Improved Chandrayaan-1 M³ data: A northwest portion of the Aristarchus Plateau and contiguous maria

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ABSTRACT

We provide and test a method to obtain significant improvement of available Chandrayaan-1 M³ data. The advance is achieved using the Gaussian λ-convolution of spectra and Fourier filtration of images. The main result is imagery of the reflectance across different wavelengths as well as parameters of 1 µm and 2 µm absorption bands with unprecedented quality. This approach can be particularly useful for further investigations using M³ data, since it produces improved imagery of various lunar surface characteristics. We studied a region comprising a portion of the Aristarchus Plateau, Montes Agricola, and a small part of the mare surface in Oceanus Procellarum to the north of Montes Agricola. We found that the lava flows in the area between the Aristarchus Plateau and Montes Agricola have a chemical/mineral composition different in comparison with mare areas to the northwest of the ridge Montes Agricola. We also identified distinct spectral properties of morphologically young craters located on the plateau and mare surface. A correlation diagram for positions of the minima of the 1 µm and 2 µm bands allows a cluster analysis of the region, and we map areas associated with a cluster corresponding to pyroclastic glasses. Relationships between geologic and spectral parameter maps were established.

1. Introduction

The Indian Chandrayaan-1 lunar probe was launched in October 2008 and operated until August 2009. One of the main goals of the mission was performing high-resolution remote sensing of the Moon in visible, NIR, and X-ray spectral ranges (Goswami and Annadurai, 2009). At a surface resolution of about 100 m/pix, hyperspectral imaging with the scanning spectrometer M³ onboard the probe provided a vast amount of data that are useful for developing new visions of the lunar surface (Goswami and Annadurai, 2009; Pieters, 2009). The M³ operated from 420 to 3000 nm, where highly diagnostic mineral absorption bands occur. Individual M³ images are long and narrow strips between lunar poles. The accumulation of contiguous image data provides global studies of the Moon, covering almost all the lunar surface at 85 wavelengths.

In this near-infrared spectral range, lunar minerals reveal crystal field bands formed, in particular, by electron transitions of the d–d type between split energy levels of Fe²⁺ ions (Burns, 1993). Being a transition element, iron has the unfilled external d-shell; hence, electrons placed on the five orbitals dₓ₂, dᵧ₂, dₓz, dᵧz, and dz² are weakly bound with the nucleus. When a Fe-cation is placed in a crystal lattice, the orbitals due to their different shapes are disturbed differently by neighboring anions. The disturbance removes the degeneracy and the energy levels split, which allows quantum transitions with photon absorption. For orthopyroxene, for instance, the splitting produces two bands centered near 950 and 1800 nm. For olivine the splitting produces 3 overlapping bands near 1 µm. The pyroxene and olivine bands are strongly overlapped near 1 µm, producing a common asymmetric absorption structure.

In this paper we study optical properties of a region of the northwestern side of the Aristarchus Plateau using a small part of image cube M3G20090612T183813 (https://pds-imaging.jpl.nasa.gov/volumes/m3.html), which covers the area shown in Fig. 1 with a resolution of about 250 m/pixel. The scene comprises not only the NW portion of the Aristarchus Plateau and Montes Agricola, but also a small portion of Oceanus Procellarum. We chose this area because of its expected

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diversity in optical and, hence, geological properties. In particular, we here anticipate conspicuous variations in depths and positions of the 1 µm and 2 µm absorption bands. The correlation between the positions of the absorption bands is diagnostic for the determination of pyroxene types, e.g. to distinguish between ortho- and clinopyroxenes (McCord and Adams, 1973; Adams, 1974; Klima et al., 2007; 2011; Whitten and Head, 2015), as well as glasses (Adams, 1974; Besse et al., 2014; Horgan et al., 2014).

The Aristarchus Plateau is among the most interesting sites on the Moon. It is located in the northwestern portion of the lunar nearside. The plateau is an elevated formation of about 170 × 220 km, which is surrounded by younger mare basalts of Oceanus Procellarum (Schultz 1976; Wilhelms, 1987). The crater Aristarchus is located at the southeastern edge of the Aristarchus Plateau and is approximately 40 kms in diameter and 3.0 kms in depth; this crater is beyond the scene in Fig. 1. The plateau is noted to be rich in optical and geologic features (Gaddis et al., 1985). Dark mantling deposits (DMD) of the volcanic pyroclastic origin cover this plateau (e.g., Zisk et al., 1977; Gaddis et al., 1985; Wilhelms, 1987). These deposits are especially dark in the UV spectral range, which were revealed more than 100 years ago by Wood (1910; 1912), who supposed that this optical feature might be a result of strong absorption of sulphur compounds. Later, this UV dark formation was unofficially named Wood’s Spot. It is interesting to note that the boundary of the Aristarchus Plateau and Wood’s spot are not coincident everywhere. We note also that the plateau has a thorium anomaly (Hagerty et al., 2009). According to LRO Diviner measurements, the Christiansen wavelength of the surface materials of the plateau and surrounding maria are similar (http://target.lroc.asu.edu/q3). A smaller abundance of rocks is observed on the plateau surface (http://target.lroc.asu.edu/q3). The scene includes also Montes Agri
cola (Fig. 1) that is a ridge. This continues for a distance of 160 km. The 20 km gap between the ridge and the plateau to the south is covered by mare basaltic flows.

