Lunar Surface Temperature and Emissivity Retrieval From Diviner Lunar Radiometer Experiment Sensor

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Abstract The lunar surface temperature (LST) derived from thermal infrared (TIR) measurements can aid in understanding the physical properties of the lunar surface. The Diviner Lunar Radiometer Experiment (herein, Diviner) sensor provides global lunar surface observation in seven TIR channels. However, its retrieval of LST constantly uses a single emissivity value (i.e., 0.95) by ignoring the spatial variation of lunar surface, thereby reducing the accuracy of temperature and day–night temperature difference. To overcome this problem, this study developed a physical method called temperature–emissivity separation (TES) algorithm to retrieve LST and lunar surface emissivity from the daytime observation in three Christiansen Feature (CF) channels (7.55–8.05, 8.10–8.40, and 8.38–8.60 μm) of the Diviner, and then used the emissivity from daytime observation to inverse LST at nighttime observation. Findings showed that the TES algorithm could retrieve LST and emissivity with an error of less than 0.8 K and 0.008, respectively. However, observation noise significantly affected the retrieval accuracy, particularly for the low-temperature pixels; moreover, high retrieval accuracy requires a surface temperature higher than 240 K. The new algorithm was applied to obtain the daytime and nighttime LST and emissivity from the Diviner images. Results showed that the LST retrieved from the algorithm differed approximately 3.9 K from that calculated from a single emissivity 0.95. Finally, an example of global surface temperature and emissivity were obtained. Consequently, the CF pixels were found to distribute in the latitude range from −60° to 60°; however, they did not have a large distribution in high-latitude and near-polar regions.

1. Introduction

The lunar surface thermal infrared (TIR) emission spectroscopy is sensitive to the lunar bulk composition. It can readily identify important lunar silicates, such as feldspar, pyroxene, olivine, and quartz in the lunar surface. The lunar surface temperature (LST) and spectral emissivity derived from the TIR measurements provide a promising way to understand the physical properties of the lunar surface (Greenhagen et al., 2010). The Diviner Lunar Radiometer Experiment (herein, Diviner) (Paige, Foote, et al., 2010; Paige, Siegler, et al., 2010) is one of the seven instruments aboard NASA’s Lunar Reconnaissance Orbiter and it started data observation from July 2009. The Diviner is a nine-channel radiometer that can observe the lunar surface in the wavelength range of 0.3–400 μm, thereby covering the reflectance and infrared emission. Among the nine channels, Channels 1 and 2 collect the solar radiance reflected by the lunar surface, whereas the remaining channels (Channels 3–9) observe the lunar surface thermal emission with different sensitivities. Channels 3 (7.55–8.05 μm), 4 (8.10–8.40 μm), and 5 (8.38–8.60 μm) are three narrow passbands and were designed to map the Christiansen Feature (CF) (Conel, 1969), which is diagnostic of the bulk silicate mineralogy (Glotch et al., 2010, 2011; Greenhagen et al., 2010). Channel 4 passband is near the observed CF emission peak (Greenhagen et al., 2010). Meanwhile, Channels 6–9 have broad passband filters of 13–23, 25–41, 50–100, and 100–400 μm, respectively. They are primarily used to observe the LST over a wide temperature range, particularly for low-temperature at nighttime observations. LST is crucial in the lunar surface balance of incoming solar flux and outgoing thermal emission; it can be applied for analyzing the near-surface environmental conditions of the Moon (Siegler et al., 2016), studying the Moon’s crustal composition at depth (Song et al., 2013), determining the ages of craters on the Moon (Hayne et al., 2017), and identifying the most recent impact craters and yield information on the recent production of lunar impact craters (Williams et al., 2018). The TIR characterization illustrates the physical properties of lunar impact ejecta and...
changes through time (Ghent et al., 2016); in this manner, the character and extent of the primary anorthositic crust can be studied (Donaldson Hanna et al., 2014). The LST is affected by the sunlight. As a result, a large temperature difference exists between daytime and nighttime, as well as between the equator and high-latitude regions. The zonal mean LST decreases with the latitude $\theta$, which is consistent with the $\cos^{1/4}(\theta)$ shape observed for daytime temperatures (Vasavada et al., 2012; Williams et al., 2017).

