A primary analysis of microwave brightness temperature of lunar surface from Chang-E 1 multi-channel radiometer observation and inversion of regolith layer thickness

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Abstract

In China’s first lunar exploration project, Chang-E 1 (CE-1), a multi-channel microwave radiometer was aboard the satellite, with the purpose of measuring microwave brightness temperature (Tb) from lunar surface and surveying the global distribution of lunar regolith layer thickness. In this paper, the primary 621 tracks of swath data measured by CE-1 microwave radiometer from November 2007 to February 2008 are collected and analyzed. Using the nearest neighbor interpolation to collect the Tb data under the same Sun illumination, global distributions of microwave brightness temperature from lunar surface at lunar daytime and nighttime are constructed. Based on the three-layer media modeling (the top dust-soil, regolith and underlying rock media) for microwave thermal emission of lunar surface, the CE-1 measured Tb and its dependence upon latitude, frequency and FeO + TiO2 content, etc. are discussed. The CE-1 Tb data at Apollo landing sites are especially chosen for validation and calibration on the basis of available ground measurements. Using the empirical dependence of physical temperature upon the latitude verified by the CE-1 multi-channel Tb data at Apollo landing sites, the global distribution of regolith layer thickness is further inverted from the CE-1 brightness temperature data at 3 GHz channel. Those inversions at Apollo landing sites and the characteristics of regolith layer thickness for lunar maria are well compared with the Apollo in situ measurements and the regolith thickness derived from the Earth-based radar data. Finally, the statistical distribution of regolith thickness is analyzed and discussed.

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1. Introduction

Investigations of lunar projects have shown that almost the entire lunar surface consists of a regolith layer that covers the underlying bedrock except for some very steep-sided crater walls and lava channels. The lunar regolith consists of fragmented materials such as surface layer dust, unconsolidated rock material, breccia, glassy fragments. The average thickness of the regolith layer is about 4–5 m for maria and about 10–15 m for highlands (e.g., McKay et al., 1991). Knowledge of the structure, composition and distribution of the lunar regolith provides important information concerning the lunar geology and resources for future lunar exploration.

Usually, the regolith layer thickness was estimated by direct measurement or indirect technique, as described by Shkuratov and Bondarenko, 2001. The direct measurement was carried out during Apollo and Luna missions, for example, using the seismic experiments (Nakamura et al., 1975) at the Apollo 11, 12 and 14–17 landing sites, and the multifrequency electromagnetic probing at the Apollo 17 landing site (Strangway et al., 1975). The indirect technique was based on examination of impact crater morphology and frequency distribution of the crater diameters. The limits of regolith layer thickness at Luna 13 and Survey 1 landing sites were estimated from laboratory studies of crater morphology and Lunar Orbiter images (Quaide and Oberbeck, 1968). Shoemaker et al. (1969) proposed the cumulative distribution function of regolith layer thickness using frequency distribution of crater diameters, and estimated the regolith layer thickness at Surveyor 7 landing site. However, all these techniques are localized to certain small areas of lunar surface. Recently, Shkuratov and Bondarenko (2001) proposed a technique for mapping the regolith layer thickness of lunar nearside by Earth-based radar and optical data. However, quantitative evaluation and mapping the global regolith layer thickness, including the lunar farside, are left for further study.

China had successfully launched her first lunar exploration satellite Chang-E 1 (CE-1) on October 24, 2007. A multi-channels microwave radiometer, for the first time, was aboard the satellite with the purpose of measuring the microwave thermal emission from the lunar surface layer. There are four frequency channels for CE-1 microwave radiometer: 3.0, 7.8, 19.35 and 37.0 GHz. The observation angle is 0°, the spatial resolution is about 30–50 km, and the radiometric sensitivity about 0.5 K (Jin et al., 2003; Fa...
and Jin, 2007a). The measurements of the multi-channel brightness temperature, Tb, are applied to invert the global distribution of the regolith layer thickness, from which the total inventory of $^3$He (Helium-3) stored in the lunar regolith layer can be estimated quantitatively. Besides, the physical properties of lunar regolith, such as grain size, bulk density, thermal conductivity, physical temperature, heat flow, can be further studied. According to the technique feature and scientific objective of CE-1 microwave radiometer, a three-layer model (the top dust-soil, regolith and underlying rock media) for numerical simulation of brightness temperature from lunar surface and a fusion technique of optical and passive microwave remote sensing for inversion of the regolith layer thickness have been developed (Fa and Jin, 2007a), and applied to estimation of the global inventory of $^3$He in lunar regolith (Fa and Jin, 2007b).