For a further geological description and chemical/mineral characterization of the region, the Chandrayaan-1 M3 spectrometer data could be very informative. Fig. 2 displays the scene shown in Fig. 1 in the context of M3 measurements. The instrument M3 is an imaging spectrometer working in a pushbroom operation. It uses an HgCdTe detector array. In each surface point, like S (see Fig. 2), a full spectrum including 85 narrow spectral bands is measured. Thus, the data set is arranged as a cube with the spatial coordinates X (along the detector array) and Y (along orbital movement) and the third coordinate λ (wavelength), which justifies the name M3 (Goswami and Annadurai, 2009; Pieters et al., 2009).

Because of some technical problems of the spacecraft (largely thermal), the M3 final images are burdened with a system of random vertical stripes, which significantly limit the data use for quantitative analysis. This especially becomes noticeable for derivative images, which involve multiple images. Fig. 3a, b illustrates this problem for distributions of the apparent albedo A(950 nm) (reflectance at λ = 950 nm) (e.g., Hapke, 2012; Shkuratov et al., 2011) and the color ratio C(950/750) = A(950 nm)/A(750 nm) located in the upper-left corner of the scene shown in Fig. 1. The clear vertical stripes have different intensity and length, and their system reveals faint periodicities. The stripes dramatically spoil derivative images such as the color ratio or more complicated combinations of spectral parameters, e.g., related to the depths and position of 1 µm and 2 µm bands. Fig. 3b shows the stripes dominating the lunar color-ratio image, allowing only qualitative conclusions on mineralogy of the surface. The shortwave slope of the 1 µm band characterized with the color-ratio A(950 nm)/A(750 nm) is widely used for estimation of the FeO content and maturity degree of the lunar surface (Lacey et al., 1995; 2000; Shkuratov et al., 1999a; Pieters et al., 2006; Shkuratov et al., 2005; 2007). As can be seen, the image striation makes it almost impossible to calculate the local regolith characteristics with any accuracy.

2. Additional data processing

In this paper we show that the current Chandrayaan-1 M3 spectral data presented in https://pds-imaging.jpl.nasa.gov/volumes/m3.html can be significantly improved by means of suppressing the striation patterns of the images across the full spectral range.

2.1. Gaussian λ-convolution

First, noticeable signal variations are found in neighboring wavelengths at the maximal spectral resolution at different points on the lunar surface. This effect is never observed in laboratory conditions,
and therefore we may treat these variations as a random (Poisson) noise. We carried out a small-scale smoothing of spectra through a wavelength convolution ($\lambda$-convolution) with a 1D Gaussian kernel. The kernel parameters were chosen empirically, considering that the quantitative criterion of their acceptability is the preservation of the mean over the image in each spectral channel with an accuracy of 0.2%. We here used the kernel width of about 4 spectral pixels on the level of half-height of the Gaussian function. We did not use wavelengths larger than 2.6 µm, since in this spectral range the number of spectral counts is small, and the smoothing may destroy the spectral structure attributed to the compounds OH/H$_2$O (Pieters et al., 2009). Moreover, standard processing may result in a residual thermal component at wavelengths greater than 2.6 µm and such wavelengths may not be attributed to the compounds OH/H$_2$O (Pieters et al., 2009). Furthermore, one cannot directly exploit Eqs. (1)–(3), because of the infinite limits in the integrals and the discrete presentation of images. Therefore, the Fourier integrals should be expressed in the following discrete form (e.g., Smith, 2002).

$$f(x, y) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \exp(-i(\omega_x x + \omega_y y)) \Lambda(C, \Omega, \omega_x, \omega_y) F(\omega_x, \omega_y) d\omega_x d\omega_y,$$

(3)

Unfortunately, one cannot directly exploit Eqs. (1)–(3), because of the infinite limits in the integrals and the discrete presentation of images. Therefore, the Fourier integrals should be expressed in the following discrete form (e.g., Smith, 2002).

$$F_{p,q} = \sum_{j=0}^{m-1} \sum_{k=0}^{n-1} \exp(i(\omega_p j + \omega_q k)) f_{j,k}$$

(4)

where $\omega_p = -\frac{2\pi p}{m}$ and $\omega_q = \frac{2\pi q}{n}$ are the coordinates in the frequency plane, $p = 0, 1, 2, \ldots m-1$, and $q = 0, 1, 2, \ldots n-1$, and $m$ and $n$ characterize the image sizes in the number of pixels. Correspondingly

$$f_{j,k} = \frac{1}{mn} \sum_{p=0}^{m-1} \sum_{q=0}^{n-1} \exp(-i(\omega_p j + \omega_q k)) \Lambda(C, \Omega, \omega_p, \omega_q) F_{p,q}$$

(5)

where

$$\Lambda(C, \Omega, \omega_p, \omega_q) = \begin{cases} C, & \text{if } \omega_p, \omega_q \text{ are inside } \Omega \\ 1, & \text{if else} \end{cases}$$

(6)

Fig. 6 displays a 3D image of the Fourier spectra of the scene shown in Fig. 5b. The vertical axis is logarithmic. We may see, that the spectral spectra has a peak related to low frequencies that are responsible for the formation of the large-scale lunar pattern of the image. We also see a comb, which is oriented along the $p$ axis; it is a bit darker than the other points. This is a location of the vertical striation. The structure of the comb is clearly seen in Fig. 7 that is the vertical projection of the 3D
Fig. 5. A portion of image M3G20090612T183813_V03 before (a) and after (b) the described Gaussian $\lambda$-convolution. The image (c) is the ratio of (a) and (b). The image M3G20090612T183813_V03 was obtained at $\lambda = 0.95$ $\mu$m.