However, Diviner observation only obtains the brightness temperature ($BT$) of the lunar surface in different TIR channels. The retrieval of the physical temperature of the lunar surface should remove the effect of emissivity. The $BT$ is lower than the physical temperature due to the non-unity emissivity for most surfaces. Obtaining the emissivity data for each pixel of the lunar surface is difficult; to overcome this problem, some authors have used a fixed emissivity (i.e., 0.95 or 0.99) to estimate the LST (Bandfield et al., 2011, 2015) or have directly used the $BT$ for applications. For example, Paige, Foote, et al. (2010), Paige, Siegler, et al. (2010) defined a bolometric $BT$, that is, the wavelength-integrated radiance, in all seven Diviner channels, which was expressed as the temperature of an equivalent blackbody because this temperature is the most fundamental and interpretable measurable quantity. Williams et al. (2017) recently generated a global dataset of such temperature at a 0.5° spatial resolution and a 0.25 h local time resolution using over 5.5 years of Diviner observation. However, the $BT$ is lower than the physical temperature because the emissivity of lunar surface shows non-unity and significant spatial variation. As a result, no account of emissivity may cause some uncertainties in the application of LST, such as the comparison between daytime and nighttime surface temperature and the calculation of the surface energy balance. In addition, the research on channel emissivity is useful for silicate mineralogy. On this basis, the emissivity effect should be removed to obtain the physical LST, which is also called surface kinetic temperature.

This study focuses on the retrieval of physical LST and emissivity from Diviner TIR channel observation. The temperature–emissivity separation (TES) algorithm is a common method for retrieving Earth’s land surface temperature and emissivity from multiple narrow channels in the wavelength range of 8–14 $\mu$m; it was first proposed for the five TIR channels of the Advanced Spaceborne Thermal Emission and Reflection Radiometer onboard the TERRA satellite of Earth Observation System (Gillespie et al., 1998). At present, the TES algorithm provides global land surface temperature and emissivity products (Hulley et al., 2015). It was also applied successfully to the Moderate Resolution Imaging Spectroradiometer (MODIS) (Hulley & Hook, 2011), which is another sensor onboard the TERRA satellite, and the Chinese Gaofen-5 satellite thermal infrared sensor (Ren et al., 2018). Previous studies have shown that at least three thermal channels are required for accurate results from the TES algorithm. The narrow Channels 3–5 of the Diviner can meet this requirement, meanwhile channels 6–9 have wide spectral ranges and are sensitive to different temperature ranges. Since the narrow channel have more accuracy in the thermal radiative transfer equation (see Eq. 1) than the wide one, the mixed use of the two kinds of channel is unsuitable for the TES algorithm. Furthermore, different noise levels may be contained during observation under the same surface temperature. Moreover, the lunar surface is more suitable for the TES algorithm than the Earth's surface. First, the Moon is an airless body; therefore, nearly no atmospheric attenuation to the TIR emission signal from the surface to the satellite occurs. This phenomenon is inevitable in the Earth observation. Second, the key technique of the TES algorithm is the usage of channel emissivity contrast, which is relatively larger for soils, rocks, and minerals but smaller for water surface, snow/ice, and dense vegetation. The lunar surface is covered by rock and soil; thus, a large channel emissivity contrast feature can ensure a high accuracy from the TES algorithm in theory. Consequently, the TES algorithm should perform well in lunar surface to obtain temperature and emissivity. On this basis, this study initially conducts the TES algorithm development and its sensitivity to observation noise. Then, this study applies the algorithm to retrieve the LST and emissivity from daytime and nighttime observations. Finally, an example of global LST and emissivity is presented, and the corresponding distribution of CF pixels is identified.

2. Temperature and Emissivity Retrieval Algorithm

2.1. Algorithm Development

No atmosphere exists from the lunar surface to the satellite; thus, the thermal radiance of the lunar surface emission observed at the thermal infrared sensor level is equal to that of the surface level, which can be expressed as follows:
where, $B_i(T_i)$ is the blackbody thermal radiance at the surface temperature $T_s$ for the $i$th channel, which is calculated from the Planck’s Law; $\varepsilon_i$ is the surface emissivity; and $T_i$ is the corresponding $BT$. Thermal emission is related to the thermal emission of the surface depth approximately several micrometers rather than a lunar soil profile. From Eq. 1, the retrieval of surface temperature $T_s$ should input $\varepsilon$. The surface temperature remains unchanged with wavelength. Hence, $N$ channel observations correspond to $N + 1$ unknowns ($N$ emissivity and 1 surface temperature). The number of the unknown is larger than that of observation equations. To solve the temperature, auxiliary assumptions, constraints, or equations are required. Some studies have assumed that emissivity is known as a fixed value, such as 0.95 or 0.99 (Bandfield et al., 2011, 2015). However, this process causes considerable error if such emissivity is far from the actual value and ignores the spatial variation of the surface emissivity.

