# New radio observations of the Moon at $L$ band 

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#### Abstract

We present results of new radio observations of the Moon at $L$ band with the synthesis telescope of the Dominion Radio Astrophysical Observatory Synthesis Telescope. The resolution and temperature sensitivity of the observations are $159^{\prime \prime} \times$ $87^{\prime \prime}$ and 1.7 K , respectively. The main results are: (1) the lunar brightness temperature averaged over the whole disk is about 233 K while the average brightness temperature for the four quadrants are $228.1 \mathrm{~K}(\mathrm{NE}), 239.7 \mathrm{~K}(\mathrm{NW}), 233.9 \mathrm{~K}(\mathrm{SW})$ and 228.8 K (SE). The observations reveal large temperature and spatial variations on the Moon for the first time. The highest brightness temperature is about 257 K and it is located along the lunar equator, to the west. The total uncertainty is about $5 \%$ due to the absolute accuracy of the fluxes of the primary calibrators; (2) the total degree of polarization is about $6 \%$. Both polarization intensity and degree of polarization increase from the disk's center to the limb, and the distribution of the degree of polarization along the limb is not uniform; (3) the new data are used to study the properties of regolith, such as dielectric constant and thickness distribution. The results show that the lunar regolith's thickness increases from the NW (mare area) to the SE (highland area) regions on the lunar surface.


Key words: techniques: high angular resolution-imaging processing - radio continuum: Moon

## 1 INTRODUCTION

The lunar regolith is a low loss dielectric mass. Basic theories describing lunar microwave emission have been proposed by pioneers such as Troitskii \& Tikhonova (1970) and Muhleman (1972). Regarding the observations and experimental studies about the properties of lunar regolith, the Apollo project brought us a lot of data measured near landing sites on the Moon (Heiken et al. 1991), and many ground-based observations have enriched our knowledge. Most of the published results of ground-based radio observations use low resolution single dish data. Among the few high resolution observations with interferometers (Baldwin 1961; Moffat 1972; Wu et al. 2005; Schloerb et al. 1976), Moffat's result is the only one giving lunar images with high resolution at $L$ band. The results of Wu et al. (2005) show lunar images with higher resolution at 5.7 GHz and 90 GHz . Baldwin's observations were performed at 0.178 GHz , measuring the 233 K brightness temperature
of the lunar disk. Lunar observations at 0.608 GHz were performed by Schloerb et al. (1976) with the Owens Valley interferometer. The main results they obtained are: (1) the dielectric constant is $2.52 \pm 0.01$, (2) the equatorial subsurface temperature is $249_{-5}^{+8} \mathrm{~K}$, (3) the mean lunar heat flow is lower than that measured at the Apollo landing sites, and (4) the 0.6 GHz data are consistent with a change in the physical properties of the regolith with respect to those of solid rock or a mixture of rock and soil at depths of 7 to 16 m .

The penetration depth $\left(d_{\mathrm{lim}}\right)$ of electromagnetic waves in lunar regolith depends on the microwave frequency. This corresponds to the depth of the deepest layer from which emission propagates through the Moon's surface layer. It is proportional to wavelength and the square root of the real part of the dielectric constant, and is inversely proportional to the imaginary part of the dielectric constant ( $d_{\lim }=\lambda \sqrt{\varepsilon^{\prime}} / \pi \varepsilon^{\prime \prime}$, $\operatorname{Jin} 2005$ ). It is widely accepted that the depth of lunar regolith is about 4-5 m for the mare area and about 10-15 m for the highland area (e.g. Fa \& Jin 2010; McKay et al. 1991; Shkuratov \& Bondarenko 2001). The microwave brightness temperature obtained by Chang-E 1 (CE-1, China's first lunar orbiter) at 3.0 GHz is first used to calculate the regolith's thickness ( Fa \& Jin 2010; Wang et al. 2009b), but the maximum measurable depth at 3.0 GHz is smaller than 6 m for most of the lunar regolith's area and values of the lunar dielectric constants (Fa \& Jin 2007). This implies that measuring the microwave brightness temperature of the Moon at a frequency lower than 3.0 GHz is needed to probe the whole regolith layer over all the Moon's surface. The varying component of lunar radio emission at $L$ band $(1.4 \mathrm{GHz})$ is smaller than $1 \%$ over a lunar month (Moffat 1972; Yuan et al. 1986). This means that lunar radio emission at the $L$ band mainly comes from the deep layer of the regolith, since emission from the upper layers would vary with daily changes in solar illumination. As a result, observing at high resolution in the $L$ band is a good method to study the properties of the deep layers of lunar regolith.

Ground-based large synthesis radio telescopes, such as the Dominion Radio Astrophysical Observatory Synthesis Telescope (DRAO ST), VLA, GMRT and WSRT have very high angular resolution and intensity sensitivity which are comparable with that of the radiometers on lunar orbiters, or are even better at low frequency bands. Among the mentioned telescopes, DRAO ST (Landecker et al. 2000) is the best one able to image the whole lunar surface (near side) because of its large field of view, while the others are suitable for resolving the fine structure of the lunar emission. The analysis of the full polarization data obtained by ground-based observations can be used to study the dielectric constant (Davies \& Gardner 1966) and the thickness of the lunar regolith. All the mutual relationships between the polarized emission distribution and the size of the observing beam, the dielectric constant of the regolith, the incidence-angle and the surface roughness has been studied by Troitskii \& Tikhonova (1970) and Alekseev \& Krotikov (1968, 1969). The last study of this kind was performed by Moffat (1972) to image the brightness temperature and polarized emission distributions over the near side of the Moon: a central symmetric distribution of the brightness was observed. Since Moffat's observation was performed in 1972 and great progress has been achieved in observing and imaging techniques in recent years, new observations at $L$ band are now needed for comparison. We present here new $L$ band observations performed in 2009 with the DRAO ST at 1.4 GHz .

