Bulk Density of the Lunar Regolith at the Chang’E-3 Landing Site as Estimated From Lunar Penetrating Radar

Wenzhe Fa

1Institute of Remote Sensing and Geographical Information System, School of Earth and Space Sciences, Peking University, Beijing, China, 2State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macau, China, 3CAS Center for Excellence in Comparative Planetology, Hefei, China

Abstract Bulk density of the lunar regolith is a key factor affecting its geophysical and geotechnical properties. In this study, a new method for estimating the bulk density of the lunar regolith is developed based on the geometric characteristic (i.e., hyperbolic shape) of radar echoes in ground penetrating radar (GPR) image. As an application, bulk density of the lunar regolith at China’s Chang’E-3 (CE-3) landing site is estimated using the Lunar Penetrating Radar data. In total, 57 hyperbolas are identified in the Lunar Penetrating Radar image and their eccentricities are used to estimate relative permittivity of the regolith. Then, bulk density of the lunar regolith is estimated using an empirical relation through its dependence on relative permittivity. The results show that bulk density of the regolith at the CE-3 landing site increases with depth from 0.85 g/cm³ at the surface to 2.25 g/cm³ at 5 m, with an average gradient much smaller than that based on the Apollo regolith samples. The bulk density corresponds to a regolith porosity of 74.5% at the surface and 32.3% at 5 m depth over the CE-3 landing region. Given that the landing site is only ~50 m from the east rim of a 500 m diameter crater, named as Zi Wei, the steady-state bulk density indicates a 29% volume fraction of subsurface rocks within the continuous ejecta of this crater.

Plain Language Summary In ground penetrating radar observations, the distance between a radar antenna and a discrete subsurface object can produce a hyperbolic curve that is very common in ground penetrating radar images. The shape of a hyperbolic curve depends on antenna height, depth of the object, and dielectric permittivity of subsurface material. Based on these relationships, relative permittivity (i.e., the ratio of the dielectric permittivity of a material to that of vacuum) of the lunar regolith at a depth of ~5 m at China’s Chang’E-3 (CE-3) landing site is first estimated using the Lunar Penetrating Radar observation. Then, bulk density and porosity of regolith and volume fraction of subsurface rocks are estimated through their dependences on relative permittivity, grain density of lunar regolith, and density of lunar rocks. The results show that bulk density increases with depth from 0.85 g/cm³ at the surface to 2.25 g/cm³ at 5 m, indicating a regolith porosity of 74.5% at the surface and 32.3% at 5 m depth. The results also indicate a volume fraction of 29% for subsurface rocks at the CE-3 landing site. All these results can improve our understanding of the subsurface property of the lunar regolith, which was not revealed by previous missions because of the limited penetration depth (e.g., Apollo core tube experiment and Diviner radiometer estimation).

1. Introduction

As a fundamental property, the bulk density of lunar regolith affects a wide range of regolith properties, such as seismic velocity, thermal conductivity, electric resistivity, dielectric permittivity, optical depth, bearing capacity, and slope stability (e.g., Heiken et al., 1991). As a consequence, the bulk density of lunar regolith not only is critical for deciphering any scientific observation of the Moon but also provides important information on engineering constraints for future lunar explorations. As examples, interpretations of remote sensing observations at infrared and microwave bands (e.g., Bandfield et al., 2011; Fang & Fa, 2014) as well as geophysical data from the Apollo lunar seismic and heat flow experiments (e.g., Langseth et al., 1976; Nakamura et al., 1975) depend strongly on bulk density of the regolith and its variation with depth. Bulk density also affects the geotechnical property of the lunar surface (e.g., slope stability and bearing capacity).
that is closely related to the landing safety and rover trafficability for future lunar explorations. In addition, any future in situ experiment implemented in the regolith will have to consider bulk density as a prerequisite through its effect on penetration resistance.

Prior to the Apollo missions, a very low bulk density of 0.3–0.4 g/cm³ for the lunar surface was inferred through remote sensing observations (Halajian, 1965; Jaffe, 1965). Subsequent in situ robotic measurements at the Surveyor and Luna landing sites indicated an average surficial bulk density of about 1.5 g/cm³ (Christensen et al., 1967; Leonovich et al., 1975; Scott & Roberson, 1968). In situ bulk density analysis of the lunar regolith was also deduced from analyses of astronaut footprint, vehicle track, boulder track, and penetration resistance, with values varying from 1.3 to 1.7 g/cm³ and an upper limit between 1.81 and 1.92 g/cm³ (Mitchell et al., 1974). With the return of the Apollo and Luna regolith samples, extensive laboratory measurements were conducted and this provided the first hand data on bulk density of lunar regolith, showing that bulk density varies both vertically and laterally (e.g., Allton & Waltz, 1980; Carrier et al., 1991; Mitchell et al., 1974). To date, the best estimate for the mean bulk density of lunar regolith in the intercrater region is 1.50±0.05 g/cm³ for the top 0.15 m, 1.58±0.05 g/cm³ for the top 0.3 m, and 1.66±0.05 g/cm³ for the top 0.60 m layer (Carrier et al., 1991). Bulk density increases rapidly from ∼1.3 g/cm³ at the surface to a steady-state value of ∼1.9 g/cm³ at a depth of ∼0.7 m, and a hyperbolic relationship between the bulk density (ρ, g/cm³) and depth (z, cm) is proposed as ρ = 1.92(z + 0.122)/(z + 0.18) (Carrier et al., 1991). Recently, Diviner thermal infrared observations at lunar nighttime were used to estimate regolith bulk density profiles at regional and global scales, suggesting a bulk density of 1.1 g/cm³ at the surface and 1.8 g/cm³ at a depth of 1 m and an H-parameter (describing how density increases with depth) of ∼7 cm on global scales (Hayne et al., 2017; Vasavada et al., 2012). Nevertheless, all these estimations/measurements are only for near-surface regolith with a maximum sampling depth less than 3 m (i.e., the Apollo core tube sampling experiments). Natural state of the regolith was destroyed during sample collection, and the sampled depth in the core tube might not represent the true depth below the lunar surface. Estimation from remote sensing observations might suffer from problems like shallow penetration depth, data calibration, and/or poorly constrained parameters in the regolith model. For example, Diviner-derived regolith density profile depends primarily on depth-, density-, and temperature-dependent thermophysical properties of lunar regolith fines, among others, such as surface slope, roughness, albedo, emissivity, and vertical structure of regolith (Hayne et al., 2017; Yu & Fa, 2016). To date, most of these parameters are not well quantified, resulting in a large uncertainty in the derived bulk density.