Fig. 6. A 3D image of the Fourier spectra of the scene shown in Fig. 5b.

Fig. 7. A Fourier spectrum of the image shown in Fig. 5b.

Fig. 8. A part of image M3G20090612T183813_V03 before (a) and after (b) Gaussian $\lambda$-convolution and Fourier filtration of the stripe pattern. The image was obtained at $\lambda = 0.95$ $\mu$m, and the filter parameters are $C = 0$; the image (c) is the ratio of ones marked as (a) and (b). The histograms (d) correspond to the images (a) and (b).
surface shown in Fig. 6. One may see that actually there are several combs that are parallel to each other. In Fig. 7 we also show the domain $\Omega$.

The filtration of the stripe structure has been carried out at $C = 0$ inside the domain $\Omega$. The main selection criterion of the filter parameters is the disappearance of the stripe pattern or at least its visual minimization on the resulting image. Another important issue is the absence of features related to the Moon on the ratio image of the initial and filtered images. Additionally, by varying the parameter values we keep the average albedo of the scene within 0.2% of the average for the original image. Fig. 8 shows images of the scene presented in Fig. 1 before (a) and after (b) application of both the Gaussian $\lambda$-convolution and the Fourier filtration of the stripe pattern. The resulting image (b) does not exhibit any detectable stripe pattern at all. The ratio (c) of the images (a) and (b) does not exhibit any lunar feature details. The histograms shown in Fig. 8(d) correspond to the images (a) and (b). Although the histograms are very similar, they, nevertheless, reveal differences related to the elimination of the stripe system.

As has been noted, the main goal of the suggested processing development is to obtain derivative spectral images that can be applied to quantitative analyses of chemical/mineral composition of the lunar surface. Fig. 9 shows a distribution of the color-ratio $A(950 \text{ nm})/A(750 \text{ nm})$ before (a), after (b) using the Gaussian $\lambda$-convolution, and after (c) using the Gaussian $\lambda$-convolution and Fourier filtering vertical streaks; (d) – (f) the same for the band minima $\lambda_{\text{min}}$ (in nm).

Fig. 9. Distributions of the color-ratio $A(950 \text{ nm})/A(750 \text{ nm})$ before (a), after (b) using the Gaussian $\lambda$-convolution, and after (c) using the Gaussian $\lambda$-convolution and Fourier filtering vertical streaks; (d) – (f) the same for the band minima $\lambda_{\text{min}}$ (in nm).

2.3. Band parameters

In lunar spectrometry, characteristics of absorption bands usually are investigated using reflectance spectra (e.g., Sunshine et al., 1990; Sunshine and Pieters, 1993). A more thorough method is based on the spectra of the absorption coefficient (e.g., Shkuratov et al., 1999a).
Light-scattering models for particulate media can be used for calculation of absorption spectra from reflectance spectra. The formula Kustbelka-Munk or its modifications are often used (e.g., Myrek et al., 2011). Such models suggesting more physical results have been widely used as well (Hapke, 2012; Shkuratov et al., 1999b). Resulting band parameters, e.g., the minimum position, determined from reflectance and absorption spectra can be slightly different due to the non-linearity of connection between reflectance and absorption (Shkuratov et al., 1999b). Thus, a standardization of the band determination is necessary. Traditionally reflectance spectra are used initially, and we use them hereafter.

The following parameters: positions of the 1 µm and 2 µm bands (λ_{min}), their depths, and general slopes of spectra in the 550 – 2600 nm range here are derived and exploited. Investigations of more complicated parameters, such as band asymmetry are very hard tasks even after the described data improvement. The listed parameters can be determined using different approaches. The approaches can be conditionally divided into two wide groups: parametric and non-parametric (Fu et al., 2007).

The first group is based on a representation of a spectrum as a set of isolated bands, the contours of which are described as a function with free parameters. The whole spectrum is the sum of these particular bands. The most suitable and widely used contour is the Gaussian function or its modifications (Sunshine et al., 1990; Sunshine and Pieters, 1993; Kaydash et al., 2018). The main advantage of such an approach is that each model band can be attributed to the absorption band of definite chemical elements. However, this advantage is difficult to realize in practice, since the spectrum of the lunar regolith is not a direct linear combination of spectra of the constituent compounds.

Several non-parametric methods of continuum removal have been considered. For instance, one may normalize the overall trend of a full spectra to one single line, i.e. approximate the overall continuum with a linear function (e.g., McCord et al., 1972). This is a rough approximation and, therefore, results of this approach are imprecise. The second approach is to determine the edges of the absorption bands and then to separately remove the continuum for each spectral band. The key problem of the method is uncertainty in the positions of the band edges, since they indefinitely abut on the continuum and are not zero, especially where bands edges overlap. A more sophisticated approach is named the convex hull, which is often used in the spectroscopy for continuum removal (e.g., Graham, 1972; Fu et al., 2007; Martinot et al., 2018). In the case of a spectrum, the convex hull is the convex polygon, for which all spectrum points lie below the polygon or are its vertexes. In this approach, we use a simple Graham Scan algorithm (Graham, 1972) to compute convex hulls of spectra. Then we use only that part of the convex set which lies above the spectrum to remove the continuum. There are two methods to do this: through subtraction, i.e. an additive continuum correction, or through division, i.e. a multiplicative normalization. We here use the second approach.

