Properties of Lunar Regolith on the Moon's Farside Unveiled by Chang'E-4 Lunar Penetrating Radar

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Abstract  The complex thermal history of the Moon leads to an unequal distribution of volcanic products between the lunar nearside and the farside. So far, no lunar materials have been sampled from the Moon's farside and no detailed properties of lunar regolith on the farside have been detected before. On January 3, 2019, Chang'E-4 (CE-4) touched down onto the Von Kármán crater on the Moon's farside. CE-4 Lunar Penetrating Radar (LPR) onboard the Yutu-2 rover is the first surface radar on the Moon's farside. Here we show the subsurface structure and properties of regolith materials at the landing region with LPR data during the first five lunar days. The thickness of lunar regolith is constrained as ∼12 m, much thicker than that at Chang'E-3 (CE-3) landing site, which is expected since CE-3 landed on lunar maria. The relative permittivity of lunar surface (<30 cm) at CE-4 landing region is identified to be 2.35 ± 0.20. The loss tangent and TiO2 + FeO content of the regolith materials layer (0–12 m) are constrained to be (4.4 ± 0.5) × 10−3 and 11.6 ± 1.1 wt.%, respectively, much lower than those at CE-3 landing site. It indicates that local surface materials possess less attenuation for radiowave, in accordance with the greater penetrating depth of CE-4 LPR than that of CE-3 LPR. Furthermore, the results also prove that the growth rate of lunar weathered regolith successively declines over time and the growth rate of lunar regolith on the Moon's farside may well be higher than that on the nearside due to the more frequent meteorite impacts.

Plain Language Summary  Lunar regolith (informally called the lunar soil) is the uppermost material on the lunar surface. It preserves vital clues about geology and impact history of the Moon. Although numerous missions to the Moon have landed on the nearside, so far, no lunar materials have been sampled from the Moon's farside. In 2019, China's Chang'E-4 (CE-4) spacecraft softly landed on the farside of the Moon for the first time and deployed its rover, Yutu-2. The Lunar Penetrating Radar (LPR) onboard Yutu-2 can transmit electromagnetic pulses to detect the lunar subsurface structure and properties of the regolith. The relative permittivity, loss tangent and TiO2 + FeO content of lunar regolith materials at landing site are constrained with LPR data in this paper. The results indicate that the farside may be bombarded more frequently, leading to different regolith accumulation rates on the lunar nearside versus farside.

1. Introduction

The lunar surface is covered by a layer of fine-grained material (lunar regolith) with different thickness range from 0 to 15 m (e.g., Shkuratov & Bondarenku, 2001; Shoemaker et al., 1970). The properties of lunar regolith vary from place to place and are dependent on the mineral composition and the impact history. The shallow subsurface structure and mineral compositions of the lunar regolith offer the key to further understand the geology and the local history of basaltic volcanism of the Moon (Fa et al., 2015). The thickness of regolith layer can be used to constrain the Moon's impact history. Therefore, the properties of lunar regolith have important implications on unraveling the lunar surface age, lava eruption volumes and the dichotomy of volcanic products between the Earth-facing side and the far-side (Wilhelms et al., 1987). In detail, the properties of lunar regolith focused in this paper include the thickness, permittivity, density, loss tangent, and TiO2 + FeO content.
The approximate thickness of lunar regolith has been estimated in large amounts by morphologic methods and remote sensing observations. During the Apollo and Luna era, that is, 1960s, in-situ experiments were initially conducted at several locations. In the following decades, modeling on the basis of the crater morphology and size-frequency distributions became the most prevailing methods (e.g., Bart et al., 2011; Gault et al., 1966; Oberbeck & Quaide, 1968; Quaide & Oberbeck, 1968; Wilcox et al., 2005). Gradually, Earth-based/space-borne radar systems were employed more frequently. For instance, the thickness of surface layer on the Moon's near-side was roughly estimated with Earth-based 70 cm Arecibo radar data by Thompson (1987) and Shkuratov and Bondarenku (2001). Fa and Wieczorek (2012) took the scattering from the surface and subsurface rocks into consideration upon previous results and obtained an improved relation among the dielectric constant, bulk density and regolith composition. In addition, Fa and Jin (2007) studied the brightness temperature of the Moon and then mapped the thickness of lunar regolith. Based on Kaguya Lunar Radar Sounder and Laser altimeter data, Kobayashi et al. (2010) also obtained the global thickness map of lunar surface regolith. Moreover, Chang'E-1 Lunar Microwave Sounder (CELMS) data were used on the basis of a back propagation neural network method to estimate the thickness of the surface layer on the Moon (Meng et al., 2014). In conclusion, the thickness of lunar regolith at large scale have been estimated with various methods.

