

# DIELECTRIC ANALYZER FOR DETECTING WATEAR AND METALIC MINERAL RESOURCES.

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**Introduction:** The presence of water and metallic resources on the Moon, asteroids, and Mars has the potential to support a wide range of future space activities, including propellant production, infrastructure construction, and in-space maintenance of spacecraft. These resources are expected to occur primarily within the shallow subsurface at depths accessible by mechanical excavation. However, as in terrestrial resource development, efficient utilization requires identifying regions where valuable resources are sufficiently concentrated rather than uniformly distributed. Therefore, exploration tools capable of rapidly assessing the presence and degree of resource concentration on the shallow subsurface would be highly valuable during the early stages of resource prospecting.

One promising technique for enabling such exploration is dielectric permittivity measurement. Although permittivity is influenced by several factors, including bulk density [1] and temperature [2], it is also known to positively correlate with the abundance of water ice and Fe–Ti–rich minerals [3]. Therefore, regions exhibiting high dielectric permittivity may indicate concentrations of water or metal-bearing resources.

To enable rapid in-situ assessment, we are developing compact dielectric measurement instruments capable of instantaneous measurements. One of these instruments is the Lunar Dielectric Analyzer (LDA), which will be deployed on the lunar surface by astronauts during the Artemis mission. In parallel, we are also developing the Surface Dielectric Analyzer (SDA), which is designed for integration with robotic spacecraft. Both instruments aim to investigate the presence of space resources by measuring the dielectric properties of the shallow subsurface.

Based on the measurement principles adopted in the LDA, we examine strategies for detecting subsurface water ice and the expected dielectric responses associated with Fe–Ti enrichment.

## Detection of Water Ice Using Temperature-Dependent Permittivity:

Our previous studies show that the dielectric permittivity of lunar regolith simulants exhibits a positive temperature dependence over the range from  $-60\text{ }^{\circ}\text{C}$  to  $20\text{ }^{\circ}\text{C}$  at UHF–SHF frequencies [2]. This behavior has been observed not only for Mare- and Highland-type regolith simulants but also for ilmenite, a mineral expected to be a potential resource on the lunar surface. In contrast, water ice is known to exhibit little to no temperature dependence in its dielectric permittivity

over this temperature range. By exploiting this difference in temperature response, it becomes possible to constrain the presence and abundance of water ice within regolith.

Assuming that lunar regolith is a heterogeneous mixture consisting of mineral grains, pore space, and potentially water ice, interpretation of the measured effective permittivity requires dielectric mixing theory. In this study, we adopt the Landau–Lifshitz–Looyenga (LLL) mixing model, which has been shown to provide a reasonable approximation for porous planetary regolith [4]. In this formulation, the effective permittivity of a three-phase mixture composed of rock, ice, and vacuum is expressed as:

$$\epsilon_{\text{eff}}^{1/3} = f_{\text{rock}}\epsilon_{\text{rock}}(T)^{1/3} + f_{\text{ice}}\epsilon_{\text{ice}}^{1/3} + (1 - f_{\text{rock}} - f_{\text{ice}})\epsilon_{\text{vac}}^{1/3} \quad (1)$$

where  $f_{\text{rock}}$  and  $f_{\text{ice}}$  represent the volume fractions of the rock and ice components, respectively, and  $(1 - f_{\text{rock}} - f_{\text{ice}})$  corresponds to the porosity. The permittivity of vacuum  $\epsilon_{\text{vac}}$  is approximately unity. This formulation provides a simplified end-member representation of the first-order dielectric behavior of lunar regolith (Figure 1).

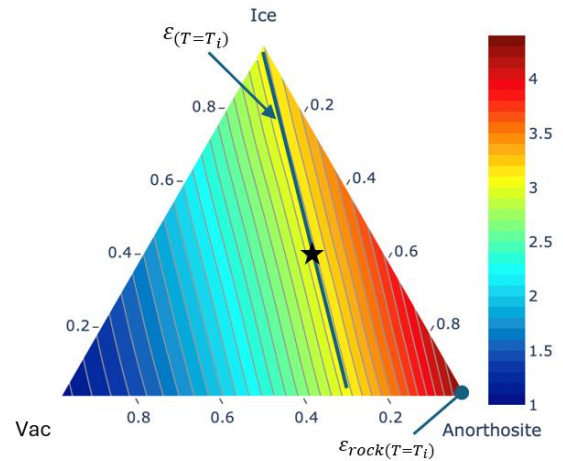


Figure 1. Ternary diagram showing the effective permittivity of a regolith–ice–air mixture at a fixed temperature, calculated using a dielectric mixing model [5]. The color scale represents the bulk permittivity as a function of the volume fractions of rock, water ice, and pore air. The star indicates an example mixture composition, illustrating how changes in ice content and packing density map onto the permittivity space.

