A visible and near-infrared photometric correction for Moon Mineralogy Mapper (M3)

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A B S T R A C T
Observations of the Moon obtained by the Moon Mineralogy Mapper (M3) instrument were acquired at various local viewing geometries. To compensate for this, a visible near-infrared photometric correction for the M3 observations of the lunar surface has been derived. Images are corrected to the standard geometry of 30° phase angle with an incidence of 30° and an emission of 0°. The photometric correction is optimized for highland materials but is also a good approximation for mare deposits. The results are compared with ground-based observations of the lunar surface to validate the absolute reflectance of the M3 observations. This photometric model has been used to produce the v1.0 Level 2 delivery of the entire set of M3 data to the Planetary Data System (PDS). The photometric correction uses local topography, in this case derived from an early version of the Lunar Orbiter Laser Altimeter data, to more accurately determine viewing geometry. As desired, this photometric correction removes most of the topography of the M3 measurements. In this paper, two additional improvements of the photometric modeling are discussed: (1) an extrapolated phase function long ward of 2500 nm to avoid possible misinterpretation of spectra in the wavelength region that includes possible OH/H2O absorptions and (2) an empirical correction to remove a residual cross-track gradient in the data that likely is an uncorrected instrumental effect. New files for these two effects have been delivered to PDS and can be applied to the M3 observations.

1. Introduction

In the last 2 years, several spacecraft (e.g., Lunar Reconnaissance Orbiter, Kaguya, Chandrayaan-1 and Change’e 2, Chin et al., 2007; Kato et al., 2007; Goswami and Annadurai, 2009) have observed the Moon with a variety of instruments, including visible to near-infrared (VIS–NIR) cameras and spectrometers. All these missions and instruments have different observation conditions and in particular different viewing geometries. Among other causes such as the mineralogical composition, roughness, and albedo, variations in lunar surface brightness are also caused by changes in the local viewing geometry, which is defined by three angles: incidence angle (i), emission angle (e) and solar phase angle (a). In order to compare different observations of the Moon, a photometric correction that empirically corrects the reflectance of the surface to a common viewing condition must be applied. The standard viewing geometry of i = 30°, e = 0°, and a = 30° is widely employed (McEwen et al., 1998; Hicks et al., 2011; Sato et al., 2011; Yokota et al., 2011), which it allows: (1) the comparison of data of the same location taken at different viewing geometries by the same instrument, and (2) the comparison of data of the same location from different instruments acquired at different geometries. Finally, this particular geometry is also used to facilitate the comparison with laboratory measurements that are typically acquired at the same geometry (i.e., 30°, 0°, 30°) (Pieters, 1983).

The ideal VIS–NIR photometric correction is one that could be applied to all observations (i.e., different instruments) of the same surface. However, each instrument is unique with different spatial and spectral sampling; thus, empirical photometric models must be developed for each one. Furthermore, photometric models of the Moon at NIR wavelengths with remote sensing observations from spacecraft are recent and still in development (Buratti et al., 2011; Yokota et al., 2011; Wu et al., 2013), although ground based
observations models were previously developed (Lane and Irvine, 1973; Kieffer and Stone, 2005). Comparing different results from different instruments helps define the photometric properties of the Moon at NIR wavelengths.

The objective of this study is to define a global photometric correction for the hyperspectral images obtained by the Moon Mineralogy Mapper (M3) instrument onboard the Chandrayaan-1 spacecraft (Pieters et al., 2009b). A global correction is an average correction that satisfies most of the data in terms of absolute reflectance and reddening. This work is built on the preliminary analysis done by Hicks et al. (2011) and the improvements by Besse et al. (2011a) to define the photometric correction of the M3 dataset used in the public delivery. The previous study by Hicks et al. (2011) used a preliminary calibration and a limited set of M3 data. Since that study, the calibration has been greatly improved, including scattered light, dark level, and non-linearity corrections (Green et al., 2011). Beyond 2 μm, the spectrum of the Moon is composed of light reflected from the surface plus thermal emission. The thermal emission is removed using the algorithm developed by Clark et al. (2011) for the M3 observations. The improved calibration and the thermal correction are used prior to defining an accurate photometric correction for all M3 observations.

The photometric correction presented here is included in version 1.0 of level 2 (L2) M3 dataset archived at the Planetary Data System (PDS). Two additional corrections are discussed in Section 5.1 to improve the phase function after 2500 nm, and in Section 5.3 to improve the cross-track residual that is still present in the version 1.0 of L2 dataset.

2. The M3 observations onboard Chandrayaan-1 spacecraft

2.1. M3 mission and observations

M3 is an imaging spectrometer onboard India’s Chandrayaan-1 mission to the Moon. It covers the VIS–NIR spectral range from 0.4 to 3 μm (Pieters et al., 2009b). From a polar orbit, the M3 observes the lunar surface with a nominal field of view of 24°, providing approximately a 42.5 km swath from a 100 km orbit (Boardman et al., 2011; Green et al., 2011). The slit moves along the orbit to create images of various lengths, some of them covering the lunar surface from pole-to-pole. Chandraayan-1 was launched the 22nd of October 2008 and M3 mapped more than 95% of the Moon (Boardman et al., 2011) during its 9 months of operation. However, M3 did not map the Moon continuously and this resulted in observations, which vary in coverage, phase angle, altitude, and spatial resolution. The observations are divided into seven optical periods (OPs). OP1A, OP1B, OP2A, OP2B observed the Moon at 140 m/pixel. These OPs are mainly located on the near side of the Moon with high phase angles (i.e., 50° on average). OP2C1, OP2C2, and OP2C3 have a resolution of 280 m/pixel with lower phase angles (i.e., 25° on average). A summary of the OPs used in this study is given in Table 1. Details of the M3 observations including the accuracy of the pointing can be found in Boardman et al. (2011).

