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## PS37

# 模擬月レゴリスの誘電率測定

# Dielectric constant measurements of simulated lunar regolith

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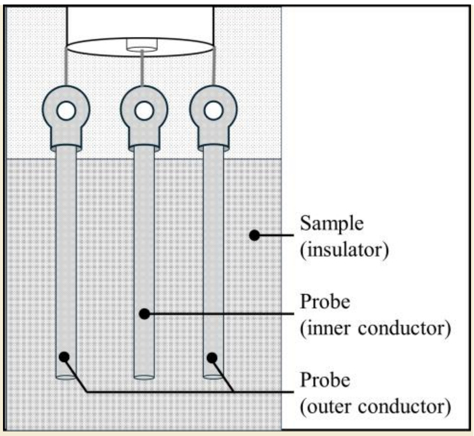


**Abstract:** Our proposed lunar permittivity measurement experiment has been accepted for NASA's Artemis program, and preparations are currently underway. We focused on the TDR method as a permittivity measurement method and measured the permittivity of alumina powder, one of the components of lunar regolith. The TDR method utilizes the property that the propagation speed of electromagnetic waves traveling through a coaxial cable changes depending on the permittivity of the insulator between the outer and inner conductors. In this experiment, we created a probe, as shown in the right figure, and inserted it into a sample to determine the permittivity of the sample from the speed at which the electromagnetic waves propagate through the probe. When we performed TDR measurements with alumina powder placed in a beaker, the permittivity of alumina was measured to be 9.09. This value is almost the same as the permittivity of solid alumina. However, because the permittivity changes depending on the porosity of the powder, it will be necessary to control the porosity in future measurements.

**Keywords:** permittivity, TDR method

## 1. Introduction

Our proposed experiment to measure the permittivity of the lunar surface has been accepted for NASA's Artemis program , and we are currently preparing to realize it. The purpose of measuring the permittivity of the lunar surface is to explore the location of $H_2O$ and locations with high Fe content. $H_2O$ on the lunar surface will serve as fuel for transport vehicles, and its location must be explored. Searching for locations with high Fe content is also important for extracting Fe from lunar regolith and using it as a material. A method is being considered to extract Fe from high Fe content lunar regolith by melting and solidifying it through internal heating with microwaves. Therefore, to understand the microwave absorption efficiency of Fe-containing lunar regolith, it is necessary to measure the complex permittivity and complex permeability of Fe-containing lunar regolith. In this study, we measured the permittivity of alumina, one of the components of lunar regolith, using the TDR method, which is used to measure the permittivity of soil, and examined the usefulness of this method.

## 2. Principle of TDR method

2.1. Basics of TDR method

Measuring the dielectric constant using the TDR method is known as a method for determining the permittivity of soil [1,2]. The basic principles are described below.

A coaxial cable consists of an outer conductor, an inner conductor, and an insulator between them. The propagation speed and impedance of a coaxial cable change depending on the insulator. The probe used in this experiment consists of three stainless steel rods. The two outer rods are connected to the outer conductor of a coaxial cable, and the inner rod is connected to the coaxial cable itself, making it the coaxial cable. When this probe is inserted into a sample, the sample acts as an insulator. The speed of the electromagnetic wave $v$ propagating between the probes can be expressed as follows Eq. (1):

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

where $\varepsilon_r$ is the relative relative permittivity of the sample, and $c$ is the speed of light. If the speed of the electromagnetic wave propagating between the probes can be calculated from the above equation, the relative permittivity of the sample can be determined. The TDR method is used to measure the speed of the propagating electromagnetic wave. **Fig. 1** shows a schematic diagram of the TDR method. A step pulse wave is input using a vector network analyzer, and the time it takes for the reflection that occurs at the end of the probe to return is measured. Let the measured time be $t$ and the length of the probe be $L$. Of course, Eq. (2) holds true.

$$v = \frac{t}{2L} \tag{2}$$

Substituting this into Eq.(1), we get the following equation:

$$\varepsilon_r = \left(\frac{ct}{2L}\right)^2 \tag{3}$$

The relative permittivity of the sample can be calculated using Eq.(3)

