ESTIMATION OF THE PERMITTIVITY AND POROSITY OF THE LUNAR UPPERMOST BASALT LAYER BASED ON THE OBSERVATION DATA OF THE SELENE SPACECRAFT
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Introduction: Permittivity is an important parameter for understanding the results obtained by various radar observations. In the Moon, radar observations were performed by using Apollo Lunar Radar Experiment (ALSE) onboard Apollo 17 and Lunar Radar Sounder (LRS) onboard the SELENE (KAGUYA) spacecraft. LRS emitted the electromagnetic wave (4 – 6 MHz), and measured the delay (Δt) between the electromagnetic waves reflected at a lunar surface and at lunar subsurface boundaries. Thus, LRS could obtain the apparent radar depth (D) between the surface and subsurface boundaries by $D = c \cdot \Delta t / 2$, where c is the speed of light in vacuum. This depth does not indicate actual depth between the surface and subsurface boundaries. The actual depth can be given as $c \cdot \Delta t / (2\sqrt{\epsilon_{bulk}})$, where ϵ_{bulk} is the bulk permittivity of a subsurface material. The "bulk" means that a pore-space in a material is considered in the measurement of the permittivity. We must know the bulk permittivity of the lunar rocks to calculate the actual depth.

The values of the bulk permittivity obtained from Apollo basalt samples were from 4.17 to 11.00 [2]. The wide range of the bulk permittivity is caused by the abundance of FeO and TiO2, and porosity [3]. We can consider that the lunar subsurface layer has various voids sources, such as the intrinsic voids (vesicles and micro cracks) [4], the impact-induced cracks (micro and macro cracks) [5], lava tubes [6], and the surface and buried regolith layers [2]. Apollo samples don't have some large-scale voids (e.g., macro cracks and lava tubes), so that we cannot easily use the permittivity obtained from Apollo basalt samples. In this study, a new estimation method of the bulk permittivity of the uppermost basalt layer is developed. Moreover, the porosity is also estimated from the estimated bulk permittivity in order to discuss the lunar geological conditions.

Estimation of the bulk permittivity: The bulk permittivity of the uppermost basalt layer (ϵ_{bulk}) is given as

$$\epsilon_{bulk} = \left(\frac{D}{d}\right)^2. \qquad (1)$$

d is the thickness of the uppermost basalt layer (Fig. 1), which is constrained from the depths of two types of impact craters (d_{non} and d_h): non-haloed crater and haloed crater [7]. The haloed crater has different ejecta composition (FeO and TiO2) from the average composition (FeO and TiO2) of the lava flow unit surrounding the crater. On the other hand, the non-haloed crater has the same ejecta composition (FeO and TiO2) as the average composition (FeO and TiO2) of the surrounding lava flow unit. For discrimination of two types of craters by the ejecta composition, we use the FeO and TiO2 maps created by the data from Multiband Imager (MI) onboard SELENE [8]. . d_{non} and d_h are measured by using Digital Terrain Map based on SELENE Terrain Camera data (TC/DTM) , in which the height resolution is < 20 m when the height of spacecraft is 100 km [9]. D is obtained from the Synthetic Aperture Radar (SAR) processed LRS data [10]. The range resolution of LRS is 75 m in vacuum [11]. In this study, the error of d_{non} and d_h is assumed as +/- 20 m, and the error of D is assumed as +/- 75 m. The minimum and maximum bulk permittivities ($\epsilon_{bulk,min}$ and $\epsilon_{bulk,max}$) are calculated by the following equations, which are given by substituting d_{non} and d_h into Eq. 1: $\epsilon_{bulk,min} = (D/d_h)^2$ and $\epsilon_{bulk,max} = (D/d_{non})^2$.

We assume (1) a horizontal boundary between uppermost basalt layer and lower basalt layer, and assume (2) that the dielectric contrast seen in the radar data corresponds to the mineral contrast seen in multi-band images (Fig. 1). As for the assumption (1) , the horizontal distance between the haloed and non-haloed craters must be short. If the subsurface boundary is oblique and the distance between the haloed and non-haloed craters is long, the thickness of the uppermost basalt layer cannot be determined correctly. In this study, the distance between the haloed and non-haloed craters is limited as short as possible. We use datasets of the haloed craters, non-haloed craters, and the LRS nadir points within a distance of 6km.