Fig. 10 shows the location of two pixels marked by the rhomb and cross, spectra of which have different convex-hulls (Fig. 11a, b). The dashed lines in Fig. 11a, b are the relative spectra after dividing by the convex hull. The difference between these two cases presented in Fig. 11a, b can be mapped. Fig. 10 displays a distribution of two kinds of areas. Marked with darker and brighter tones correspond to the hulls presented with a single line (Fig. 11a) and several lines (Fig. 11b), respectively. As could be anticipated, there are rather large areas that reveal convex hulls more complicated than linear in the spectral range 550 – 2600 nm.
In the convex hull analysis we always used the upper wavelength limit at 2.6 µm, since at longer wavelengths the thermal component may noticeably influence results.

3. Results and discussion

3.1. Mapping band parameters

Using the Gaussian $\lambda$-convolution and Fourier filtration of Chandrayaan-1 M$^3$ images we produce maps of several color ratios for our test area. Fig. 12 represents distributions of the color ratios $A(0.75 \mu m)/A(0.54 \mu m)$, $A(1.30 \mu m)/A(0.75 \mu m)$, and $A(2.6 \mu m)/A(1.7 \mu m)$ in which a longer wavelength image is the numerator of the ratio. We note that all three images are fairly similar. The color-ratio $A(950 nm)/A(750 nm)$ (see Fig. 9b) also resembles the color ratios shown in Fig. 12. Bright young craters reveal smaller spectral slopes than other units; this effect is minimal for the color ratio $A(0.75 \mu m)/A(0.54 \mu m)$. The material located in the Aristarchus Plateau is the most red. Even mare material between the plateau and Montes Agricola (see Fig. 1) is red, although in the case of the ratio $A(2.6 \mu m)/A(1.7 \mu m)$ this effect is smaller. This suggests noticeable difference of the chemical/mineral composition of this material and lava flows to the north-west of

![Fig. 12. (a): Color ratio $A(0.75 \mu m)/A(0.54 \mu m)$; (b): Color ratio $A(1.30 \mu m)/A(0.75 \mu m)$; (c): Color ratio $A(2.6 \mu m)/A(1.7 \mu m)$.](image)

![Fig. 13. Position of $\lambda_{min}$ for 1 µm (a) and 2 µm bands. Scales are given in nm.](image)

![Fig. 14. A correlation diagram between $\lambda_{min}$ for 1 µm and 2 µm bands (a); a map of optical glasses determined with the correlation diagram (b). To calculate the minima, we used cubic splines.](image)
minima have been approximated by a cubic spline, and then for each pixel of the scene, the minimum was calculated. Fig. 13 shows high quality images (especially in the case of the 2 µm band) that are very rich in details. As distinct from the Montes Aglicola, the Aristarchus Plateau has fairly large values of $\lambda_{\text{min}}$ for the 1 µm band. According to laboratory spectral measurements (e.g., Adams, 1974), this is a characteristic of iron-bearing glasses. The plateau and Montes Aglicola have relatively small values of $\lambda_{\text{min}}$ for the 2 µm band.

Fig. 14a shows a correlation diagram between the positions of the minima of the 1 µm and 2 µm bands. The diagram has a clear cluster structure that is diagnostic. In particular, its main domains can be classified as glass and pyroxene, deduced from laboratory measurements by Adams (1974) (see the ellipses on the diagram in Fig. 14a). In the upper right corner of the diagram, we show a legend to the classification map (Fig. 14b) corresponding to the clusters seen in the diagram. As we may observe, the materials of the Aristarchus Plateau include a large percentage of glasses, perhaps, of pyroclastic origin. The material of the lava flows between the Aristarchus Plateau and Montes Aglicola form a distinctive cluster in the diagram. This material can be found to the north of Montes Aglicola. The red and brown clusters surprisingly divide the ordinary mare surface located to the north of the Aristarchus Plateau in two portions. Unclassified dark spots in the map occupy a small percentage of the area and can be ignored in the analysis.

The depths of the 1 µm and 2 µm bands depend on pyroxene abundance, type of pyroxenes, and the maturity degree of the lunar surface. The depths were calculated using the convex hull method and are shown in Fig. 15. We here used two definitions of the depth. The first one $h_{\text{min}}$, defined in Fig. 11a, is counted from the lowest point in a band (Fig. 15a,b) and the second one is $1-h_{\text{min}}$ (Fig. 15c,d) that introduced by Clark (1983). These two pairs of maps reveal complicated patterns. The depths of bands 1 µm and 2 µm are weakly correlate with each other independently of the band depth presentation (e.g., Fig. 16). The images of the band depths almost do not correlate with the maps of the band minimum positions shown in Fig. 13. The 2 µm depth distribution (Fig. 15b) appears almost insensate to the craters on the Aristarchus Plateau. Craters with immature regolith having deep 2 µm bands (dark spots in Fig. 15b) can be observed on the surface to the northwest of the Aristarchus Plateau. In some measure the 1 µm depth distribution shows the same features (Fig. 15a), although some craters here look like bright spots on the Aristarchus Plateau. The lava materials lying between Montes Aglicola and the plateau have larger values of the depth of 2 µm band; whereas, the 1 µm band has here no peculiarities.