On 14 December 2013, China’s Chang’E-3 spacecraft successfully landed on the east rim of a 500 m diameter crater (named Zi Wei crater) in the northern Mare Imbrium (e.g., Fa et al., 2015). For the first time, a rover deployed dual-frequency (60 and 500 MHz) Lunar Penetrating Radar (LPR) was used to characterize subsurface structure and dielectric property of the lunar regolith (Fa, 2013; Fang et al., 2014). During its surface traverse of ∼110 m, the LPR at 500 MHz reveals many hyperbolic curves with varying geometrical shape in the radargram, which are most probably caused by subsurface rocks within the continuous ejecta of Zi Wei crater (Fa et al., 2015). Lai et al. (2016) and Feng et al. (2017) investigated the geometric relation of the hyperbolic curves in the CE-3 LPR image and then estimated the relative permittivity of the lunar regolith using hyperbolic fitting method. However, in these two studies, the height of LPR antenna is assumed to be zero, leading to an overall increase in the estimated relative permittivity. In this study, an improved estimation method for relative permittivity and bulk density of lunar regolith is developed based on the geometric characteristic of the hyperbolic curve in GPR image (section 2). The improved method considers the antenna height in deriving the geometry of a hyperbolic curve and hence gives a more accurate estimate of the relative permittivity. Then, the CE-3 LPR observation and data processing are briefly introduced (section 3). Finally, bulk density of the lunar regolith at the CE-3 landing site is estimated according to its dependence on relative permittivity. The estimated bulk density and regolith porosity are also compared with results from the Apollo core tube experiments and Diviner radiometer inversion (section 4).

Note, by definition, that the relative dielectric permittivity (also known as dielectric constant, a deprecated but still-used term) of a material is the ratio of its dielectric permittivity to the permittivity of vacuum (8.85×10⁻¹² F/m), and it is in general a dimensionless, complex-valued number. For convenience, the term “relative permittivity” (ε) is used to represent the real part of relative dielectric permittivity throughout the paper following the convention in Carrier et al. (1991) and Ulaby et al. (2014). For a few times, the term “complex relative permittivity” means the complex value of the relative dielectric permittivity.
2. Methodology
2.1. Method
In this study, an infinite homogeneous media (e.g., lunar regolith) with a buried rock is assumed (Figure 1). As GPR instrument moves over a buried rock along the survey line, the direct line distance between the radar antenna and the subsurface rock decreases until the GPR is over the rock and then increases as the GPR moves away. As a result, the trace of GPR echoes from a buried rock appears as a convex-up hyperbola (Figure 2) that is very common in GPR images (e.g., Fa et al., 2015; Liu et al., 2013).

In Figure 1, the height of the antenna is \( h \), the depth of the buried rock is \( d \), and the relative permittivities of vacuum and the subsurface media (e.g., lunar regolith) are \( \varepsilon_0 = 1 \) and \( \varepsilon \), respectively. The relative permittivity of the regolith, \( \varepsilon \), is an unknown parameter to be estimated from GPR observation. As the GPR moves along the survey line, the one-way apparent range (\( R \)) between the GPR antenna and the rock is

\[
R = h \sec \theta_i + d \sqrt{\varepsilon} \sec \theta,
\]

where \( \theta_i \) and \( \theta \) are the incidence and transmission angles, and they are related by Snell’s law as \( \sqrt{\varepsilon_0} \sin \theta_i = \sqrt{\varepsilon} \sin \theta \). Apparent range is defined as the equivalent range between radar antenna and a subsurface rock by assuming that a radar wave propagates in the subsurface at the speed of light in vacuum. Therefore, the apparent range (\( R \)) can be calculated directly as the product of the time delay (\( t \)) between transmission of a radar wave and reception of its echo from the rock and the speed (\( c \)) of light in vacuum, that is, \( R = ct/2 \).

One can use time delay (\( t \)) in equation (1) as well, but apparent range is preferred in this paper because it has the same dimension as antenna height and rock depth, making it convenient to deal with a hyperbolic curve in GPR image. The horizontal distance between the antenna and the rock, \( x \), can be expressed as

\[
x = h \tan \theta_i + d \tan \theta.
\]

From equations (1) and (2), the relationship between the apparent range and the horizontal distance is

\[
\frac{R^2}{\varepsilon d^2} = \frac{x^2}{d^2} = 1 + \frac{2 \cos \theta_i}{d} \frac{h}{d} + \frac{1 - \varepsilon \sin^2 \theta_i}{\varepsilon \cos^2 \theta_i} \frac{h^2}{d^2}.
\]

