Estimation of Bulk Permittivity of the Moon’s Surface Using Lunar Radar Sounder On-board Selenological and Engineering Explorer

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Abstract

Site-dependent bulk permittivities of the lunar uppermost media with thicknesses of tens to hundreds meters were estimated based on the data from Lunar Radar Sounder onboard the Selenological and Engineering Explorer (SELENE). It succeeded in sounding almost all over the Moon’s surface in a frequency range around 5 MHz to detect subsurface reflectors beneath several lunar maria. However, it is necessary to estimate the permittivity of the surface regolith of the Moon in order to determine the actual depths to those reflectors instead of apparent depths assuming a speed of light in the vacuum. In this study, we determined site-dependent bulk permittivities by two-layer models consisting of a surface regolith layer over a half-space with uniform but different physical properties from the layer above. Those models consider the electrical conductivity as well as the permittivity, whose trade-off was resolved by utilizing the correlation between iron-titanium content and measured physical properties of lunar rock samples. Distribution of the iron-titanium content on the Moon’s surface had already been derived by spectroscopic observation from SELENE as well.

Four lunar maria, Mare Serenitatis, Oceanus Procellarum, Mare Imbrium, and
Mare Crisium, were selected as regions of evident reflectors, where we estimated the following four physical properties of each layer, i.e., bulk permittivity, porosity, loss tangent and electrical conductivity to conclude the actual depths of the reflectors are approximately 200m on average. The bulk permittivity ranges from 2.96 at Mare Imbrium to 6.37 at Oceanus Procellarum, whereas the porosity takes the values between 1.8% to 41.1% in the respective maria. It was found that although the bulk permittivity of the four lunar maria differs from a mare to a mare, it shows a good correlation with their composition, viz., their iron-titanium content.

Keywords

Selenological and Engineering Explorer, frequency modulated continuous wave radar, bulk permittivity, loss tangent, subsurface reflectors

1. Introduction

The first exploration of the Moon’s subsurface structure was conducted by Apollo Lunar Sounder Experiment (ALSE; Porcello et al., 1974) aboard Apollo 17 launched in
1972. ALSE observed the reflected echoes of the radar transmitted from the mother
ship orbiting above the lunar equator. Objectives of ALSE were subsurface
exploration of the Moon and profiling/imaging of its surface. To achieve those, ALSE
was operated at a few frequency bands of 5, 15 and 150MHz with linearly increasing
frequency (chirp signals) so as to improve the penetration depth and the ranging
resolution. The largest penetration depth of approximately 1.3km was achieved by the
5MHz operation with an apparent resolution of 300m. However, both the depth and
the resolution are dependent on the permittivity inside the Moon. ALSE detected
horizontal reflectors at an apparent depth of about 1km beneath Mare Serentatis and
Mare Crisium (Peeples et al., 1978; Phillips et al., 1973a, b) by its limited observation
from several orbits.

Lunar Radar Sounder (LRS; Ono and Oya, 2000) is a Frequency Modulated
Continuous Wave radar equipped with SELenological and ENgineering Explorer
(SELENE; Kato et al., 2008) launched in 2007. Because it was the first Japanese
spacecraft to the Moon, it also has a Japanese name of KAGUYA coined after a
princess believed to live on the Moon. Like ALSE, LRS also aimed at subsurface
exploration of the Moon using high frequency chirp signals ranging from 4 through 6MHz. Major differences, however, from ALSE were its deeper penetration depth and finer resolution, which were 5km and 75m in vacuum and were much better than those of ALSE (Ono and Oya, 2000; Ono et al., 2008). Spatial coverage of SELENE was excellent in the sense that almost all of the Moon’s surface including the far side was covered by the sounder observation from SELENE’s polar orbits with an averaged altitude of 100km above the Moon’s surface. The total duration of the sounder observation summed up to as long as 100 days. As a result, Ono et al. (2009) reported presence of subsurface reflectors beneath several lunar maria. Apparent depths to those reflectors were a few hundreds of meters but we need to know the permittivity beneath the Moon’s surface for conversion of those values to the true depths. Furthermore, quantitative delineation of the Moon’s subsurface structure such as the true depths to the reflectors leads to understanding the origin and evolution of our Moon. It, therefore, is very important to analyze the LRS data of SELENE, which provided unprecedented radar sounding in terms of both quality and quantity. Another example of planetary radar sounding can be found in Mars. Mars
Advanced Radar for Subsurface and Ionosphere Sounding on-board Mars Express in 2003 detected presence and quantity of water ice accumulated in the Mars’s polar cap (Picardi et al., 2005; Plaut et al., 2007). Presence of water ice on Mars was further confirmed by Shallow Radar Sounder aboard Mars Reconnaissance Orbiter in 2005. Karlsson et al. (2015) found the water ice even in Mars’s mid-latitudes, while Holt et al. (2010) revealed a complex sedimentary structure beneath the Mars’s northern polar cap. These new findings are expected to elucidate the past Mars’s climate and/or traces of paleo-oceans on Mars.