2.2. M3 data used in this study

The M3 data used in this study are from OP2C1. The selection of the OP2C1 data was motivated by the fact that this period provides single coverage of nearly the entire lunar surface. This allows us to avoid bias introduced by observing the same spot on the surface of the Moon several times (e.g., Mare Orientale which is covered in 4 OPs, more than any other region on the Moon). The OP2C1 observations total 175 images and are taken at 280 m/pixel. As presented in Fig. 1, the OP2C1 period covers a much larger phase range with a larger number of observations than the OP1B and OP2A data used for the preliminary photometric correction developed by Hicks et al. (2011). Therefore, this optical period is more suitable for defining the phase function of the M3 observations. For this study, the version 3.0 of Level 1B (L1B) data archived in the PDS are used and are calibrated following the procedure of Green et al. (2011) with additional improvements for scattered light and linearity (Lundeen et al., 2011). The L1B data are in radiance; here they are converted to radiance factor (RADF; e.g., (Hapke, 1993, p. 262), which is defined as:

\[
\text{RADF}(i, e, x) = \left( \frac{I(i, e, x)}{J_e} \right) \times \pi \times R^2
\]

where \(I_i\) is the observed radiance at a given wavelength, \(J_e\) the solar spectrum at a given wavelength at 1 AU, \(R^2\) is the normalized Sun–Moon distance, \(i\) is the incidence angle, \(e\) is the emission angle, and \(x\) is the phase angle. Once the RADF is computed, the algorithm developed by Clark et al. (2011) is applied to remove the thermal contribution to the spectrum, which occurs mainly after 2000 nm for the warmer regions (closer to the equator). Thus, the M3 data used to derive the phase function are RADF corrected for the thermal emission.

2.3. PDS archive: version 3.0 of L1B data

Since the publication of the L1B calibration steps (Green et al., 2011), improvements have been implemented for the version 3.0 of the L1B data (Lundeen et al., 2011; Malaret et al., 2011). A better algorithm has been developed to remove scattered light (for the first channels, from 446 to 515 nm) and the linearity of the data has been improved for very low signal. Since the beginning of the mission, the spacecraft encountered thermal problems, which lead to M3 operated well outside its nominal temperature (156 ± 3 K, Green et al., 2011). In addition, observations of the same location of the lunar surface at the same viewing geometry have been made at different detector temperatures. Fig. 2 presents a mosaic of the crater Plato using observations from both OP1B and OP2C1. The phase angle between adjacent strips from different OPs does not change by more than 2°; however, the absolute radiance varies by a factor of 2 between the two OPs. Careful examinations of these data have shown that the shapes of the spectra are also different. Although the science team did not find the cause of these changes, an empirical correction has been applied to the delivery version 3.0 of the L1B data to correct the shape of the

<table>
<thead>
<tr>
<th>Sub-OP name</th>
<th>Time period</th>
<th>Cold or warm?</th>
<th>Resolution (m/pix)</th>
<th>Phase in degrees</th>
<th>Lunar surface coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>OP1A</td>
<td>2008 November 18–2009 January 18</td>
<td>Warm</td>
<td>140</td>
<td>5–100 (limited)</td>
<td>Commissioning phase, very limited coverage</td>
</tr>
<tr>
<td>OP1B</td>
<td>2009 January 19–2009 February 14</td>
<td>Cold</td>
<td>140</td>
<td>35–90</td>
<td>Almost entirely the near-side and Orientale</td>
</tr>
<tr>
<td>OP2A</td>
<td>2009 April 15–2009 April 27</td>
<td>Cold</td>
<td>140</td>
<td>40–90</td>
<td>Western near-side and eastern far-side</td>
</tr>
<tr>
<td>OP2B</td>
<td>2009 May 13–2009 May 16</td>
<td>Warm</td>
<td>140</td>
<td>25–100 (limited)</td>
<td>Around Copernicus, very limited</td>
</tr>
<tr>
<td>OP2C1</td>
<td>2009 May 20–2009 June 23</td>
<td>Warm</td>
<td>280</td>
<td>6–90</td>
<td>Almost entirely the Moon</td>
</tr>
<tr>
<td>OP2C2</td>
<td>2009 June 23–2009 July 22</td>
<td>Warm</td>
<td>280</td>
<td>5–90 (limited)</td>
<td>Mainly far-side</td>
</tr>
<tr>
<td>OP2C3</td>
<td>2009 July 22–2009 August 16</td>
<td>Cold</td>
<td>280</td>
<td>25–100 (limited)</td>
<td>Eastern far-side, Crisium and Fecunditatis</td>
</tr>
</tbody>
</table>

Table 1 Description of the different M3 optical periods, see Boardman et al. (2011).
errors in the geometry of observations. The pointing geometry has been largely recovered by Boardman et al. (2011) but is still not perfect. Some images still have large offsets that can be of several hundreds of meters, particularly towards the poles. As a result, the topography used in the photometric model can be offset and lead to artifacts (e.g., offsets in crater location). Artifacts from the topography may also be due to the 1st generation of the Lunar Orbiter Laser Altimeter (LOLA) topography used in the pointing recovery. These topographic artifacts will hopefully be corrected in a near future with the updated and more accurate LOLA topography. All of these residual calibration artifacts in the L1B data will affect the photometric corrections of this study.