From equation (3), the apparent range depends on antenna height (\( h \)), depth of the buried rock (\( d \)), and relative permittivity of the lunar regolith (\( \varepsilon \)). Figure 2 shows the apparent range as a function of horizontal...
Figure 2. Apparent range ($R$) between GPR antenna and a subsurface rock as a function of horizontal distance ($x$) along the survey line with different (a) antenna height, (b) target depth, and (c) relative permittivity. In (a) and (b), the relative permittivity of subsurface media is set to 3.0, a typical value for lunar regolith; in (b) and (c), the antenna height is set to 0.273 m as the case of the CE-3 LPR.

distance with different antenna height, rock depth, and relative permittivity. Radar echoes at these apparent ranges are usually strong, and as GPR instrument moves along the survey line, their traces form a smooth, bright curve in radargram. As can be seen, all the curves exhibit a hyperbolic-like characteristic, and their shapes depend on $h$, $d$, and $\epsilon$. In fact, for a general case when the antenna height is much smaller than the depth of a buried rock, that is, $h \ll d$, the second and third terms on the right-hand side (RHS) of equation (3) are much smaller than the first term. As a result, equation (3) can be approximated as a hyperbolic function.

If the antenna is on the surface (as most GPR operating on the Earth), that is, $h = 0$, it can be easily proved that the relationship between the apparent range and the horizontal distance follows a rigorous hyperbolic function,

$$\frac{R^2}{\epsilon d^2} - \frac{x^2}{d^2} = 1.$$  \hfill (4)

For a standard hyperbolic curve with the mathematical expression of $y^2/a^2 - x^2/b^2 = 1$ ($a > 0$ and $b > 0$), its eccentricity ($e$) can be calculated as $e = \sqrt{(a^2 + b^2)/a}$, which is a dimensionless number greater than one.

In relative permittivity estimation, the eccentricity of a hyperbola is introduced for two reasons. First, the geometrical shape of a hyperbola is completely described by its eccentricity. Second, a quantitative relation among the eccentricity of a hyperbola, relative permittivity of lunar regolith, and rock depth can be established (Figure 3). From equation (3) and Figure 2, the eccentricity of a hyperbola in GPR image depends on the relative permittivity of lunar regolith, depth of a buried rock, and antenna height. Antenna height is usually fixed in GPR observation, and hence, the eccentricity depends on $d$ and $\epsilon$. Theoretical simulations based on equation (3) show that, for a buried rock with a fixed depth, the eccentricity of a hyperbola decreases with the increase of relative permittivity (Figures 2c and 3a). On the other hand, for a given relative permittivity, the eccentricity decreases with increasing depth of the buried rock. For the ideal case when $h = 0$, the eccentricity of the hyperbola can be expressed as

$$e = \sqrt{1 + 1/\epsilon}.$$  \hfill (5)
In such a case, the eccentricity of a hyperbola depends only on the relative permittivity of the regolith, regardless of the depth of the buried rock (the thick line in Figure 3a). For a general case with \( h > 0 \), no analytical expression among eccentricity, relative permittivity, and rock depth exists. One has to resolve equation (3) numerically to obtain the relations among these three parameters (Figure 3a).

For the CE-3 LPR, the antenna height is fixed to 0.273 m, and the two unknown parameters are \( \varepsilon \) and \( d \). For a buried rock with a given depth, the eccentricity of the hyperbola decreases with the relative permittivity of regolith (Figure 3a). When the LPR is direct over a rock, the minimum apparent depth of the rock (\( d_{\text{min}} \)) is the product of the rock depth and the square root of the relative permittivity, that is, \( d_{\text{min}} = d\sqrt{\varepsilon} \). Note that the apparent depth is apparent range minus antenna height, so an apparent depth of zero corresponds to the surface. As the eccentricity and the minimum apparent depth of a hyperbola are obtained from the LPR image, the relative permittivity of lunar regolith and the depth of a buried rock can be estimated as the intersection point in Figure 3b based on these two relationships.

As the relative permittivity of lunar regolith is estimated from the LPR image, the bulk density can be inverted through its dependence on relative permittivity. Laboratory measurements of the Apollo regolith samples show that the relative permittivity of lunar regolith depends primarily on its bulk density (e.g., Carrier et al., 1991; Olhoeft & Strangway, 1975). The relation between the relative permittivity (\( \varepsilon \)) and bulk density (\( \rho \), g/cm\(^3\)) of lunar regolith is usually fitted using a power law function as

\[
\varepsilon = a\rho^n,
\]

where \( a \) is a constant. Olhoeft and Strangway (1975) analyzed 92 measurements of the Apollo lunar regolith samples using regression analysis and found that \( a = 1.93 \pm 0.17 \). The last systematic analysis of all the available Apollo regolith measurements by Carrier et al. (1991) shows that \( a = 1.919 \), but no uncertainty is given in the study. There are also other regressions of the Apollo regolith sample measurements in literature (e.g., Campbell, 2002; Fa & Wieczorek, 2012), and the difference in the predicted relative permittivity is generally less than 10%. In this study, the regression result of \( a = 1.93 \pm 0.17 \) by Olhoeft and Strangway (1975) will be used for bulk density estimation.

A similar method is proposed for relative permittivity estimation using the CE-3 LPR data by Lai et al. (2016) and Feng et al. (2017). However, the antenna height is not considered in these two studies, leading to an overall increase in the estimated relative permittivity. What is important, bulk density and porosity profiles of lunar regolith, which are the main topics of the current study, were not discussed in Lai et al. (2016) and Feng et al. (2017).