On the other hand, JUpiter ICy moon Explorer (JUICE) by European Space Agency (ESA) is planned to launch in 2022. According to ESA (2014), Radar of Icy Moon Exploration aboard JUICE is going to conduct radar sounding of three icy Galilean satellites, i.e., Europa, Ganymede and Calisto so as to explore the subsurface structures, ice, water and their composition. Those sounding will be of great help for detecting subsurface oceans of those moons, which may constitute cradles for extraterrestrial lives.

Unlike the sample return missions, the past and future radar sounding from spacecraft illustrates efficiency, certainty and wide spatial coverage of planetary-scale
exploration by radar sounders. In order to improve applicability of radar sounding, the LRS data have been combined with model calculation of electromagnetic (EM) wave propagation (Ono et al., 2009; Bando et al., 2015) and data by laser altimetry to estimate the thickness of the regolith layer on top of the Moon as well as to improve the ranging resolution of LRS itself by application of data processing techniques originally developed for synthetic aperture radars (Kobayashi and Ono, 2007; Kobayashi et al., 2012).

Ono et al. (2009) argued the possibility of detection of the subsurface regolith layer sandwiched between basaltic layers above and below as reflectors. This is because the reflectors are detected at shallower depths than the thickness of the basaltic layers estimated by crater analyses in lunar maria (De Hon, 1979; Williams and Zuber, 1998). Oshigami et al. (2009) further claimed that the correlation between the surface age and detection rate of the reflectors means thicker regolith layers in older regions. Another correlation, which is negative though, between the detection rate and surface distribution of ilmenite suggests that metals such as titanium may prevent penetration of radar pulses to interfere the reflector detection (Pommerol et al., 2010;
Olhoeft and Strangway, 1975; Carrier et al., 1991; Shkuratov and Bondarenko, 2001). The composition of the Moon’s surface was revealed by spectroscopic studies of SELENE data. This means that not only the permittivity that determines the speed of light in the medium but also the loss tangent that is defined as the ratio of the conduction current to the displacement current and plays a role in attenuation of the radar pulses is important. Analyses of lunar rock samples strongly imply the correlation between the loss tangent and the iron-titanium content, whereas the permittivity does not show significant dependence on rock composition. It has, in turn, a strong correlation with rock density (Olhoeft and Strangway, 1975; Carrier et al., 1991; Shkuratov and Bondarenko, 2001). The different dependence of physical properties of the Moon’s surface suggests regional dependence of those properties, and thus implies necessity of determination of those properties from place to place. Porosity is another factor of consideration here. Effects of bulk porosity are inevitably included in the results of radar sounding in a form of bulk density. If we can also estimate porosity from our LRS data, it can be another important database, since Rust et al. (1999) pointed out that porosity is indicative of volcanism/tectonics of
Ishiyama et al. (2013) performed combined analyses of the delay of echoes from the subsurface reflectors and the depth of subsurface reflectors excavated at the impact craters based on data from LRS, Multiband Imager (MI) and Terrain Camera (TC) onboard the SELENE spacecraft, and determined the speed of the radar wave in uppermost layers in several maria. Based on the speed, they also estimated bulk permittivity and porosity. The estimated bulk permittivities were between 1.6 and 14.0 in Mare Serenitatis, and between 1.3 and 5.1 in Oceanus Procellarum. They also pointed out that the estimated porosity, up to about 80 %, was much larger than that of Apollo soil samples, and discussed possible contributions of intrinsic voids of lava and impact-induced cracks.

In this study, we aim for estimation of the relative permittivity of the Moon’s surface by comparison of echo intensities from the surface and subsurface reflector. We will approximate the Moon by two-layer models with different permittivities and electrical conductivities in each layer and determine those model parameters by calculation of EM wave propagation according to the radar range equation. In the
course of estimation, we newly introduce correlation between the electrical conductivity and the iron-titanium content to resolve the non-uniqueness appeared in previous studies. This study will also provide spatial dependence of the true depths to the detected reflectors, which may lead to better understanding of the Moon’s subsurface structures. Furthermore, those true depths can be applied to estimation of erupted lava volumes, which are useful in unraveling the Moon’s volcanism in the past. Finally, the estimated loss tangent and porosity contribute to the understandings of the Moon’s evolution and thermal history as well.

2. Data of Lunar Radar Sounder

A pair of mutually orthogonal 30m dipole antennas was used for LRS. The pulse width \( T \), sweep rate \( \dot{f} \) and output power \( P_t \) of the transmitted chirp signals were 200\( \mu \)s, 10kHz/\( \mu \)s and 800W, respectively. Each pulse was further shaped by a sinusoidal wave to minimize sidelobe effects at the time of Fast Fourier Transform (FFT) and is given by:

\[
V_{TX}(t) = V_{RX0} \sin \left( \frac{\pi \dot{f}}{2} \right) \sin \left( \int_0^t 2\pi (f_0 + \dot{f} t') dt' \right).
\] (1)
where $V_{TX0}$ is the amplitude of the transmitted pulse and $f_0 = 4$MHz.