3. Photometric models and fitting

As described previously, the photometric model corrects the reflectance of an illuminated surface to the standard geometry. In this study, the normalization is done to the geometry with $i = 30^\circ$, $e = 0^\circ$, and $a = 30^\circ$. Therefore, the photometric correction re-projects the $\text{RADF}_k(i,e,a)$ to $\text{RADF}_k(30^\circ,0^\circ,30^\circ)$. In order to do so, the equation of Yokota et al. (2011) (see Eq. (11)) is used to define the photometric function of the lunar surface:

$$
\text{RADF}_k(30^\circ,0^\circ,30^\circ) = \frac{\text{RADF}_k(i,e,a)}{\text{XL}(i,e,a)} \cdot \frac{f_k(30^\circ)}{f_k(a)}
$$

where $\text{RADF}_k(i,e,a)$ is the radiance factor of the lunar surface as described previously (see Section 2.2), $X_L(i,e,a)$ is the limb darkening correction and $f_k$ is the phase function. $\text{RADF}_k(i,e,a)$ and $f_k$ are functions of the wavelength. This correction is applied to every M3 measurement. Therefore, the phase function $f_k(a)$ is the only term that is not known in this equation. Its value is empirically determined using the M3 data. As discussed below, the modeling of the phase function can be done using different photometric models, as can the limb darkening correction.

3.1. Limb darkening correction

There are typically three different approaches to model the limb darkening. The Lambert model applies a simple $\cos(i)$ factor to correct for the variation of brightness as a function of latitude. The Lommel–Seeliger model combines the incidence and the emission using the function:
Finally, the McEwen’s model (McEwen, 1996; McEwen et al., 1998) combines the two previous approaches:

\[ X_l(i, e, x) = \frac{\cos(i)}{\cos(i) + \cos(e)} \]

where \( L \) is described by a 3-order polynomial.

The McEwen model was used for the Clementine observations of the Moon and it has been also used by Yokota et al. (2011) to correct the data from Spectral Profiler (SP) onboard the Kaguya mission (Matsumaga et al., 2001). More recent studies (Buratti et al., 2011; Hicks et al., 2011; Sato et al., 2011; Hapke et al., 2012) and previous study (Hillier et al., 1999) have used the Lommel–Seeliger approach. A detailed review by Shkuratov et al. (2011) addresses the pros and cons of the limb darkening correction. In this study, the Lommel–Seeliger approach to correct the limb darkening is used (see Section 4.1).

3.2. Photometric models

Different models exist to describe the phase function, some of them with parameters describing the physical characteristics of the surface (e.g., roughness, scattering properties). The most frequently used models include Hapke’s (Hapke, 1993, 2002), Skuratov’s (Shkuratov et al., 1999), Minnaert’s (Minnaert, 1941), although the phase function can be described by a simple polynomial equation (Hillier et al., 1999; Buratti et al., 2011; Hicks et al., 2011).

For the Lunar Reconnaissance Orbiter Camera (LROC) data, a multiple scattering Hapke function was used (Sato et al., 2011; Hapke et al., 2012). For the Spectral Profiler (SP), Yokota et al. (2011) used a single scattering Hapke function. For the M3 data, a polynomial equation as in the previous study by Hicks et al. (2011) is used. A function with a 4th order polynomial was found to be smoother than a 6th order used by Hicks et al. (2011):

\[ f(x) = A_0 + A_1 x + A_2 x^2 + A_3 x^3 + A_4 x^4 \]

This formulation is similar to the model used by Hillier et al. (1999) but without the exponential term for the opposition effect, which is poorly constrain by the M3 observations due to the limited coverage at small phase angles. To a first order, the polynomial function describes the phase function very well, although the opposition surge might not be as well constrained as in the Hapke or Hillier models. The polynomial function works well with the high phase angles (>75°), a range where the Hapke model needs an additional function (see Yokota et al., 2011).

3.3. Distinction of mare and highland materials

It has been shown that the photometric properties of the mare and highland materials are not the same (Helfenstein and Veverka, 1987; Hillier et al., 1999). For the photometric correction of the SP data, Yokota et al. (2011) used statistics of the data to define the reflectance value that separates the highlands and the mare. Ultimately, the SP team derived two separate photometric models for the mare and the highlands and will provide their entire dataset with two spectra for each pixel, one derived with the mare photometric model and one with the highland model.