The dielectric properties (permittivity and loss tangent) of the regolith layer are influenced by its ilmenite content and density (porosity) (Olhoeft & Strangway, 1975; Ulaby et al., 1990). Numerous previous studies measured relative dielectric permittivity with radar experiments performed in Surveyor and Luna programs at high-frequency, for example, 2.00–3.28 at ~13 GHz (Muhleman et al., 1969) and 1.7–4.4 at ~1.8~10 GHz (Kroupenio, 1972, 1973, Kroupenio, et al.,1975). In addition, the results of the Apollo program and laboratory studies on lunar samples have confirmed that most lunar soils have dielectric constant about 3, while solid rocks have dielectric constant about 7.5 (Gold et al., 1970; Strangway & Olhoeft, 1977). More recently, a common method is to use spectral analysis to deduce the permittivity of lunar regolith (e.g., Shkuratov & Bondarenku, 2001): first, the ilmenite content of lunar regolith can be identified according to the spectrograph or gamma-ray spectrometer (GRS) data, and then the dielectric constant can be reversely obtained based on the existing fitting relationships between permittivity and TiO$_2$ + FeO abundance (e.g., Olhoeft & Strangway, 1975). Moreover, Ishiyama et al. (2013) improved the method by combining the thickness of regolith derived from spectral data with the Kaguya lunar radar sounder (LRS) data. The velocity of electromagnetic waves within the regolith layer is completely influenced by the average permittivity of regolith materials, which can be constrained by the propagating time between the surface and subsurface echoes in radargrams. Vijayan et al. (2015) proposed a method to estimate both the permittivity and thickness of the lunar regolith with simulated brightness temperature data from a dual frequency SAR of Chandrayaan-2 mission. So far, the permittivity of lunar regolith has been roughly estimated using many indirect methods.

With regards to all these experiments, space-borne/rover-deployed ground penetrating radar (GPR) is the most direct and effective geophysical tool to characterize the physical properties of the lunar regolith (Seu et al., 2007). GPR could map the structure versus depth by detecting dielectric discontinuities, differs from other observations (e.g., infrared or optical analysis). Several such experiments have been conducted: the Apollo Lunar Sounder Experiment (ALSE) operated during NASA's Apollo 17 mission (Peeples et al., 1978; Porcello et al., 1974) and the LRS onboard Japan's Kaguya mission (Ono et al., 2009) profiled lunar surface topographic variations and inferred subsurface structure along the spacecraft ground track. However, satellite-borne radar sounders lead to coarse resolution at depth and low signal-to-noise ratio (SNR) due to the inherent bandwidths and environmental clutters, respectively, inadequate to identify the detailed fine structure and electrical properties of lunar surface regolith. The maximum penetrating depths of these two space-borne radar systems are greater than ~1 km, but their vertical resolutions are only ~75–400 m. The first attempt to conduct a rover-deployed GPR to detect the lunar subsurface was made during China's Chang'E-3 (CE-3) mission (Morgan et al., 2016). Although CE-3 LPR collected only 114 m of scientific data before dormancy, many significant results with respect to the structure and properties of lunar regolith materials at the landing region on the Mare Imbrium were interpreted and revealed (e.g., Dong et al., 2017; Ling et al., 2015; Xiao et al., 2015; Zhang et al., 2015). However, so far, no detailed subsurface structure and properties of lunar regolith on the Moon's farside has ever been detected before Chang'E-4 (CE-4) mission due to surface clutter, coarse range resolution and problems in data interpretation, and no lunar samples on the Moon's farside has ever been returned, either.
On January 3, 2019, China’s Chang‘E-4 mission touched on the Moon at 45.4446°S, 177.5991°E and subsequently employed the Yutu-2 rover (Wu et al., 2019) (Figure 1a). The CE-4 LPR onboard Yutu-2 is the first surface radar system on the Moon’s farside, enabling an investigation of the subsurface with a higher range (i.e., vertical) and horizontal spatial resolution than that from orbital sounders. The landing site is located at the southeast of the Von Kármán crater (diameter = ∼186 km; central coordinates as 44.4°S, 176.2°E) (Figure 1b) which formed in the pre-Nectarian, within the largest known impact structure in the solar system: the South Pole-Aitken (SPA) basin. It is a key area to figure out internal structure, geological history and thermal evolution of the Moon (Hiesinger, 2006; Huang et al., 2018). Parts of the Von Kármán crater were flooded by mare basalts during the Imbrian Period (Huang et al., 2018; Morota et al., 2011; Spudis et al., 1994) (Figure 2a), and then several large Imbrian or post-Imbrian impact craters were formed around the Von Kármán crater, including the Von Kármán M crater, the Leibnitz crater, the Alder crater, the Finsen crater, and the Von Kármán L crater (Figure 1b). The ages of these craters are suggested to be: Von Kármán M > Von Kármán > Leibnitz > Alder > Finsen > Von Kármán L on the basis of Wilhelms Geological Maps (Fortezzo & Hare, 2013; Wilhelms et al., 1979) (Figure 2d). The CE-4 landing site is a generally flat region with an observed gravity anomaly, which probably suggests a distinctive subsurface geological framework (Andrews-Hanna et al., 2014) (Figure 2b). This region also shows fairly high-level optical maturity (Lemelin et al., 2016) (Figure 2c), which suggests the local surface regolith has been weathered for a long period and has probably accumulated a fairly thick regolith layer. The topography of the landing site is relatively flat (Figure 1c). The landing site lies with an area of secondary scour from Finsen crater and is surrounded by three craters whose diameters are 26, 22, and 28 m, respectively (Figure 1d). The northwest trending Yutu-2
traverse skirts around the north side of a degraded 40 m crater and then continues along an approximately straight northwest trending traverse (208–402) (Figure 1d).