In general, radars are associated with a trade-off between the penetration depth, which is a function of the output power, and the ranging resolution, which is a function of the pulse width. However, the pulse compression technique using chirp signals gives us a radar with a large output power and a narrow pulse width at the same time, which improves both the penetration depth and the ranging resolution. In the case of LRS, they are 5km and 75m in vacuum as mentioned before, but they are also dependent on both the permittivity and the loss tangent beneath the Moon’s surface.

The LRS operation throughout the mission was done by 20Hz transmission for 72 days, while it was operated with a transmission rate of 2.5Hz for the remaining 27 days. The LRS data are now open to the public at:

http://darts.isas.jaxa.jp/planet/pdap/selene/.

and all the data used in this study were downloaded from this Japan Aerospace Exploration Agency website.

2.1 A-scope Data
Received echoes of LRS are not original waveforms of the reflected echoes themselves but resampled waveforms multiplied by a local signal, which were further transferred to the Earth from the spacecraft. The observed data, therefore, are different from the original waveforms of the reflected echoes.

Specifically, let the original waveform be:

\[ V_{RX}(t) = V_{RX0} \sin \left( \frac{\pi (t - \tau_{RX})}{T} \right) \sin \left( \int_0^{t-\tau_{RX}} 2\pi(f_0 + \dot{f} t') dt' \right), \quad (2) \]

where \( V_{RX0} \) is the amplitude of the reflected echo and \( \tau_{RX} \) is a two-way travel time of the echo, by which the apparent depth to the reflector, \( d_A \), can be given by:

\[ d_A = \frac{c_0 \tau_{RX}}{2} \quad (3) \]

where \( c_0 \) is the speed of light in vacuum. In chirp radars, the received echoes are further mixed with an inherent local signal of the receiver typically given by the following formula:

\[ V_{LO}(t) = V_{LO0} \sin \left( \int_0^{t-\tau_{LO}} 2\pi(f_0 + \dot{f} t') dt' \right), \quad (4) \]

where \( V_{LO0} \) is the amplitude of the local signal and \( \tau_{LO} \) is the time of the mixing onset. The waveform after mixing becomes:

\[ V_{RX}(t)V_{LO}(t) = V_{RX0}V_{LO0} \sin \left( \frac{\pi (t - \tau_{RX})}{T} \right) \sin \left( \int_0^{t-\tau_{RX}} 2\pi(f_0 + \right) \]
\[ \int_0^{t-t_{LO}} 2\pi (f_0 + \dot{f} t') dt' \sin \left( \frac{\pi (t-t_{RX})}{T} \right) \sin \left[ 2\pi \left\{ f_0(t - \tau_{RX}) + \frac{1}{2} \dot{f}(t - \tau_{LO})^2 \right\} \right]. \] 

Using a formula for the trigonometric functions, Eq. (5) can be further modified into a sum of the high frequency part and the low frequency part as:

\[ V_{RX}(t)V_{LO}(t) = -\frac{1}{2} V_{RX0}V_{LO0}\sin \left( \frac{\pi (t-t_{RX})}{T} \right) \left( \cos \left[ 2\pi \left\{ f_0(2t - \tau_{RX} - \tau_{LO}) + \frac{1}{2} \dot{f}(2t^2 + \tau_{RX}^2 - 2(t \tau_{RX} + \tau_{LO})t + \tau_{LO}^2) \right\} \right] \right) - \cos \left[ 2\pi \left\{ \dot{f}(\tau_{RX} - \tau_{LO})t + f_0(\tau_{RX} - \tau_{LO}) - \frac{1}{2} \dot{f}(\tau_{RX}^2 - \tau_{LO}^2) \right\} \right]. \] 

Equation (6) is then low-pass filtered with a cut-off frequency of 2MHz to eliminate the first term in the right hand side (R.H.S.) and resampled for 2048 points with a sampling frequency of 6.25MHz. Figure 1 shows a sample plot of thus processed and transferred to the Earth.

Although filtered and resampled, the waveforms of the reflected echoes preserve the information of the two-way travel times in the form of frequency.