For the M3 data, the delivery to PDS includes only one photometric correction that is optimized for the lunar highlands. While it is impossible to obtain only one photometric correction that will satisfy both the mare and highland materials, a photometric correction optimized for the highlands was chosen as highlands cover more than 2/3 of the Moon. To derive this model, highland materials must first be identified. In this work, highland and mare deposits are separated based on absolute reflectance and the strength of the 1 μm absorption band. This is a more robust approximation of the highland/mare distinction than used for SP (Yokota et al., 2011), which uses only reflectance levels. To define the properties of the 1 μm absorption band, the reflectance factor (REFF), the radiance factor divided by cosine of the incidence angle, is used as a first approximation of the photometric effects (REFF is also sometimes called apparent reflectance). Three constraints are applied and the material is considered highland only if all the criteria are met:

1. REFF750nm > 0.088
2. REFF950nm/REFF750nm > (1.22 – 0.5 × (REFF750nm))
3. REFF950nm/REFF750nm < 1.5

Although not perfect, the approach does an excellent job of identifying highland materials as shown in Fig. 3. In particular, the typical mare materials of the near side and the far side, as well as South Pole Aitken terrain are separated from the highlands. Two side effects are (1) the removal of some heavily shadowed terrains near the poles because of their low reflectance, and (2) the removal of some immature craters of the highlands that display a strong ferrous absorption at 1000 nm.

3.4. Local topography

As shown in the Eq. (3), the limb darkening correction uses the incidence and emission angles of the observations. Previous photometric corrections used for lunar orbital missions (e.g., Clementine Hillier et al., 1999, Kaguya Yokota et al., 2011) use the incidence and emission angles calculated assuming the Moon is a perfect sphere. In this study, the incidence and the emission angles are calculated based on the pixel scale topography of the surface of the Moon (Boardman et al., 2011). The topography was derived from LOLA data (Smith et al., 2010) as of December 2010. Due to differences in the spatial resolution and coverage of M3 and LOLA, the resulting base map may include artifacts due to interpolation of
the topography. Some artifacts were also introduced, especially close to the pole, by the recovery and recomputation of geometric information for M³ observations acquired when the Chandrayaan-1 spacecraft had pointing problems. However, despite these issues, use of topography for M³ data at scales of 100’s meters improves the photometric correction versus spherical assumptions.

The use of local lunar topographic data in the photometric correction results in the removal of most topographic shading from the M³ images. Indeed, using the topography, the photometric correction will theoretically re-project every pixel to the same viewing geometry, consequently erasing the topography. However, because of the nature of the LOLA observations, the interpolation of the topography increases toward the equator. The consequence is that not all of the topography is removed, especially for small craters. Fig. 4 shows the difference between the correction based on a sphere (4A) and the photometric correction based on the topography (4B). The topography of the craters is removed when the topography is used, although some small craters do not change because of the coarser resolution of LOLA compared to M³.

4. Results

4.1. Limb darkening

As described previously, the Lommel–Seeliger limb darkening function is used as it is a fairly simple model that has been used previously for lunar data (Buratti et al., 2011; Hicks et al., 2011; Sato et al., 2011). As presented later (see Sections 4.3 and 4.4), the Lommel–Seeliger limb darkening function works well with the M³ observations.

The Lunar-Lambert function used previously by McEwen (1996) and Yokota et al. (2011), darkens the M³ measurements at small phase angles, while the Lommel–Seeliger does not. Fig. 5 presents the result of the two limb darkening functions applied to M³ observations. Fig. 5D clearly shows that the Lunar-Lambert function darkens the measurements by a factor of 2 at small phase angles. The difference between the two functions is less important when the phase angle is higher although the Lunar-Lambert function describes better the lunar surface radiance at high phase angle (Yokota et al., 2011). As described later in Section 4.4, the M³ L² data are slightly darker than previous observations of the Moon, which implies that the use of the Lommel–Seeliger model is appropriate.

As discussed previously, the topography of the surface is used to compute the limb darkening function (see Eq. (3)). Because M³ is nominally a nadir imaging spectrometer with ±12° FOV, variations of the incidence are much greater than the emission but rarely exceed 80°. However, by using the local topography, incidence and emergence can be very high (>85°). When the full equation of the limb darkening (see Eq. (3)) is computed with high incidence or emission angles, the reflectance can become negative or much greater than unity. To avoid negative reflectance or reflectance higher than one, the incidence and emission angle equal are set to 85°; they are higher than 85°.

4.2. Phase function fitting

Fig. 6 presents examples of the fits of the phase function using Eq. (5) at two wavelengths: 750 nm and 1500 nm for OP2C1 data. As shown in Figs. 5 and 6, tens of observations with different brightness are obtained for every phase angles. This results in a spread of the radiance factor as a function of phase angle. In order to limit the spread, the approach from Yokota et al. (2011) is used and the M³ data are binned every 0.1° to facilitate the fitting. In each bin, all the data are averaged without weighting. The binned fit is presented in green in Fig. 6A and B; the result of the fit without binning is presented in red. The fits are plotted on top of a density plot of the data used for the fits. The result shows that the photometric curve varies more realistically when the data are binned, especially at higher phase angles. This result is not surprising because this is the part of the phase function where fewer measurements were obtained, and as a consequence the fitting is of lower quality. Fig. 6 also shows that the polynomial function works well over the opposition surge although the function is not optimized for it. The values are extrapolated beyond 85° due to a lack of observations. Consequently, users of such observations (i.e., with phase angle higher than 85°) should be aware that the photometric correction is less reliable.