Some results about the spectral properties of the lunar thermal emission at millimeter wavelengths have already been published, such as Troitsky et al. (1968), Fisher \& Staelin (1977) and Hagfors (1970). Troitskii \& Tikhonova (1970) gave models of the dependence of the lunar radio emission on observing wavelength $(0.46 \mathrm{GHz}-15 \mathrm{GHz})$ for different parameters of regolith depth, heat flow and variations in polarization degree along the radius of the lunar disk for different observing beam sizes and dielectric constants. The lunar orbiter CE-1 has recorded the brightness temperature distribution over the whole lunar surface at four frequencies, i.e. $3.0 \mathrm{GHz}, 7.8 \mathrm{GHz}, 19.35 \mathrm{GHz}$ and 37.0 GHz (Jiang 2009; Li et al. 2010a). Combining the CE-1 observations with our 1.4 GHz data sets in this work, we study the spectral properties of the lunar emission with high resolution over the frequency range from 1.4 to 37.0 GHz .

In Section 2, we introduce the observations with the DRAO ST and the related data reduction. Studies of radiation properties of lunar emission and thickness of the lunar regolith are presented in Section 3. A summary is given in Section 4.

## 2 OBSERVATIONS

The observations were performed on 2009 January 7 and 8 with the DRAO ST (Landecker et al. 2000). The main parameters describing the observation and telescope are listed in Table 1. Because the Moon is located near the Earth and moves quickly in the sky, both the antenna tracking and the phase tracking programs were modified to keep the center of the Moon at the center of the telescope's field of view for the duration of data acquisition. The DRAO ST has seven antennas, of which three antennas are moveable. Usually, to get all base-lines, seven sets of observation, each requiring a 12 hour duration, are needed. However, this observational mode makes the data reduction more complex because of the movement of the Moon. A simple observing mode with the synthesis telescope was adopted to observe the Moon. An observation of $2 \times 12$ hours was arranged, which contains a considerable base-line distribution.

Figure 1 shows the $U V$ coverage of this observation, i.e. base-line distribution. A total of 36 base-lines were used for this observation, ranging from 12.86 m to 617.18 m . The asymmetric $U V$ coverage seen on this figure results in an elliptic synthesized beam.

The shortest spacing between the physical antennas for this observation is about $60 \lambda$. At some hour-angle, the projected short spacing can reach $45 \lambda$ without the shadowing effect. However, as the lunar angular size reaches about $33^{\prime}$ during the observation, the shorter base-lines that were missed (including the 0 base-line) need to be compensated for to obtain a higher accuracy in the lunar radio images. The data measured with the 25 m antenna, which is located in Urumuqi (China), were used to perform the compensation because data from the Urumuqi telescope contain information of all the missed base-lines due to its aperture size. In addition, the lunar integral flux density was obtained by using the 25 m antenna. Radio source 3C 144 and the Baars's scale were adopted (Baars et al. 1977) to calibrate the 25 m single dish data. The lunar integral flux density is about 1533 Jy at 1.66 GHz . Each antenna in the DRAO ST array is about 9 m in diameter, so that attenuation near the limb of the Moon caused from its primary pattern is not negligible.

Figure 2 compares the size of the Moon to the primary beam and shows that the maximum of the primary beam attenuation is about $6 \%$ near the lunar limb. The corrections of the primary attenuation have been applied to our data reduction. This correction is necessary to equalize the accuracy of the observed distribution of lunar brightness temperature over the whole lunar surface. The amplitudes and phases of the observed data were calibrated using standard DRAO software and the AIPS software package. The residual errors of the calibrated $U V$-data are smaller than $10 \%$ in amplitude and 5 degrees in phase. The AIPS CLEAN deconvolution procedure is used to compose

Table 1 Main Specifications of the DRAO ST and Observation Parameters

| Observing dates | 2009 Jan. 7 | 2009 Jan. 8 |
| :--- | :--- | :--- |
| Observing time (UT) | $7 \mathrm{~d} / 22 \mathrm{~h} 47 \mathrm{~m} 45 \mathrm{~s}-8 \mathrm{~d} / 11 \mathrm{~h} 15 \mathrm{~m} 22 \mathrm{~s}$ | $8 \mathrm{~d} / 23 \mathrm{~h} 43 \mathrm{~m} 39 \mathrm{~s}-9 \mathrm{~d} / 12 \mathrm{~h} 11 \mathrm{~m} 18 \mathrm{~s}$ |
| Apparent radius | $987.8^{\prime \prime}-993.0^{\prime \prime}$ | $997.2^{\prime \prime}-1000.3^{\prime \prime}$ |
| Parallax | $60.419^{\prime}-60.737^{\prime}$ | $60.996^{\prime}-61.187^{\prime}$ |
| Observing frequency | 1420 MHz |  |
| Antenna | $8.53 \mathrm{~m}(5$ dishes $) ; 9.14 \mathrm{~m}(2$ dishes $)$ |  |
| Base-lines | $12.86 \mathrm{~m}-617.18 \mathrm{~m}$ |  |
| Field of view | $2.65^{\circ}$ (primary beam down to 20\%) |  |
| Synthesis beam | $120^{\prime \prime} \times 60^{\prime \prime}$ |  |
| Radius of the first grating ring | $2.82^{\circ}$ |  |
| System temperature | 60 K |  |
| Continuum band width | 30 MHz |  |



Fig. 1 The $U V$ coverage of the DRAO ST observations of the Moon performed on 2009 January 7-8, unit: $k \lambda$ for both $U$ and $V$.