The TES algorithm can estimate temperature and emissivity simultaneously from multiple-channel radiance. Previous studies have shown that at least three thermal channels are required for accurate results from the TES algorithm. Channels 3 (7.55–8.05 μm), 4 (8.10–8.40 μm), and 5 (8.38–8.68 μm) of the Diviner can meet this requirement. This algorithm adds an empirical relationship among those channels’ minimum emissivity ($\varepsilon_{\text{min}}$) and their maximum–minimum normalized emissivity difference ($\text{MMD}$) to ensure the mathematical solutions of temperature and emissivity, as shown in Eq. 2:

$$\varepsilon_{\text{min}} = a + b \cdot \text{MMD}$$

where, the $\text{MMD}$ value is calculated from the normalized emissivity $\hat{\varepsilon}_i$ in the ratio module as follows:

$$\text{MMD} = \max(\hat{\varepsilon}_i) - \min(\hat{\varepsilon}_i)$$

In Eq. 4, $\varepsilon_i$ is the initial guess of the emissivity in the $i$th channel estimated from the normalized emissivity module (NEM). The NEM initially uses a fixed value of emissivity (i.e., 0.99) in Eq. 1 to calculate the $T_s$ in different channels, and then applies the maximum $T_s$ among those channels to obtain their $\varepsilon_i$ using Eq. 1. With those emissivity $\varepsilon_i$, Eq. 4 obtains $\hat{\varepsilon}_i$ and then Eq. 3 gets the MMD value, which will then be used in Eq. 2 to calculate the $\varepsilon_{\text{min}}$. The $\varepsilon_{\text{min}}$ corresponds to the $\hat{\varepsilon}_{\text{min}}$ in Eq. 4, and the other $\varepsilon_i$ is then calculated as $\varepsilon_i = (\hat{\varepsilon}_i/\hat{\varepsilon}_{\text{min}})\varepsilon_{\text{min}}$. After this step, those $\varepsilon_i$ are the retrieved value of the emissivity, and consequently they input again to Eq. 1 to calculate the temperature $T_s$ in the channels, and the maximum $T_s$ is the final determined value of the LST.

The key technique of the TES algorithm is to obtain the coefficients $a$, $b$, and $c$ of the MMD module that actually needs the emissivity of lunar surface samples in Channels 3–5 of the Diviner. We have downloaded 56 lunar or lunar-like surface samples’ emissivity spectra from the NASA Planetary Data System (PDS) at Washington University in St. Louis (http://speclib.rsl.wustl.edu/search.aspx) (Bishop et al., 1995; Pieters, 1983; Pieters & Mustard, 1989), as shown in Figure 1(a). Along with the spectral filters of the three channels of the Diviner (see Figure 1(a)), the channel-effective emissivity is calculated using the channel spectral filters (Paige, Foote, et al., 2010; Paige, Siegler, et al., 2010), as shown in Figure 1(b). Using the channel emissivity, the coefficients of Eq. 2 are regressed as $a = 0.990$, $b = -0.638$, and $c = 0.728$, with root mean square error (RMSE) of $\varepsilon_{\text{min}}$ as 0.007 and the determination coefficient $R^2$ as 0.96, as shown in Figure 1(c). Although additional channels can reduce the RMSE of the MMD regression, Channels 6–9 are not used because they are designed with broad wavelength range and are mainly for low-surface temperature observations. Therefore, these channels have different noise levels compared with the used three channels. Moreover, the wavelength of the samples’ emissivity is only up to 25 μm, which cannot cover the spectral filter of these thermal channels (up to 400 μm). Note that, the above lunar emissivity spectra were measured in a laboratory under Earth conditions. The Earth’s atmosphere and the different thermal gradient in the sample in Earth measurement condition, the emissivity value and even the position and magnitude of the CF feature may differ from those in really lunar surface condition (Donaldson Hanna et al., 2012; Greenhagen et al., 2011; Thomas et al., 2012). However, in...
current moment we cannot get the emissivity from lunar surface measurement and the PDS provides the only way for the sample emissivity spectra sources.

