ESTIMATION OF THE BULK PERMITTIVITY AND POROSITY OF THE LUNAR UPPERMOST MARE BASALT BASED ON THE SELENE OBSERVATION DATA. K. Ishiyama[1], A. Kumamoto[1], T. Ono[1], Y. Yamaguchi[2], J. Haruyama[3], M. Ohtake[3], Y. Katoh[1], N. Terada[1], and S. Oshigami[4], [1]Graduate School of Science, Tohoku University, [2]Graduate School of Environmental Studies, Nagoya University, [3]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, [4]National Astronomical Observatory of Japan (Aramaki Aza-Aoba, Aoba-ku, Sendai 980-8578, Japan. E-mail: ishiyama@stpp.gp.tohoku.ac.jp)

Introduction: Investigating the subsurface bulk permittivity is significant for the planetary radar observation. Lunar Radar Sounder (LRS) onboard the SELENE (KAGUYA) spacecraft emitted the frequency-modulated electromagnetic wave (4 – 6 MHz), and measured the delay time (Δt) between the electromagnetic waves reflected at the lunar surface and subsurface boundaries. Therefore, LRS can measure the thickness of the uppermost basalt layer ($d = c \cdot \Delta t / \left(2\sqrt{\epsilon_{bulk}}\right)$) [1], where *c* is the speed of light in vacuum, and ϵ_{bulk} is the bulk permittivity of the uppermost basalt layer. The information of the thicknesses of the subsurface layers is important for understanding the evolution of the lunar volcanic activity [e.g., 2]. However, in order to determine the thickness, we must know not only the delay time but also the bulk permittivity of the uppermost basalt layer. Because the bulk permittivity values of Apollo basalt samples are from 4 to 11 [3], bulk permittivity values of 8 – 9 were often assumed in the previous lunar radar observations [e.g., 4, 5]. In our previous study [6], we have performed the estimation of the bulk permittivities of the uppermost basalt layer in two lava units of Mare Serenitatis and Mare Humorum (Unit S13 [7] and Unit 85 [8]). The bulk permittivity in Unit 85 of Mare Humorum was estimated to be smaller than ~8. In Unit S13 of Mare Serenitatis, however, we could not obtain the sufficiently small upper limit of the bulk permittivity. In this study, we estimate the bulk permittivity in three lava units of Mare Serenitatis and Oceanus Procellarum (Unit S15, S28 [7], and Unit P10 [9]) using the method used in the previous study [6].

In addition, the porosity of the uppermost basalt layer is also estimated from the estimated bulk permittivity. Based on the both results of the previous study [6] and this study, we can make more reliable evaluation of the porosity source of the uppermost basalt layers. This information will be important for discussing the frailty of the uppermost basalt layer and the lunar thermal history.

Estimation method of the bulk permittivity: The method for estimating the bulk permittivity of the uppermost basalt layer (ϵ_{bulk}) is based on the previous study [6]. The bulk permittivity is estimated from

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

The apparent radar depth (d_{radar}) is defined as $c \cdot \Delta t/2$, and d is the thickness of the uppermost basalt layer. In order to constrain this thickness, we consider a lunar subsurface model (Fig. 1) [6]. This model is composed of two layers: uppermost basalt layer and the underlying basalt layer. These layers have a different composition (FeO and TiO_2). The uppermost basalt layer has a few hundred meters in thickness, and is formed from some thin lava flows. The thin regolith layer is deposited on the uppermost basalt layer and the underlying basalt layer. Since the lunar regolith (i.e., soil) has a high porosity, its bulk permittivity is smaller than that of rock. The thickness of the regolith layer is enough thin that it cannot be resolved by LRS whose range resolution is 75 m in vacuum [1].

d is constrained from the excavated depths of two types of impact craters (d_{non} and d_h): non-haloed crater and haloed craters. The haloed crater has ejecta whose FeO and TiO_2 abundances are different from those of the uppermost basalt layer (Fig. 1). On the other hand, the non-haloed crater has ejecta whose FeO and TiO_2 abundances are the same with those of the uppermost basalt layer. We discriminate the crater types using the FeO and TiO_2 maps produced from the SELENE Multiband Imager (MI) data [10]. d_{non} and d_h are calculated from the diameter (D) of the crater [11]: $d_{non\ or\ h} = 0.1 \times 0.84 \times D$. The diameter is measured from Digital Terrain Map (DTM), which is produced from Terrain Camera (TC) onboard SELENE [12]. The height resolution of TC/DTM is less than 20 m when the height of spacecraft is 100 km [12]. d_{radar} is obtained from the Synthetic Aperture Radar (SAR) produced from LRS data [13]. The minimum and maximum bulk permittivities ($\epsilon_{bulk,min}$ and $\epsilon_{bulk,max}$) are given by substituting d_h and d_{non} into Eq. (1): $\epsilon_{bulk,min} = (d_{radar}/d_h)^2$ and $\epsilon_{bulk,max} = (d_{radar}/d_{non})^2$.