**2.2. Uncertainty Analysis**

A well-designed GPR field experiment with in situ measurements of bulk density and relative permittivity or a sample return mission to the Moon with a GPR experiment (such as China’s Chang’E-5 mission; see...
section 4 for detail) can provide ground truth data to validate the proposed method. Lacking of GPR field experiment data, the uncertainty of the proposed method is analyzed using forward simulation and Monte Carlo method. Possible sources of the uncertainty in the estimated bulk density include the approximation of a hyperbolic curve (equation (3)), the simplified regolith model, and the empirical relation between relative permittivity and bulk density. As the proposed method depends only on the shape of a hyperbolic curve, the uncertainty of the method relies on how accurate the eccentricity obtained from GPR image is. Simulations of hyperbolic curves using equation (3) with random noise and/or uncertainty in model input parameters (i.e., $h$ and $d$) are taken as GPR “experiment data,” which are then used to estimate the relative permittivity. The estimated relative permittivity is compared with model input values to provide a quantitative measure of the estimation uncertainty.

Strictly speaking, equation (3) is not a hyperbolic function as the second and third terms on its RHS are not zero. The approximation of equation (3) as a hyperbolic curve results in errors in the estimated relative permittivity. The traces of GPR echoes for a subsurface rock with different depth and relative permittivity of lunar regolith are simulated and then the relative permittivity is estimated using the simulations. Figure 4a shows the relative error in the estimated permittivity as a function of relative permittivity of lunar regolith for different rock depths. The relative error increases with the increase of relative permittivity and decreases with increasing rock depth. With increasing rock depth, the second and third terms on the RHS of equation (3) decrease and equation (3) is better approximated as a hyperbolic function, and therefore, the relative error in the estimated relative permittivity decreases. For a typical value of 3.0 for the relative permittivity of lunar regolith, the relative error is less than 10% when rock depth is deeper than 2.0 m.

The assumption of a flat surface in Figure 1 is another source of estimation uncertainty. Topographic relief along the survey line changes the height of a GPR antenna relative to the mean surface, and surface normal is probably neither vertical nor spatially constant. Taken a subsurface rock at 3.0 m depth as an example, in GPR echo trace simulations the antenna height is changed by ±10% and ±20% of the LPR height, and in relative permittivity estimations a constant antenna height of 0.273 m is used. The relative error caused by uncertainty in antenna height increases with the relative permittivity of lunar regolith, and for a given relative permittivity, the relative error decreases with increasing magnitude of the underestimated antenna height (and vice versa; Figure 4b). For lunar regolith with a relative permittivity of 3.0, a 20% uncertainty in antenna height (or an equivalent change in surface height) results in an uncertainty of ~11% in the relative permittivity. Additional simulations show that the relative error caused by uncertainty in antenna height decreases systematically with the increase of rock depth, and vice versa. As an example, if rock depth increases from 3.0 to 4.0 m, the ~11% relative error caused by a 20% uncertainty in antenna height would reduce to ~8%. High-resolution topography data generated from CE-3 landing camera show that the landing site is relatively flat, with a slope generally less than 5° (Liu et al., 2015). Therefore, it is expected that surface slope would not produce any significant error in the estimated relative permittivity.

A homogeneous regolith model is assumed in Figure 1. In addition, there could be packets of materials with varying density that refract the incident radar wave away from the path in Figure 1. To quantify this effect, a Gaussian distributed relative permittivity of lunar regolith with a mean value of 3.0 and a standard deviation of 1.0 is used in calculating the apparent range of a GPR echo. A buried rock with a depth of 3.0 m is used, and 500 realizations of GPR echoes are simulated using Monte Carlo method. The distribution of the estimated relative permittivity is non-Gaussian with a long tail (Figure 4c), and therefore, its median value (3.5) is a more robust measure of the estimation. This corresponds to a relative uncertainty of 16% in the estimated relative permittivity.

Considering the three major factors above, the estimation uncertainty of the method is estimated to be less than 20% for a typical regolith permittivity of 3.0 and a buried rock at 3.0 m. The estimation uncertainty decreases with increasing rock depth. There could be other factors affecting the estimation, such as surface roughness, size of buried rocks, and a subsurface rock that is away from the survey line. A feasible way to quantify estimation uncertainty caused by these factors might be directly modeling GPR echoes using numerical method (e.g., finite difference time domain method) and then compare the estimated value with that in the model.
Figure 4. (a) Relative error in the estimated relative permittivity as a function of model input relative permittivity for different rock depths. (b) Relative error in the estimated permittivity caused by uncertainty in antenna height as a function of model input relative permittivity, where the rock depth is set to 3.0 m. (c) Probability distribution of the estimated relative permittivity from Monte Carlo simulation (gray bars) and a Gaussian distribution of relative permittivity (black line) with a mean value of 3.0 and a standard deviation of 1.0.