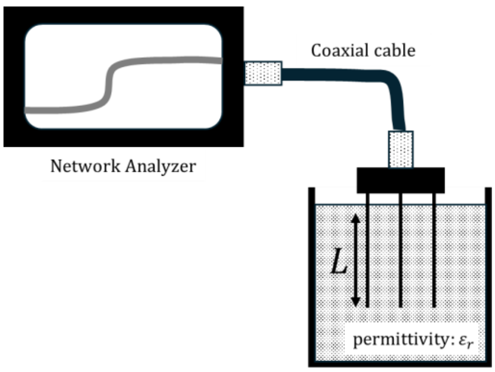


**Figure 1.** Schematic diagram of the TDR device

2.2. How to analyze the data obtained

The TDR method utilizes the property that when a pulse wave is injected into a cable, it is reflected at parts of the cable with different impedance. In this case, the reflectance $\alpha$ when the impedance is injected from $Z_0$ to $Z_1$ can be written as follows:

$$\alpha = \frac{Z_1 - Z_0}{Z_1 + Z_0} \tag{4}$$

The impedance of the probe depends on the relative permittivity of the inserted sample. If the relative permittivity is relatively large, the probe impedance will be smaller than the cable impedance, and the reflectance will be positive according to Eq.(4). On the other hand, if the relative permittivity is small, the probe impedance will be larger than the cable impedance, and the reflectance will be negative according to Eq.(4). Therefore, the waveform obtained will differ depending on the relative permittivity of the inserted sample.

In this experiment, the points shown in **Fig. 2**for each waveform were considered to be the times when the reflected waves returned, and the permittivity was measured.

## 2.3. Calibration Method

To accurately measure the relative permittivity using the TDR method, the following two points must be taken into consideration. One is that a certain amount of time passes when the electromagnetic wave passes through the jig that holds the stainless steel rod, and this time must be calibrated. This time is called $\Delta t$. The other is that when the probe is inserted into the sample, the length of the probe that is inserted must be accurately measured. The length of the probe is designated as $L$.

In this experiment, two materials with different relative permittivity were prepared and the values of $\Delta t$ and L were calibrated. The relative relative permittivity of the standard samples used for calibration were set to $\varepsilon_1$ and $\varepsilon_2$, respectively, and TDR measurements were performed. If the time it takes for the reflected wave to return is $t_1$ and $t_2$, then the following equation holds from Eqs.(5)-(6):

$$\sqrt{\varepsilon_1} = \frac{c(t_1 - \Delta t)}{2L} \tag{5}$$

$$\sqrt{\varepsilon_2} = \frac{c(t_2 - \Delta t)}{2L} \tag{6}$$

By combining these two equations, we obtain the following equation

$$L = \frac{c(t_1 - t_2)}{2(\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2})} \tag{7}$$

$$\Delta t = t_1 - \frac{\sqrt{\varepsilon_1}(t_1 - t_2)}{(\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2})} \tag{8}$$

From this formula, we can see that if we prepare two types of standard samples and perform TDR measurements on each, we can find $\Delta t$ and $L$.

## 3. Experimental method

A vector network analyzer (NanoVNA-H4**)** was used for the TDR measurements. The probe was made by fixing three stainless steel rods to a jig. The probe length was 10 cm and the probe spacing was 1 cm.

Water of different temperatures was prepared as a standard sample for calibration. The relative permittivity of water varies depending on the temperature. The relative permittivity of water is E, and its magnitude is written as follows[3)]:

$$\varepsilon_w(t) = 88.15 - 0.414t + 0.131 \times 10^{-2}t^2 - 0.046 \times 10^{-4}t^3 \tag{9}$$

In this experiment, we used distilled water at room temperature and distilled water heated by a heater. Each was placed in a beaker, and a probe was inserted to perform TDR measurements. The waveform of the reflected wave obtained by the TDR method was used to determine the time ($t_1$ and $t_2$) it took for the pulse wave to travel back and forth through the probe using the method shown in Figure 3. The temperature at the time of measurement was determined using a red liquid thermometer and converted into the dielectric constant ($\varepsilon_1$ and $\varepsilon_2$)of distilled water using Eq.(9). The time and relative dielectric constant were substituted into equation Eqs.(7)-(8) to determine $\Delta t$ and $L$. At this time, the height of the water surface in the beaker and the mass of the water in the beaker were also recorded. The height of the water surface needs to be recorded every time the probe length $L$ during calibration matches the probe length during sample measurement. The mass of the water in the beaker is also used to calculate the volume of the sample. Once the volume of the sample is known, the porosity can be calculated by weighing the sample. The bulk density of the powder sample is $\rho_s$, the true density is $\rho_t$, and the porosity $P$ is defined by the Eq.(10). If the volume of the water used for calibration and the powder sample used for measurement are the same, the mass of the water used for calibration is $m_w$, the mass of the measurement sample is $m_s$, and the density of the water is $\rho_w$, then the porosity $P$ can be calculated from the Eq.(10):

