PERMITTIVITY OF LUNAR SUBSURFACE AT UFH BAND BASED ON LABORATORY EXPERIMENT: IMPLICATIONS FOR LUNAR GPR MISSIONS.

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Introduction: Ground Penetrating Radars (GPRs) are the powerful tool to visualize subsurface structures and detect the buried water-ice and liquid water. On the moon, Lunar Penetrating Radar (LPR) onboard Chang'E rovers has been successful to reveal the stratigraphies up to hundreds of meters [1,2]. Furthermore, several missions such as LUnar Polar EXploration (LUPEX) by JAXA are planned to load the GPRs for the detection of the water-ice buried in the regolith of the lunar polar region. These observations can help us to understand the geological processes and the surface evolution, and the detection of the water-ice would provide us the information of the potential resource for the future manned space explorations.

GPRs measure the round-trip time of electromagnetic (EM) waves between the surface and the boundary of different materials. The behavior of EM waves is determined by the combination of the permittivity, permeability, and conductivity of the medium that the EM waves propagate. Considering the geological materials such as rocks and minerals, the permittivity is the most dominant parameter for EM propagation through soils or rocks [3]. The reflection power of EM waves between materials is also determined by differences of the permittivity of each material. Then, the determination of the permittivity is essential for the analysis of GPR data.

Permittivity of materials is affected by several parameters such as frequency, water content, chemical composition, bulk density (porosity), temperature, and so on [e.g., 4-8], which makes it difficult to estimate the permittivity of the materials under the lunar condition. The water content and temperature are especially different from those of the terrestrial soil. The water content in soils increases the real part of the bulk permittivity dramatically under the terrestrial (moisture) condition because the permittivity of liquid water is 10 times or higher than that of rocks [8]. However, the lunar regolith has no liquid water, and the effect of water should be significantly limited. Besides, the lunar surface temperature is much lower [9]. While the real part of the permittivity is reported to decrease about 50 % theoretically at the lunar surface temperature [10], the measured value experimentally of lunar regolith simulant (JSC-1A) decreases only a few % from at 30 °C to -50 °C [11]. The consideration of these factors on the permittivity is essential for the analysis of the radar data obtained on the moon.

Here, we report the result of the laboratory experiment that measures the relative permittivity of rocks which can exist on the moon under dry and low-temperature conditions (up to -60 °C). Especially, we focus on the measurement at the UHF-SHF band which is applied for the future GPRs on the moon. Considering the measurement value, we estimate the permittivity of the lunar shallow subsurface to make it possible to analyse the GPR data more accurately.

Sample and method: We prepare three samples that typically exist on the moon; such as anorthosite, basalt, and dunite. After crushed with jaw crusher and stamp mill, they are sieved with a mesh opening of 45 or 500 μm. All samples are baked in the oven at 90 °C for a day to exclude the water content. To remove the effect of porosity on permittivity, we carefully arrange each sample to have the same porosity of 40%.

The coaxial probe method is used to measure the permittivity of the powdered samples due to excluding the heterogeneity. We select the coaxial probe and cable (85070E Dielectric Probe Kit; Keysight) and VNA (8753ES S-parameter Network Analyzer; Keysight) for the measurement. The frequency is between 1 MHz to 6 GHz in 1601 points. For the measurement stably, we warm it up 60 min before measurements.The calibration is conducted by the standard method using the coaxial probe method [12] . The measurement temperature is at room temperature, -20 °C, and -60 °C. For the measurement at low temperatures, the coaxial probe is put into the freezer (Figure 1). The temperature dependence of the instrument has been checked, and we should take care of the temperature change of the probe to put it in the freezer for time enough to become stable. Besides, we measure the relative permittivity of air before and after the measurement of each sample to confirm the validity of the measurements.

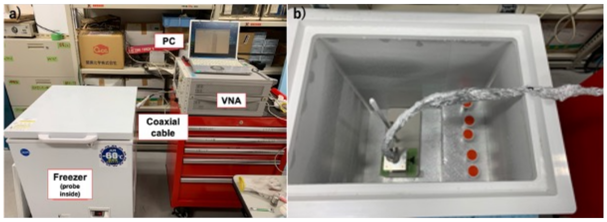

Fig. 1. Developed measurement system at low temperature. a) Instruments used for our measurements. The coaxial probe is put in the deep freezer. To make the temperature of the probe stable, the lid is closed. b) The coaxial cable is covered with aluminum foil to prevent frost formation on the cable surface.