The examples described in this section show that quantitative information can be obtained from the Chandrayaan-1 M3 images of the Moon in the parameters, such as $\lambda_{\text{min}}$ and band depths $h_{\text{min}}$ of both the spectral bands, if the Gaussian $\lambda$-convolution and Fourier filtration are applied. It should be emphasized that the depth distribution of the 1 µm band (Fig. 15a) and the corresponding color ratio $A(950\,\text{nm})/A(750\,\text{nm})$ (Fig. 9b) do not show a significant correlation, which suggests that the color ratio determined using the short-wave wing of the band is not an adequate characteristic of band depth variations of the pyroxene bands.

### 3.2. Geologic characterization

We here present a geological description of the region under study in order to show relationships with the maps of the spectral parameters. We use mosaics produced from Kaguya images (the Terrain camera, resolution is $\sim 7\,\text{m/px}$ and the 750 nm reflectance map constructed from the Kaguya Multiband Imager (Ohtake et al., 2013) to describe the composition of the region. The standard procedure of photogeologic analyses reveals that two major types of deposits make up the area: (1) autochthonous materials form the main geological bodies of the Aristarchus Plateau and its immediate surrounding maria and (2) surficial

Fig. 15. The maps of the depths of the 1 µm (a, c) and 2 µm (b, d) bands. The upper and lower pairs correspond to the definition of depth $h_{\text{min}}$ counted from the lowest point in a band (Fig. 11a) and the second one is $1-h_{\text{min}}$ that introduced by Clark (1983).

Fig. 16. A correlation diagram of the depths of the 1 µm and 2 µm spectral bands.
deposits that are related to both ejecta and ray systems of remote craters and the emplacement of dark mantling materials likely related to pyroclastic activity (Head, 1974; Gaddis et al., 2000, 2003; Weitz et al., 1998).

The highland autochthonous deposits include two material units in our geological map shown in Fig. 17. The first one corresponds to high-standing massifs (designated **hhi**) that occur as isolated, approximately equidimensional hills (usually 5–6 km across) with morphologically smooth slopes. The height of the largest hills is $\sim$500–600 m; one of them corresponds to Mons Herodotus at the eastern margin of the map area, which is $\sim$800 m high. The hills are scattered throughout the NW portion of the Aristarchus Plateau, form the SW end of Montes Agricola, and occur within the mare area between the Aristarchus Plateau and Montes Agricola (Zisk et al., 1977). The shape of these **hhi** units suggests that they represent exposures of blocky ejecta of basin-like impact events; some of them may be related to the Imbrium impact. Occurrences of the **hhi** units at the edges of Montes Agricola correspond to **plr** units, pre-Imbrian rugged material, shown in different localities in the geological map of the near side of the Moon (Wilhelms and McCauley, 1971). The second units correspond to lower highland terrains (designated **hlo**) form the majority of the Aristarchus Plateau within the map area and the main portion of Montes Agricola. This unit represents dark mantling materials of uncertain age from Imbrian to Copernican (Wilhelms and McCauley, 1971). We ascribe the index **hlo** to a complex of materials underlying an apparently thin veneer of dark mantling material. This unit has a gently undulating surface with typical topographic variations $\sim$100–200 m, except for the larger ($>2$–$3$ km) impact craters that are several hundred meters deep. Materials of the **hlo** unit embay the high-standing massifs of the **hhi** unit and are younger. This unit probably represents a mixture of the Imbrium ejecta and volcanic materials related to volcanic activity in the Aristarchus Plateau.

Mare autochthonous deposits in the NW portion of Oceanus Procellarum embay the highlands of the Aristarchus Plateau and Montes Agricola. Morphologically, the mare surfaces appear to be homogenous. The 750 nm reflectance map allows us to define conditionally two types of materials within the maria: darker and brighter deposits (Fig. 17). The latter (**mmb** unit) form the surroundings of the Aristarchus Plateau. This unit mostly coincides with the **Im** unit, designating Imbrian mare material (Wilhelms and McCauley, 1971). The surface of **mmb** unit is morphologically smooth, without evidence of individual lava flow fronts recognizable at the Kaguya resolution ($\sim$7 m/px). Systems of wrinkle ridges oriented in the meridional direction deform the surface of the mare deposits. The darker mare deposits

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**Fig. 17.** A geological map of the studied region.
(mmd) form isolated equidimensional and elongated patches a few tens of kilometers across. The largest areas of the mmd unit are localized within the basin-like topographic depressions near the western edge of the map area where they correspond to the Em unit, designating Era- tosthenian mare material (Wilhelms and McCauley, 1971). Near the eastern edge of the map, an occurrence of the darker plains is spatially associated with a lava channel (Rima Cleopatra) and is confined within local topographic depression. In this area, materials of the darker plains (mmd) embay the brighter plains (mmb).