In this paper, the primary 621 tracks of swath data by CE-1 microwave radiometer from November 2007 to February 2008 are collected and analyzed. According to the relation between the brightness temperature and the Sun incidence angle in observations, the global distributions of microwave brightness temperature from lunar surface at lunar daytime and nighttime are constructed using the nearest neighbor interpolation approach. Using the three-layer model for microwave thermal emission of lunar surface, the Tb measurements and its dependence upon latitude, frequency and FeO + TiO$_2$ content, etc. are discussed. On the basis of the ground measurements at Apollo landing sites, the CE-1 observed multi-channel Tb at these locations are validated and calibrated using theoretical three-layer modeling. Physical temperatures of the lunar layered surfaces at Apollo landing sites are first determined by Tb at high frequency channels, 19.35 and 37 GHz. Using the empirical dependence of physical temperature upon the latitude verified by Apollo landing sites, the global distribution of regolith layer thickness is inverted from the CE-1 Tb measurements at lower 3 GHz channel. Those inversions at Apollo landing sites are well comparable with the in situ measurements, and the characteristics of regolith layer thickness for lunar maria are consistent with that of regolith thickness derived from the Earth-based radar observation (Shkuratov and Bondarenko, 2001). Finally, the statistical property of regolith thickness distribution is analyzed and discussed.

2. Microwave brightness temperature over lunar surface

The primary 621 tracks of swath data by CE-1 microwave radiometer from November 2007 to February 2008 are collected. All the swath data are in 2C level that after the system calibration and geometric correction, and their archive format is Planetary Data System (PDS). For each swath, the data correspond to serial observations of each resolution cell as the radiometer flies descending from the north pole to the south pole and then ascending from the lunar south pole to the north pole. For each resolution cell of the radiometer, the metadata include observation time, four channels Tb measurements, Sun incidence angle and azimuth angle, selenographic latitude and longitude, orbit altitude and data quality state. The Sun incidence angle is the angle between the Sun incident direction and the lunar surface normal at a lunar surface point, e.g. with a value less than 90$^\circ$ indicating lunar daytime and a value greater than 90$^\circ$ indicating lunar nighttime. In other words, a small value of the Sun incident angle indicates that the observation is much close to the lunar noon, while a larger Sun incidence angle means that the observation is much close to lunar midnight. In this paper, both the analysis of brightness temperature over the lunar surface and inversion of regolith layer thickness are based on the swath data with 2C level.

As an example, Fig. 1 shows one swath observation of brightness temperature (orbit number 0247) by CE-1 radiometer on November 28, 2007. It can be seen that in lunar daytime, the higher the frequency, the higher the brightness temperature; while in lunar nighttime for channel 7.8, 19.35, 37.0 GHz, the higher the frequency, the lower the brightness temperature. These behaviors are consistent with the theoretical predictions from the three-layer model of the lunar surface microwave emission (Fa and Jin, 2007a). But, brightness temperature of 3 GHz channel at nighttime seems too low, which might be caused by the calibration at this channel, or some other reasons, e.g. inhomogeneous temperature profile in the regolith layer.

Brightness temperature measurements of each CE-1 swath are closely dependent upon the observation time and surface geolocation. To obtain global Tb distribution of the lunar surface, the observations with specified orbit condition are first chosen from the whole dataset, and then certain interpolation and mapping technique are employed for global brightness temperature.

Multi-channel brightness temperatures have functional dependence of the physical properties of the regolith layer, such as regolith thickness, physical temperature, dielectric permittivity of regolith (Fa and Jin, 2007a). Generally, the regolith layer thickness is closely correlated with the relative age of lunar surface, while the dielectric permittivity of regolith mainly depends upon the regolith bulk density $\rho$ (g/cm$^3$) and the FeO + TiO$_2$ content $S$ in the regolith (Carrier et al., 1991). During one year period of CE-1 observation, no variation in the regolith layer thickness and the dielectric permittivity can be assumed. Therefore, the main uncertain factors affecting brightness temperature are the physical temperature and geolocation with different regolith thicknesses. The physical temperature of the lunar surface layer depends upon the incident solar flux, heat conduction through the subsurface, the reradiation outward and internal energy flux, etc., and varies with selenographic latitude and longitude at specific lunar time. Ignoring the influence from the surface topography and thermal proper-

![Fig. 1. Brightness temperature of CE-1 microwave radiometer on November 28, 2007: (a) nighttime and (b) daytime. The orbit number is 0247, where the radiometer flew descending from the north pole (UTC 2007-11-28 02:56:58) to the south pole (UTC 2007-11-28 04:00:40) at lunar nighttime and then ascending from the lunar south pole to the north pole (UTC 2007-11-28 05:04:30) at lunar daytime (corresponds to the other side of the Moon).](image-url)
ties of the regolith on a small scale, the physical temperatures of two points with the same Sun incident flux can be regarded as the same.

The swath data at the same time (or nearly at the same time) of each lunation are chosen and then interpolated and regressed to construct the global Tb distribution. One orbit period of CE-1 is about 127 min, which is much less than one lunation of the Moon (about 29.53 days with ~15 h maximum deviation). Thus, in each CE-1 flight period around the Moon, the local lunar time as CE-1 passed can be regarded as the same. And, for two swath data with the same (or nearly the same) Sun incidence angle at lunar equator area, their Sun incident conditions in the periods can be regarded as the same.

