ is sufficient to approximate the observing geometry. However, if the observing geometry changes in a wide range such as observed during spacecraft flybys (e.g. Galileo EM1 and EM2 and Clementine), or by the surface topography with increasing resolution, then the simultaneous changes of all observing geometry parameters ($i$, $e$, $\alpha$) have to be considered seriously in order to correctly describe the reflectance behaviour of a surface.

We have investigated the photometric properties of the lunar surface by using multispectral Wendelstein observatory CCD camera data (12 filters), Galileo SSI EM1 and EM2 data (7 filters) and Clementine UV-VIS data (5 filters). In all the data sets we observed effects of primary angle dependence of $i$, $e$ and $\alpha$ (fig. I). The telescope measurements before and after full moon exhibit significant differences in the phase curves (fig. II). Until recently the Galileo data could not be combined with the telescopic data for spectrophotometric investigations because it is necessary to allow for an additional parameter which affects the observational geometry, namely topography (surface tilt). The orientation of individual surface elements has to be known in order to determine the photometric surface properties accurately or to correct for photometric effects. The surface orientation is dependent on the direction of the normal of a local surface element and hence upon topography.

In order to investigate this orientation problem we studied the Hapke model [1,2] which is usually applied to describe the reflectance properties of the lunar surface, expressed by the bidirectional reflectance function $I/F = r(i, e, \alpha; w, h, \theta, b, c)$. This is the ratio of the reflected $I$ and incoming $F$ radiation. The orientation of surface elements has been varied with respect to the illumination ($i$) and observation angles ($e$) for fixed photometric parameters ($w, h, B_0, \theta, b, c$) which are given by Helfenstein [3]. For all possible angle combinations ($i$, $e$, $\alpha$) we obtained large variations for $I/F$. In addition, both variables $i$ and $e$ will not only change the phase curve by adding an offset but will also influence the shape (fig. III). The same variations occur for telescope data (little variation of $e$, but significant variation of $i$ and $\alpha$) and for spacecraft data (for one orbit session $i$ is approximately constant, while $e$ and $\alpha$ vary). In the spectrophotometric investigations of the Apollo landing sites we detected relative differences of 20% between ground-based telescopic and the Galileo data. Such discrepancies can be explained by the different observation geometries. We obtained the same deviation, when we calculated the reflectances using the Hapke model and the given geometries.

For determining the exact illumination and observation geometry, the local surface normal has to be computed from topographic information. Such terrain information was lacking in previous studies and the surface normals have been approximated by using the planet's center radial vector. This may be applicable for images of low spatial resolution where topographic effects are minor. However, when the spatial resolution increases topographic effects will dominate the viewing geometry. For comparison, we derived the photometric functions for both the approximated and the correct local surface normals (fig. IV). Our results show that in case of approximation the surface structure affects the photometric parameter significantly and a non-negligible error will be introduced. This indicates that the orientation of surface elements gets more and more important with the increasing resolution of the images.

Figure I. Illumination and observation geometry; $i$ illumination angle, $e$ emission angle and $\alpha$ phase angle.

Figure II. Wendelstein observatory CCD camera measurements of filter 6 ($\lambda = 852.2$ nm). Measure points: bright area: lon = 20.44° west, lat = 13.14° north, average area: lon = 10.85° west, lat = 14.27° north, dark area: lon = 21.85° west, lat = 17.22° north. [4]
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However, if the topography is known, the correct observing geometry can be reconstructed and accurate photometric corrections can be applied to the observations.

**Figure III.** Different plots of the Hapke function in dependence to the angles $i$ and $e$. The photometric parameters are the Helfenstein parameters [3] for bright lunar areas: $w = 0.33$, $h = 0.05$, $B_\alpha = 1.83$, $\theta = 24.0^\circ$, $b = 0.26$, $c = 0.45$.

**Figure IV.** For the phase angle $\alpha = 30^\circ$ the Hapke function is plotted for tilted surfaces. The illumination direction is defined by $\mathbf{s} = (\sin(\alpha/2), 0, \cos(\alpha/2))^T$, observation direction by $\mathbf{v} = (-\sin(\alpha/2), 0, \cos(\alpha/2))^T$ and the local surface normal by $\mathbf{n} = \frac{(-\tan(nx), -\tan(ny), 1)^T}{\sqrt{\tan^2(nx) + \tan^2(ny) + 1}}$.

The photometric parameters are the same as in fig. III. The tilting angle $nx$ is given by $\tan(nx) = \frac{dz(x, y)}{dx}$ and $ny$ by $\tan(ny) = \frac{dz(x, y)}{dy}$.

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