In this study, we unveil the properties (including permittivity, loss tangent and TiO$_2$ + FeO abundance) of regolith materials at CE-4 landing region on the Moon’s far-side with CE-4 LPR data, and then the thickness, shallow stratigraphy and weathering rate of local lunar regolith are constrained. The comparison of our results and previous studies at CE-3 landing site or other regions on the Moon’s nearside is also analyzed.

2. Materials and Methods

CE-4 LPR adopts the same mode as CE-3 LPR which is composed of two independent channels with respective operating frequency (Channel-I: 60 MHz, Channel-II: 450 MHz) and bandwidth (Channel-I: 40 MHz, Channel-II: 500 MHz) (Fang et al., 2014), to balance the penetrating depths and range resolution of radarograms. The Channel-I is for detecting subsurface structure of lunar crust, while the Channel-II is for shallow lunar regolith exploration. The preliminary detected results demonstrate that the penetrating depths of Channel-I is up to ~300 m deep with a vertical resolution of ~3 m, while the vertical resolution of Channel-II could be less than ~30 cm within the upper ~50 m depth. Therefore, the structure and properties of lunar regolith materials were revealed with LPR Channel-II data in this study.

Figure 2. Geological background at Chang’E-4 (CE-4) landing region. (a) Mosaic of high-resolution LROC images of the lunar surface. The green areas indicate where was flooded by mare basalts. The southeast part of Leibnitz crater is presumably covered by ejecta from the Finsen crater. (b) Bouguer gravity filtered from degree 6 to 660 to emphasize regional anomalies, which are derived from the GRAIL GRGM00 C gravity mode. Colors indicate different intensity of gravity field in mGal. (c) Derived Optical Maturity (OMAT) mosaic created from Mineral Mapper reflectance data acquired by the Kaguya mission. Colors indicate different local reflectivity. (d) Wilhelms Geologic Map at CE-4 landing region. Symbols marked on various colors indicate different geological units. Im, Ip, Ec, Nc, Ic1, and Ic2 indicate mare material, plains material, crater material younger than most mare material, crater material younger than Nectaris basin but older than Imbrian basin, lower Imbrian crater materials, and upper Imbrian crater materials, respectively.
2.1. Data Processing of LPR Data

A trace of the receiving signals of CE-4 LPR Channel-II consists of 2,048 sampling points within 640 ns (Fang et al., 2014). Yutu-2 drove 178.9 m before the restarting of its fifth working lunar day (May 29, 2019) (Figure 1d). The LPR begins to collect data as soon as Yutu-2 rover is awakened every lunar day and has collected a mass of data along the whole track of Yutu-2. For the sake of the consistency of radargrams and in-situ subsurface structures, we removed the data received when Yutu-2 rover cruised in very slow motion or stopped. Finally, 4,844 high-quality traces of Channel-II data were obtained between waypoints X to LE402 (Figure 1d).