Fig. 2 The one-dimensional primary beam of the DRAO ST antenna (the curve) and the size of the Moon.
the lunar image. The CLEAN deconvolution will produce spurious fluctuations on the plane of the map (Thompson et al. 1986) when imaging an extended source such as the Moon. To reduce the residual oscillation features on the map's plane, a smoothing procedure was applied to the map, which results in a lower resolution, $159^{\prime \prime} \times 87^{\prime \prime}$, instead of the highest resolution, $120^{\prime \prime} \times 60^{\prime \prime}$. The final dynamic range reached 150 . The map's background fluctuation was about 1.7 K .

The variation in the apparent lunar radius was about $10^{\prime \prime}$ during the observation. It can be neglected given the large size of the synthesized beam ( $159^{\prime \prime} \times 87^{\prime \prime}$ ). The lunar phase varied from $316^{\circ}$ to $330^{\circ}$ (phase of the full Moon was $360^{\circ}$ ) during the observation. During the observation, the Moon was located near its perigee, so the libration in longitude was negligible. About $80 \%$ of the lunar surface was illuminated by sunlight during the observation and a small dark area with a narrow arc-shape was located near the NW limb.

## 3 RESULTS

### 3.1 Total Intensity Emission

The left panel of Figure 3 presents the brightness temperature distribution at the $L$ band derived from the observations with the DRAO ST on 2009 Jan. 7-8. The average brightness temperature over the disk is about 232.7 K while the fluctuation of the background of this map is about 1.7 K , and the resolution is $159^{\prime \prime} \times 87^{\prime \prime}$. The average brightness temperature is in good agreement with the previous results deduced from the $L$-band observations with different spatial resolution: 233 K (Baldwin 1961), 225 K (Moffat 1972), 232 K (Heiles \& Drake 1963), 230 K (Razin \& Fedorev 1963) and 250 K (Mezger \& Strassl 1959). The average brightness temperature of the brightest region, which is denoted by the boxed-region in Figure 4, along the lunar equator is about 257 K and the average brightnesses for the four quadrants are $228.1 \mathrm{~K}(\mathrm{NE}), 239.7 \mathrm{~K}(\mathrm{NW}), 233.9 \mathrm{~K}$ (SW) and 228.8 K (SE). They are 145 K and 163 K in the south pole and "north pole" regions, respectively. Because of the lunar latitude libration, the lunar north pole cannot be seen by the radio telescope during the observation, i.e. the real north pole is not at the top of Figure 3 (left panel). This explains why the average brightness temperature around the "north pole" is higher than that in the area of the south pole. Although the average brightness temperatures of these regions are different, the deviations from the mean value over the whole surface are still small and the lunar emission on average can be fitted with a disk model (Fig. 5). Contrary to previously published results, the new observations reveal the fine structure of the lunar brightness temperature distribution for the first time. We discovered the large variations in bright regional temperatures along the lunar equator at the $L$ band. This feature is also confirmed by the independent observations of lunar orbiter CE- 1 at 3.0 GHz (the right panel in Fig. 3, Wang et al. 2009a). Both maps show similar variation features along the lunar equator. All the 3.0 GHz data used in making Figure 3 were obtained by night observations of CE-1 without any effect from solar illumination (i.e. the 3 GHz data are not affected by the lunar phase). As mentioned previously, the 1.4 GHz data are also almost not affected by solar illumination, so the two data sets are comparable, hence both brightness temperature variations along the lunar equator are reasonable. In the latitude direction, the mean distribution of the lunar brightness temperature derived from the


Fig. 3 Left: Lunar brightness temperature distribution at 1.4 GHz observed with the DRAO ST. The contours represent values of $155,190,210,230,250,255,260$ and 265 K . The lunar equator is to the north of the center of the disk due to the libration in latitude. Right: lunar brightness temperature distribution recorded by the night observations of the Chinese lunar orbiter CE-1 at 3.0 GHz (Wang et al. 2009a).


Fig. 4 Average brightness temperatures at 1.4 GHz over different regions. The lunar equator is north of the center of the disk due to the libration in latitude.


Fig. 5 Lunar brightness temperature profile (thin line) at 1.4 GHz along the lunar equator and the fitted disk model (thick line).
new observations shows a polar cooling proportional to $\cos ^{0.2}$ (latitude). This is in good agreement with the results of Moffat (1972).

Radio sources 3C 48 and 3C 295 are the primary calibrators of the DRAO ST observations, which were used to scale the raw data to flux densities, Jy Beam ${ }^{-1}$. Their absolute calibration accuracy is about 5\% (Baars et al. 1977). In this sense, the new observations at the $L$ band have uncertainty of about $5 \%$ in intensity calibration while on the map plane of the lunar image, the uncertainty is about $1 \%$ due to the self-calibration and decovolution programs.