The fit of the phase function is carried out for all wavelengths independently; for 84 channels from 460 nm to 2976 nm in global mode. The target mode has a better spectral resolution with 286 channels in the same wavelengths range. The technical issues of the Chandrayaan-1 spacecraft did not allow for many observations in target mode. Consequently, there were not enough measurements in the target mode to independently derive the phase function. Instead, the target mode phase function was interpolated from the global mode.

The last step of defining the phase function is a smoothing in the wavelength domain. Artifacts can be seen in the phase function such as the absorption band around 900 nm presented in Fig. 7. This absorption is more important at higher phase angle. This artifact is likely related to the characteristic absorption bands of mafic minerals and to the phase dependence on albedo (see also Fig. 9 of Yokota et al., 2011), or, to artifacts from the calibration of the data. Either way, the photometric function should not introduce such a shape, as it is not related to variation in the viewing geometry. Therefore, the phase function is fit with a 4th order polynomial as a function of wavelengths to produce a smooth wavelength variation free from any residual calibration artifacts or spectral signatures.
4.3. M³ validation

In order to validate the photometric model developed here, the reflectance of the Apollo 16 landing site obtained by M³ at three different times during the mission are compared as summarized in Table 2. These observations not only differ in phase angle, but also in incidence, emission, altitude, and detector conditions (i.e., warm and cold). Fig. 8 presents the images of the three observations, and

![Comparison of two limb darkening corrections on M³ OP2C1 observations at 750 nm: (A) is the RADF, (B) the RADF/Lunar-Lambert, (C) the RADF/Lommel–Seeliger, and (D) the ratio of the two corrections. The Lunar-Lambert correction makes the measurements systematically darker than the Lommel–Seeliger.](image)

![Fit of the phase function for the OP2C1 observations. (A) is at 750 nm, (B) at 1508 nm. The green curve corresponds to the phase function after binning of the data; the red one is before binning (see Section 4.2 for details). The curves are plotted on top of a density plot of all the highland only data (see Section 3.3 for details). The binned results smooth the phase functions and improve the high phase angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 5.](image)
Fig. 7. Phase functions at 20°, 40°, 60°, and 80° before smoothing in the wavelengths domain, with the resulting fit overplotted. Each plot symbol represents the 84 wavelengths of the global model. The absorption at 900 nm, more prominent for higher phase angles, should not be present and therefore is treated as an artifact. The vertical lines bracket the absorption.

Fig. 9 presents the result of the photometric correction of the three sub-sampled areas shown in Fig. 8. Before the photometric correction (Fig. 9A), the M3 measurements are significantly different; these differences are greatly reduced after the photometric correction (Fig. 9B). The differences still visible after the photometric correction are likely due to the off-nominal and different conditions of the three observations and their effect on the L1B calibration (e.g., variations in temperature). In addition, note that the gradient in absolute reflectance from the top M3 measurements of Fig. 9B (dashed-dotted line) to the bottom (dotted line) is well correlated with an increase of the emission angles from 1° to 9°, which may reflect a cross-track calibration residual (see Section 5.3). The artifacts that remain in the L1B calibration (see Section 2.3) more likely explain some of the differences. It is also interesting to notice that M3 observations of Apollo 16 are evening and morning, thus resulting in different shadows.

Globally, the effect of the photometric correction can be seen in Fig. 3A, where the brightness is now quite constant as a function of latitude. Figs. 10 and 11 present detailed mosaics of the Tsiolkovsky and the Marius Hills regions. Figs. 10A and 11A are the L1B radiance data; Figs. 10B and 11B correspond to the L2 reflectance after the photometric model is applied. Although the variations between two adjacent images are not entirely suppressed, the model improves the images and in particular reduces the cross-track dependence that is due to the variation in incidence and emission angles. In the case of Marius Hills (Fig. 11), the vertical stripes are related to noise in the image because the signal is much lower than in the case of Tsiolkovsky (Fig. 10). Figs. 10C and 11C are the ratio of two wavelengths (2200 nm and 1200 nm); the cross-track residual is evident for Tsiolkovsky in Fig. 10C but is more effectively removed for Marius Hills in Fig. 11C. This emphasizes the complexity of the residual cross-track that will be discussed in Section 5.3.

However, the cross-track issues are greatly suppressed by the photometric correction.

4.4. Absolute reflectance level

Numerous instruments have recently observed the Moon, and it is reasonable to assume that the surface has not changed during that time frame and therefore the signal received should be the same as long as the geometric conditions of observations are the same (i.e., i, e, x). However, observations are not all done at the same geometry and it is the goal of the photometric correction to adjust all observations as though they were acquired under the same geometric conditions. In order to validate the photometric model developed here, a comparison of the reflectance of the Apollo 16 landing site obtained by M3 and the USGS ROBOTic Lunar Observatory (ROLO) (Kieffer and Stone, 2005) is done. The summary of the ROLO observations are presented in the Table 2, individual images of AP16 are used (Staid and Stone, 2007) rather than disk integrated results. Fig. 9B presents the measurements of the Apollo 16 landing site after the photometric correction using Eq. (3) for M3 and for ROLO, which was measured at 30° phase. Therefore, only the limb darkening needs to be applied. After the photometric correction, the observations agree within 10% and exhibit a similar red slope. Comparisons between M3 and SP radiances have already shown that M3 tends to be slightly darker (Besse et al., 2011b). The comparison with ROLO confirms that M3 tends to be slightly darker than other instruments. However, it is also possible that the ROLO measurements are brighter because of the larger spatial sampling (7.12 km/pixel in the VNIR and 14.3 km/pixel in the SWIR) that may include some immature highlands even though the same region of mature soils was targeted.