Surficial deposits in the area occur as dark pyroclastic mantles that overlay some portion of the Aristarchus Plateau (Fig. 17) and as bright patches, elongated strips, and clusters of small (a few hundred meters) secondary craters consistently oriented in several directions and representing ejecta of remote craters. The dark mantles, seen better at high Sun, are confined within the Aristarchus Plateau and show no evidence of possible source features. Three types of bright surficial deposits represent materials ejected from the rather fresh impact craters. The most abundant are ejecta from the crater Aristarchus (23.8°N, 47.5°W, 39 km diameter, unit eja). Materials ejected from craters Glushko (8.1°N, 77.7°W, 39.5 km, unit ejg) and Ohm (18.4°N, 113.8°W, 61.8 km, unit ejo) occur exclusively within the mare deposits northward of Montes Agricola. The units are formed by either clusters of secondary craters or elongated strips of brighter material.

3.3. Age assessments

In planetary geology, the absolute model ages (AMA) of units defined and mapped at a specific resolution are derived from crater size-
frequency distribution (CSFD) measurements. This technique, including a discussion of model assumptions, strengths and shortcomings, and an error analysis, has been summarized in detail elsewhere (e.g., Neukum et al., 2001; Hiesinger et al., 2000, 2010; Wagner et al., 2002; Michael and Neukum, 2010) and is beyond the scope of this work. In our study, we seek chronological constraints of volcanic and impact events that caused the formation of a complex of deposits surrounding the Aristarchus Plateau and Montes Agricola. In order to obtain these constraints, we have counted craters using the WAC photo mosaics with resolution 100 m/px (Robinson et al., 2010). The relatively low resolution of these images reduces the effects of the small-scale resurfacing events and contamination of the count areas by small (less than ∼300 m) secondary craters. Clusters of the larger secondary craters are clearly seen in the WAC mosaics and have been excluded from the count areas. In our study, we counted craters using the CraterTools application to the ESRI ArcGIS (Kneissl et al., 2011) and approximated the size-frequency distribution curves using the CraterStats program (Michael and Neukum, 2001), which applies the chronology by Neukum et al. (2001) and production functions to fit the curves.

Our study area includes only a small portion of the Aristarchus Plateau, which may not be representative of the entire complex structure. Because of this, we adopt the Lower Imbrian age, 3.8 Ga (Zisk et al., 1977) for the units (hhi and hlo) that make up the Aristarchus Plateau in the study region.

The surfaces of the mare units (mmb and mmd) appear to be at slightly different elevations, with the darker plains (mmd) being preferentially confined within local topographic depressions. These topographic positions of the mare units suggest a younger relative age of the darker plains. We conduct the CSFD measurements within five individual fields of the darker plains and three fields of the brighter plains. The areas of the fields range from ∼170 to 690 km². When all recognizable craters have been mapped and counted, the areas corresponding to each specific mare unit were merged in order to increase the total number of craters and, thus, the reliability of the AMA estimates. The isochron fitting of the CSFD curves within the merged areas gives the model ages of 2.49 ± 0.13 Ga and 1.70 ± 0.09 Ga for the brighter (mmb, Fig. 18a) and darker (mmd, Fig. 18b) plains, respectively. These values are close to the AMA of unit P53 of 1.68 ± 0.12 Ga determined from Clementine spectral data (Hiesinger et al., 2003). The spectral data, however, have lower spatial resolution that prevented division of a single spectral unit into a set of finer sub-units. Our AMA determinations for the lava plains to the north of the Aristarchus Plateau completely overlap the range of ages of mare units to the south of the Plateau, from 2.81 ± 0.38/−0.61 Ga to 1.03 ± 0.16 Ga, determined from the crater counts on the WAC mosaics (Stadermann et al., 2018).

We also perform a photometric characterization of the region to provide independent qualitative assessments of the ages of the geologic formations seen in Fig. 17. The technique is based on mapping the phase-function parameters. This has been described in detail by Korokhin et al. (2014; 2016a; 2018) and Shkuratov et al. (2016). The NASA Lunar Reconnaissance Orbiter mission (LRO) allows high-quality
data for lunar photometric studies (Robinson et al., 2010). The spacecraft is equipped with the wide angle camera (WAC). The camera images the lunar surface in the visible (415, 566, 604, 643, and 689 nm) spectral range, ensuring multiple coverage of the same area at different illumination and observation angles. We here use images acquired at λ = 689 nm as source data to determine photometric parameters of the studied area. Parameters characterizing the optical micro-roughness were mapped with a resolution of approximately 90 m. To approximate the phase-angle dependence of the apparent albedo \( A(\alpha, i, e) \), we use a 3-parameter empirical equation suggested by Korokhin et al. (2016b):

\[
A(\alpha, i, e) = A_0 \exp(-\eta \alpha^2) \cos \frac{2}{\pi} D(\alpha, i, e),
\]

(7)

although modifications of this equation have been considered theoretically (e.g., Shkuratov et al., 1994; 2018a), where \( A_0 \) is the normal albedo (its pattern is very similar to \( A \)), \( \eta \) is the parameter of nonlinear phase-curve slope, and \( \rho \) is the characteristic of nonlinearity of the phase curves. We here use Akimov’s disk function as the most reliable in lunar photometry (Shkuratov et al., 2011):

\[
D(\alpha, \beta, \gamma) = \cos \left( \frac{\pi}{\pi - \alpha} \left( \frac{\gamma - \alpha}{2} \right) \right) \frac{(\cos \beta)^{(\alpha - \gamma)}}{\cos \gamma},
\]