According to the basic theories (Troitskii \& Tikhonova 1970, Muhleman 1972, Jin 2005), lunar radio emission depends on the profiles of the physical temperature and dielectric constant as well as on the vertical structure of the regolith, including ilmenite content and depth. The higher regional brightness temperatures shown in Figure 4 may be caused by several factors, particularly the physical temperature and the dielectric constant. It is well known that the mare area has a lower albedo $(\sim 0.08)$ than that of the highland area $(\sim 0.16)$. The lower albedo could cause a higher physical temperature, i.e. a higher brightness temperature. Based on the Apollo regolith samples, the mare surfaces have a higher ilmenite content, hence leading to the higher dielectric constant, especially for the loss tangent. On a large scale, the lunar mare areas (mainly in the NW region) show a higher brightness temperature whereas most of the highland areas (mainly in the SE region) have a lower brightness temperature. The results are consistent with our former knowledge. The lunar emission at the $L$ band on small scales is not strongly correlated to any individual lunar topographical features, such as mountain rings or ring plains. This is in agreement with results described by Moffat (1972). High frequency lunar emission mainly comes from the upper layer of the lunar regolith and strongly depends on the solar incidence angle and reflection rate, so that its intensity is correlated with individual lunar topographical features. The lunar emission at $L$ band mainly comes from deep layers and is not correlated with topographical features on the lunar surface.

### 3.2 Polarized Emission

### 3.2.1 Polarization intensity and degree

With this new observation, the polarization of the lunar emission at the $L$ band has been measured. Figure 6 shows the new results for the distributions of the polarization intensity, $\mathrm{PI}=\left(Q^{2}+U^{2}\right)^{0.5}$, and the polarization position-angle, $\mathrm{PA}=\arctan (U / Q)$. Both the distributions of polarization intensity and polarization position-angle are in agreement with the results of Moffat (1972) and Poppi et al. (2002). Polarization intensities increase from the center of the disk to its limb and reach a maximum (about $0.8 \mathrm{Jy} \mathrm{beam}^{-1}$ ) near the limb. Polarization intensities become relatively weak near both the south and the north polar regions. Polarization emission depends on Fresnel coefficients, which are a function of dielectric constant and observing angle (Davies \& Gardner 1966). The ring shape of the polarization intensity is mainly due to the variation of observing angles. Near the two polar regions, the lower brightness temperature, i.e. the total intensity emission, contributes to the lower polarization intensities. This feature, recorded by the new data, is in agreement with the result of Moffat (1972). The inhomogeneous distribution of the polarization intensity along the limb is probably caused by inhomogeneities in the distribution of dielectric constant (Poppi et al. 2002).

The distribution of polarization degree, $\mathrm{PD}=\mathrm{PI} / I$ where $I$ is the total intensity, is given in Figure 7. The averaged polarization degree over the whole surface is $6 \%$. The degree of polarization also increases from the disk's center to its limb, but the increase is not the same in different radial directions. It has a minimum of $13 \%$ in the SW part of the limb, but it is about $20 \%$ near the other limb. Being different from the polarization intensity, the degree of polarization only has one minimum, whereas the polarization intensity has two minima.

### 3.2.2 Dielectric constant in the limb regions

Degree of polarization is a function of relative dielectric constant and observing angle. According to our new polarization degree measurements, we calculated the real part of the relative dielectric constant in the lunar limb area. Here the imaginary part is assumed to be zero because it is much smaller than the real part and it cannot be obtained simultaneously since we have only one equation with two variables. The relation between the degree of polarization ( DoP ), the relative dielectric constant $(\varepsilon)$ and the observing angle ( $\theta$, angle between the incident ray and the normal to the surface)


Fig. 6 Distributions of the polarization intensity (grey and contours) and the polarization position angle (indicated by the orientation of the bars) of the Moon at 1.4 GHz .


Fig. 7 Distributions of the degree of polarization for the thermal emission of the Moon at 1.4 GHz .


Fig. 8 Calculated real part of the distribution of the dielectric constant.
can be represented by the following formula (Davies \& Gardner 1966)

$$
\begin{equation*}
\mathrm{DoP}=\frac{1}{2}\left(R_{\perp}-R_{\|}\right) /\left\{1-\frac{1}{2}\left(R_{\perp}+R_{\|}\right)\right\} \tag{1}
\end{equation*}
$$

where $R_{\perp}$ and $R_{\|}$are the reflection coefficients of power in the two perpendicular planes which are equal to the square of the usual Fresnel coefficients expressed as

$$
\begin{align*}
& R_{\perp}(\theta)=\left|\frac{\cos \theta-\left(\varepsilon-\sin ^{2} \theta\right)^{\frac{1}{2}}}{\cos \theta+\left(\varepsilon-\sin ^{2} \theta\right)^{\frac{1}{2}}}\right|^{2}  \tag{2}\\
& R_{\|}(\theta)=\left|\frac{\varepsilon \cos \theta-\left(\varepsilon-\sin ^{2} \theta\right)^{\frac{1}{2}}}{\varepsilon \cos \theta+\left(\varepsilon-\sin ^{2} \theta\right)^{\frac{1}{2}}}\right|^{2} . \tag{3}
\end{align*}
$$

From Equations (1), (2) and (3), we calculated the distribution of the dielectric constant, which is presented in Figure 8. The relative dielectric constant was only calculated in limb regions where the signal to noise ratio for the degree of polarization is high enough. Dielectric constants are calculated only for regions where $s n r>10$. From Figure 8, one can find that the real part of the relative dielectric constant is about $2-2.5$ in the SW limb region of the Moon while it is about 2.5-3.0 in the rest of the limb region. These values of the relative dielectric constants are in agreement with other measurements, such as the bistatic-radar investigation using the Apollo spacecraft in lunar orbit (Tyler \& Howard 1973) and ground-based radio observations (Moffat 1972).