Some details of the TES algorithm can be found in the literatures (Gillespie et al., 1998; Hulley & Hook, 2011; Sabol et al., 2009). The procedure using this algorithm for retrieving LST and multiple-channel emissivity is shown in Figure 2. The input data are the observed $B_T$ or radiance of the three CF channels (Channels 3–5). The output is the surface temperature and the emissivity of the three channels ($\varepsilon_3$, $\varepsilon_4$, and $\varepsilon_5$). Given that the surface temperature is unchanged with different channels, the retrieved $T_s$ is consequently used in Eq. 1 to solve the surface emissivity of the remaining four thermal channels ($\varepsilon_6$, $\varepsilon_7$, $\varepsilon_8$, and $\varepsilon_9$) as $\varepsilon_i = L_i/B_i(T_s)$. The TES algorithm performs well only in daytime observation, resulting in accurate daytime $\varepsilon_6$, $\varepsilon_7$, $\varepsilon_8$, and $\varepsilon_9$, which then can be further applied to retrieve nighttime surface temperature from the radiance observed at nighttime, as shown by the gray blocks in Figure 2.

2.2. Algorithm Accuracy Analysis

The algorithm retrieval accuracy can be affected by the uncertainty of the TES algorithm itself and the noise included in the observation. On the basis of the radiative transfer equation (Eq. 1), a dataset of the radiance in Channels 3–5 is initially simulated with the aforementioned 56 emissivity samples and 47 levels of the surface temperature ranging from 170 K to 400 K at a step of 5 K to check the algorithm accuracy. Then, the

Figure 1. (a) Emissivity spectra of lunar surface samples and spectral filters of the three bands, (b) Channel emissivities of samples, (c) MMD regression. The sample emissivity and MMD module for diviner.
Figure 2. Procedure of retrieving LST and multiple-channel emissivity from the daytime and nighttime observations of the diviner.

Figure 3. (a) Temperature error, (b) Emissivity error in the three channels. TES algorithm retrieval error under different surface temperatures.
dataset is applied to retrieve surface temperature and emissivity by using the newly developed TES algorithm. The RMSE of the retrieved temperature and emissivity under different temperature conditions are shown in Figure 3. The result shows that the temperature error increases with the surface temperature. A large error occurs at 400 K as 0.75 K, whereas the smallest error occurs at 170 K as 0.14 K. The temperature bias is approximately −0.05 K. Meanwhile, the emissivity errors for the three channels are approximately 0.0082, 0.0080, and 0.0077, although they nearly remain stable for all temperature ranges. This emissivity error level is nearly equal to that of the MMD module (0.007) shown in Figure 1(c). Normally, surface emissivity is regarded as an essential feature; thus, it is assumed to be the same under different surface temperatures if no phase change occurs for the surface. Results from Figure 3(b) show that the emissivity retrieved from a specified temperature can be used in other cases with different surface temperatures.

The results in Figure 3 are based on the accurate observation without any noise. However, noise is inevitable in actual images and constantly varies with the observed temperature. The noise-equivalent differential temperature (NEDT) of the three thermal channels, as shown in Figure 4 (Paige, Foote, et al., 2010; Paige, Siegler, et al., 2010), mostly decreases rapidly as BT increases. For a low temperature at 170 K, the NEDT can reach approximately 4.0, 6.4, and 5.5 K for the three channels but is lower than 0.1 K at a high temperature of 400 K.

We add a Gaussian noise (10,000 times, with a mean of 0.0 K and a standard deviation of NEDT) into the BT in the preceding simulated dataset to investigate the TES algorithm error in an actual image. Then, we calculate the error of the retrieved temperature and channel emissivity under different surface temperatures. The result is shown in Figure 5, from which two important points can be drawn as follows.

1. The retrieved temperature error is significant in the low temperature range (<200 K) and can reach approximately 46 K, whereas the corresponding emissivity error is up to approximately 0.55. The combination of the three channels enlarges the final retrieval uncertainty. Therefore, temperature error is several times of the single-channel NEDT. Therefore, as shown in Figure 5(a), the TES algorithm is not
recommended if the LST or the observed \( BT \) (e.g., in the shadow or at nighttime) is no more than 200 K. By contrast, the inversion of Eq. 1 \((T_s = B^{-1}\frac{B(T_s)}{\varepsilon})\) is appropriate on the basis of the data of Channel 3 (i.e., 7.8 \( \mu \)m channel, which has a relatively low \( NEDT \); see Figure 4) or other channels with long wavelength using a fixed emissivity value (e.g., 0.95) or the emissivity retrieved from the observation at a high surface temperature.