In all the 621 tracks of swath data, the Sun incidence angle at lunar equator varies from 0° to 50° during lunar daytime and from 130° to 180° during lunar nighttime. Fig. 2a and b shows brightness temperature at 37 GHz versus the Sun incidence angle at lunar equator. The anomalous data that inside the red circle deviates obviously from the regression line, which might be caused by the calibration problem, or some other reasons. Actually, those anomalous data are not used in the subsequent process.

Based on the relation in Fig. 2a, selecting 264 tracks of swath data with the Sun incidence angle 0–14° at lunar equator and using the nearest neighbor interpolation approach, Fig. 3 shows the brightness temperature distribution at lunar daytime. The dark blue stripes are the tracks without brightness temperature available under the specified condition (i.e. Sun incidence angle 0–14° at lunar equator), which can be easily improved when more data become available.

Following Fig. 2b in the same way, 264 tracks of swath data with the Sun incidence angle 166–180° at lunar equator and using the nearest neighbor interpolation approach, Fig. 4 shows the brightness temperature distribution at lunar nighttime. Figs. 3 and 4 are simple cylindrical projections, and there are totally 180 × 360 pixels in each figure, i.e. 1 pixel represents 1° in both latitude and longitude direction. The radius of the Moon is \( R = 1738 \) km and let \( \phi \) indicate the selenographic latitude. Thus, the grid resolution is written as \( 2\pi R \cos \phi / 360° \approx 30.3 \cos \phi \) (km/°) along latitude direction, and \( \pi R / 180° \approx 30.3 (\text{km}/°) \) in longitude direction, which are close to the spatial resolution of the CE-1 microwave radiometer (30–50 km). Note that by selecting the Sun incidence angle in lunar daytime 0–14° and nighttime 166–180° can effectively avoid the anomalous data inside the red circle in Fig. 2.

In the global Tb distribution over lunar surface as shown in Figs. 3 and 4, brightness temperature is high at lunar equatorial area and decreases as latitude increases, and finally reaches the minimum at the pole area. This variation trend of brightness temperature from equator area to lunar poles is dominant by the temperature decrease toward the poles, which was explained by Keihm and Gary (1979) as the polar cooling phenomena. Also, the significant difference in brightness temperature between daytime and nighttime (e.g. about 50 K at 37 GHz channel) is due to the extremely high variation of physical temperature of lunar media during a whole lunar day. Some craters can be easily recognized, especially at high-latitude areas. Note that if the variation scope of each Figs. 3 and 4 is re-scaled, more craters in each figure can be identified.

It has been well known that high frequency channels, e.g. 19.35 and 37 GHz, have small penetration depth through the loss media and are only sensitive to superficial variation of the top soil layer, while low frequency channel such as 3 GHz can penetrate much deeper, e.g. ~10 m or so in regolith layer. It makes the Tb measured at 3 GHz applicable to inversion of regolith thickness. Under the Sun illumination during lunar daytime and the thermal inertia of regolith, physical temperature of the top soil layer quickly becomes much higher than the underneath regolith media, while during lunar nighttime the situation becomes opposite because of the internal energy flux, i.e. quick cooling of the top soil layer makes physical temperature much lower than the regolith layer. As a result, during lunar daytime shown in Fig. 3, the high frequency channel has high brightness temperature, and during lunar nighttime as shown in Fig. 4, the situation turns opposite. However, the measured Tb data at 3 GHz in Fig. 4 seems lower than 37 GHz, which might be caused by the calibration problem, or some other reasons, such as the inhomogeneous temperature or perturbation of the dielectric properties in the regolith media.

Comparing the Tb distribution in Fig. 3 and FeO + TiO₂ content in Lucey et al. (2000), brightness temperature at 7.8, 19.35 and 37 GHz in lunar daytime look similar to the distribution of FeO + TiO₂ content, i.e. high FeO + TiO₂ content corresponds to high brightness temperature. In Fig. 3, the maria with high FeO + TiO₂ content have a large Tb value, while the highlands with low FeO + TiO₂ content have a small value of Tb, and the difference between maria and highlands is large. These observations well match the theoretical predication from the three-layer modeling (Fa and Jin, 2007a).

However, at lunar nighttime as shown in Fig. 4, the difference in brightness temperature between maria and highlands is small, and it is almost impossible to distinguish the maria and highlands only by brightness temperature.

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Fig. 2. Correlation between brightness temperature at 37 GHz and the Sun incidence angle at lunar equator: (a) daytime and (b) nighttime. The anomalous data that inside the red circle might be caused by calibration problem, changes of satellite attitude or some other reasons, which are not used in the subsequent process. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Temperature variation of lunar soil media in one lunation is dramatically large due to the influence of the Sun illumination. Suppose that the thickness of lunar soil layer is $d_1 = 0.2$ m, the regolith thickness of maria is 5 m and FeO + TiO$_2$ content is 20%, the regolith thickness of highlands is 12 m and FeO + TiO$_2$ content is 10%, the physical temperature of regolith layer is $T_2 = 250$ K, and the physical temperature of underlying rock layer is $T_3 = 250$ K, and the temperature of soil layer in one lunation varies from 100 K to 450 K.