Results: We show the relative permittivity of basalt at three temperatures (Figure2). Our measurement value at room temperature is consistent with the compile data of Apollo samples [5]. Although the permittivity decreases with decreasing the temperature, the decreasing differences between at room temperature and -60 °C are larger than the value reported by [11].

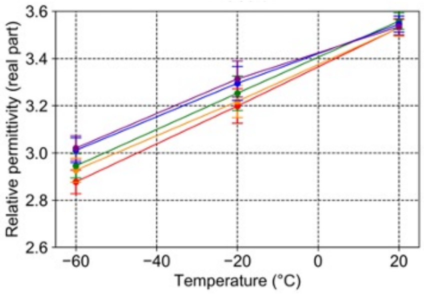

Fig. 2. Real part of the relative permittivity of basalt measured at different temperatures at 2-6 GHz. Each value shows the average of 10 points before and after each frequency. The color means the frequency (red: 2 GHz; orange: 3 GHz; green: 4 GHz; blue: 5 GHz; purple: 6 GHz).

Lunar subsurface permittivity profile: We calculate the permittivity on the lunar subsurface using mixing rules. The subsurface density up to 3 m is assumed based on [5]:

$$\rho = 1.92^{\frac{z+12.2}{z+18}} \ldots (1)$$

$$\rho = 1.39 z^{0.056} \ldots (2)$$

where z is the depth. The subsurface porosity is calculated by the combination of eq. (1) or (2) and the true density of the basalt and anorthosite (Figure 3a). Figure 3b and 3c shows the relative permittivity calculated using the Looyenga-Landau-Lifshitz (LLL) mixing rule [13], which is the most appropriate mixing rule at the low temperature [14], and the apparent permittivity (ε_{app}) which is an integral over the full depth of the material, H [15]:

$$\varepsilon_{eff}^{\frac{1}{3}} = \sum_i f_i \varepsilon_i^{\frac{1}{3}} \ldots (3)$$

$$\varepsilon_{app} = \left[\frac{1}{H} \int_0^H \sqrt{\varepsilon_{eff}(z)} dz \right]^2 \ldots (4)$$

where ε_{eff} and ε_i is the relative permittivity of the mixture and each component (i.e., porous and rocks), respectively, and f_i is the volume fraction of each component. This shows the relative permittivity of the fitting equation by [5] that is used for the depth estimation by GPR data most frequently underestimates about 1.0 than our calculation. Finally, the estimated depth using GPRs is calculated by:

$$d = \frac{ct}{2\sqrt{\varepsilon_{app}}} \ldots (5)$$

where c is the speed of the light. Figure 3d shows the relationship between the delay time of EM waves which is measured by GPRs and the estimated depth. This shows that the previous estimation based on [5] is overestimated by about 15 % at most. This difference is critical for the estimation of geological structures and detection of anomalies such as buried boulders and cavities under the surface. For example, LUPEX's GPR is going to be used for a preliminary survey of excavation. Although the excavation will provide the chance to detect the water-ice and/or other volatiles, it would be with the danger that for example, boulders buried in the ground could damage the excavation instrument. The overestimation of the estimated depth would result in crucial damage for the mission. Besides, a new Japanese lunar mission, TSUKIMI (Lunar Terahertz Surveyor for Kilometer-scale MappIng), aims to detect the subsurface water-ice globally with THz sensing. The permittivity change with the existence of water-ice in the regolith would be very small, then we are planning to measure the permittivity of lunar simulant at the THz band under the low-temperature and dry condition for the detection of the burie water-ice. At these points, this temperature dependence should be treated with caution for the analysis.

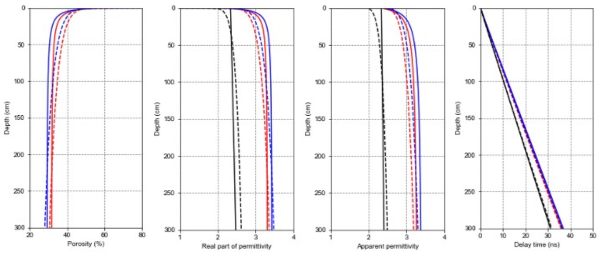

Fig. 3. Calculated a) porosity, b) the real part of the relative permittivity and c) the apparent permittivity of the lunar subsurface up to 3 m, and d) the relation between delay time and reflection depth estimated based on GPR data. The red and blue line shows the result of basaltic and anorthothic regolith, respectively, and the solid and dashed one is based on eq. (1) and (2), respectively. The black line shows the permittivity based on the fitting equation [5].

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