5. Discussion and implications

5.1. Wavelengths and phase dependence

Fig. 12 is a 3D representation of the phase function derived for M3. Fig. 12A corresponds to the phase function table used for the data delivered to PDS (i.e., including the wavelength smoothing presented in Section 4.2); Fig. 12B is an updated version for wavelengths long ward of 2500 nm. The PDS version includes two small absorptions at 2.81 and 2.94 μm that are possibly related to the water/hydroxyl as reported by M3 previously (Pieters et al., 2009a). At high phase angles (>60°) the blue slope of the phase function after 2500 nm is not expected and is probably an artifact. To avoid possible misinterpretation of spectra in the region with possible OH/H2O absorptions, wavelengths greater than 2500 nm are extrapolated. A linear extrapolation of the phase function from 1500 to 2500 nm is applied to the phase function between 2500 and 3000 nm. This extrapolation is done after the fitting of the phase function by Eq. (5). Examples of the two phase functions is also presented in Fig. 13. From Figs. 12 and 13, it appears that the wavelength dependence is very smooth. In Fig. 12, the higher density of the grid between 750 nm and 1500 nm is representative of the spectral resolution of the instrument, which has higher spectral

<table>
<thead>
<tr>
<th>Mission</th>
<th>Image number</th>
<th>Phase angle (°)</th>
<th>Incidence angle (°)</th>
<th>Emission angle (°)</th>
<th>M3 optical period</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROLO</td>
<td>mm270903–270907</td>
<td>30.0</td>
<td>20.5</td>
<td>11.0</td>
<td>N/A</td>
</tr>
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<td></td>
<td>mm270953–270957</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>M3C20090108TF4645 (Fig. 8A)</td>
<td>22.8</td>
<td>23.6</td>
<td>1.0</td>
<td>OP1A</td>
</tr>
<tr>
<td></td>
<td>M3C20090204T113444 (Fig. 8B)</td>
<td>42.0</td>
<td>50.8</td>
<td>8.8</td>
<td>OP1B</td>
</tr>
<tr>
<td></td>
<td>M3C20090607T110414 (Fig. 8C)</td>
<td>13.4</td>
<td>13.7</td>
<td>3.6</td>
<td>OP2C1</td>
</tr>
</tbody>
</table>
resolution near the mineralogical diagnostic 1 μm absorption. Although the photometric model used is not optimized for the opposition effect, the phase function retrieves a steep opposition effect along the wavelengths domain. The first two top curves of Fig. 13, which correspond to small phase angles (e.g. 0° and 10°), have very small differences and steeper slopes in the visible. However, tiny elongated white spots concentrated near the equator are still visible on Fig. 3A, although they are greatly reduced from original images. This suggests that the phase function does no account for the entire opposition effect. Finally, the extrapolation of the phase function after 2500 nm mainly affects measurements taken at phase angle higher than 60°. This is well coupled with the
possible OH/H₂O absorptions, which are stronger as closer to the lunar poles (Pieters et al., 2009a). The M³ phase function presented in this manuscript is very smooth both in spectral and spatial direction and is presented in Fig. 12A. The updated $f(\alpha)$ table (including the correction longward of 2500 nm) has been delivered to PDS as a supplemental file and is available at http://pds- imaging.jpl.nasa.gov/data/m3/CH1M3_0004/EXTRAS/.

5.2. Comparison with previous models

Fig. 14 presents several phase functions of the lunar highlands derived from a variety of instruments. The phase function presented in this work is compared to the phase function obtained earlier with the M³ data (Hicks et al., 2011), and to the phase functions of Clementine (Hillier et al., 1999), ROLO from Buratti et al. (2011), and SP (Yokota et al., 2011). Efforts are focused on the highland phase function for M³, thus the comparison is done only for phase functions derived for lunar highlands at 750 nm. The phase function from SP has been modified so that the limb darkening is a Lommel–Seeliger type. This allows an absolute comparison of the phase functions without changing the results of the photometric correction because the ratio of the limb darkening to 30°/C//176 is used (see Eq. (2)). The phase functions are not normalized and thus reflect the absolute brightness of the Moon derived from the instruments. The phase functions are nearly identical around 40°/C/176 and they tend to be similar for higher phase angles. However, for small phase angles, the differences between the phase functions are important and can be greater than 50%. The previous work on M³ (Hicks et al., 2011) suffers from a lack of data below 30° and above 80° phase angles, which therefore explains the large differences. The phase function from Clementine shows a higher albedo than SP although the observations were made with roughly the same viewing geometry. M³ has an opposition effect in the range of other phase functions. The discrepancy of the phase functions at small phase angles reflects the complexity of the lunar phase function for the opposition effect and that the M³ phase function did not try explicitly to model the opposition effect. The large differences at small phase angles are most likely due to the models that treat the opposition effect differently and may not account for all the properties of light scattering on planetary surfaces.