Namely, if one makes Fourier transforms of the echoes and finds specific frequencies, \( f_{IF} \)’s, for each peak reflection, then the following relation holds:

\[ f_{IF} = \dot{f}(\tau_{RX} - \tau_{LO}). \]
Equations (3) and (7) are combined to give:

\[ d_A = \frac{c_0 \tau_{RX}}{2} = \frac{c_0 \tau_{LO}}{2} + \frac{c_0 f_{IF}}{2f}. \]  

The first term on R.H.S. of Eq. (8) is called the ‘altitude origin for ranging’ and recorded in the LRS data together with the received waveform itself, the time stamp, the selenographic latitude/longitude and the spacecraft’s altitude. Figure 2(a) shows Fourier transforms of the reflected echo shown in Fig.1. Plots of this kind are called ‘A-scope’. In Fig. 2(b), three echoes are evident, one is from the Moon’s surface and the other two from the subsurface reflectors.

2.2 B-scan Data

B-scan is a sort of dynamic spectrum using A-scope with echo intensity in color, and is called ‘radargram’, a pseudo section of the Moon’s subsurface structure. Figure 3(a) shows a B-scan image over Mare Imbrium. The height of the steps seen on the Moon’s surface is approximately 75m, which is in good harmony with the ranging resolution of LRS in vacuum.

Reflected echoes do not always come from the nadir direction. If there is
significant undulation of the Moon’s surface, the subsurface reflectors are possibly
masked by strong reflected echoes on the surface. Figure 3(b) shows a typical
example of the surface echoes, which have clear parabolic shapes because the distance
between the spacecraft and the reflection points on the Moon’s surface can vary with
time as the spacecraft maneuvers along its orbit.

Taking running means on the B-scan images is known to give a better
protection against the surface echoes (Ono et al., 2010), provided that the subsurface
reflectors are horizontal. It is also desirable to compare the running means of adjacent
orbits so as to confirm the echoes coming from not ‘surface’ but ‘subsurface’. Figure
3(c) shows a B-scan image by taking a running mean of successive 21 raw B-scan
images (Ono et al., 2010). It is noteworthy that the continuity of the subsurface
reflectors is much clearer than Fig. 3(a).

3. Methods

3.1 Two-layer Model

Because the regions with two subsurface reflectors like the one shown in Fig. 3(c) were
very limited, we decided to model the majority of the LRS data by two layers, which the
transmitted waves entered normal to the surface. Figure 4 shows a schematic diagram
of the assumed model. Using the radar range equation (e.g., Phillips, 1973a), the
reflected powers, \( P_{rs} \) and \( P_{rss} \), are respectively given by;

\[
P_{rs}(\varepsilon_1) = \frac{P_t G^2 \lambda^2}{4(4\pi R)^2} r_{01}, \quad (9)
\]

and

\[
P_{rss}(\varepsilon_1, \varepsilon_2, \sigma_1) = \frac{P_t G^2 \lambda^2}{4[4\pi(R+R_D)]^2} e^{-2\omega R_D \tan\delta_1} t_{01} r_{12} t_{10}, \quad (10)
\]

where \( G, \lambda, \omega, \tan\delta_1, \) and \( R_D \) are the gain of the antenna, the wavelength and angular
frequency of the transmitted wave, the loss tangent of the first layer and the true
thickness of the first layer, respectively. \( c_1 \) is the speed of light in the first layer and
given by;

\[
c_1 = \frac{1}{\sqrt{\varepsilon_1 \mu_0}} = \frac{c_0}{\sqrt{\varepsilon_1}} \quad (11)
\]

where \( \varepsilon_0 \) and \( \mu_0 \) are the permittivity and magnetic permeability in vacuum, respectively.
The loss tangent in the first layer can be written by:

\[
\tan\delta_1 = \frac{\sigma_1}{\omega \varepsilon_0 \varepsilon_1}, \quad (12)
\]
as well. \( r_{ij} \) and \( t_{ij} (i, j = 0, 1, 2) \) denote the reflection and transmission coefficients at
each interface and satisfy the following relation according to the Fresnel equations:

\[ t_{01} = t_{10} = \frac{4\sqrt{\varepsilon_1}}{(1 + \sqrt{\varepsilon_1})^2}, \quad (13) \]

\[ r_{01} = \left( \frac{1 - \sqrt{\varepsilon_1}}{1 + \sqrt{\varepsilon_1}} \right)^2, \quad (14) \]

\[ r_{12} = \left( \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} \right)^2. \quad (15) \]

Equation (15) allows solutions of both \( \varepsilon_1 > \varepsilon_2 \) and \( \varepsilon_1 < \varepsilon_2 \). However, if one takes \( \varepsilon_1 > \varepsilon_2 \), it yields \( 1 < \varepsilon_2 < 2 \), which is incompatible with the results of the Moon rock analyses (e.g., Olhoeft and Strangway, 1975). It, therefore, is assumed \( \varepsilon_1 < \varepsilon_2 \) throughout this study.