The raw LPR data are attenuated signals with low signal-to-noise ratio (SNR) due to the inherent electrical noise, the spatial clutter and noise, and the attenuation of radar wave by lunar materials (Dong et al., 2017). Consequently, employing effective noise removal and enhancing methods is one of the prerequisites for further analysis. In this work, amplitude compensation, direct-current-removing, background-removing and band-pass filtering, as commonly applied for GPR data on the Earth, are carried out for Channel-II data (Supporting Information). The quality and SNR of the processed results have been obviously enhanced compared with those of the raw data, facilitating the explanation and estimation of the structure and properties of regolith materials at the landing region. In addition, a modified trace correlation method (Dong et al., 2017) is also employed to extract subsurface layers and to identify in-situ shallow stratigraphy (Supporting Information).

2.2. Estimation of Properties of Lunar Regolith

Referring to the GPR applications in civil engineering and geophysical exploration (Dong et al., 2016), the stratigraphic model at CE-4 landing region can be simplified as three two-dimensional layers that includes vacuum, regolith materials (Layer 1) and subsurface lunar materials (Layer 2) from top to bottom (Figure 3).

Based on this model, the relative permittivity of the vacuum-surface interface ($\varepsilon_{r,\text{surface}}$) is given by Equation 1 (Supporting Information):

$$\varepsilon_{\text{surface}} = \varepsilon_{r,0} \left( \frac{1 - A_0}{1 + A_0} \right)^2$$

(1)

Where $\varepsilon_{r,0}$ is the relative permittivity of vacuum, equals to 1. $A_0$ is the relative reflected amplitude that indicates the ratio of amplitudes between the surface reflection and the incident pulse. Therefore, both the amplitudes of the surface echo and the incident signal are required to derive the value of $A_0$. However, only the amplitude of the surface reflected pulse can be identified with the LPR data. In order to obtain the amplitude of the incident pulse, a calibration experiment had been carried out on the Earth before the LPR was launched. We placed the LPR on an adequately large plate which is made of copper. Then, the reflection occurring at the surface of the plate can be approximated as total reflection, which means the amplitude of the surface reflected pulse is equal to that of the incident pulse (Dong et al., 2016). As a result, the value of $A_0$ can be obtained to calculate the relative permittivity of lunar regolith materials.

Thus, we can use the average relative permittivity ($\varepsilon_{r,\text{average}}$) and the two-way propagating time within the regolith materials ($t_1$) observed from LPR radargram to accurately estimate the thickness of lunar regolith layer ($d_1$):

$$d_1 = \frac{ct_1}{2\sqrt{\varepsilon_{r,\text{average}}}}$$

(2)
The results measured by lunar regolith samples returned from Apollo missions suggest that the relative permittivity ($\varepsilon_r$) has a relationship with its bulk density (porosity) (Carrier et al., 1991). The bulk density ($\rho$ (g/cm$^3$)) can be constrained as:

$$\varepsilon_r = 1.919^\rho$$

(3)

Furthermore, the conductivity ($\sigma$) of the regolith materials (layer1), is given by the following equation (Supporting Information):

$$\sigma_1 = \frac{\varepsilon_{r,1}}{d_1} \frac{1}{\eta_0} \log \left[ \frac{1 - A_0^2}{-A_1} \left( \frac{\varepsilon_{r,2}}{\varepsilon_{r,1}} - \sqrt{\varepsilon_{r,2} - \varepsilon_{r,1}} \right) \right]$$

(4)

where, $\varepsilon_{r,1}$ and $\varepsilon_{r,2}$ are the relative permittivity of regolith materials and subsurface materials. $A_0$ and $A_1$ are relative amplitudes (signed) as referred in Equation 1. Then, the loss tangent ($\tan \delta_1$) of the regolith materials (layer1) can be determined as follows:

$$\tan \delta_1 = \frac{\sigma_1}{\omega \varepsilon_0 \varepsilon_{r,1,\text{average}}}$$