(8)

where the photometric (luminance) coordinates \( \alpha, \beta, \) and \( \gamma \) are the phase angle, and photometric latitude and longitude, respectively. The angles \( \beta \) and \( \gamma \) can be expressed through the incident and emerging angles \( i \) and \( e \) using the following formulas (e.g., Hapke, 1993; Shkuratov et al., 2011):

\[
\cos i = \cos \beta \cos (\alpha - \gamma),
\]

\[
\cos e = \cos \beta \cos \gamma.
\]

(9)

We calculate distributions of the parameters \( A_0 \) and \( \eta \) for each point of the lunar surface in the scene using the mean-square method and hundreds of LROC WAC images acquired at different \( \alpha \) from a range of 7–80°. These images were accurately coregistered with each other. The value of parameter \( \rho \) is fixed 0.6; the average number of points for the phase-curve approximation is about 100. A detailed description of the processing is presented by Korokhin et al. (2014, 2016a,b, 2018). Maps of the parameters \( A_0 \) and \( \eta \) are shown in Fig. 19a, b. It should be emphasized that images are seamless mosaics, which were produced with the technique described by Korokhin et al. (2014, 2016a, b, 2018), which takes into account many different factors including the local surface topography. The algorithm used in this work has been somewhat modified (Korokhin et al., 2018). Instead of using the longitudinal component (E-W direction) of the topography slopes calculated from the external DEM, we fit them simultaneously with parameters \( A_0 \) and \( \eta \) (\( \rho \) is fixed 0.6) directly in the optimization procedure. Fig. 19c shows a model topography image. In other words, we use a photoclinometry technique that produces better quality maps of \( A_0 \) and \( \eta \), and suggests independent information about topography of the scene under study.

The parameter \( \eta \) characterizes optical roughness of the surface. Rougher surfaces have higher values of \( \eta \), assuming they have the same albedo. At higher albedo, the parameter \( \eta \) is reduced due to multiple scattering in the lunar regolith (Kaydash et al., 2012, 2014; Shkuratov et al., 2012, 2016; Velikodsky et al., 2016). Fig. 19b does not reveal a conspicuous difference in roughness between mare and plateau areas, although the plateau surface seems rougher in the topography image (Fig. 19c). This suggests the absence of formations with the young surface, as in the case of the crater Giordano Bruno (Shkuratov et al., 2012). Traces of surface erosion of elevated topographic formations are clearly seen in Fig. 19a, b (arrows 1–4). These are probably the result of ejecta hits from the craters Aristarchus, Ohm, and Glushko (Shkuratov et al., 2018b). We also point to two areas that are not obviously connected with an albedo feature (arrows 5 and 6). Finally the ejecta deposits around a fresh crater are shown by arrow 7. All these areas are smooth in terms of Eq. (7). It should be noted that correlation of the optical roughness \( \eta \) and albedo is unexpectedly weak.

### 3.4. Relationships between spectral and geological data

It is interesting to establish relationships between optical and geological data for this area. Using Adam’s \( \lambda_{\text{min-1}} - \lambda_{\text{min-2}} \) diagram, we can find irregularities in the localizations of the geological provinces. Results of such investigations are shown in Fig. 20. The grey color corresponds to the whole scene, and the dark color represents a particular geological formation. Thus, dark spots in Fig. 20a, b correspond to the areas of the Aristarchus Plateau and Montes Agriculta, respectively. In spite of the morphologic similarity, their positions in the diagram are a bit different. The darker (mmld) and lighter (mml) maria are almost in the same location of the diagrams (Fig. 20c, d).

The ejecta materials (eja, ejjo, and ejg) are presented in different locations in the diagram depending on where they are located on the surface. The ejecta placed on the plateau and mare regions can be seen inside the plateau and mare clusters, respectively (Fig. 20e). We additionally consider a group of craters sited on the Aristarchus Plateau (Fig. 21). As can be seen in Fig. 20f, the craters form a faint cluster located in the lowest part of the diagram. The diagrams presented in Fig. 20 help to assess the possible nature and timing of the formation of various materials composing the Aristarchus Plateau, Montes Agriculta, and the surrounding maria. Although the Aristarchus Plateau and Montes Agriculta represent parts of apparently the same morphological complex, their spectral characteristics are different (Fig. 20a, b). The characteristic points that represent the surface of the Aristarchus Plateau form a dense cloud, which is almost completely confined within the glass branch of the Adams diagram (Fig. 20a). In contrast, the points corresponding to Montes Agriculta are preferentially concentrated within the pyroxene branch of the diagram (Fig. 20b). These spectral differences of morphologically similar units likely reflect a predominant concentration of glassy pyroclastic particles...
within the plateau, whereas the area of Montes Agricola is deficient of pyroclastic materials. It is in agreed with lower albedo of plateau areas that are beyond craters in comparison with Montes Agricola. This suggests that the explosive volcanic activity was located mostly within the plateau, and its deposits did not reach the nearby massif of Montes Agricola. The pyroxene branch of the Adams diagram, thus, may characterize the pre-pyroclastic composition of the plateau highlands.