3. The CE-3 LPR Observations

The CE-3 landing site (44.1213°N, 19.5115°W) is in the northern Mare Imbrium, about 50 m from the east rim of Zi Wei crater (unofficially named as the CE-3 crater by Fa et al., 2015). During its 2-month lifetime, the Yutu (Jade Rabbit) rover traveled for a distance of about 110 m (Fa et al., 2015). According to morphology prominence (e.g., the distribution of surface rocks, inner wall slope, and depth/diameter ratio), the age of Zi Wei crater is estimated to be about 100 Myr (Basilevsky, 1976; Fa et al., 2015). Considering that Zi Wei
crater is very young, most of its geological structure at the time of formation should be preserved because of less later surface modification. The LPR exploration region is within the lateral extent of the continue ejecta of Zi Wei crater that extends about one crater radius from its rim (Melosh, 1989). According to the ejecta thickness model in McGetchin et al. (1973), the ejecta thickness of Zi Wei crater at the landing site is estimated to be $\sim 4.0$ m (Fa et al., 2015). There are two channels for the CE-3 LPR, with center frequencies of 60 and 500 MHz. The low-frequency LPR observations did not reveal any obvious hyperbolic curves because of its coarse range resolution (Li et al., 2018). Therefore, in this study, the high-frequency channel observations will be used for relative permittivity estimation. From the Lunar Prospector gamma ray spectrometer data (Prettyman et al., 2006), the FeO and TiO$_2$ abundances at the landing site are 19.5 and 5.2 wt.\%, respectively. Using the relationship between the complex relative permittivity, bulk density, and composition of lunar regolith in Fa and Wieczorek (2012), the complex relative permittivity is estimated to be $3 + 0.03i$ with a typical porosity of 0.45. This corresponds to a penetration depth (also known as skin depth) of about 5.5 m for the high-frequency channel. Considering a 4 m ejecta thickness of the Zi Wei crater, most of the observed high-frequency LPR echoes are from the ejecta layer (Fa et al., 2015). In this study, CE-3 LPR data at 2B level are used, and each trace contains a zero-time reference point (Su et al., 2014). The zero-time reference point is further checked by examining the time delay of the first maximum positive peak, and the results are quite consistent among difference traces. Therefore, zero-time correction is not necessary for LPR level 2B data processing. The observed raw signals at 500 MHz were processed through horizontal band removal, band-pass filtering, and compensation for geometric spreading and dielectric attenuation (using a complex relative permittivity of $3 + 0.03i$) and are then displayed in B-scan format as a function of lateral distance and apparent depth (Figure 5a) (Fa et al., 2015). With the assumption that radar waves propagate in vacuum, the apparent depth is defined as the product of the time delay and the speed of light in vacuum. An apparent depth of zero corresponds to the level of the lunar surface.
4. Results and Discussion

In the LPR image (Figure 5a), a rock is identified as the vertex of a convex-up hyperbola. Given the large dynamic range of the received radar echoes, the brightness and contrast of local image were adjusted in order to identify a rock confidently. Only fully developed hyperbolas were selected, which are characterized by a continuous, smooth curve that is symmetric with respect to a well-defined vertex. In total, 57 hyperbolas (dots in Figure 5a) were identified, and the apparent depths of their vertexes vary from 1.2 to 13.6 m. The traces of these hyperbolic curves were identified and extracted visually and then each curve was fitted to a hyperbola to obtain its eccentricity. At the same time, the minimum apparent depth of each hyperbolic curve was also recorded. Using the fitted eccentricity and the minimum apparent depth of each hyperbolic curve, relative permittivity and rock depth were estimated from the relationship in Figure 3b and are shown in Figure 5b.

The estimated relative permittivity varies from 1.1 to 6.1, with a mean value of 3.2. The mean value is consistent with the model predicted relative permittivity of 3.0 based on the regolith composition and a typical porosity of 45%. Though lateral variation in the relative permittivity is large, there is no obvious trend given the short exploration line of the CE-3 LPR. It is obvious that the relative permittivity increases with depth, which probably reflects the increasing of bulk density with depth. The estimated relative permittivities are within the measurement range (1.66–11) of the Apollo regolith samples (Table A9.16 in Heiken et al., 1991). Natural state of the returned regolith was disturbed during the sampling, and the samples might be contaminated by moisture during their curation on the Earth. The regolith at the CE-3 exploration region was observed at natural state by the LPR, and therefore, the estimated relative permittivity does not have such problems. The overall consistence between the LPR estimation and the Apollo regolith measurements indicates that the contamination of the regolith by moisture produces no significant difference in relative permittivity. The most probable reason might be that moisture content in the contaminated regolith samples is extremely low and hence does not affect the measured relative permittivity. A tiny moisture content could increase the loss tangent in a noticeable manner, but this effect cannot be tested with the LPR observation using the method in this paper. Two LPR estimates are smaller than the minimum relative permittivity of 1.66 in the Apollo regolith measurements, reflecting the differences in bulk density, composition, and particle size of the regolith at different sampling region and depth.

With the estimated relative permittivity and its dependence on bulk density, the mean bulk density of the lunar regolith from the surface to the depth of the corresponding rock can be inverted. Here, the regression relation between the relative permittivity and bulk density of lunar regolith in Olhoeft and Strangway (1975), \( \varepsilon = (1.93 \pm 0.17) \rho_s \), is used, and the maximum uncertainty in the estimated bulk density is 16%. The inversion results (the dots in Figure 5) show that mean bulk density increases with depth and that there is no obvious trend in lateral variation of the bulk density. The density estimates also show a high degree of heterogeneity of the regolith down to a depth of 6 m, reflecting the chaotic distribution of ejecta materials over the landing site. To study how bulk density varies with depth, an exponent density profile is given as \( \rho(z) = \rho_s - (\rho_d - \rho_s) e^{-z/H} \), where \( z \) is depth (in m), \( H \) is an e-folding depth scale, and \( \rho_s \) and \( \rho_d \) are surface and subsurface bulk densities, respectively (Vasavada et al., 2012). Analytical form for the mean bulk density as a function of depth can be obtained by integrating this formula from zero to a given depth. The best fit between the LPR estimations and the analytical form of the mean bulk density (the black line in Figure 6a) indicates a surface density of \( \rho_s = 0.85 \text{ g/cm}^3 \), a subsurface steady-state density of \( \rho_d = 2.25 \text{ g/cm}^3 \), and an e-folding factor of \( H = 1.03 \text{ m} \). For comparison, a linear fit of the bulk density is obtained as \( \rho(z) = 1.41 + 0.21z \).