2. The retrieval temperature error decreases to less than 1.0 K for temperature \( >230 \) K and nearly remains constant at approximately 0.5 K from 240 K to 400 K (Figure 5(a)) because the errors caused by the \( NEDT \) and TES algorithm are generally small in this temperature range. Such temperature error is sufficiently low for the application in various fields, such as component analysis and mineral exploration. Accordingly, the emissivity error also decreases rapidly as the surface temperature increases from 170 K to 200 K and finally becomes stable (approximately 0.008) for surface temperatures higher than 240 K (Figure 6(b)). The emissivity error is small and independent of the surface temperature. Hence, the emissivity retrieved from one observation under high temperature conditions can be used to estimate the surface temperature in another observation using the inverse of Eq. 1 as stated previously, especially for conditions with low temperature surface. Moreover, the surface thermal emission mainly comes from several microns deep of the lunar surface interface; the emissivity is an intrinsic feature and can thus be assumed to be unchanged with surface temperature when no change occurs in the surface phase and when its angular dependence is ignored (Bandfield et al., 2015).

As shown in Figure 5, the TES algorithm performs considerably better for the high temperature range than for the low temperature (<200 K). If the temperature error of the actual retrieval process is required to be lower than 1.0 K, then the surface temperature should be higher than 220 K. If the emissivity error is required to be less than 0.01, then the surface temperature should be higher than 240 K. Although the surface temperature is unknown before the retrieval, the observed \( BT \) can be used as a basis because its difference with surface temperature is insignificant. As a result, the TES algorithm is mostly available in the lunar daytime observation (defined as 6 a.m. to 6 p.m. in local solar time). Moreover, the terrain shadow from the craters or mountains can cause low-temperature pixels. However, to achieve spatial continuity of the surface temperature image, the surface temperature value of the shadow pixels at daytime is directly calculated from the observed channel radiances by inversing Eq. 1 and using the average emissivity of the surrounding sunlit pixels whose temperature is higher than 240 K. Furthermore, the daytime surface emissivity can be applied to estimate the nighttime surface temperature from the radiance of Channels 6–9 observed at nighttime (Figure 2).

3. Application of LST and Emissivity Retrieval

The Diviner datasets are produced by the Diviner Science Team at the University of California, Los Angeles. The \( BT \) images with a spatial resolution 0.0156° (64 pixels per degree) are obtained from the NASA PDS Geosciences Node archives (http://pds-geosciences.wustl.edu/missions/lro/diviner.htm) (Paige et al., 2011) as the Global Data Records format with global cylindrical projection. The images in Channels 3–9 on December 15, 2015 and in Channels 6–9 on July 5, 2015 are obtained to investigate the performance of the developed TES algorithm. The first date is observed in lunar daytime; its images in Channels 3–5 are initially used into the TES algorithm to obtain daytime LST and emissivity in the three channels. Then, the LST is applied to inverse the emissivity of Channels 6–9 on the basis of Eq. 1. The images of the second date are observed at nighttime and are used to estimate nighttime surface temperature using the corresponding channel emissivity estimated from the daytime observation. This process is shown in Figure 2.

3.1. Estimation of Daytime LST and Multiple-Channel Emissivity

We take the region with longitude from 137.4° to 158.3° and latitude from 68.2° to 74.8° as an example and use the images of Channels 3–5 on December 152,015. The TES algorithm retrieves the LST and emissivity. Figure 6 shows the region’s images of (a) Channel 4 \( BT \) (\( BT_4 \)), the peak channel of CF emission, (b) the retrieved LST and (c) the temperature histogram and temperature difference histogram (LST – \( BT_4 \)). The color white indicates no observation. As shown in Figures 6(a) (a)nd 6(b), the \( BT_4 \) ranges from 150 K to 346 K, whereas the LST ranges from 156 K to 348 K. Both temperature images present a similar spatial distribution. However, the LST becomes larger than \( BT_4 \) due to the removal of the emissivity effect, as shown in their difference histogram in Figure 6(c).
Moreover, the sunlight goes from the southwest; thus, the sunlit surface has a high temperature of constantly higher than 270 K. However, the shadow pixels (blue pixels in Figures 6(a) and 6(b)) have low temperature (<170 K). On the basis of the preceding algorithm analysis, such low-temperature condition can result in significant error in the retrieval of temperature and emissivity. To solve this problem, we use BT4 of 200 K as a threshold to identify sunlit and shadow pixels. The emissivity of the shadow pixels of Channels 3–5 are then calculated as the average of the retrieval emissivity of the surrounding high-temperature (>240 K) pixels in a 50 × 50 window. If no pixels have high temperature in the window, then the average emissivity of all high-temperature pixels in the study region is used. Consequently, the emissivity is further used to estimate the surface temperature of the three channels in the shadow pixel using Eq. 1. The maximum of the calculated surface temperatures of the three channels is finally regarded as the shadow pixel LST.