Figure 8 shows for the first time the two-dimensional distribution of the relative dielectric constant derived from high resolution observations of the degree of polarization.

### 3.3 Spectra of Lunar Emission

Using the new 1.4 GHz data combined with the CE-1 data at $3.0,7.8,19.35$ and $37.0 \mathrm{GHz}(\mathrm{Li}$ et al. 2010b), we have computed high-resolution maps of the spectral index of the Moon's thermal emission. Spectral index $(\alpha)$ is defined as $I \propto \nu^{\alpha}$ where $I$ is the emission intensity and $\nu$ is the observing frequency. The CE-1 image at 3.0 GHz (resolution is 50 km at 3.0 GHz , about $30^{\prime \prime}$ ) has been smoothed to the resolution of the DRAO ST image for the spectral index calculation of the $1.4 / 3.0 \mathrm{GHz}$ frequency pair. The other three CE-1 maps have the same spatial linear resolution ( 35 km ) and were used directly to calculate the spectral index distributions for 7.8/19.35 and $19.35 / 37.0 \mathrm{GHz}$ frequency pairs. All the CE- 1 data of the four frequencies are night-time data, i.e. without the effect of solar illumination, so they are comparable to the DRAO ST data. These CE-1 data are taken from the database of the Lunar Science Exploration Center of National Astronomical Observatories, China (Li et al. 2010b).

Figure 9 shows the spectral index distributions for the $1.4 / 3.0 \mathrm{GHz}$ (upper-left), $7.8 / 19.35 \mathrm{GHz}$ (upper-right) and $19.35 / 37.0 \mathrm{GHz}$ (lower-left) frequency pairs. Although the average spectral indices over the whole disk for the three frequency pairs are in the range -0.1 to 0.0 , as expected for thermal emission (flat spectra), deviations from the average spectral indices are present in all the maps. The region where the spectral indices are the lowest depends on the frequency pair and moves from the NW (1.4/3.0 pair) to the equatorial area (7.8/19.35) and then to the SE region (19.35/37.0). The spectral index distributions for the $3.0 / 7.8 \mathrm{GHz}$ frequency pair show a uniform distribution around zero, i.e. no obvious regional feature is found. As a result, they are not included in Figure 9. As mentioned previously, all the CE-1 data and the DRAO ST data are not affected by the solar illumination and the spectral properties deduced from them represent the intrinsic properties of the lunar regolith. The NW quadrant of the Moon is mainly mare area whereas the SE quadrant is mainly highlands. Based on the Apollo samples (Heiken et al. 1991), the mare area with higher ilmenite content (indicated by $\mathrm{TiO}_{2}$ ) should have a higher dielectric constant, especially for the loss tangent (Fa \& Jin 2007). Also, the mare area has a higher physical temperature than that of the highland area. The multi-frequency spectral information shown by Figure 9 indicates that it is in agreement with the change in dielectric constant (from NW to SE) obtained independently by Fa \& Jin (2007), whose study is based on the distribution of ilmenite content. More detailed theoretical studies on the


Fig. 9 The lunar spectral index distributions of frequency pairs of $1.4 \mathrm{GHz} / 3.0 \mathrm{GHz}$ (upperleft), $7.8 \mathrm{GHz} / 19.35 \mathrm{GHz}$ (upper-right) and $19.35 \mathrm{GHz} / 37.0 \mathrm{GHz}$ (lower-left). The lower-right panel shows the distribution of the imaginary part of the dielectric constant (Fa \& Jin 2007).
properties of lunar regolith are needed because the effects of several parameters are mixed together (temperature, dielectric constant, heat flow, etc).

Troitskii \& Tikhonova (1970) studied the spectral properties of lunar regolith for a frequency range from 0.46 to 15 GHz . According to their model, the difference in brightness temperature between 1.4 and 3.0 GHz is about $8-10 \mathrm{~K}$ for a lunar regolith thickness of 5 m and a heat flow of $q=0.65 \times 10^{-6} \mathrm{cal} \mathrm{cm}^{-2} \mathrm{~s}^{-1}$, but for the same model the differences between high frequency pairs are lower than 5 K . This means that the spectral index derived from the $1.4 / 3.0 \mathrm{GHz}$ frequency pair should be lower than that derived from the high frequency pairs. Our new data show that the spectral index of the $1.4 / 3.0 \mathrm{GHz}$ pair is in the range of -0.15 to -0.05 for the major part of the lunar surface, but it is in the range of -0.05 to 0.0 for the $7.8 / 19.35 \mathrm{GHz}$ and $19.35 / 37.0$ pairs. This indicates that the new observational results are consistent with the model of Troitskii \& Tikhonova (1970).