(5)

The dielectric properties of Apollo lunar samples were measured in different lab conditions (e.g., in air, nitrogen, and vacuum) with different frequencies (1–450 MHz) in previous studies. In addition, atmospheric moisture contamination also affects the measurement of lunar samples (Olhoeft et al., 1975). Based on lab experiments, the correlation between the bulk density, the TiO$_2$ + FeO content and the loss tangent of regolith materials has been studied. Therefore, the TiO$_2$ + FeO content (%TiO$_2$ + %FeO) of Layer1 can be derived from the loss tangent ($\tan \delta_1$) and bulk density ($\rho_{\text{bulk,1}}$) of Layer1 with a best-fit empirical relationship expressed as (Carrier et al., 1991):

$$\tan \delta_1 = 10^{(0.038 \cdot (\%\text{TiO}_2 + \%\text{FeO}) + 0.312 \cdot \rho^{0.326})}$$

(6)

As a result, the properties of lunar regolith materials (Layer1) including the relative permittivity, the thickness, the density, the loss tangent and the TiO$_2$ + FeO abundance can be estimated as the procedures mentioned above in sequence.

3. Results

We calibrated and processed the CE-4 LPR Channel-II data with the methods in Section 2.1 and obtained a radargram with high resolution and improved SNR as shown in Figure 4a. The surface regolith layer was identified with the modified trace correlation method and the lower interface was marked with yellow line in Figure 4a. The two-way time delay of this layer is $\sim 150$ ns and varies with a range of $\sim 20$ ns along Yutu-2's track, which indicates a variation of regolith depth over small area on the Moon (Wilcox et al., 2005). The layer 1 (0–12 m) displays relatively uniform characteristics with weak internal reflections, which suggest homogenous and fine-grained materials with a small quantity of buried rocks, while the layer 2 ($\sim 12$–35 m) shows abundant and cluttered reflections within which there are numerous obvious parabola-shaped diffractions that probably indicate various-sized subsurface boulders or fragments. Together, these observations suggest that the upper $\sim 35$ m of lunar material were originally deposited as ejecta from surrounding craters, and that the uppermost $\sim 12$ m were subsequently modified, mixed and overturned by the bombardment of numerous micrometeorites, forming the surface layer (0–12 m) with reworked ejecta and the subsurface layer ($\sim 12$–35 m) with remnant ejecta deposits. The uppermost fine-grained regolith
and the underlying multi-layered ejecta (∼12−35 m) have been commonly accepted based on the obvious radar features, spectral data, and local geological context (Lai et al., 2019; Li et al., 2019, 2020; Zhang et al., 2020), but the materials below ∼35 m is a controversial layer, which is speculated to be coarse ejecta from other craters (Li et al., 2020; Zhang et al., 2020), or fragmented basalt (Lai et al., 2019). A trace of processed LPR signal was plotted in Figure 4b with easily recognized surface echo and subsurface echo of which amplitudes can be used to calculate the relative permittivity of lunar regolith.

The relative permittivity of the regolith layer was calculated trace by trace using the methods described in Section 2.2 and the estimated results were shown in Figure 5a. The calculated relative dielectric constants range from ∼2 to 4 and vary along Yutu-2’s track. It is probably due to the surrounding small craters and small-sized rocks exposed on the lunar surface. According to the waypoints marked in Figure 1d, we divided the estimated results into segments, and then statistics and error analysis were carried out. The average permittivity and one standard deviation (1σ) error within each subsection are identified as shown in Figure 5b.

The relative permittivity (εr,surface) of the lunar surface at CE-4 landing region is constrained to be 2.35 ± 0.20, consistent with the measurements from lunar regolith samples (Carrier et al., 1991), lower than the estimated results of 2.9 ± 0.4 at CE-3 landing region (Dong et al., 2017). Note that this result indicates the relative permittivity of the vacuum-surface interface (<∼30 cm allowing for the vertical resolution of LPR) because it is calculated from the surface echo (Figure 3). In addition, the bulk density of surface regolith materials (<∼30 cm) at CE-4 landing region is estimated to be 1.31 ± 0.203 g/cm³ with Equation 3.