Fig. 5 shows the variation of brightness temperature with physical temperature of the soil layer for maria and highlands calculated using the three-layer model. It can be seen that the $T_b$ difference between maria and highlands surface increases as the physical temperature difference increases. In lunar daytime, the physical temperature of regolith layer at equator area can be as high as 400 K, resulting in the $T_b$ difference as high as 40 K. Significant difference of physical temperature between lunar soil and regolith layer yields large $T_b$ difference between the maria and highlands surface, and make them easily identified. On the contrary, if the difference of physical temperature between lunar dust-soil and regolith layer is small, so is the difference of brightness temperature between maria and highlands surface. As shown in Fig. 5, maria and highlands cannot be well distinguished.

3. Validation and calibration of brightness temperature

Calibration of CE-1 multi-channel microwave radiometer is a crucial issue for high precision brightness temperature of lunar surface. The calibration of CE-1 microwave radiometer is a real-time and periodical on-orbit calibration system that uses a calibration antenna pointing towards to the cold space (2.73 K) and a match-loaded hot reference (Zhang et al., 2008). During observation, as the satellite flies at different attitudes (e.g. forward-flight, sideward-flight), the cold calibration antenna points toward different radiation sources, e.g. cold space, the Earth, the Sun, etc. If the solar or the Earth’s radiance (with $T_b$ about 200–250 K) happens to enter the view field of the cold calibration antenna, the radiance input to the calibration antenna might not be seen as the cold space (which is about 2.73 K). Actually, these swath data can be simply excluded based on the information of the satellite attitude. The influence of other planets, such as Jupiter (about 300 K), Venus (about 700 K), can be ignored since their view angle is very small (about 1°). Calibration technique of microwave radiometer is to be further studied in our future work when more information and data are released.

Theoretical brightness temperature at Apollo landing sites is used as a reference for validation and calibration. In the three-layer model, brightness temperature of lunar surface are related with
the thickness of soil and regolith layers, $d_1$ and $d_2$, physical temperature of the top dust-soil, regolith and underlying rock layer, $T_1$, $T_2$, and $T_3$, and FeO + TiO$_2$ content $S$ in the regolith. The regolith layer thickness at Apollo landing sites is available from direct measurement during Apollo missions, and dielectric constant and FeO + TiO$_2$ content of Apollo regolith samples are also available from laboratory measurement.

Table 1 gives the geolocation, topography, regolith thickness, FeO + TiO$_2$ content and the number of orbits with available CE-1 radiometer data at Apollo landing sites. By estimating the physical temperature of the soil, regolith and underlying rock layers, theoretical brightness temperature is numerically calculated from the three-layer model, which is taken as a reference for brightness temperature calibration.

Taking into account the spatial resolution of CE-1 radiometer and restricting the observation points within 0.5° around Apollo landing sites, there are in total 27 swath observations passing through the Apollo landing sites, where 13 swaths are in lunar daytime and the other 14 swaths are in lunar nighttime (Table 1).

Fig. 6 shows the brightness temperature at Apollo landing sites observed by CE-1 radiometer, where the horizontal axis is regolith layer thickness, and the vertical axis is the brightness temperature. Note that the regolith layer thickness at Apollo 11 and 15 landing sites are both 4.5 m. In order to distinguish them, the regolith layer thickness at Apollo 11 is set to 4.8 m on purpose.

Given the regolith layer thickness and FeO + TiO$_2$ content at Apollo landing sites, let the thickness of soil layer change from 0 m to 0.3 m, the physical temperature of soil layer change from 320 K to 420 K during lunar daytime, the physical temperature of regolith layer change from 230 K to 270 K and the temperature of underlying rock media be equal to that of the regolith layer. Then the theoretical brightness temperature, $T_B$, at Apollo landing sites is calculated from the three-layer model. The root-mean-square (RMS) difference of brightness temperature between theoretical $T_B$ and CE-1 observation $T_{O_B}$ is defined as

$$\Delta T_B = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ T_B(d_1, T_1, T_2) - T_{O_B} \right]^2}$$

where $i$ indicates the $i$th channel, and $N$ is total channels number. For example, $N = 4$ means that brightness temperatures of four channels are chosen for comparison between theoretical $T_B$ and CE-1 observation $T_{O_B}$.

Selecting the 13 swath data at Apollo landing sites in lunar daytime and calculating the RMS Tb difference with changing $d_1$, $T_1$ and $T_2$, physical temperature of soil and regolith layer, and thickness of soil layer are obtained as the RMS difference of brightness temperature reaches the minimum. Comparing the RMS difference of brightness temperature at three and four channels in turn, Fig. 7 shows the minimum RMS Tb difference when three channels, 7.8,
19.35 and 37 GHz, are taken into account, where the abscissa axis scale is the Apollo mission number. Note the acquired value of \( d_1 \), \( T_1 \) and \( T_2 \) as the RMS Tb difference reaches to minimum will be used as a guidance for the thickness and physical temperature of the top soil layer in the next inversion of regolith layer thickness.