### 3.2 Correlation among Physical Properties

The previous analyses of the lunar rock samples (Shkuratov and Bondarenko, 2001; Olhoeft and Strangway, 1975) revealed correlation among the physical properties of the rocks such as loss tangent, density, permittivity and iron-titanium content. In short, they are expressed by the following formulae:

\[ \tan \delta = 8.8 \times 10^{-4} e^{\frac{1-p}{2} \rho_{\text{grain}}(S) + 0.085S}, \quad (16) \]

\[ \rho_{\text{grain}}(S) = 0.0165S + 2.616, \quad (17) \]
\[ \varepsilon_{\text{grain}} = 1.919 \rho_{\text{grain}}, \]  

(18)

where \( S, p \) and \( \rho \) are the total content of titanium and iron [wt\%], porosity and density \([10^{-3} \text{ kg m}^{-3}]\), respectively. The subscript, grain, denotes the properties of the lunar return sample material itself. The porosity, therefore, is defined by:

\[ \rho_{\text{bulk}} = \rho_{\text{grain}}(1 - p). \]  

(19)

The bulk estimate of permittivity in the 1st layer, \( \varepsilon_1 \), should also be compared with \( \varepsilon_{\text{grain}} \).

3.3 Flow of Data Analysis

First, the following quantities are considered as constants: \( P_t = 800 \text{W}, \lambda = 0.06 \text{km} \) for the center frequency (5MHz) for a range of 4-6MHz and \( G = 1.64 \) from the theoretical value of the dipole antenna. It follows from Eqs. (9), (14) and observed \( P_{rs} \) that \( \varepsilon_1 \) can be determined. Equation (18) allows us to convert thus obtained \( \varepsilon_1 \) to \( \rho \).

Lawrence et al. (2002) analyzed the spectroscopic data by Lunar Prospector to yield 5\(^\circ\) by 5\(^\circ\) grid data of the surface content of iron and titanium as:

http://pds-geosciences.wustl.edu/lunar/lp\-1\-grs\-5\-elem\-abundance\-v1/lp_9001/data/lpgrs_high1_elem_abundance_5deg.tab
Substitution of the above iron and titanium contents (S) into Eq. (17) gives $\rho_{\text{grain}}$.

Once $\rho$ and $\rho_{\text{grain}}$ are known, the porosity, $p$, can be estimated using Eq. (19). The remaining model parameters, $\sigma_1$ and $\varepsilon_2$, can be determined using Eqs. (10), (12) and (16) in addition to observed $P_{\text{rss}}$ as shown as shown in the flow chart (Fig. 5).

In this analysis, we need absolute values of the echo powers in unit of W. They are determined based on the prelaunch calibration of the LRS's receiver. Of course, it was not confirmed by the end-to-end calibration including extended antenna and spacecraft because such test was quite difficult to perform on the ground. So, we roughly check validity of the absolute calibration of the echo powers used in this study by comparison between bulk permittivities estimated in Ishiyama et al. (2013) and those in this study (see Section 5.1).

4. Results

4.1 Analyzed Regions

We analyzed four lunar maria, viz., Mare Serenitatis, Oceanus Procellarum, Mare Imbrium, and Mare Crisium. This is partly because clear subsurface reflectors were
recognized by radargrams of several adjacent orbits in those lunar maria, and partly because it is difficult to completely eliminate the effect of surface echoes, which are especially intense in the highland areas of the Moon. Figure 6 shows the four target regions of this study. Note that the values described in this section are mainly field estimates, namely, bulk properties and not those of laboratory (i.e., grain) estimates in most cases.

### 4.2 Estimated Physical Properties of All Maria

Because reflected echoes from the Moon’s surface were observed everywhere, the bulk permittivity of the first layer, $\varepsilon_1$, was estimated using Eq. (9) every 371 shots, which were approximately equivalent to one selenographic latitude. $\varepsilon_{\text{grain}}$ was estimated using Eqs. (17) and the iron-titanium content of this region by Lawrence et al. (2002).

Unlike the surface echoes, the subsurface echoes were not always detected. To circumvent this, 21 stacks of A-scope were taken using the surface echo as a reference. Figure 7 shows an example of the stacked A-scope. Using those stacked echoes, estimates of $\varepsilon_2$ were obtained in the respective latitudinal ranges using the previously estimated $\varepsilon_1$ and Eq. (10).
Radargrams of all regions are shown in Figs. 8, 10, 12 and 15, while estimates of $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_{\text{grain}}$ are plotted in Figs. 9, 11, 13 and 15 for all lunar maria. Table 1 shows estimated porosity (%), loss tangent, electrical conductivity (S/m) in addition to the derived relative permittivities. The Fe + Ti content, $S$ (wt%), tabulated in Table 1 was used to estimate $\varepsilon_{\text{grain}}$. The table also includes the averaged apparent depths (m) as well as the calculated actual depths (m), and the number of identified subsurface echoes.

In Mare Serenitatis and Oceanus Procellarum, the derived ranges of $\varepsilon_1$ (1.6 ~ 14.0 and 1.3 ~ 5.1) are almost compatible with those reported by Ishiyama et al. (2013).