The bulk density of the lunar regolith below ∼6 m at CE-4 landing site has been estimated as ∼1.9 g/cm³ (Li et al., 2020), which corresponds to the relative permittivity of the upper 6 m thick regolith materials of ∼3.5. Considering that the permittivity of lunar regolith increases rapidly at shallow depth, but increases more slowly at deeper depths (Carrier et al., 1991; Li et al., 2020), we assumed the average permittivity (εr,average) of regolith materials as ∼3.6, consistent with that estimated from empirical functions of bulk density and regolith thickness (e.g., ρ = 1.92 z + 12.2 z + 18, where ρ is bulk density in g/cm³, z is thickness in m) (Carrier et al., 1991). Figure 4a shows that the two-way time delay of the regolith layer is about 140–150 ns. Then, the thickness of regolith layer is calculated to be ∼11.5–12.4 m along Yutu-2’s track. The time-to-depth conversion is marked in Figure 4a according to the derived relative permittivity, higher than the estimated results (2.5–7.5 m) based on crater morphology by Huang et al. (2018).
Furthermore, the relative permittivity of the subsurface layer (Layer 2) is estimated using a common hyperbolic fitting method (Supporting Information) (Jol, 2009). Three subsurface hyperbolic features are identified in subsurface layers, as marked in Figure 4a, give estimated relative permittivity of 4.0, 4.0, and 4.1, respectively. Therefore, the relative permittivity ($\varepsilon_{r,2}$) of the subsurface layer is assumed as 4.0, and then the loss tangent ($\tan \delta_1$) of the regolith layer is derived from each LPR trace as shown in Figure 6a. The average value and 1σ error are calculated within each segment as well (Figure 6b).

The results show that the loss tangent of the regolith layer at CE-4 landing region is constrained to be $(4.4 \pm 0.5) \times 10^{-3}$ at the frequency of $\sim 450$ MHz, consistent with $(5 \pm 2) \times 10^{-3}$ found by Li et al. (2020), higher than $\sim 1 \times 10^{-3}$ measured at the frequency of 450 MHz from Apollo 14 lunar samples (Gold et al., 1972), but lower than $\sim 0.01$ at CE-3 landing site (Dong et al., 2017). Note that the LPR data are wideband signals ($\sim 200$–700 MHz), so here the conductivity and loss tangent of regolith materials are estimated with a central frequency ($\sim 450$ MHz), which may cause potential uncertainty with respect to the dependence of the loss tangent and conductivity on frequency.

Similarly, the TiO$_2$ + FeO abundance of lunar regolith that estimated from each LPR trace by Equation 6 and the statistics within each segment are obtained as shown in Figure 7. The surface TiO$_2$ + FeO content at CE-4 landing region is constrained to be $11.6 \pm 1.1$ wt.%, in agreement with the range 11.4%–15.9% measured by Kaguya Multiband Imager (MI) (Ohtake et al., 2008), a little higher than $9 \pm 4$ wt.% or $11 \pm 4$ wt.% found by Li et al. (2020), lower than $\sim 23$ wt.%–30 wt.% at CE-3 landing site (Dong et al., 2017; Ling et al., 2015), which is expected given that CE-3 landed on basaltic lunar mare that should be high in ilmenite compared to predominantly anorthositic highlands material. It is consistent with that the higher loss tangent at CE-4 landing region than that at CE-3 landing site. Respectively, the variation of loss tangent ($\tan \delta_1$) and TiO$_2$ + FeO abundance in this layer of regolith materials are constrained within a range of $\sim 1.0 \times 10^{-3}$ and $\sim 1$% if the subsurface relative permittivity ($\varepsilon_{r,2}$) changes $\pm 0.1$.

### 4. Discussions

CE-4 LPR is an in-situ radar system working on the lunar surface, not like previous satellite-borne exploration systems. The heights of Channel-II antennas are approximately 30 cm, which indicates a radar cross section (RCS) less than $1 \times 1 \text{ m}$, according to its designed antenna beam angle (Fang et al., 2014). In
addition, Yutu-2 is inclined to choose potential direction and track with a tendency to be flat and smooth using the real-time data of Panorama Camera (PC) onboard the rover, so the Channel-II antenna almost keeps horizontally moving all the time. Therefore, only the small-sized (<1 m²) local roughness and slope or some large-sized surface objects, for example, boulders and pits under the rover, would affect the estimated results of the relative permittivity. Figures 8a and 8b show relatively flat and smooth lunar surface with no obvious rough terrain or large-sized rocks along Yutu-2’s track. As a result, we are inclined to attribute the varied estimated results of relative permittivity to the diversified dielectric properties of the regolith materials instead of the surrounding roughness.