Furthermore, Fig. 8 shows a comparison of \( T_B \) and \( T_{\text{ref}} \) at each channel. It can be seen that all the observations of 7.8, 19.35 and 37 GHz channels agree well with the theoretical value. The observation at 3 GHz can also match well if 18 K is added as a calibration reference.

4. Inversion of regolith layer thickness

As the CE-1 observation angle is 0°, brightness temperature of lunar surface using the three-layer model is written as (Fa and Jin, 2007a)
the bulk density of regolith are assumed to be known.

Measurements of calibrated brightness temperature at 3 GHz are very small, they are totally insensitive to regolith layer thickness. Since the penetration depths at 19.35 and 37 GHz channel are 3.0, 7.8, 19.35, 37.0 GHz, the penetration depth at 7.8 GHz channel with a large penetration depth are employed to invert the regolith layer thickness of Apollo regolith sample shows that the dielectric constant of regolith, \( \varepsilon_r = \varepsilon'_r + i\varepsilon'_e \), is given by the bulk density \( \rho \) and FeO + TiO2 content \( S \) as (Carrier et al., 1991)

\[
\varepsilon'_r = 1.919^\rho \\
\tan \delta = 10^{0.0385 - 0.312\rho - 3.26}
\]

where \( \tan \delta = \varepsilon''/\varepsilon' \) is the loss tangent of regolith.

According to McKay et al. (1991), the bulk density of soil layer is about 1.3 g/cm\(^3\), and according to McKay et al. (1991) and Hagfor (1964), the typical value of the real part of the dielectric constant for regolith sample is about 2.7, which corresponds to a bulk density of 1.5 g/cm\(^3\) for regolith layer.

The penetration depth of electromagnetic wave mainly depends upon the imaginary part of dielectric constant of the media, which correlates largely with the FeO + TiO2 content \( S \) in lunar regolith. The FeO + TiO2 content in lunar regolith has been studied based on optical reflectance of lunar surface and laboratory measurement of the Apollo samples. For example, global imaging data were collected by the ultraviolet visible (UVVIS) camera in Clementine mission, and FeO and TiO2 contents were derived from five-band multispectral optical data (Lucey et al., 2000). Besides, the FeO and TiO2 content can also be obtained by \( \gamma \)-ray observation, such as the \( \gamma \)-ray spectrometer of Lunar Prospector (Lawrence et al., 2002; Shkuratov et al., 2005). The spatial resolution of optical remote sensing is about 100–325 m, and the FeO + TiO2 content is derived within 1 \( \mu \)m in the lunar surface. However, because of the extreme lighting condition due to lunar topography for the area with latitude greater than 70\(^\circ\), the results seem unreliable for those areas. For example, the FeO content in this region is not correct as less than 0\%, and the TiO2 content is too high as 50\%. The \( \gamma \)-ray observation is independent of the Sun incidence condition, and can penetrate 1 m below the lunar surface to derive the average FeO + TiO2 content within this depth. The spatial resolution of \( \gamma \)-ray spectrometer aboard Lunar Prospector is about 45–150 km, which is on the same order of the spatial resolution of CE-1 microwave radiometer.

Fig. 7. Root-mean-square (RMS) difference of brightness temperature between theoretical value and observation at Apollo landing sites, the abscissa axis scale is the Apollo mission number.

\[
T_B = (1 - r_{01})(1 - e^{-\frac{s_t}{C_1}})\left(1 + r_{12}e^{-\frac{s_t}{C_1}}\right)T_1 + (1 - r_{01})(1 - r_{12}) \\
\times (1 - e^{-\frac{s_a}{C_2}})\left(1 + r_{31}e^{-\frac{s_a}{C_2}}\right)T_3 + (1 - r_{03})(1 - r_{12}) \\
\times (1 - e^{-\frac{s_d}{C_2}})e^{-\frac{s_a}{C_2}}e^{-\frac{s_d}{C_2}}T_3
\]

(2)

where \( d_t \) and \( d_a \) are the thickness of the top dust-soil and regolith layer; \( T_1 \), \( T_2 \), and \( T_3 \) are the physical temperature of the soil, regolith and underlying rock layer, respectively. Definitions of all the other parameters in Eq. (2) are referred to Fa and Jin (2007a).

Since the penetration depths at 19.35 and 37 GHz channel are very small, they are totally insensitive to regolith layer thickness. Measurements of calibrated brightness temperature at 3 GHz channel with a large penetration depth are employed to invert the regolith layer thickness, when the physical temperature and the dielectric constant of each layer, and the thickness of soil layer are assumed to be known a priori.