### 4.3 Summary of Data Analyses

All results described in this section are summarized in Table 1 along with estimated ages of the lunar maria determined by crater density (Hiesinger et al., 2000; 2003; 2011). Values of the bulk permittivity show correlation with $S$. Table 1 also shows that each tabulated value has small spatial variation in the latitude difference of $5^\circ$ to $10^\circ$. Figure 16 was created from Table 1 using values of $\varepsilon_1$ and their 95 % confidence intervals shown in Figs. 9, 11, 13, and 15. Table 1 shows a clear positive correlation of
the bulk permittivity, $\varepsilon_1$, derived in this study with the reported Fe and Ti content, $S$

(Lawrence et al., 2002). The bulk permittivity can be expressed by $\varepsilon_1 = 0.297S + 0.0107$ with a correlation coefficient of $R^2 = 0.881$.

5. Discussion

5.1 Validity of Applied Methods

Because many of A-scope data showed peaks of a single subsurface reflector that can be identified on adjacent orbits as well, it is reasonable to assume two-layer models for the LRS data. However, the analyzed results show that there are several regions of anomalously large errors for bulk permittivity. It is very difficult to consider those errors due to actual spatial variations of $\varepsilon_1$ and $\varepsilon_2$. It can be rather interpreted as a result of scattering of surface echoes by rugged topography. The radargrams over the large error regions suggest that those regions are characterized by combinations of intense and weak echoes. In this study, relatively flat regions were selected to yield radargrams by taking running means for better protection against rugged topography. However, the results showed that it is not sufficient for all regions. It, therefore, will
be desirable to do more accurate numerical simulations of EM wave propagation by incorporating known topography on the Moon’s surface, to estimate more precise bulk permittivity over broader regions in the future. As confirmed in Subsections 4.2 and 4.3, the bulk permittivities derived in Mare Serenitatis and Oceanus Procellarum in this study were almost in the range reported in Ishiyama et al. (2013).

5.2 Bulk Permittivity

The derived bulk permittivity of the lunar uppermost layer was in a range from 2.96 (at Mare Imbrium) to 6.37 (at Oceanus Procellarum), which supports the actual depth to the reflectors in those maria to be around 200 m. Olhoeft and Strangway (1975), and Carrier et al. (1991) reported that the bulk permittivity of the Moon rock samples shows values ranging from 1.1 to 11, majority of which falls between 4 and 9. However, this study yields somewhat smaller bulk permittivity not only in Mare Serenitatis and Oceanus Procellarum, which was already reported by Ishiyama et al. (2013), but also in Mare Imbrium and Mare Crisium. This can be partly attributed to the effect of porosity as discussed by Ishiyama et al. (2013)
but also explained by the effect of composition, i.e., iron-titanium content.

Olhoeft and Strangway (1975) showed that the bulk permittivity is primarily a strong function of bulk density. This means that the bulk permittivity depends on not only how porous the medium in concern is, but also how dense and dielectric the rest of the medium other than cavity is. Titanium bearing minerals such as ilmenite is typical of those that have both large density and high permittivity. The good correlation between the bulk permittivity derived in this study and the known FeO + TiO₂ content of the lunar maria surface shown in Fig. 16 can be regarded as possible presence of enriched titanium bearing minerals in each lunar mare such as Mare Imbrium.

The analysis method used in this study enabled us to derive bulk permittivity and porosity in wide area of multiple maria. A new suggestion brought by the comparison of porosity in multiple maria in this study will be described in the next subsection. The estimates of \( \varepsilon_2 \) showed larger shot-by-shot scatter than \( \varepsilon_1 \). It was assumed throughout this study that \( \varepsilon_1 < \varepsilon_2 \) in applying the two-layer models. However, its validity for multiple layer models should be examined in the future.
5.3 Porosity

Based on the bulk permittivity from 2.96 to 6.37, the porosity takes the values between 1.8% to 41.1%. Porosity of the Moon rock samples is less than 10% in most cases, and hence samples with porosity larger than 20% are rare (Olhoeft and Strangway, 1975). However, this study yielded larger porosity, which possibly represents macroscopic (bulk) porosity rather than microscopic as was pointed out by Ishiyama et al. (2013).