Estimation of the porosity: The porosity (ϕ) of the uppermost basalt layer is calculated from [6]:

$$\phi = 1 - \frac{1}{\rho_{grain}} ln\left(\frac{\epsilon_{bulk}}{1.919}\right), \quad (2)$$

where the grain density (ρ_{grain}) of the uppermost basalt is given by $\rho_{grain}\ [g \cdot cm^{-3}] = 0.0273\,FeO + 0.0110\,TiO_2 + 2.773$ [14]. The grain density indicates the density of the uppermost basalt layer without any pore space. In order to determine the grain density, we use TiO_2 and FeO abundances of the ejecta of the deepest non-haloed crater, which constrains a maximum value of the bulk permittivity. The minimum and maximum porosities are calculated by substituting the minimum and maximum bulk permittivities into Eq. (2).

Results: We estimated the bulk permittivities in Unit S15 and S28 of Mare Serenitatis, and Unit P10 of Oceanus Procellarum. The results are summarized in Table 1. In Unit S15 of Mare Serenitatis, the depths of the non-haloed and haloed craters (d_h and d_{non}) are respectively 144 m and 279 m, and the apparent radar depth (d_{radar}) is 380 m. Thus, the bulk permittivity is estimated to be 1.9–7.0 from Eq. (1), and the porosity is estimated to be 9%–71% from Eq. (2). Likewise, the bulk permittivities in Unit S 28 and Unit P10 are estimated to be respectively 1.6–14.0 and 1.3–5.1. Based on them, the porosities are estimated to be 0%–78% in Unit S28 and 21%–86% in Unit P10.

Discussion and Conclusions: The estimated bulk permittivity is consistent with the result of the previous study [6]. If the uppermost basalt layer has a homogeneous bulk permittivity, the bulk permittivity is limited to be 4.2–5.1, and then the porosity is also limited to be 21%–33%. This porosity would be formed from three porosity sources: the volcanic ash [15], the intrinsic voids of lava [16], and micro/macro impact-induced cracks [17, 18].

The limited porosity is higher than the average porosity (~7%) of Apollo basalt samples [17]. The samples include the intrinsic voids of lava and the micro impact-induced crack, so that the volcanic ash and the macro cracks would explain the rest of the porosity. The uppermost basalt layers analyzed in this study and the previous study [6] has experienced the meteorite-impact during ~3 billion years. Accordingly, the uppermost basalt layers can be a friable layer; in which the main porosity source may be the macro impact-induced cracks. As another explanation of high porosity, we might have to reconsider the porosity due to the intrinsic voids included in lunar basalt rocks. We should note that Apollo basalt sample 15016 has ~50% in porosity. If such porous rocks form the uppermost basalt layer, the limited porosity would be also explained.

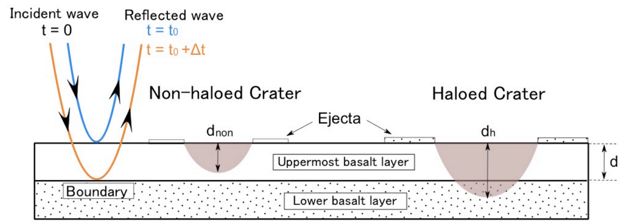

Fig. 1. A lunar subsurface model used in this study [6].

Table 1. Results of the bulk permittivity and porosity.

Unit	ϵ_{bulk}	d_{radar} [m]	d_{non} [m]	d_h [m]	ϕ [%]	ρ_{grain} [g cm^{-3}]
			Mare Humorum			
85	2.8–5.5	500	214	300	19–51	3.2
			Mare Serenitatis			
S13	4.2–18.0	429–500	118	209	0–33	3.3
S15	1.9–7.0	380	144	279	9–71	3.3
S28	1.6–14.0	380	102	299	0–78	3.3
			Oceanus Procellarum			
P10	1.3–5.1	523	231	454	21–86	3.2

The results of Unit 85 and S13 are based on the previous study [6].

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