### 3.4 Study of the Lunar Regolith Properties

### 3.4.1 Thickness of lunar regolith

The maximum measurable depth of the lunar regolith depends on the observing wavelength and the complex dielectric constant (eq. (4), Jin 2005).

$$
\begin{equation*}
d_{\lim }=\frac{\lambda \sqrt{\varepsilon^{\prime}}}{\pi \varepsilon^{\prime \prime}} \tag{4}
\end{equation*}
$$

where $\lambda$ is the observing wavelength, and $\varepsilon^{\prime}$ and $\varepsilon^{\prime \prime}$ are the real and imaginary parts of the dielectric constant, respectively. On the basis of this equation, the distributions of maximum measurable depth at 3.0 GHz (CE-1 data) and 1.4 GHz (DRAO ST data) were estimated. It is not possible to use the distribution of dielectric constant deduced from the study of the degree of polarization measured in the DRAO ST data (Section 3.2.2) because it is not available for the whole lunar surface. The distribution used is that of $\mathrm{Fa} \& \mathrm{Jin}$ (2007) which is in agreement with the results from measurements of the Apollo samples (Heiken et al. 1991). At 3.0 GHz , we find that the regions where the maximum measurable depth reaches $\geq 6 \mathrm{~m}$ are very limited. This means that the CE- 1 data are not well suited to probe the deeper layers of the lunar regolith, particularly for the highland region. The maximum measurable depth at 1.4 GHz is about two times that of 3.0 GHz , and reaches up to 15 m in the SE region. The DRAO ST measurements are thus complementary to the CE-1 data in the study of lunar regolith thickness.

A schematic view of a cross section of the lunar regolith layer is shown in Figure 10 in which $h_{\text {dep }}, d_{\text {lim1.4 }}$ and $d_{\lim 3.0}$ represent the regolith depth and the maximum detectable depth at 1.4 GHz and 3.0 GHz , respectively. We only discuss the case of $d_{\lim 3.0}<h_{\text {dep }}<d_{\lim 1.4}$, because 1.4 GHz observations are not necessary if $h_{\text {dep }}<d_{\lim 3.0}$ and lower frequency observations are needed if $h_{\text {dep }}>d_{\text {lim1.4 }}$.

According to the theory of radiation ( $\operatorname{Jin} 2005$ ), the lunar brightness temperature $T_{B}$ is expressed as follows

$$
\begin{equation*}
T_{B}=\int_{-\infty}^{0} F(h, \theta, \nu) T(h) d h \tag{5}
\end{equation*}
$$

where $F$ is the weighting function which depends on the depth $h$, the observing angle $\theta$ and the observing frequency $\nu ; T(h)$ is the physical temperature of the lunar regolith at depth of $h$. We do not perform the direct integration of Equation (5) because this strongly depends on the weighting function used. In order to avoid this problem, it is more convenient to study the difference between the temperature of two different frequencies. The expression of the difference between the brightness temperatures measured at $1.4 \mathrm{GHz}(\mathrm{DRAO} \mathrm{ST})$ and $3.0 \mathrm{GHz}(\mathrm{CE}-1), \Delta T_{B}$ is given in Equation (6),


Fig. 10 A schematic view of a cross section of the lunar regolith layer.


Fig. 11 The distribution of the differences in lunar brightness temperature between the new DRAO ST 1.4 GHz data and the CE-1 3.0 GHz data (Li et al. 2010b).


Fig. 12 Calculated thickness of the lunar regolith.
where the maximum detectable depths at 1.4 GHz and 3.0 GHz are used as integration boundaries. The distribution of $\Delta T_{B}$ is presented in Figure 11.

$$
\begin{equation*}
\Delta T_{B}=\int_{-d_{\lim 1.4}}^{0} F\left(h, \theta, \nu_{1.4}\right) T(h) d h-\int_{-d_{\lim 3.0}}^{0} F\left(h, \theta, \nu_{3.0}\right) T(h) d h \tag{6}
\end{equation*}
$$

The night time data set of the 3.0 GHz observations is adopted because it is not affected by variations in solar illumination and can be compared to 1.4 GHz data. $\Delta T_{B}$ can be expressed in an approximate form, when we assume that the received radio emission from the lunar bedrock can be neglected, i.e. using $-h_{\text {dep }}$ instead of $-d_{\lim 1.4}$ as the lower bound of the first integration (Eq. (7)). This is acceptable as the attenuation of the radio emission becomes large when it passes through the layer of lunar bedrock. Equation (7) is more accurate in regions where $d_{\lim 1.4}$ is not far from the depth of the bedrock layer.

$$
\begin{equation*}
\Delta T_{B}=\int_{-h_{\mathrm{dep}}}^{-d_{\mathrm{lim} 3.0}} F\left(h, \theta, \nu_{1.4}\right) T(h) d h+\int_{-d_{\mathrm{lim} 3.0}}^{0}\left[F\left(h, \theta, \nu_{1.4}\right)-F\left(h, \theta, \nu_{3.0}\right)\right] T(h) d h . \tag{7}
\end{equation*}
$$

The temperature $T(h)$ under the lunar equator is taken as a constant, 240 K , because the physical temperature of the lunar regolith below 1.0 m is stable (Heiken et al. 1991, Wang et al. 2009b). The variation of $T(h)$ with lunar latitude has been taken into account, as done in Wang et al. (2009b). The weighting function $F$ is calculated according to the model of Jin (2005) with the distribution of dielectric constant given by Fa \& Jin (2007).