Estimation of the porosity: The porosity (P) of the uppermost basalt layer is calculated by [3]:

$$P = 1 - \frac{1}{0.85 \cdot \rho_{grain}} ln\left(\frac{\epsilon_{bulk}}{0.74}\right) \qquad (2)$$

where the grain density of the lunar basalt is given by $\rho_{grain} = 0.0273 FeO + 0.0110 TiO_2 + 2.773$ [12]. The mineral composition (TiO_2 and FeO) is based on the ejecta composition (TiO_2 and FeO) of the deepest non-haloed crater, which constrains a maximum value of the bulk permittivity. The ejecta composition of deepest non-haloed crater can give an average composition of the uppermost basalt layer (see Fig. 1). The minimum and maximum porosities are calculated by substituting the minimum and maximum bulk permittivities into the above equation. The error of these porosities is calculated from the errors of d_{non}, d_h, and D.

Result: We analyzed all mare regions, but we could obtain the bulk permittivity only in Unit 85 of Mare Humorum [13] and Unit S13 of Mare Serenitatis [14] because we couldn't find favorable combinations of the haloed craters, non-haloed craters, and subsurface radar echoes in other lava flow units. In Unit 85 of Mare Humorum, the depths of the non-haloed and haloed craters (d_h and d_{non}) were respectively 243 ± 20 m and 331 ± 20 m, and the apparent radar depth (D) is 500 ± 75 m. Using Eq. 1, the bulk permittivity is estimated to be $2.3^{+1.1}_{-0.8} - 4.2^{+2.4}_{-1.6}$. Based on them, the porosity of $36^{+18}_{-16} - 58^{+16}_{-14}$ % is estimated using Eq. 2. Likewise, the bulk permittivity in Unit S13 of Mare Serenitatis is estimated to be $1.8^{+1.0}_{-0.7} - 13.1^{+10.6}_{-5.9}$. Based on them the porosity of $-3^{+21}_{-22} - 68^{+18}_{-16}$ % is estimated. The estimated porosity less than 0 is due to including the shallowest non-haloed crater in the analysis.

Discussion and Conclusions: The estimated permittivity is $2.3 - 4.2$ in Unit 85 of Mare Humorum and $1.8 - 13.1$ in Unit S13 of Mare Serenitatis. The estimated porosity of Unit 85 of Mare Humorum is limited within a range of $36 - 58$ %. Apollo samples have a porosity of ~7 % on average, which is formed by the vesicles and micro cracks [15]. The rest porosity (> 29 %) can be explained by other void sources: macro cracks [5], lava tubes [6], and regolith layers [2]. However, regolith layers may hardly contribute to the estimated porosity because the thickness of regolith layers (a few meters) is much thinner than that of the uppermost basalt layer (a few hundred meters). In addition, the lunar pits, implying the existence of lava tubes, have not been found in the analyzed areas [16], so that the lava tubes may not exist in the analyzed units. Therefore, we can confirm the existence of the voids of macro cracks that are not contained in Apollo samples. The average abundances of macro cracks is roughly estimated to be $> \sim 29$ %.

As mentioned above, our method to estimate the bulk permittivity enables us to investigate the lunar geological conditions up to depths of a few hundred meters for the first time. This method should be applied and proved also in the investigation of near-surface geological conditions of other planets, satellites, and asteroids in future.
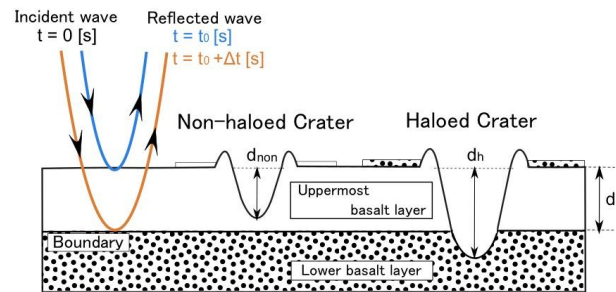

Fig. 1. Schematic cross-section of a lunar simple geological structure model. An uppermost basalt layer overlies a lower basalt layer. The different shading (stippled and clear) indicates the different bulk permittivities, or chemical compositions and porosity of each layer. The range of the thickness of the uppermost basalt layer (d) is determined by the depths of a shallowest haloed crater and a deepest non-haloed crater (d_h and d_{non}).

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