A key aspect of this formulation is that the permittivity of the silicate component  $\epsilon_{\text{rock}}(T)$  is treated as a function of temperature, whereas the permittivity of water ice  $\epsilon_{\text{ice}}$  can be considered nearly constant ( $\approx 3.15$ ) under the relevant low-temperature UHF conditions. From this formulation, the difference in effective permittivity measured at two temperature states  $T_1$  and  $T_2$  can be expressed as:

$$\epsilon_{\text{eff}}(T_2)^{1/3} - \epsilon_{\text{eff}}(T_1)^{1/3} = f_{\text{rock}}[\epsilon_{\text{rock}}(T_2)^{1/3} - \epsilon_{\text{rock}}(T_1)^{1/3}] \quad (2)$$

In this expression, the contributions of the temperature-independent ice and vacuum components cancel out. As a result, the observed temperature-dependent change in permittivity is primarily controlled by the rock fraction. By solving this equation, the volume fraction of the rock component  $f_{\text{rock}}$  can be estimated. The obtained value can then be substituted back into the original mixing equation to constrain the volume fraction of ice  $f_{\text{ice}}$  and the porosity.

This differential approach using temperature-dependent dielectric measurements reduces the degeneracy between bulk density and composition that commonly affects static permittivity measurements, enabling estimation of the presence and abundance of water ice within the regolith. This principle forms the fundamental measurement strategy adopted in the LDA.

**Dielectric Response Associated with Fe–Ti Enrichment:** Compositional variations in lunar regolith can also influence dielectric properties. In particular, iron and titanium oxides (FeO and TiO<sub>2</sub>) are known to affect the dielectric response of lunar materials. Previous laboratory studies of Apollo samples have shown that the real part of the dielectric constant generally increases with FeO+TiO<sub>2</sub> concentration [1]. However, these measurements also demonstrated that dielectric permittivity is strongly controlled by bulk density and porosity. Because Apollo samples exhibit substantial variations in density, porosity, and mineral composition, the individual contributions of these factors have been difficult to isolate, leaving the quantitative relationship between Fe–Ti abundance and dielectric permittivity poorly constrained.

To address this issue, we conducted controlled dielectric measurements on lunar regolith simulants with independently varied FeO+TiO<sub>2</sub> concentrations and bulk densities [6]. This experimental design allows the compositional contribution to dielectric permittivity to be evaluated separately from density effects. The results show that the real part of the dielectric constant increases systematically with FeO+TiO<sub>2</sub> concentration (Figure 2b). At the same time, a strong exponential relationship between bulk density and permittivity is observed, consistent with previous Apollo measure-

ments (Figure 2a). After normalizing the dielectric constant to a reference bulk density, a clear compositional trend emerges. Notably, both highland-type (anorthosite-based) and mare-type (basalt-based) simulants exhibit nearly identical slopes describing the dependence of permittivity on FeO+TiO<sub>2</sub> concentration, despite differences in their absolute dielectric values.

These results indicate that Fe–Ti enrichment produces a systematic increase in dielectric permittivity that is largely independent of lithology once density effects are accounted for. For LDA observations, this implies that Fe–Ti–rich regolith may generate dielectric anomalies that could mimic signatures expected from volatile materials. Consequently, distinguishing dielectric variations caused by compositional enrichment from those associated with water ice is essential for interpreting in-situ measurements. By combining temperature-dependent dielectric observations with constraints on bulk density and porosity derived from dielectric modeling, the LDA framework provides a practical approach for separating volatile-related signals from compositional dielectric effects.

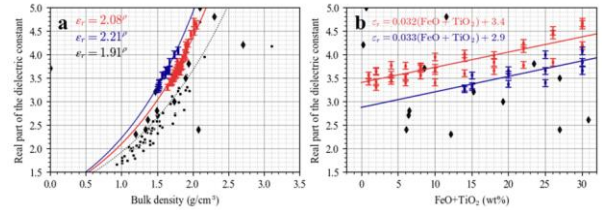


Figure 2. (a) Relationship between bulk density and the real part of the dielectric constant. (b) Relationship between FeO+TiO<sub>2</sub> concentration and the real part of the dielectric constant. Red and blue symbols indicate lunar samples composed of anorthosite and basalt mixed with ilmenite, respectively. Black diamond and square symbols indicate the laboratory measurements of Apollo samples at 1 GHz and 450 MHz, respectively [1]. Each color line represents exponential fitting curves for the respective datasets.

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