The dielectric permittivity of regolith is mainly dependent upon the bulk density of regolith \( \rho \) (g/cm\(^3\)) and the FeO + TiO2 content \( S \) in lunar regolith. Laboratory measurement of the dielectric constant of Apollo regolith sample shows that the dielectric constant of regolith, \( \varepsilon_r = \varepsilon'_r + i\varepsilon'_e \), is given by the bulk density \( \rho \) and FeO + TiO2 content \( S \) as (Carrier et al., 1991)

\[
\varepsilon'_r = 1.919^\rho \\
\tan \delta = 10^{0.0385 - 0.312\rho - 3.26}
\]

where \( \tan \delta = \varepsilon''/\varepsilon' \) is the loss tangent of regolith.
Fig. 9 shows the global distribution of FeO + TiO2 content over lunar surface from the γ-ray spectrometer aboard Lunar Prospector, provided by the US Geological Survey (USGS) Astrogeology Research Program’s Map-a-Planet project (http://www.mapaplanet.com/explorer/moon.html). In this paper, Fig. 9 and Eq. (2) are used to calculate the dielectric constant over the lunar surface.

Physical temperature of lunar surface depends on the incident solar flux, heat conduction through the subsurface, reradiation outward, internal energy flux, etc. The top dust layer is highly insulating and the regolith layer is conductive; as a result, the temperature of top dust layer is strongly dependent upon solar insolation while the temperature of the regolith layer is independent of insolation. Therefore, temperature variation of the top dust layer is extremely large in one lunation, while temperature variations in the regolith layer and underlying rock media are small (Vasavada et al., 1999). In general, the temperature of lunar surface varies with selenographic latitude and longitude at a specific lunar time; while at a certain point on lunar surface, the variation of physical temperature depends on the incident solar flux, which is temporally changing.

In Fig. 3, the observations are at lunar daytime under the similar solar illumination within the incidence angle between 0° and 14°, which indicate that the observations are made at the same lunar local time. If the influence of surface topography and the thermal properties of regolith on a small scale are ignored under CE-1 spatial resolution, the physical temperature of two points with the same latitude can be regarded as the same. In other words, the temperature of lunar surface is only dependent upon lunar latitude and independent of longitude.

On the basis of Clementine infrared data, Lawson et al. (2000) proposed that the physical temperature of lunar surface varies with latitude ϕ

\[ T = T_0 \cos^a(\phi) \]  

(4)

where \( T_0 \) is the physical temperature at lunar equator, and \( a \) is a constant that determining how the temperature varies with latitude. Vasavada et al. (1999) numerically solved the one-dimensional thermal diffusion equation and obtained the temperature distribution over lunar surface, which is also close to the result of Lawson et al. (2000).

To invert the regolith layer thickness, the temperatures of soil and regolith layer are calculated using Eq. (4). Suppose \( T_0 = 390 \) K for soil layer, \( T_0 = 250 \) K for regolith layer and \( a = 0.3 \). The solid lines in Fig. 10 show the variation of physical temperature with latitude for the soil and regolith layers, calculated from Eq. (4), where \( T_1 \) is for the soil layer and \( T_2 \) is for the regolith layer, the circles and squares indicate the physical temperature of soil and regolith layer at Apollo landing sites calculated from Eq. (1) when the RMS Tb difference between theoretical value and observation reaches the minimum. It can be seen that variation of the soil temperature is rather large and the difference calculated from Eq. (4) is also large, while the physical temperature of regolith layer matches well the theoretical value.

Comparison of the brightness temperature difference between theoretical value and observation at Apollo landing sites using Eq. (1) shows that the average thickness of soil layer equals to 0.13 m when the difference reaches the minimum (as shown in Fig. 7). In lunar regolith thickness inversion, the physical temperature of lunar soil and regolith layers are calculated using Eq. (4), where \( T_0 = 390 \) K for soil layer, \( T_0 = 250 \) K for regolith layer and \( a = 0.3 \), also under the assumption that the temperature of underlying rock layer is the same as that of the regolith layer. According to Fig. 8a, 18 K is added to the brightness temperature at 3 GHz as shown in Fig. 3a. After all those parameters are assumed to be known as a priori, the regolith layer thickness is inverted using Eq. (2) (Fa and Jin, 2007a).

Fig. 11 shows the inversion result of global distribution of the regolith layer thickness. Because of the large geometry distortion at polar area in simple cylinder projection, the interpolation error at lunar pole area is large, which causes the bright (red) stripe of regolith layer thickness at lunar polar area in Fig. 11.

Fig. 12 gives the global distribution of regolith layer thickness after a simple interpolation. The results shown in Figs. 11 and 12 are only preliminary, and improvement of the inversion depends on whole process governing the parameters, such as the physical temperature of the layering media, dielectric properties, top layer thickness, as well as the calibration and sensitivity of the CE-1 radiometer technology. Inversion of \( T_1 \) is mainly governed by the Tb data of high frequency channels, such as 19 and 37 GHz. The regolith thickness is inverted by the Tb data at low 3 GHz because main emission contribution to Tb observation comes from the regolith layer. The accuracy of FeO + TiO2 content as high as 2% might be good enough to ensure good inversion. As a sensitivity test, it is calculated from Eq. (2) that a 0.5 K radiometric uncertainty might cause an inversion error about 0.65 m for a mare surface with regolith thickness 5 m and FeO + TiO2 10%. The most uncertainty might come from the thickness of top soil layer and physical temperature of the regolith layer, which might cause the inversion error about 1 m.