An iterative digital algorithm of least error is adopted to calculate $h_{\text {dep }}$ using Equation (7) and $\Delta T_{B}$ measured between the DRAO ST and CE-1 data (the distribution of $\Delta T_{B}$ presented in Fig. 11). The derived distribution of $h_{\text {dep }}$ is presented in Figure 12. From the map, one can find that the thickness of the lunar regolith is between 3 m and 13 m for most regions in the lunar disk (near side), while in about $50 \%$ of these regions the thickness is greater than 6 m and in about $3 \%$ greater than 11 m . The large scale distribution of the lunar regolith shows that, in general, the thickness in the SE
area (highland) is deeper than that in the NW area (mare). This tendency is in agreement with other published results (Fa \& Jin 2010, Shkuratov \& Bondarenko 2001). The calculations in a ring area near the whole limb of the lunar disk, |longitude $\mid>60^{\circ}$ and $\mid$ latitude $\mid>60^{\circ}$, were not performed because of the larger difference in observing angles between the ground-based observation and the lunar orbiter data. The results of Shkuratov \& Bondarenko (2001) also showed the same area in which no thickness information is given.

### 3.4.2 Uncertainties in regolith depth estimations

The uncertainties in inversion of regolith depth in this study are mainly due to measurement errors in the brightness temperature and in the assumed distribution of dielectric constant. The rms of fluctuations in brightness temperature of the DRAO ST map is about 1.7 K and the CE- 1 data have a better sensitivity of about 0.5 K , so that the rms of $\Delta T_{B}$ is 1.8 K . To test the uncertainties caused by the errors in measurements of brightness temperature of both DRAO ST and the CE- 1 data, 2 Krms brightness temperature with a Gaussian distribution were randomly added to the brightness temperature difference (Fig. 11) map before we recalculated. The differences of the regolith depth between the two calculations are lower than 0.7 m over a major part of the lunar surface. We have examined our data reduction procedure by including self-calibration, an imaging program and a conversion from flux density to temperature. No error larger than $1 \%$ was found. Furthermore, it is found that all the distributions of lunar regolith thickness obtained by our study, Shkuratov \& Bondarenko (2001) and Fa \& Jin (2010) showed that the depth distributions are similar to that of the imaginary component of the dielectric constant. This suggests that the errors in the distribution of dielectric constant affect the thickness calculation more than the errors in the distribution of brightness temperature.

The distribution of complex dielectric constant affects both the weighting function profile and the parameters $d_{\lim 3.0}$, as well as $d_{\lim 1.4}$, all of which are boundary conditions in the calculation, so it is important to use a very accurate distribution of complex dielectric constant. The distribution of complex dielectric constant we used is taken from Fa \& Jin (2007). It was calculated using the formula $\varepsilon^{\prime}=1.919^{\rho}$ and $\tan \delta=10^{0.038 S+0.312 \rho-3.260}$ (Carrier et al. 1991) where $\tan \delta=\varepsilon^{\prime \prime} / \varepsilon^{\prime}$, $\rho$ is the bulk density of the lunar regolith, and $S$ is the $\mathrm{FeO}+\mathrm{TiO}_{2}$ content. The two expressions used in the calculation of the dielectric constant were first derived from the regression analysis of the Apollo sample (Olhoeft \& Strangway 1975). Shkuratov \& Bondarenko (2001) derived the dielectric constant using the same Apollo samples with a slightly different regression expression. The maximum difference of the complex dielectric constant between the two studies is lower than $5 \%$ over the range of $\mathrm{FeO}+\mathrm{TiO}_{2}$ content varying from $1 \%$ to $30 \%$. This means that the accuracies of the complex dielectric constant from the two studies are at the same level.

In addition, we have tried to compute the regolith thickness with another published distribution of dielectric constant (Wang et al. 2009b) to investigate the effects of this parameter. The result shows a distribution with an almost opposing pattern in which the thickness of the lunar regolith decreases from NW (mare area) to SE (highland area). This is not consistent with the calculated distribution of regolith depth (Shkuratov \& Bondarenko 2001 and Fa \& Jin 2010). The main difference between the distributions of dielectric constant calculated by Wang et al. (2009b), Shkuratov \& Bondarenko (2001) and Fa \& Jin (2010) is that the equation used by Wang et al. does not include the effect of the $\mathrm{FeO}+\mathrm{TiO}_{2}$ content (eq. (12) in Wang et al. 2009b). This results in the distribution of dielectric constant calculated by Wang et al. showing quite a different distribution from that calculated by the others.

In Table 2, we compare the estimations of regolith thickness obtained by this study for different sites on the Moon with the results of Shkuratov \& Bondarenko (2001). The results indicate that the two estimations are globally in agreement. The mean deviation between the two works is only $0.8 \pm 1.33 \mathrm{~m}$.


Fig. 13 Correlation between regolith thickness from this study ( $\mathrm{dep}_{\text {this work }}$ ) and the data from the seismic experiments at the Apollo landing sites (dep apollo , Nakamura et al. 1975).