Figure 6. (a) Daytime BT of Channel 4 (unit: K), (b) Retrieved daytime LST (unit: K), (c) Temperature histogram (left) and temperature difference histogram (right). Retrieved daytime LST and emissivity on December 15, 2015.
The emissivity image of Channel 4 is shown in Figure 7(a). The surface thermal radiance is dominated by the temperature rather than the emissivity. Thus, similar to the result of the TES algorithm used in Earth’s surface, the spatial distribution of emissivity is not as clear as that of the LST (Figure 6(b)). The emissivity of the southwest part (shadow pixels) of the center crater is from the spatial average. As a result, this part appears smoother in comparison with the other places. Figure 7(b) shows the emissivity histograms of Channels 3–5.

From the figure, the emissivity mainly ranges from 0.80 to 0.98, and the maximum frequency in the study area is located near 0.97, 0.96, and 0.94 for Channels 3–5, respectively. The emissivity images of Channels 6–9 are estimated on the basis of Eq. 1 using the retrieved LST. These images have a similar spatial pattern to Figure 7(a) and are thus not presented here. We further calculate the mean and standard deviation of each channel emissivity for the pixels with LSTs higher than 240 K (corresponding to high-accuracy emissivity). The results are presented in Figure 8, which shows a significant channel variation for the emissivity of the study area. The mean emissivity in Channels 7–9 is primarily from 0.70 to 0.85; thus, using a fixed emissivity value (e.g., 0.95) to retrieve the nighttime LST from the observation of the three channels will cause large uncertainty to the result. Nevertheless, as shown in Eq. 1, channel emissivity determines the shape of channel thermal radiance and $BT$. Thus, the shape of the $BT$ of the observed channels can reflect that of emissivity. As a result, the shape of the retrieved channel emissivity (Figure 8(a)) is consequently similar with that of the sensor-observed $BT$ (Figure 8(b)).

3.2. Estimation of Nighttime LST

For nighttime observation, Channels 3–5 lose sensitivity, which results in some anomalous low or negative anisothermality values (Williams et al., 2017). Therefore, they are not used due to their significant noise at relatively cold lunar nighttime temperatures. In this case, Channels 7–9 are available for LST retrieval. However, Bandfield et al. (2011) found that significant drifts in $BT$ are present in Channel 9 data immediately following calibration observations. Therefore, Channel 9 (100–400 μm) is not the primary data source. Finally, Channels 7 and 8 are used. Channel 7 is the most sensitive for 69–178 K, whereas Channel 8 is the most sensitive for 49–69 K (Paige, Foote, et al., 2010; Paige, Siegler, et al., 2010). Hence, the pixel surface temperature is calculated from Channel 7 if the $BT$ is within 69–178 K; otherwise, it is calculated from
Channel 8. As previously mentioned, the emissivity images of Channels 7 and 8 are estimated from daytime observation and assumed to remain unchanged in months because the Moon surface condition without atmosphere is stable.

Using the aforementioned method, the nighttime LST on July 5, 2015 is obtained and shown in Figure 9(b). In comparison with the BT of Channel 7 in Figure 9(a), the LST ranges from 55 K to 115 K, thereby increasing the temperature value up to 10 K. The warm pixels at daytime (Figure 6(b)) still have a high temperature at nighttime. As shown in the temperature histograms (left of Figure 9(c)), the BT has the largest percentage at approximately 75 K, whereas the LST has a remarkable percentage at approximately or higher than 80 K. Moreover, their temperature difference histogram (right of Figure 9(c)) obviously shows that the LST is higher BT, which is up to more than 3 K in most cases.

Moreover, we retrieve the LST using a fixed emissivity of 0.95 for Channels 7 and 8 to investigate the effect of emissivity on nighttime LST. As shown in Figure 10, the temperature difference (ΔT) between the LST in Figure 9(b) and the newly retrieval (ε = 0.95) increased with LST, and can be up to approximately 8 K. The mean of ΔT is approximately 3.9 K. On this basis, the accurate retrieval of LST requires an accurate emissivity input, especially for relatively high temperature conditions. Although the rock and soil component in different pixels may not vary significantly, their fractions in different pixels change among pixels; consequently, different pixels should have different values of emissivity that also change with observation channels. Therefore, the use of a fix emissivity value for all pixels cannot guarantee a highly accurate LST retrieval.