**Figure 7.** Estimated ilmenite content of the regolith materials layer. (a) Calculated results of the TiO₂ + FeO content of regolith materials (Layer 1) for each trace along the track. (b) Statistics between each two waypoints as marked in Figure 1d. The spots indicate the mean values and the error bars indicate 1σ error.

**Figure 8.** Lunar surface images. (a) Lunar surface image with high resolution at Chang’E-4 (CE-4) landing site taken by the CE-4 Landing Camera. (b) Yutu-2’s track taken by the CE-4 Panorama Camera (PC). (c) The image of Chang’E-3 (CE-3) landing region taken by the CE-3 PC.
It can be seen from Figure 4a that CE-4 LPR Channel-II received clear radar echoes at the depths more than \(\sim 40\) m, greatly exceeding the lowest radar echoes from CE-3 LPR Channel-II data of \(\sim 10\) m (Xiao et al., 2015). The improved penetrating depth at CE-4 landing region suggests that local regolith materials are more transparent for electromagnetic waves, consistent with its lower loss tangent \((4.4 \pm 0.5) \times 10^{-2}\) than that \((\sim 0.01)\) of the CE-3 landing region. The radiowave attenuation of regolith materials depends primarily on the FeO + TiO\(_2\) abundance: The lower the abundance of ilmenite, the lower the loss tangent and radiowave attenuation rate are. This is also shown by the lower FeO + TiO\(_2\) abundance \((12.1 \pm 1.1\) wt.\%) at CE-4 landing region compared with that \((\sim 23\) wt.\%--30 wt.\%) at CE-3 landing site (Dong et al., 2017; Ling et al., 2015).

Additionally, the thickness \((\sim 12\) m) of the regolith materials at CE-4 landing site is much thicker than the average level in lunar maria which was estimated as \(4\sim 5\) m by Mckay et al. (1991), also much thicker than the thickness of \(\sim 1\) m at CE-3 landing region on the Mare Imbrium (Dong et al., 2017), consistent with the high maturity degree at CE-4 landing region. Figures 8b and 8c show the lunar surface images at CE-4 and CE-3 landing region, respectively, which were taken by Panorama Camera (PC) onboard the rovers. It can be seen that there are numerous surface rocks (up to meters-sized) that widely distributed at CE-3 landing region. Such immature local material deposition was produced by a Copernican crater named “Zi Wei” (diameter = \(\sim 420\) m) beside the CE-3 landing site (Figure 8c). The model age of the “Zi Wei” crater was constrained to be only \(\sim 27\sim 81\) Ma (Xiao et al., 2015), which leads to a thinner regolith layer of \(\sim 1\) m. On the contrary, there are seldom surface rocks at CE-4 landing region and the grain size of local regolith is fairly tiny (Figure 8b), which indicate a fine-weathered process and thus a thicker regolith layer was accumulated.

Moreover, the estimated thickness of local surface regolith can help to constrain the lunar regolith growth rate. Visible and Near Infrared Spectrometer (VNIS), another payload onboard Yutu-2, indicates that the uppermost materials at CE-4 landing site came from the Finsen crater (Li et al., 2019). In addition, higher albedo linear features on the mare basalt of the Von Kármán crater were observed to converge toward the Finsen crater, also indicating that the local surface material were excavated from Finsen crater (Huang et al., 2018). Therefore, the surface regolith at CE-4 landing site was probably weathered from the ejecta deposits from the Finsen crater. The age of the last basalt eruption of the Von Kármán crater was dated 3.15–3.6 Ga (Haruyama et al., 2009; Huang et al., 2018), which provides a key reference to constrain the formation age of local surface regolith.