To evaluate the inverted regolith thickness of Fig. 11, Fig. 13 gives a comparison of the inverted thickness and in situ measurements at Apollo landing sites, where the horizontal error bars
indicate the error range of the measurements, and the vertical error bars in magenta, blue, red and black colors, respectively, denote the error ranges caused by the uncertainties due to $10\, \text{K}$ of $T_1$, $10\%$ of $d_1$, $10\%$ of $q_2$ and $3\, \text{K}$ of $T_2$. It can be seen from Fig. 13 that a $10\, \text{K}$ uncertainty of $T_1$ may cause a 0.4 m inversion error at most, and $10\%$ uncertainty of $d_1$ may cause an error not more than 0.5 m. However, a $10\%$ uncertainty of $q_2$ can cause a 2 m inversion error at Apollo 12 landing sites, and a $3\, \text{K}$ uncertainty of $T_2$ can make an error more than 1 m. Thus, main error in inversion is caused by the temperature and bulk density of the regolith layer, since most of the thermal emission comes from the regolith layer at 3 GHz. Actually, as the regolith thickness or regolith dielectric constant become much large, the brightness temperature becomes saturated and makes the inversion impossible. Note that the inversion error varies from site to site because of different regolith properties, i.e. thickness, FeO + TiO$_2$ content, etc., at different sites.

In comparison with in situ point measurements at Apollo landing site, due to coarse resolution of CE-1 radiometer, 30–50 km, the inversion result around the landing site is actually the averaged value over a larger area (a resolution cell), where any unknown variation is most likely possible. However, good comparison between our inversion and measurement at Apollo 12 landing site, which is a fairly homogeneous surface with rather small variation of regolith thickness in the southeastern Oceanus Procellarum (Hiesinger and Head, 2006), demonstrates that our inversion works well.

In Figs. 11 and 12, the large area of the low regolith thickness is mare, and the large area of the high regolith thickness is highland. The systematic difference of regolith thickness between mare and highland reflects the age difference of lunar surface, since the highlands surface is much older than maria surface. The polar area has a thin regolith thickness, which might due to the impact probability of the meteorite at lunar poles is small.

Fig. 14 shows the statistical histogram of regolith layer thickness. It can be seen that the bimodal distribution of the regolith thickness histogram shows two peaks around 5.3 m and 7.5 m, which correspond to the mean regolith thickness of maria and highlands.

The lunar mare is characterized by the regolith layer thickness variation from 1.2 to 11 m. Generally, the FeO + TiO$_2$ content is high for maria area and low for highlands area. Taking FeO + TiO$_2$ content 10% as the dividing line between maria and highlands, statistical result shows that the average regolith thickness of maria is...
4.5 m, which is close to the average result of maria surface 4–5 m as pointed out by McKay et al. (1991).

Table 2 shows the mean regolith thickness and its the standard deviation for the maria, and some comparisons with the Earth-based radar inversion (Shkuratov and Bondarenko, 2001). Considering many uncertainties in both inversions, our inversion results match well with that of Shkuratov and Bondarenko (2001), especially for those maria, i.e. Mare Serenitatis, Mare Tranquilitatis, Mare Vaporum, Mare Nubium, Mare Cognitum, Oceanus Procellarum, and Sinus Iridium. Our results show that the thinnest regolith thickness occurs in Mare Imbrium, and the thickest regolith layer occurs in Mare Fecunditatis and Mare Nectaris. Also, it shows that the regolith thickness of Mare Tranquilitatis (one of the oldest maria) is larger than that of the relatively young Oceanus Procellarum, which confirms that the regolith thickness depends on the age of the region.

The inversion result shows that the thickness of the highlands varies from 1.0 to 15 m. In lunar farside, the regolith layer thickness for most of the intermediate latitude is large, with a value greater than 8 m. The mean thickness of the highlands at intermediate latitude area (60°S–60°N) is 7.6 m, which is less than the average result of 10–15 m for highlands from McKay et al. (1991). The regolith thickness estimation approach by examination of impact crater morphology and frequency distribution of the crater diameters might overestimate the regolith layer thickness. The lunar regolith mainly results from continuously impacting of large and small meteoroids. At the early stage, shortly after bedrock is exposed for the first time and the regolith is thin, both large and small impacts can penetrate the regolith and excavate fresh bedrock. As time goes on and regolith thickness increases, only the larger impacts penetrate the regolith and bring new bedrock. At this later stage, the small impacts make no contribution to the increase of regolith thickness. However, those impacts can change the frequency distribution of crater diameters, thus causing overestimation of the regolith layer thickness. Another possibility is that the regolith layer thickness is too thick that cause the brightness temperature saturated, and the brightness temperature is not sensitive to the regolith layer thickness, and making the inversion smaller.

Due to the formation mechanism of the crater, the regolith thickness at crater rim is larger than that of crater floor, making it easier to identify larger craters, as shown in Fig. 12. Because of the shadowing effect, the crater floors at the lunar polar regions are permanently dark and very cold. Eq. (4) might overestimate the surface temperature at these regions, which causes large inversion error. This issue is left for further study.