### 3.3. Global LST and Emissivity

The TES algorithm can generate global LST and emissivity images. In this manner, a remarkably convenient access is provided to retrieve LST from daytime observation data and further improve the identification of lunar surface composition. This section shows our algorithm of generating the global LST and emissivity and then discusses the identification of the lunar surface CF pixels on basis of the global emissivity image.

### 3.4. Example of Global Surface Temperature and Emissivity

Only the daytime solar light can ensure that the three short 8 μm channels have low noise level in their observation to guarantee high-accuracy retrieval results. By contrast, the shadow pixels at daytime and nearly all pixels at nighttime cannot be used in the TES algorithm. Moreover, the global image from a short-term (e.g., 1 month) observation constantly suffers from spatial discontinuity due to lack of observation in the period. Our solution is to compose lunar global images initially using each pixel’s maximum BT of all daytime observations in one year or during lunar summer. Using the maximum BT can improve the probability of high-temperature pixels (>240 K) and reduce the ratio of the shadow pixels.

Figures 11(a) and 11(b) show the examples for the global LST and Channel 3 emissivity in 2015, respectively. The LST ranges from 170 K to 470 K and is relatively high in low-latitude regions and low in high-latitude
regions. However, temperatures are not corrected for variations in the Moon–Sun distance and solar inclination angle effect. In comparison with the LST, the emissivity is from 0.75 to 0.98 and shows a significant spatial variation as follows. The middle-latitude regions have relatively low emissivity, whereas the high-latitude regions have high emissivity. However, no valid observation is conducted for the near-polar regions and other regions. Moreover, spatial discontinuity still exists.

3.5. Identification of Lunar Surface CF

Nine small regions (1° × 1°) are selected for analysis to investigate the CF (Figure 11(b)). They comprise three regions (P1, P2, and P3) around the lunar equator, three (P4, P5, and P6) with the north high latitude, and three (P7, P8, and P9) with south high latitude. Figure 12 presents the average emissivity of Channels 3–5 denoted as
Moreover, we calculate the percent of CF pixels in the latitude and longitude directions at a step of 1°. The results are shown in Figure 14. In the latitude direction, the percent of CF pixels is larger than 60% in the latitude range from −60° to 60°. The maximum 83% is obtained at the equator but becomes relatively small in near-polar regions. In the longitude direction, the longitudes from 0° to 100° have a relatively small percentage. Nonetheless, the general variation of the percent is not as notable as that in the latitude direction and mostly from 50% to 62%. On the basis of the preceding results, the mapping of silicate mineralogy using CF should be aware about the mineral content in the latitude direction.

4. Discussions

This study aims to develop a new TES algorithm to separate LST and emissivity from three short 8 μm TIR channels of the Diviner sensor during daytime and then provide the pixel emissivity for the nighttime observation in TIR channels to retrieve the LST. The error and sensitivity analysis of the algorithm is conducted with respect to the NEDT in the observations. The findings show that a fixed value of emissivity cannot ensure an accurate LST retrieval. However, the study still requires considerable attention on some topics.

The key technique of the TES algorithm is using the channel emissivity contrast (MMD) to estimate the emissivity and LST. Generally, the increase in the contrast of channel emissivity can improve the accuracy. The emissivity retrieval of different channels indicates that the emissivity variation of all channels (Channels 3–9) is considerably larger than that of Channels 3–5. Therefore, the addition of Channels 6–9 into the TES algorithm can improve the algorithm accuracy and robustness. However, the upper wavelength of the current samples’ emissivity in the database is limited to approximately 25 μm and does not cover the long wavelength range of Channels 7–9, thereby resulting in a lack of the emissivity data source in those channels. If possible, our future work can re-measure the spectral emissivity of the lunar samples in a broader wavelength range, which can cover all spectral responses of the Diviner channels. Moreover, the retrieved LST and emissivity cannot be validated using lunar ground-measured data in current existing technologies. Nevertheless, in the future, some indirect methods (e.g., the application of LST and emissivity on mineral identification and rock and soil fraction) may provide feedback for LST and emissivity accuracy. Moreover, some of Earth’s satellites (e.g., MODIS (Xiong & Barnes, 2006)) constantly observe the lunar surface for radiometric calibration. The TIR channels can also retrieve LST and emissivity that can be further used to conduct cross-evaluation on our results. Besides, for the global LST and emissivity, we use the maximum BT in one-year observation to reduce the observation noise influence and ensure retrieval accuracy. Nonetheless, invalid pixels still exist in near-polar regions, and some pixels suffer failure retrieval. Using
more than one-year observations or multi-year lunar summer observations can possibly improve the global
temperature and emissivity results.