To date, direct measurements of the bulk density profile of lunar regolith are only available at the Apollo 15, 16, and 17 landing sites through core tube samples (Mitchell et al., 1973) (the red, blue, and green lines in Figure 6b). For comparison, the bulk density estimated from the LPR observations is averaged within a depth bin of 0.5 m, and the density profile is plotted as the black line in Figure 6b. As can be seen, to a depth of 3 m, the LPR estimated bulk density is comparable to the Apollo core tube measurements, though it is slightly smaller at depth between 1 and 2 m. For depth larger than 3.5 m, the LPR-derived bulk density is larger than the Apollo core tube sample measurements. The best fit of the Apollo core tube measurements suggests a hyperbolic relationship between the bulk density and depth as \( \rho(z) = 1.92(z + 0.122)/(z + 0.18) \) for intercrater regions (Carrier et al., 1991). This indicates a surface bulk density of 1.3 \text{ g/cm}^3 and a maximum subsurface bulk density of 1.92 \text{ g/cm}^3. Hayne et al. (2017) mapped globally the thermophysical properties of lunar regolith fines using Diviner radiometer observations, and their results suggest a surface bulk density
of 1.1 g/cm³, a steady-state bulk density of 1.8 g/cm³ at 1 m depth, and an $H$ factor of 0.07 m. Compared with the Apollo core tube sample measurements and Diviner radiometer inversion, estimations from the LPR image show a smaller surface bulk density and a larger steady-state subsurface density (Figure 6c). The bulk density gradient is smaller than those based on the Apollo regolith measurements and Diviner radiometer inversion, as indicated by an $H$ value of 1.03 m. The $H$ value is also consistent with the thickness (about 1 m) of the surface regolith layer produced after the formation of Zi Wei crater (Fa et al., 2015). Based on the FeO and TiO$_2$ abundances of 19.5 and 5.2 wt.%, zero-porosity density of the regolith at the CE-3 landing site is estimated to be 3.32 g/cm³ according to the relation between bulk density and regolith composition (Huang & Wieczorek, 2012). This implies that regolith porosity is about 74.5% at the surface and 32.3% at a depth of 5 m at the CE-3 landing site.

Since ejecta thickness at the Yutu exploration region is about 4 m (McGetchin et al., 1973), the LPR echoes at the high-frequency channel are mainly from the ejecta. The estimated subsurface density of 2.25 g/cm³ is much larger than the regression of the Apollo measurements with a value of 1.92 g/cm³, which is most probably caused by an overabundance of subsurface rocks. Suppose that the bulk density of the fine-grained regolith is 1.9 g/cm³ at a depth of 5 m and that the bulk density of lunar rock is 3.1 g/cm³, a steady-state subsurface density of 2.25 g/cm³ indicates a rock abundance of 29.1%. Study of the Diviner radiometer data indicates a surface rock abundance of 1–2% at the CE-3 landing site (Bandfield et al., 2011), which is much smaller than the LPR-based estimation. The reason might be that Diviner radiometer at infrared band is only sensitive to surface rocks at scales larger than 1 m. In contrast, the LPR observation is sensitive to rocks at centimeter scales and larger, and in addition, it is sensitive to a depth at least 5 m where rocks within the continuous ejecta are overabundant. It is probable that a significant number of large rocks should have been present at the surface directly after the formation of Zi Wei crater. Over the past 100 Myr, the CE-3 landing region was bombarded by numerous large and small meteoroids, and near-surface rocks were pulverized. As a result, surface rocks become smaller and the abundance of large rocks decreased. Nevertheless, ejecta at a depth of 5 m are less affected by meteorite bombardments and therefore their abundance could retain its initial high value at the formation of Zi Wei crater.

In China's Chang'E-5 lunar sample return mission, regolith samples with a total mass of ∼2 kg will be collected from the Mons Rümker region in northern Oceanus Procellarum (Qian et al., 2018). A sampling core tube will be utilized to drill the surface down to a depth of ∼2 m. Before sampling the regolith, a GPR named Lunar Regolith Penetrating Radar (LRPR) with a frequency range of 1–3 GHz will be employed to imaging the regolith structure at the landing site in order to guide the drilling process (Feng et al., 2019). Once the LRPR image is obtained, the method proposed in this study can be utilized to estimate the relative permittivity and bulk density of the regolith at the sampling site. The LRPR estimated results can be further compared with laboratory measurements of the returned regolith samples. This can help to quantify how sampling process disturbs natural state of regolith and affects its relative permittivity and bulk density.
the other hand, laboratory measurement of the returned regolith samples may act as a reference to validate the proposed method for estimating relative permittivity and bulk density.

5. Conclusions

In this study, a new method is developed to estimate the bulk density of the lunar regolith based on the geometric characteristic of the radar echoes in GPR image. In total, 57 hyperbolas in CE-3 LPR image were identified, and their eccentricities were used to estimate the relative dielectric permittivity and bulk density of the regolith at the CE-3 landing site. The results show a surface bulk density of 0.85 g/cm³ and a subsurface bulk density of 2.25 g/cm³ at 5 m depth. The surface bulk density corresponds to a surface porosity of 74.5%, indicating that lunar surface is more porous than previously thought. The subsurface bulk density also indicates a 29% volume fraction of subsurface rocks within the continuous ejecta blanket of Zi Wei crater. All these results provide valuable information on the nature of lunar regolith from surface to a larger depth over the crater ejecta region that was not investigated by previous missions.

In the next few years, one GPR will be deployed on the Moon and three GPRs will be sent to Mars with the purpose of investigating subsurface structure and regolith property of these two bodies (Ciarletti et al., 2017; Feng et al., 2019; Hamran et al., 2015; Zhou et al., 2016). The proposed method in this study can be used to estimate the bulk density and relative permittivity of regolith over the landing regions, which can help to improve our understanding of the nature of subsurface of the Moon and Mars.