Table 2 The comparison of the lunar regolith thickness for some sites between estimations of Shkuratov \& Bondarenko (2001) and this paper.

| Target name | Location | Estimation $(\mathrm{m})^{a}$ | Estimation $(\mathrm{m})^{b}$ | Difference $(\mathrm{m})$ |
| :--- | :---: | :---: | :---: | :---: |
| Apollo 11 | $0.7^{\circ} \mathrm{N}, 24.3^{\circ} \mathrm{E}$ | $4.5 \pm 1.0$ | 3.8 | +0.7 |
| Apollo 12 | $3.2^{\circ} \mathrm{S}, 23.4^{\circ} \mathrm{W}$ | $3.8 \pm 2.0$ | 5.5 | -1.7 |
| Apollo 14 | $3.7^{\circ} \mathrm{S}, 17.5^{\circ} \mathrm{W}$ | $8.6 \pm 2.0$ | 6.4 | +2.2 |
| Apollo 15 | $26.1^{\circ} \mathrm{N}, 3.7^{\circ} \mathrm{E}$ | $4.5 \pm 2.4$ | 6.2 | -1.7 |
| Apollo 16 | $9.0^{\circ} \mathrm{S}, 15.5^{\circ} \mathrm{E}$ | $12.5 \pm 2.4$ | 10.1 | +2.4 |
| Apollo 17 | $20.2^{\circ} \mathrm{N}, 30.8^{\circ} \mathrm{E}$ | $8.4 \pm 2.2$ | 5.1 | +3.3 |
| Mare Serenitatis | $28.0^{\circ} \mathrm{N}, 17.5^{\circ} \mathrm{E}$ | $4.1 \pm 1.2$ | 5.1 | -1.0 |
| Mare Tranquillitatis | $8.5^{\circ} \mathrm{N}, 31.4^{\circ} \mathrm{E}$ | $4.3 \pm 1.5$ | 3.1 | +1.2 |
| Mare Imbrium | $32.8^{\circ} \mathrm{N}, 15.6^{\circ} \mathrm{W}$ | $5.9 \pm 1.5$ | 4.0 | +1.9 |
| Mare Nectaris | $15.2^{\circ} \mathrm{S}, 35.5^{\circ} \mathrm{E}$ | $8.5 \pm 1.7$ | 7.8 | +0.7 |
| Mare Vaporum | $13.3^{\circ} \mathrm{N}, 3.6^{\circ} \mathrm{E}$ | $5.3 \pm 1.5$ | 5.0 | +0.3 |
| Mare Nubium | $21.3^{\circ} \mathrm{S}, 16.6^{\circ} \mathrm{W}$ | $5.4 \pm 1.6$ | 4.1 | +1.3 |
| Mare Cognitum | $10.0^{\circ} \mathrm{S}, 23.1^{\circ} \mathrm{W}$ | $4.9 \pm 1.5$ | 4.5 | +0.4 |

Notes: ${ }^{a}$ After Shkuratov \& Bondarenko (2001); ${ }^{b}$ Obtained by this study.
Figure 13 shows the correlation between regolith thickness from this study ( dep $_{\text {this work }}$ ) and data from the seismic experiments at the Apollo landing sites (depapollo, Nakamura et al. 1975). In Figure 13, the relative error of this study is assumed to be about $30 \%$.

## 4 SUMMARY

The main results are:
(1) We measured the brightness temperature distribution of the Moon in the $L$ band with an rms of 1.7 K . The average lunar brightness temperature over the whole disk is about 233 K while the average brightness temperatures of the four quadrants are $228.1 \mathrm{~K}(\mathrm{NE}), 239.7 \mathrm{~K}(\mathrm{NW}), 233.9 \mathrm{~K}$ (SW) and $228.8 \mathrm{~K}(\mathrm{SE})$. The average brightness temperature in the brightest region (see Fig. 4)
is about 257 K . It is the first time that a large variation in the brightness temperature (larger than 20 K ) along the lunar equator has been discovered at the $L$ band. This result is in agreement with the observation of the CE-1 lunar orbiter.
(2) The total degree of polarization is about $6 \%$. Both polarization intensity and degree of polarization increase from the disk's center to the limb and the degree of polarization reaches a maximum of about $20 \%$ near the limb. The distributions of the degree of polarization and polarization intensity along the limb are not uniform: the degree of polarization has a minimum of $13 \%$ near the SW limb indicating a smaller relative dielectric constant (real part) in that area.
(3) The mean values of lunar emission spectral indices are about -0.1 over the frequency range from 1.4 GHz to 37.0 GHz . The distributions of spectral indices over the whole lunar surface are not uniform. The variation of spectral index distribution with frequency reveals the difference of the regolith properties between the NW area and the SE area. This phenomenon is similar to the tendency of distribution of the brightness temperature, dielectric constant and regolith thickness.
(4) Thickness of the lunar regolith generally increases from NW (mare area) to SE (highland area). This result is in agreement with other published results. The derived thickness is between 3 m to 13 m for most of the lunar disk regions (near side) but the thickness is greater than 6 m and 11 m over $50 \%$ and $3 \%$ of the whole lunar surface, respectively. The results strongly depend on the assumed distribution of complex dielectric constant (Fa \& Jin 2007). Comparisons of estimated regolith thickness between the results of Shkuratov \& Bondarenko (2001) and ours for different sites on the Moon indicate that the two estimations are globally in agreement. The mean deviation between the two works for these sites (Table 2) is $0.8 \pm 1.33 \mathrm{~m}$.

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