Actually the lunar surface temperature is not a single temperature inside the single Diviner pixel. The sur-
f ace of one pixel will be rough with some parts in shadow and some in direct sunlight. The parts in shadow
will be very cold (<200 K), and the parts in direct sunlight will be hot (>200 K). This will create a spatial sur-
face temperature distribution across the lunar pixel. The best way of dealing with this problem is to retrieve
the component (sunlit and shadowed lunar soil and rocks) temperatures in the Diviner pixel rather than the
pixel average temperature. On basis of the current technique in the earth thermal infrared observation, the
retrieval of component temperatures requires multiple-angle observation and the calculation of component
area fractions from optical remote sensing image (Li et al., 2013). However, from the single angle observation
and the optical images of the Diviner sensor, it is impossible to identify how many components exist in the
pixel footprint, their corresponding area fractions and then the component temperature.

Figure 11. (a) Global lunar surface temperature (K), (b) Global lunar surface emissivity of Channel 3. An example of
global lunar surface temperature and emissivity from 2015 observation data.
Moreover, there is a solid-state greenhouse effect that occurs in the top few microns of the lunar soil (Hertsberg et al., 2010). During lunar daytime, the lunar regolith absorbs the radiation from the sun and transports it inward and is stored in a layer approximately 50 cm thick. As the moon passes into night, although the radiation from the sun quickly approaches zero, the regolith then proceeds to transport the stored heat back onto the surface, thus warming it up significantly. The sunlight in the visible, near-infrared and short-infrared wavelengths can warm up the lunar surface and increase its surface temperature and under soil temperature in vertical profile. As a result, a strong thermal gradient in the upper few microns of the lunar soil may appear, which should be taken into account in the temperature retrieval. The retrieval of the vertical soil temperature profile is more complicated because it requires to solve the soil heat conduction in combination with the thermal conductivity of the lunar soil that, however, is unknown to us and impossible to observe at globally in the current technical level. As a result, according to the common way of the earth land surface temperature retrieval from thermal infrared image, this paper is only able to get the pixel average surface temperature.

Figure 13. Global distribution of CF pixels and non-CF pixels.
Figure 14. Latitude and longitude variations of the percent of CP pixels.

5. Conclusions

The lunar surface temperature (LST) is a key parameter to study the lunar surface environment and lunar mineral composition. This study has developed a physical method, namely, the temperature-emissivity separation (TES) algorithm, to retrieve LST and lunar surface emissivity from three short 8 μm channels (Channels 3–5) for daytime observation of the Diviner sensor. The emissivity from daytime observation can be used to inverse LST from nighttime observation in other thermal channels. Findings show that (1) the TES algorithm can retrieve LST and emissivity with an error of less than 0.8 K and 0.008, respectively, if no noise is included in the observed data. (2) Observation noise significantly affects the retrieval accuracy, especially for low-temperature pixels. Sensitivity analysis on sensor’s NEDT variation with temperature and in different channels indicate that the surface temperature must be no more than 240 K to guarantee that the error of the retrieved LST and emissivity will be less than 1.0 K and 0.01, respectively. We apply the TES algorithm to obtain the daytime LST and emissivity images of different channels (Channels 3–9) in the study region, and then use the daytime emissivity images to estimate the LST from nighttime observation in Channels 7 and 8. The comparison results show that the retrieved LST differs approximately 3.9 K from the LST calculated only using a fixed emissivity value of 0.95.

Finally, we retrieve the global surface temperature and emissivity using the TES algorithm. The global temperature shows a generally increasing trend with the latitude. Meanwhile, the global emissivity has a significant spatial variation. As such, pixel-by-pixel emissivity should be used in LST retrieval instead of a fixed value. On the basis of the emissivity image in the three short 8 μm channels, the CF pixels are distributed in the latitude range from −60° to 60°. By contrast, they do not have a large distribution in high-latitude and near-polar regions. Nonetheless, the algorithm needs improvement. Result validation and the manner in which global surface temperature and emissivity images is generated are also required in future works.

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