5.3. Cross-track residual and models

Although the result of our photometric model is acceptable both in terms of absolute reflectance for the spectra and visually for the image, a cross-track feature that remains in the images cannot be ignored (see Section 4.3). This cross-track feature in the image strips can have several causes: (1) photometric modeling of the different emission (waning versus waxing), (2) incompleteness of the photometric correction, and (3) instrumental artifacts. First, it is unlikely that the variations in emissions have a very important role. The Wide Angle Camera (WAC) onboard LRO has a very large FOV (≈60°), and does not suffer similar cross-track issues as seen in the publically released global mosaics. M³ has a smaller field of view but has a more significant effect. Second, the M³ photometric model presented here works better in some cases than others. For example, the Marius Hills mosaic of Fig. 11 has fewer cross-track residuals than the one of Tsiolkovsky in Fig. 10. This result is surprising because, as previously stated, the photometric model is optimized for the OP2C1 observations, which corresponds to the Tsiolkovsky mosaic. This seems to rule out the second cause (i.e., incompleteness of the photometric correction) otherwise the opposite effect for these two mosaics will be seen. Additionally, it has been shown that the global mosaic of the Moon is correct.
and that the Apollo 16 measurements are brought together at the same reflectance level, with some uncertainties likely related to the L1B calibration (see Section 4.3). It is however possible that the challenging recovery of the M3 pointing information such as roll, pitch and yaw, may degrade the capability of the M3 photometric model, this does not correlate with the cross-track residuals.

Finally, the third possible cause of the cross-track feature is investigated. M3 has faced several calibrations challenges and all the artifacts have been reduced as much as possible but are not completely removed from the L1B data. If so, it may be possible to derive an empirical model to reduce the cross-track gradient in the L2 images. The developed model is fairly simple and uses the latest photometrically corrected images. This approach cannot be used with the L1B data because it will alter the photometric properties and will then complicate the photometric correction afterwards. The model is developed in three steps, (1) the down-track pixels (y-direction) are averaged for each M3 image resulting in a 304 × 84 line image array for each M3 image, (2) the resulting arrays are each normalized to zero to ensure that the cross-track model does not change the mean of the reflectance, and (3) and average taken over all of them give the cross-track correction model as the end result for the entire dataset. During these steps, the poles have been eliminated (higher than 75°) because the shadows are too prominent and skew the correction. Small images (i.e., <5000 lines) are also not used. The cross-track model consists on an image of 304 samples and 84 channels. The target mode is again interpolated from the global mode because of the limited number of observations. This cross-track image is then added to individual images to improve the cross-track artifacts. The result of this empirical model is presented in Fig. 15. Fig. 15A shows the average correction for the L2 data along with corrections derived from an average of all OP1B and OP2A separately. These two optical periods have comparable phase angles but the Sun changes sides (morning versus evening). Fig. 15B plots the correction derived from the L1B radiance data for OP1B and OP2A. The shape of the curve is the same as the L2 data, only the slope has changed. This slope is directly related to the variation in incidence in the image, variation corrected by the photometric model in the reflectance image, which has no x-direction slope (Fig. 15A). Given its polar orbit, the illumination condition variations (i.e., mainly the incidence) along the M3 slit correspond to approximately a straight line. In Fig. 15B, it is seen that the x-direction averages have stronger variation than a line close to the edge of the detectors and cannot be

**Fig. 11.** Mosaics of the western part of the Marius Hills plateau using OP1B observations. (A) Corresponds to the radiance at 750 nm (L1B data), (B) corresponds to the reflectance at 750 nm (L2 data), and (C) corresponds to the ratio of the reflectance at 2200 nm by 1200 nm. Although there are some vertical residuals in the L2 and the ratio images, careful examination shows that most of them are not located at the edges of the images and are therefore due to noise in these low SNR data. The boundaries between the individual images are well removed and the cross-track effects are limited. (D) Corresponds to the same mosaic after the empirical cross-track correction (see Section 5.3).
due to the geometry. This result shows that the source of the cross-track artifact is likely to be the result of incomplete calibration of the L1B data. Furthermore, the variations of the x-direction average are asymmetric with one side of the detector having stronger increase. There is ~20% overlap between the M3 images. Thus, the mosaicking process matches the strong increase of one side of the detector with the smaller increase of the other side, creating a gradient between the mosaiced images.