Acknowledgments

This work was originally presented at the 47th Lunar and Planetary Science Conference in Houston, USA, March 2016 (Fa, 2016). The author thanks three anonymous reviewers for their helpful and constructive comments on the manuscript. The CE-3 LPR data were provided by the Lunar and Deep Space Exploration Department, National Astronomical Observatories, Chinese Academy of Sciences (NAOC) and are available online (http://moon.bao.ac.cn/); the derived data in this paper can be downloaded online (https://zenodo.org/record/3479989#.XaUuyURUUE). This work was supported partly by the National Natural Science Foundation of China (41941002 and 11573005), the Science and Technology Development Fund of Macau (043/2016/A2), and the B-type Strategic Priority Program of the Chinese Academy of Sciences (XDB41000000). This is PKU PRSL contribution 12.

References

Allton, J. H., & Waltz, S. R. (1980). Depth scales for Apollo 15, 16, and 17 drill cores, Proceedings of the 11th Lunar Science Conference (pp. 1463–1477). New York: Pergamon Press.
B bindfeld, J. L., Ghent, R. R., Vasavada, A. R., Paige, D. A., Lawrence, S. J., & Robinson, M. S. (2011). Lunar surface rock abundance and regolith fines temperatures derived from LRO Diviner Radiometer data. Journal of Geophysical Research, 116, E00H02. https://doi.org/10.1029/2011JE003866
Basilevsky, A. T. (1976). On the evolution rate of small craters, Proceedings of the 7th lunar science conference (pp. 1005–1020). New York: Pergamon Press.
Campbell, B. A. (2002). Radar remote sensing of planetary surfaces. Cambridge: Cambridge University Press.
Carrier, W. D., Olhoeft, G. R., & Mendell, W. (1991). Physical properties of the lunar surface. In G. H. Heiken, D. T. Vaniman, & B. M. French (Eds.), Lunar source book: A user's guide to the Moon (pp. 530–552). New York: Cambridge University Press.
Christensen, E. M., Batterson, S. A., Benson, H. E., Chandler, C. E., Jones, R. H., Scott, R. F., et al. (1967). Lunar surface mechanical properties—Surveyor 1. Journal of Geophysical Research, 72(2), 801–813. https://doi.org/10.1029/JZ072i02p08001
Ciarletti, V., Clifford, S., Plettemeier, D., Le Gall, A., Hervé, Y., Dorison, S., et al. (2017). The WISDOM radar: Unveiling the subsurface beneath the ExoMars Rover and identifying the best locations for drilling. Astrobiology, 17(6-7), 565–584.
Fa, W. (2011). Simulation for ground penetrating radar (GPR) study of the subsurface structure of the Moon. Journal of Applied Geophysics, 99, 98–108. https://doi.org/10.1016/j.jappgeo.2013.08.002
Fa, W. (2016). Ejecta properties of Zi Wei crater as revealed by Chang‘E-3 Lunar Penetrating Radar. In The 47th Lunar and Planetary Science Conference Abstract 1185.
Fa, W., & Wieczorek, M. A. (2012). Regolith thickness over the lunar nearside: Results from Earth-based 70-cm Arecibo radar observations. Icarus, 218(2), 771–787. https://doi.org/10.1016/j.icarus.2012.01.010
Fa, W., Zhu, M. H., Liu, T., & Plescia, J. B. (2015). Regolith stratigraphy at the Chang‘E-3 landing site as seen by lunar penetrating radar. Geophysical Research Letters, 42, 10,179–10,187. https://doi.org/10.1002/2015GL066537
Fang, T., & Fa, W. (2014). High frequency thermal emission from the lunar surface and near surface temperature of the Moon from Chang‘E-2 microwave radiometer. Icarus, 232, 34–53.
Fang, G. Y., Zhou, B., Ji, Y. C., Zhang, Q. Y., Shen, S. X., Li, Y. X., et al. (2014). Lunar Penetrating Radar onboard the Chang‘E-3 mission. Research in Astronomy and Astrophysics, 14(12), 1607–1622.
Feng, J., Su, Y., Ding, C., Xing, S., Dai, S., & Zou, Y. (2017). Dielectric properties estimation of the lunar regolith at CE-3 landing site using lunar penetrating radar data. Icarus, 284, 424–430. https://doi.org/10.1016/j.icarus.2016.12.005
Feng, J., Su, Y., Li, C., Dai, S., Xing, S., & Xiao, Y. (2019). An imaging method for Chang‘E-5 Lunar Regolith Penetrating Radar. Planetary and Space Science, 167, 9–16. https://doi.org/10.1016/j.pss.2019.01.008
Halajian, J. D. (1965). The case for a cohesive lunar surface model. Annals of the New York Academy of Sciences, 123(2), 671–710. https://doi.org/10.1111/j.1749-6632.1965.tb20394.x
Hamran, S., Berger, T., Brovoll, S., Damsgård, L., Hellenen, O., Oyan, M. J., et al. (2015). RIMFAX: A GPR for the Mars 2020 rover mission. In the 8th International Workshop on Advanced Ground Penetrating Radar (IWAGPR) (pp. 1–4). Florence, Italy. https://doi.org/10.1109/IWAGPR.2015.7292690
Hayne, P. O., Bandfield, J. L., Siegler, M. A., Vasavada, A. R., Ghent, R. R., Williams, J. P., et al. (2017). Global regolith thermophysical properties of the Moon from the Diviner Lunar Radiometer Experiment. Journal of Geophysical Research: Planets, 122, 2371–2400. https://doi.org/10.1002/2017JE005387
Heiken, G. H., Vaniman, D. T., & French, R. M. (1991). Lunar source book: A user's guide to the Moon. New York: Cambridge University Press.
Huang, Q., & Wieczorek, M. A. (2012). Density and porosity of the lunar crust from gravity and topography. Journal of Geophysical Research, 117, E00K03. https://doi.org/10.1029/2012JE004062
Jaffe, L. D. (1965). Strength of the lunar dust. Journal of Geophysical Research, 70(24), 6139–6146. https://doi.org/10.1029/JZ070i024p06139
Lai, J., Xu, Y., Zhang, X., & Tang, Z. (2016). Structural analysis of lunar subsurface with Chang‘E-3 lunar penetrating radar. Planetary and Space Science, 120, 96–102. https://doi.org/10.1016/j.pss.2015.10.014
Langseth, M. G., Keihm, S. J., & Peters, K. (1976). Revised lunar heat-flow values. In *Proceedings of the 7th Lunar Science Conference*, pp. 3143–3171.