$$P = 1 - \frac{\rho_s}{\rho_t} = 1 - \frac{m_s m_w \rho_w}{\rho_t} \tag{10}$$

A volume of powdered alumina equal to the volume of water used for calibration was placed in a beaker. The volume of the alumina added was recorded and the porosity was calculated using Eq.(10). A probe was inserted, and TDR measurements were performed, and the dielectric constant was calculated from the waveform of the reflected wave.

## 4. Experimental results

**Figure 2** shows the TDR measurement results for water at different temperatures used during calibration. The time it took for the input electromagnetic wave to travel through the probe and back was calculated from the waveform. Furthermore, a red liquid thermometer measured the temperature of distilled water at room temperature as 20°C, and the temperature of water heated by a heater as 65°C. These results were converted to permittivity using Eq.(9), and T and L were calculated using Eqs.(7)-(8).

**Figure 2** shows the results of TDR measurement of alumina placed in a beaker. The mass of the alumina placed in the beaker was also measured. From these results, the porosity of the alumina in this experiment was determined to be 78%. The relative permittivity of alumina was calculated from the time it took for the input electromagnetic wave to travel through the probe and back, resulting in a value of 9.09.

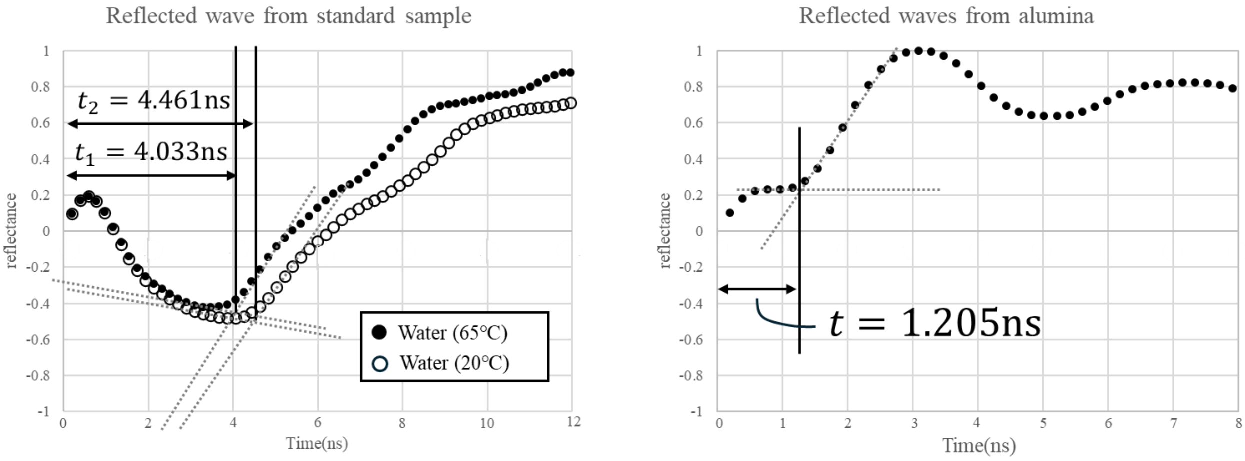


**Figure 2.** Waveform of the reflected wave measured by TDR and the time it takes to travel through the probe. Left: Standard sample [white circle: water at room temperature (20°C), black circle: Heated water (65°C)], Right: Alumina.

## 5. Conclusions and future prospects

The relative permittivity of solid alumina is between 8.0 and 11.0, and the results of this measurement are within that range. However, this time we used powdered alumina, and the permittivity of powder changes depending on its porosity. Because we were unable to control the porosity in this experiment, we cannot claim that the measurement results are completely accurate. Furthermore, alumina has a relatively high permittivity among the components of lunar regolith, and measuring materials with lower permittivity would require a longer probe than in this experiment, due to the resolution of the network analyzer.

In the future, we are considering using the cavity resonator method to measure the dielectric constant of materials with even lower dielectric constants more accurately. In fact, there are examples of measuring the dielectric constant while controlling the porosity using this method.

**Conflicts of Interest**

The authors state no conflict of interest.

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