Sizes of the Moon rock samples are of the order of centimeter, while the spatial resolution of LRS is at most a few tens of meters. This means that the LRS data are subject to effects of large-scale cracks. Hence, the large bulk porosity may be due to cracks by degassing at the time of volcanic eruptions, by quenching of lavas or by meteorite impacts. However, it turned out that porosity shows a weak negative correlation with formation ages of lunar maria (see Fig. 17). This may reflect effects of volcanic eruptions rather than those of meteorite impacts, because repeated meteorite impacts might have cultivated the Moon’s surface well enough to give a ‘positive’ correlation with formation age.
5.4 Loss Tangent

The estimated range of loss tangent was \(5.3 \times 10^{-3} - 1.53 \times 10^{-2}\) in this study. Olhoeft and Strangway (1975) derived a range of \(7.53 \times 10^{-3} - 1.92 \times 10^{-2}\) at \((\text{Fe + Ti wt\%}) = 15\) by their laboratory experiments of the Moon rock samples. The smaller loss tangent range of this study may also be attributed to the macroscopic porosity. Substitution of \((\text{Fe + Ti wt\%}) = 15\) into Eqs. (16) and (17) yields a width of \(4.6 \times 10^{-3}\) for the loss tangent range, if porosity is changed from 0% through 30%. If the observed loss tangent is corrected by this range width, the two ranges, i.e., the field and laboratory ranges, agree very well. Furthermore, Bando et al. (2015) investigated the ratio between the powers of echoes from subsurface reflectors at different depths measured by LRS to yield a loss tangent range of \(1.07 \times 10^{-2} - 1.13 \times 10^{-2}\), which corresponds to the median value of the observed loss tangent by this study. It, therefore, can be concluded that the loss tangent by this study may reflect the true loss tangent near the lunar surface (10 ~ 100m spatial scale) with possible variations produced by macroscopic porosity.
6. Conclusions

Assuming incident EM waves from LRS being normal to the horizontally stratified two-layer models, bulk permittivity, porosity and loss tangent near the lunar surface were estimated using the observed LRS data by calculating EM wave propagation according to the radar range equation. Combined use of the estimated FeO + TiO$_2$ content distribution by spectroscopy of the lunar surface (Lawrence et al., 2002) and the empirical relations among physical quantities in concern derived from analyses of the Moon rock samples (Shkuratov and Bondarenko, 2001; Olhoeft and Strangway, 1975) enabled unique determination of otherwise degenerated physical quantities. The results are summarized in Table 1, in which all the analyzed regions, viz., Mare Imbrium, Oceanus Procellarum, Mare Crisium and Mare Serenitatis, are included. It is obvious by the table that the actual depth to the subsurface reflectors of the Moon is around 200m except for Mare Crisium and one part of Mare Serenitatis. The estimates of each physical quantity do not change much within a latitudinal difference of 5° to 10°, whereas bulk permittivity shows a positive correlation with FeO + TiO$_2$ content. Since porosity, in turn, shows a weak negative correlation
with formation ages of lunar maria (see Fig. 17), it may reflect effects of volcanic eruptions rather than those of meteorite impacts. Finally, Table 1 will make a good reference for future studies, because discrepancy between the field and laboratory estimates is turned out to be reconciled by the effect of porosity.

**Declarations**

**List of abbreviations**

- ALSE: Apollo Lunar Sounder Experiment
- EM: electromagnetic
- ESA: European Space Agency
- JUICE: JUpiter ICy moon Explorer
- LRS: Lunar Radar Sounder
- RIME: Radar of Icy Moon Exploration
- SELENE: SELenological and ENgineering Explorer

**Availability of data and materials**

The datasets used and/or analyzed during the current study are available
from the following links:

The LRS data:

http://l2db.selene.darts.isas.jaxa.jp/

The Fe and Ti content distribution:

http://www.mapaplanet.org/data_local/Lunar_Prospector/lp_fe_5d.asc

http://www.mapaplanet.org/data_local/Lunar_Prospector/lp_ti_5d.asc

Competing interests

The authors declare that they have no competing interests.

Funding

This work was partly supported by JSPS KAKENHI Grant Number JP25420402.

Authors’ contributions

KH carried out data processing, modelling and figure and table drawings.

HT supervised KH throughout this study to achieve a master degree, and converted his master thesis in Japanese to the draft manuscript in English. AK guided the data processing and modelling by providing
raw time-series of reflected echoes together with their metadata and
necessary information for modelling/interpretation. All authors read
and approved the final manuscript.

Acknowledgements

We are indebted to Professors A. Yamaji at Graduate School of Science,
Kyoto University and M. Yamamoto at Research Institute for Sustainable
Humanosphere, Kyoto University for their help that was indispensable to
complete this work.

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Figure legends

Figure 1 An example of received waveforms. This 327.68µs long time-series of a
reflected echo was received at 00:57:15.181 UTC on May 4, 2008 when SELENE
was flying over Mare Imbrium, i.e., (40.226N°, 345.304E°) in the selenographic
coordinate. It is filtered and resampled as described in the text.

Figure 2 (a) A-scope of the reflected echo of Fig. 1. We used the 2nd term of Eq. (8)
for x-axis instead of $d_A$. (b) A zoom-in plot of Fig. 2(a). The first three
reflections including the Moon’s surface are clearly seen.

Figure 3 (a) B-scan over Mare Imbrium at the selenographic longitude of 345.3E°.