The average regolith growth rate at CE-4 landing site was constrained as 1 cm per \(\sim 3\) million years, which is much less than that of 1 cm per \(\sim 0.6\sim 0.7\) million years at CE-3 landing site (Dong et al., 2017; Fa et al., 2015). It indicates that the growth rate of lunar weathered regolith successively declines over time, which proves the previous conjectures about the regolith growth rate: Carrier et al. (1991) supposed three models of regolith accumulation rate, which assumed linear and nonlinear impact flux models at Apollo 11 and 12 landing sites. Ishiyama et al. (2013) modified the model as the regolith accumulation rate decreases with time: 5 m/Ga in 4.0–3.5 Ga ago, 2 m/Ga in 3.5–3.0 Ga ago, and 1 m/Ga in 3.0–0 Ga ago, as shown in Figure 9.

In general, the obtained results of the accumulated thickness of lunar weathered regolith conform to the trend that proposed by Ishiyama et al. (2013). Our results suggest that the accumulated thickness of surface regolith materials tends to be a logarithmic function with time instead of linear relations such as the accumulated rate of 1.2 m/Ga estimated at the Apollo11 landing site (Melosh, 1989) or the accumulated rate of approximate 1 cm per 2–3 million years estimated by DiGiuseppe et al. (2009).

However, the regolith layer at CE-4 landing region is a little thinner than that constrained by the previous models (e.g., \(\sim 2.5\sim 7.5\) m by Huang et al., 2018). This is probably because the landing region is located on the farside of the Moon. Several factors affect the formation and weathering process of lunar regolith and the continuous impact of large and small meteoroids is the most significant one. As a result, the growth rate of lunar regolith on the Moon’s farside may well be higher than that on the nearside due to the more frequent meteorite impacts.

So far, no lunar materials have been sampled from the Moon’s farside; no detailed stratigraphy and properties of lunar regolith on the farside have been detected before, either. CE-4 LPR which directly works on the lunar surface is the most effective tool to detect the structure and properties of regolith materials on the farside at present. It is expected that more detailed and important information will be returned from CE-4.
LPR with its on-going detection. Our results also help the selection of landing site for future exploration missions such as China’s Chang’E-6 mission, a sample return mission to the lunar farside for the first time.

5. Conclusions

CE-4 LPR is the first surface radar system on the farside of the Moon. With the latest LPR data, we studied the structure and properties of lunar regolith at CE-4 landing region and draw the main conclusions as follows:

1. We processed the LPR Channel-II data and obtained a high-quality radargram with improved SNR. The surface echo and subsurface echoes can be clearly recognized in both the radargram and a trace of LPR data.
2. The thickness of lunar regolith at CE-4 landing region was constrained to be $\sim 11.5 \pm 12.4$ m along Yutu-2’s track. It is much thicker than that at CE-3 landing region on the Mare Imbrium and also thicker than the estimated average thickness in lunar maria.
3. The relative permittivity of surface regolith materials (<30 cm) at CE-4 landing region was identified to be $2.35 \pm 0.20$, which is lower than that at CE-3 landing site, consistent with the difference of grain size, exposed rocks, and maturity of lunar surface between CE-3 and CE-4 landing regions. The bulk density of surface regolith materials (<30 cm) at the landing region was estimated to be $1.31 \pm 0.20$ g/cm$^3$.
4. The loss tangent of the $\sim 12$ m-thick layer of regolith materials at CE-4 landing region was constrained to be $(4.4 \pm 0.5) \times 10^{-3}$ at the frequency of $\sim 450$ MHz, much lower than $\sim 0.01$ at CE-3 landing region, in accord with the greater penetrating depth of CE-4 LPR than that of CE-3 LPR.
5. The TiO$_2$ + FeO content of the $\sim 12$ m-thick layer of regolith materials at CE-4 landing region was constrained to be $11.6 \pm 1.1$ wt.%, lower than that at CE-3 landing region.
6. The growth rate of lunar weathered regolith successively declines over time and the accumulated thickness of lunar regolith tends to be a logarithmic function with time instead of linear relations. The growth rate of lunar regolith on the Moon’s farside may well be higher than that on the nearside due to the more frequent meteorite impacts.

Data Availability Statement

The data of CE-4 LPR Channel-II radargram in this paper are available in Dong (2021) properties of lunar regolith on the moon’s farside unveiled by Chang’E-4 lunar penetrating radar (Data set, Zenodo, http://doi.org/10.5281/zenodo.4724190). The source data for CE-4 LPR are available at Data Publishing and
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