Also, to resolve the uncertainty for global mapping of the regolith thickness needs future study with improving calibration of Chang-E 1 and Chang-E 2 radiometer technology, as well as the more in situ surface measurement of Chang-E 3 and fusion of other lunar explorations become available.

5. Conclusions

On the basis of 621 tracks of swath data from CE-1 multi-channel microwave radiometer from November 2007 to February 2008, the global distribution of brightness temperature over lunar surface at lunar daytime and nighttime under the same solar illumination is constructed. It can be seen that brightness temperature decreases as latitude increases, with a maximum value at lunar equator area and minimum value at lunar polar area. In lunar daytime, the higher the frequency, the higher the brightness temperature. Brightness temperature at higher frequency channel looks similar to the distribution of FeO + TiO2 content especially during lunar daytime. All these phenomena can be explained by the three-layer model of microwave emission from lunar surface.

On the basis of the ground measurements at Apollo landing sites, the observed brightness temperature at these locations are validated and calibrated using the theoretical three-layer modeling. Using the physical temperature at Apollo landing sites inverted by brightness temperature at high frequency channels, and taking the empirical variation of physical temperature with latitude as a priori knowledge, global distribution of regolith layer thickness is inverted by brightness temperature at 3 GHz. The inverted results of the regolith layer thickness at Apollo landing sites match well

Table 2

Characteristics of regolith layer thickness for lunar maria.*

<table>
<thead>
<tr>
<th>Mare</th>
<th>Location</th>
<th>Diameter (km)</th>
<th>&lt;d&gt; (m)</th>
<th>σ₁ (m)</th>
<th>&lt;d&gt; (m)</th>
<th>σ₂ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mare Serenitatis</td>
<td>28.0°N, 17.5°E</td>
<td>707</td>
<td>4.1</td>
<td>0.8</td>
<td>4.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Mare Tranquilitatis</td>
<td>8.5°N, 31.4°E</td>
<td>873</td>
<td>4.1</td>
<td>1.1</td>
<td>4.9</td>
<td>1.5</td>
</tr>
<tr>
<td>Mare Crisium</td>
<td>17.0°N, 59.1°E</td>
<td>418</td>
<td>4.6</td>
<td>1.6</td>
<td>7.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Mare Fecunditatis</td>
<td>7.8°S, 51.3°E</td>
<td>909</td>
<td>5.9</td>
<td>1.4</td>
<td>7.8</td>
<td>1.3</td>
</tr>
<tr>
<td>Mare Frigoris</td>
<td>15.0°E, 4.1°E</td>
<td>1596</td>
<td>7.4</td>
<td>2.1</td>
<td>5.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Mare Imbrium</td>
<td>32.8°N, 15.6°W</td>
<td>1123</td>
<td>6.2</td>
<td>2.0</td>
<td>3.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Mare Humorum</td>
<td>24.4°S, 38.6°W</td>
<td>389</td>
<td>4.0</td>
<td>0.9</td>
<td>6.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Mare Nectaris</td>
<td>15.2°S, 35.3°E</td>
<td>333</td>
<td>9.6</td>
<td>2.3</td>
<td>7.7</td>
<td>0.5</td>
</tr>
<tr>
<td>Mare Vaporum</td>
<td>13.3°N, 16.6°E</td>
<td>245</td>
<td>5.4</td>
<td>1.1</td>
<td>5.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Mare Nubium</td>
<td>21.3°S, 16.6°W</td>
<td>715</td>
<td>5.7</td>
<td>1.7</td>
<td>5.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Mare Cognitum</td>
<td>10.0°S, 23.1°W</td>
<td>376</td>
<td>4.9</td>
<td>0.7</td>
<td>4.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Sinus Roris</td>
<td>54.0°N, 56.0°W</td>
<td>202</td>
<td>7.5</td>
<td>1.9</td>
<td>4.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Sinus Iridium</td>
<td>44.1°N, 31.3°W</td>
<td>236</td>
<td>4.6</td>
<td>0.6</td>
<td>4.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Sinus Aestuum</td>
<td>10.9°N, 8.8°W</td>
<td>256</td>
<td>6.5</td>
<td>1.4</td>
<td>4.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Oceanus Procellarum</td>
<td>18.4°N, 57.4°W</td>
<td>2568</td>
<td>4.8</td>
<td>1.6</td>
<td>4.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* <d> and σ₁ are the mean regolith layer thickness and its standard deviation from Shkuratov and Bondarenko (2001); <d> and σ₂ are the mean regolith layer thickness and its standard deviation from Chang-E 1 radiometer.
with the Apollo measurements. The histogram of regolith thickness is a bimodal distribution to indicate two peaks corresponding to the average regolith thickness of maria and highlands. Statistical result shows that the average regolith thickness of maria is 4.5 m, and that of the highlands at intermediate latitude area (60°S–60°N) is 7.6 m.

This work is a preliminary data study of Chinese CE-1 radiometer observation. The calibration–validation and some relevant technologies including fusion of other remote sensing means are left for further study.

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