The origin of the apparent depth is taken at the Moon’s surface assuming the averaged radius of the Moon to be 1737.4km.  (b) Another B-scan image at the selenographic longitude of 345.0E°.  Several strong echoes of parabolic shape are due to craters nearby.  (c) Taking running means highlighted the subsurface reflectors especially for those starting from the horizontal black arrows, which continue to ~42N°.

Figure 4 The two-layer model adopted by this study.  SELENE transmitted a radar pulse every 0.05 (or 0.4) second with an output power of $P_1 \, [W]$.  The surface and subsurface reflection are $P_{rs} \, [W]$ and $P_{rss} \, [W]$, respectively.  $R \, [m]$ and $R_D \, [m]$ are respectively the altitude of the spacecraft and the apparent depth to the subsurface reflector.  Both relative magnetic permeability $\mu$ and permittivity $\varepsilon$ between SELENE and the Moon’s surface are assumed to be unity, while those of the 1st layer are unity and $\varepsilon_1$.  The electrical conductivity of the 1st layer is $\sigma_1$, and the bulk permittivity of the 2nd layer is $\varepsilon_2$. 
Figure 5 The flow chart of data analysis of this study. $\rho$, $p$ and $\delta_1$ denote density, porosity and loss tangent of the 1st layer, respectively, while subscript “grain” indicates laboratory estimates. As for $\varepsilon_1$, $\sigma_1$ and $\varepsilon_2$, refer to the caption of Fig. 4.

Figure 6 The topographic map of the northern hemisphere on the far side of the Moon. The base map was downloaded from Geospatial Information Authority of Japan (http://gisstar.gsi.go.jp/selene/Maps/Stereo_En-800.tif.zip), which is jointly operated by National Astronomical Observatory of Japan and Japan Aerospace Exploration Agency. The four red ellipses denote the location of the target areas of this study.

Figure 7 The stacked A-scope. $P_{rss}$ indicates the location of the subsurface echo.

Figure 8 Radargrams of Mare Serenitatis for (a) 20 – 25°N and (b) 25 – 30°N.

Figure 9 Estimates of $\varepsilon_1$ (red), $\varepsilon_2$ (blue) and $\varepsilon_{grain}$ of Mare Serenitatis for (a) 20 – 25°N and (b) 25 – 30°N. The regional representatives of $\varepsilon_{grain} = 6.49$ (for 20 – 25°N) and 6.39 (for 25 – 30°N) are shown by horizontal green lines. The vertical error bars for $\varepsilon_1$ and $\varepsilon_2$ show 95% confidence intervals, while horizontal error bars denote their spatial extent.
Figure 10 Radargrams of Oceanus Procellarum for (a) 40 – 45°N and (b) 45 – 50°N.

Figure 11 Estimates of $\varepsilon_1$ (red), $\varepsilon_2$ (blue) and $\varepsilon_{\text{grain}}$ of Oceanus Procellarum for (a) 40 – 45°N and (b) 45 – 50°N. The regional representatives, i.e., $\varepsilon_{\text{grain}} = 6.41$ (for 40 – 45°N) and 6.29 (for 45 – 50°N) are shown by horizontal green lines. The vertical error bars for $\varepsilon_1$ and $\varepsilon_2$ show 95% confidence intervals, while horizontal error bars denote their spatial extent.

Figure 12 Radargrams of Mare Imbrium for (a) 35 – 40°N and (b) 40 – 45°N.

Figure 13 Estimates of $\varepsilon_1$ (red), $\varepsilon_2$ (blue) and $\varepsilon_{\text{grain}}$ of Mare Imbrium for (a) 35 – 40°N and (b) 40 – 45°N. $\varepsilon_{\text{grain}} = 6.60$ (for 35 – 40°N) and 6.56 (for 40 – 45°N) are values representative of this region, while $\varepsilon_1$’s are latitudinal averages. The vertical error bars for $\varepsilon_1$ and $\varepsilon_2$ show 95% confidence intervals, while horizontal error bars denote their spatial extent.

Figure 14 Radargrams of Mare Crisium for (a) 10 – 15°N and (b) 15 – 20°N.

Figure 15 Estimates of $\varepsilon_1$ (red), $\varepsilon_2$ (blue) and $\varepsilon_{\text{grain}}$ of Mare Crisium for (a) 10 – 15°N and (b) 15 – 20°N. The regional representatives of $\varepsilon_{\text{grain}} = 6.17$ (for 10 – 15°N)
and 6.29 (for 15 – 20°N) are shown by horizontal green lines. The vertical error bars for $\varepsilon_1$ and $\varepsilon_2$ show 95% confidence intervals, while horizontal error bars denote their spatial extent.

Figure 16 Correlation between the bulk permittivity of the 1st layer, $\varepsilon_1$, and the surface metal content in lunar maria under study. A regression line is also drawn in red.

Figure 17 Correlation between the bulk porosity of the 1st layer, $\rho$, and the formation age of each lunar mare.