Although the exact cause remains unknown, applying a globally averaged cross-track correction on L2 data improves the data and does not change the absolute level of reflectance. Figs. 10D and 11D present the result of the empirical cross-track correction on the previous mosaics of Tsiolkovsky and Marius Hills. The improvements are clearly visible for the ratio of 2200–1200 nm of Tsiolkovsky; the ratio of Marius Hills after correction is not that much better, mainly because the mosaic without the empirical correction is already good enough. Fig. 16 presents another result of the empirical cross-track correction. Fig. 16A corresponds to the L2 mosaic of the Sinus Aestuum region and Fig. 16B corresponds to the L2 data corrected with a cross-track model derived from all the images. A clear improvement is seen in the cross-track direction; the boundaries between images are less pronounced. For Fig. 16C, a cross-track model derived only from the images of the mosaic itself is used. The best result is achieved with this approach; nearly all the boundaries are eliminated. Fig. 16D–F, ratios of 950–750 nm, illustrate the improvements when applying the cross-track correction to all the wavelengths. The result is a mosaic without boundaries thus showing that the cross-track correction works along the wavelengths domain. In principle, it should be possible to derive individual in-scene cross-track correction for all data. However, the cross-track artifact is a complex artifact and for some images an in-scene approach does not work. Therefore, we proceed with an average correction. The boundary between two images of the Fig. 16A shows a variation of signal of ~20% in L2 data. After the cross-track correction is applied, the variation is reduced to ~12% (Fig. 16C).

The cross-track correction files (i.e., global and target) averaged from data from the entire mission have been delivered to PDS as supplemental files and are available at http://pds-imaging.jpl.nasa.gov/data/m3/CH1M3_0004/EXTRAS/. Users of M3 data are encouraged to add this correction to the L2 images to improve the cross-track residuals.

5.4. Artifacts in the M3 L2 data delivered to the PDS

The photometric model described in this paper corrects the majority of the M3 observations. As described previously, the selection of the data used to derive the phase function optimizes this model for the lunar highlands and for the OP2C1 observations acquired from 20 May 2009 to 23 June 2009 (see Table 1).
Fig. 15. The cross-track correction to the M3 L2 data at 750 nm. The average reflectance has been scaled to zero. (A) Is the correction to the reflectance data (i.e., L2). The dashed line is derived from all the M3 observations, the solid line from OP1B and the dashed-dotted line from OP2A acquired during morning and evening lightening. (B) Is the correction derived from radiance data (i.e., L1B) before any photometric correction (units is in W/(m² μm sr)). Here, the x-direction effects also include a steep slope due to the variation of the incidence angles, which are removed by the photometric correction in (A).

Fig. 16. Mosaics of 20 M3 L2 images at 1500 nm in the region of Sinus Aestuum. (A) is a L2 mosaic, (B) a L2 mosaic with an additional cross-track correction derived from all observations, (C) a L2 mosaic with optimized cross-track correction derived internally using observations from the mosaic itself. (D–F) are ratios of the reflectance at 950 nm by 750 nm, using the respective mosaic-based correction. There is a clear improvement with the empirical cross-track correction from (A–C), the ratios also exhibit a less pronounced improvements.
The detector temperature regime changed significantly throughout the mission resulting in different responses from the lunar surface (Isaacson et al., 2012). This difference is evident in the M3 images when reflectance of the same areas from different optical periods are compared. In some cases, a small change in phase angle (<2°) can result in a change in L1B radiance by a factor of two. Consequently, although the photometric model re-projects all the data to the same viewing geometry, it is difficult to compare observations from different OPs where differences in the absolute L1B radiance are still present (see Fig. 2). This difference is more important when studying dark areas and can turn into a 20% relative brightness difference for the same region observed at two different detector temperatures. Unfortunately, these differences complicate global studies of the Moon where data from different OPs are needed because of the uneven spatial coverage by M3.

The photometric correction is derived from local topography. An effect of this approach is that in photometrically corrected data topography is mostly removed allowing spectral comparison over regions with significant topographic variation. However, offsets in registration between M3 and LOLA data will negatively impact the L2 photometrically corrected data. In extreme cases, virtual mounds or depression can be created from the offset in registration (Lundeen et al., 2011).

The photometric model described in this paper takes into uses the phase function delivered to PDS with updates to remove possible misinterpretation of spectra longward of 2500 nm with possible OH/H2O absorptions.

6. Conclusions

Using the latest L1B calibration of the M3 data, an improved photometric correction has been derived. This correction was included in the version 1.0 L2 delivery of the M3 data of November 2011 to the PDS. The reddening and the absolute reflectance of the data are consistent with observations of the Moon from other instruments. The phase functions derived from highlands show some differences, particularly at small phase angles. These differences are probably due to the nature of the M3 measurements that use different emission and incidence angles compared to other missions because M3 was not always at a nadir viewing geometry. These variations in emission angles might not be well constrained in the photometric model and in the limb darkening. The simplified model used to derive the phase function does not address the opposition effect in detail and this could be improved in the future by using other models (Hiller et al., 1999; Shkuratov et al., 2011; Hapke et al., 2012).

An updated version of the phase function has been derived by extrapolating after 2500 nm to avoid possible misinterpretation in the OH/H2O domain. Despite the fact that the photometric model corrects the data well, some artifacts are still present in the data, particularly in cross-track. This effect is more likely a residual of the L1B calibration and an empirical correction derived from the L2 data removes most of the cross-track artifacts and supports the creation of more useful mosaics.

Finally, an improvement in the pointing and selenolocation of the M3 observations needs to be done in order to apply a better photometric correction to the L1B data. First, it will improve the emission, incidence, and phase angles based on topography used in deriving the phase function. Second it will limit the artifacts created in the L2 data by incorrect position of the geometrical features.

Acknowledgments

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