In developing the comparison of geological and optical data, we study correlation coefficients of albedo at different wavelengths for the different provinces. That is for each combination of wavelength \( \lambda_1 \) and \( \lambda_2 \) from the range 540–2617 nm, we calculate the correlation coefficient using all the pixels in the scene and then construct a diagram that we show in Fig. 22. This results in a fanciful pattern that is symmetrical relative to the bisector, on which the correlation coefficient is maximal and equals 1. The contours of equal correlation coefficient are not regular; e.g., the contours extend from the bisector toward the 1 \( \mu \)m and 2 \( \mu \)m bands. It means that in the spectral sub-ranges centered near 1 \( \mu \)m and 2 \( \mu \)m spectra of the pixels of the scene are variable.

As can be seen from Fig. 22a-f the correlation coefficient diagrams are different for different geological provinces. We see that the Aristarchus Plateau and Montes Agricola have noticeably different diagrams: the variability of the 1 \( \mu \)m band is higher for Montes Agricola. The diagrams for lighter and darker maria are fairly similar, but clearly distinct from the Aristarchus Plateau and Montes Agricola. The materials of the ejecta deposits and peculiar craters that are in Fig. 21 have variable 2 \( \mu \)m band, which are not the case of all the former diagrams. The spectral variability near 1 \( \mu \)m is also high. Thus, the diagrams of the

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**Fig. 22.** Correlation coefficient diagrams of albedos at different wavelengths for different geological provinces.

**Fig. 23.** Average spectra of LSCC samples [http://www.planetary.brown.edu/relabdocs/LSCCsoil.html](http://www.planetary.brown.edu/relabdocs/LSCCsoil.html).
correlation coefficients suggest unusual, but useful information.

It is interesting to compare the lunar correlation coefficient diagrams with the analog those for lunar samples. We exploit here spectral data obtained by the Lunar Sample Characterization Consortium (LSCC) (Taylor et al., 1999, 2001; Pieters et al., 2002, 2006) that include regolith samples selected to be representative of various lunar basalt compositions having different maturity. Since the optical properties of lunar soils are controlled by the smaller size fractions and space weathering processes (Pieters et al., 2000), the LSCC concentrated on detailed analysis of the < 45 µm components of lunar soils. Coordinated compositional and spectral measurements of the samples were carried out for soils subdivided into three size fractions (< 10 µm, 10–20 µm, and 20–45 µm) in addition to a “bulk” < 45 µm sample (Taylor et al., 2001). Altogether the LSCC analyzed 52 samples of different size fractions. Bi-directional spectra of a high spectral resolution were acquired for each subsample in the RELAB at Brown University. All spectra were measured over the spectral range 0.3–2.6 µm with a 5 nm sampling resolution at a phase angle of 30° (i = 30°, e = 0, the angles of incidence and emergency, respectively) (Pieters and Hiroi, 2004). Examples of LSCC spectra averaged for each size fraction are shown in Fig. 23. As anticipated, the bulk spectrum lies between the fine and coarse fractions. All the separate spectra used and composition data are available at http://www.planetary.brown.edu/relabdocs/LSCCsoil.html.

Fig. 24 shows that the correlation coefficient diagrams of the sample suite do resemble those of the lunar measurements, especially, in the case of mare areas. The sample fraction d < 10 µm has almost no variability near the 1 µm and 2 µm bands, although this fraction should significantly influence the lunar spectra. The behavior of the bulk and coarse fraction 20 µm < d < 45 µm on the diagrams is similar to that of the materials of the ejecta deposits and peculiar craters.

4. Conclusion

The main result of this study is the lunar imagery produced from the 1 µm and 2 µm bands using the Chandrayaan-1 M3 data. This was made possible by processing the images using a Gaussian λ-convolution and Fourier filtration, which was carried out in the discrete form. This approach seems to be very prospective for further investigations using M3 data, since it allows unprecedented image quality, allowing us to extract a variety of lunar surface characteristics. In particular, we have mapped different color-ratios A(0.75 µm)/A(0.54 µm), A(950 nm)/A(750 nm), A(1.30 µm)/A(0.75 µm), A(2.6 µm)/A(1.7 µm), positions of the minima (λ_{min}) of the absorption bands and their depths. The band depth is determined using the convex hull technique that is rather universal and wide-spread in diagnostic spectroscopy.

We here studied an area comprising a portion of the Aristarchus Plateau, Montes Agricola, and a small part of the mare surface in Ocean Procellarum to the north of Montes Agricola. It was found, e.g., that the lava flows in the place between the Aristarchus Plateau and Montes Agricola have a chemical/mineral composition different in comparison with mare areas to the north-west of the ridge Montes Agricola. Differences in optical properties of the Aristarchus Plateau and Montes Agricola are found. In addition, we showed that the spectral properties of craters located on the plateau and mare surface are different. The cluster structure of the Adams (1974) correlation diagram λ1 – λ2 allows an optical classification map of the region under study. In particular, we found a lunar cluster corresponding to glasses in the Adams diagram constructed using laboratory samples. This lunar cluster is formed by pyroclastic materials of the Aristarchus Plateau and Montes Agricola. The diagram allows us to establish relationships between geologic and spectral parameter maps.

Further studies can be developed with the application of the Gaussian λ-convolution and Fourier filtration to many other lunar
areas. Correlation diagrams by Adams (1974) for pyroxene can be applied to numerous regions of the Moon.

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