Leonovich, A., Gronov, V., Semyonov, P., Penetrigov, V., & Shvaryov, V. (1975). Luna 16 and 20 investigations of the physical and mechanical properties of lunar soil. In *Space Research XV*, 1, pp. 607–616.

Li, C., Xing, S., Lauro, S. E., Su, Y., Dai, S., Feng, J., et al. (2018). Pitfalls in GPR data interpretation: False reflectors detected in lunar radar cross sections by Chang'E-3. *IEEE Transactions on Geoscience and Remote Sensing*, 56(3), 1325–1335.

Liu, Z., Di, K., Peng, M., Wan, W., Liu, B., Li, L., et al. (2015). High precision landing site mapping and rover localization for Chang'E-3 mission. *Science China Physics, Mechanics & Astronomy*, 58(1), 1–11. https://doi.org/10.1007/s11433-014-5612-0

Liu, L., Li, Z., Arcone, S., Fu, L., & Huang, Q. (2013). Radar wave scattering loss in a densely packed discrete random medium: Numerical modeling of a box-of-boulders experiment in the Mie regime. *Journal of Applied Geophysics*, 99, 68–75.

McGetchin, T., Settle, M., & Head, J. (1973). Radial thickness variation in impact crater ejecta: Implications for lunar basin deposits. *Earth and Planetary Science Letters*, 20(2), 226–236.

Melosh, H. J. (1989). *Impact cratering: A geologic process*. New York: Oxford University Press.

Mitchell, J., Houston, W., Carrier III, W., & Costes, N. (1974). Apollo soil mechanics experiment S-200. Final report. Berkeley: Space Sciences Laboratory Series 15, Issue 7. NASA Contract NAS 9–11266.

Mitchell, J. K., III, W. D. C., Costes, N. C., Houston, W. N., Scott, R. F., & Hovland, H. J. (1973). Soil mechanics, *Apollo 17 preliminary science report* (pp. 1–22). Washington DC: NASA.

Nakamura, Y., Dorman, J., Duennebier, F., Lammlein, D., & Latham, G. (1975). Shallow lunar structure determined from the passive seismic experiment. *The Moon*, 18(1-3), 57–66. https://doi.org/10.1007/BF00567507

Olhoeft, G. R., & Strangway, D. W. (1975). Dielectric properties of the first 100 meters of the Moon. *Earth and Planetary Science Letters*, 24, 394–404.

Prettyman, T. H., Hagerty, J. J., Elphic, R. C., Feldman, W. C., Lawrence, D. J., McKinney, G. W., & Vaniman, D. T. (2006). Elemental composition of the lunar surface: Analysis of gamma ray spectroscopy data from Lunar Prospector. *Journal of Geophysical Research*, 111, E12007. https://doi.org/10.1029/2005JE002656

Qian, Y. Q., Xiao, L., Zhao, S. Y., Zhao, J. N., Huang, J., Flahaut, J., et al. (2018). Geology and scientific significance of the Rümker Region in northern Oceanus Procellarum: China's Chang'E-5 landing region. *Journal of Geophysical Research: Planets*, 123(6), 1407–1430. https://doi.org/10.1029/2018JE005595

Scott, R. F., & Roberson, F. I. (1968). Soil mechanics surface sampler: Lunar surface tests, results, and analyses. *Journal of Geophysical Research*, 73(12), 4045–4080. https://doi.org/10.1029/JB073i012p04045

Su, Y., Fang, G. Y., Peng, J. Q., Xing, S. G., Ji, Y. C., Zhou, B., et al. (2014). Data processing and initial results of Chang'E-3 lunar penetrating radar. *Research in Astronomy and Astrophysics*, 14(12), 1623–1632. https://doi.org/10.1088/1674-4527/14/12/010

Ulaby, F. T., Long, D. G., Blackwell, W. J., Elachi, C., Fung, A. K., Ruf, C., et al. (2014). *Microwave radar and radiometric remote sensing*. Ann Arbor: University of Michigan Press.

Vasavada, A. R., Bandfield, J. L., Greenhagen, B. T., Hayne, P. O., Siegler, M. A., Williams, J. P., & Paige, D. A. (2012). Lunar equatorial surface temperatures and regolith properties from the Diviner Lunar Radiometer Experiment. *Journal of Geophysical Research*, 117, E00H18. https://doi.org/10.1029/2011JE003987

Yu, S., & Fa, W. (2016). Thermal conductivity of surficial lunar regolith estimated from Lunar Reconnaissance Orbiter Diviner Radiometer data. *Planetary and Space Science*, 124, 48–61. https://doi.org/10.1016/j.pss.2016.02.001

Zhou, B., Shen, S. X., Ji, Y. C., Lu, W., Zhang, F., Fang, G. Y., et al. (2016). The subsurface penetrating radar on the rover of China's Mars 2020 mission. The 16th International Conference on Ground Penetrating Radar (GPR), pp. 1–4. https://doi.org/10.1109/ICGPR.2016.7572700