

DIELECTRIC SPECTROSCOPY FOR SCIENTIFIC AND RESOURCE CHARACTERIZATION OF LUNAR REGOLITH. D. E. Stillman and R. E. Grimm, Department of Space Studies, Southwest Research Institute, 1050 Walnut Street, Suite 300, Boulder, CO 80302, dstillman@boulder.swri.edu.

Introduction: Dielectric spectroscopy (DS) can non-invasively detect electrical properties over a wide frequency range (1 mHz – 10 kHz) at depths ranging from 10s cm to 10s m. Electrical properties vary directly with density and mineralogy. Therefore, DS can determine the subsurface distribution of water ice, adsorbed water, ilmenite, and possibly Fe⁰. Understanding the subsurface distribution of these minerals is an important first step for in-situ resource utilization. The presence and subsurface distribution of these minerals can also be used to address scientific questions such as if adsorbed water exists in the subsurface, ice and/or adsorbed water are the source of the enhancement in hydrogen near the poles, and to locate immature regolith that has trapped the composition of the ancient solar wind.

Dielectric Spectroscopy: Induced polarization (IP), precursor to DS, measures the resistive-dielectric properties of the earth and has been employed for nearly a century to explore for minerals and groundwater and to characterize subsurface geology. DS was created about 30 years ago, and now encompasses multiple frequencies from 1 mHz – 10 kHz [e.g., 1]. The first DS planetary instruments have flown on Huygens, Phoenix, and the Rosetta lander. These instruments lack the bandwidth and depth of penetration of terrestrial DS. We are developing a DS system for planetary applications with the capabilities of a terrestrial system, but capacitively coupled. This requires larger electrode arrays, high-impedance (~10 TΩ), low-capacitance (~1 pF) coupling, and mitigation of coherent noise such as leakage and eddy currents using buffering, shielding, and guarding of electrodes.

DS works by injecting current I into the ground via two electrodes and then measuring the magnitude and phase of the voltage V response with two other electrodes. The frequency of the injected current is varied over the bandwidth of the instrument. Electrical properties are derived at each frequency from the impedance (V/I) and electrode geometry. The geometry also controls the subsurface depth of investigation with larger electrode spacing allowing for deeper penetration. The depth of investigation is around 1/3 of the largest electrode separation.

The electrodes can be accommodated in lander legs, rover wheels, a robotic arm, or in a ballistically deployed string (Fig. 1). Our present efforts are aimed

toward the design of a transmitter and receiver requiring a few kilograms and a few watts, plus electrodes.

Electrical Properties of Lunar Materials: Electrical properties describe how a material responds to an external electric field. If the material's resistivity is frequency independent, then the material behaves as a simple resistor, or resistively. If the material's resistivity varies inversely with frequency, then it behaves as a simple capacitor, or dielectrically. The mineralogy, temperature, frequency, and presence and state of water determine if the subsurface behaves resistively or dielectrically. DS can only be applied in limited terrestrial environments because the conductivity of liquid water makes the subsurface behave as a simple resistor below 100 kHz. However, due to the lack of liquid water, the lunar subsurface will behave dielectrically even at very low (<1 Hz) frequencies. Dielectric relaxations occur as additional polarization mechanisms occur. These relaxations are unique to a mineral, and thus can be used to identify the mineral and its concentration (Fig. 2) [2].

Over the last three years, we have been making electrical properties laboratory measurements of planetary regolith analogs at lunar temperatures. These data are crucial as they are used to determine which lunar minerals can be uniquely identified with DS. Below is a summary of our measurements.

Water ice and adsorbed water (originally measured for DS on Mars) both produce strong dielectric relaxations at low frequencies due to the intrinsic dipole of the water molecule. The dielectric relaxation of ice is a relatively narrow (Debye) relaxation with a frequency near 100 Hz near 180 K (Fig. 2). The temperature dependence of the dielectric relaxation of water ice depends on the number of defects in its crystal structure [4]. These defects are produced by the solubility of Cl⁻ and F⁻, and possibly by radiation damage. A forward calculation using present estimates of the intrinsic properties of ice and its moderation due to regolith mixing illustrates that an ice-detection limit of ~1% or better is possible using DS.

The dielectric signature of adsorbed water is dependent on the number of monolayers (MLs). If <1 ML exists, the adsorbed water produces a low-frequency very broad dielectric relaxation that can be measured over the entire frequency range [2]. If >1 ML exist, then the previous relaxation is additive to a mid- and high-frequency narrow dielectric relaxation [2]. The

high-frequency relaxation occurs at higher frequencies than ice as the water molecules are bound less tightly to each other compared to ice. The mid-frequency relation occurs at a frequency lower than ice. The number of MLs increases both the strength and relaxation frequency of the mid- and high-frequency relaxations with 3 ML at 180 K having relaxation frequencies near 10 Hz and 10 kHz, respectively.

At high (≥ 1 MHz) frequencies, the water and ice relaxations disappear and the real part of the dielectric constant is determined by electronic polarization. For lunar regolith, this has been determined via laboratory measurements on lunar samples to be a simple function of density [3]. The imaginary (lossy) part of the dielectric constant is proportional to its ilmenite concentration [3]. At low frequencies, the real and imaginary part of the dielectric constant both increase when ilmenite is present due to the mineral's low-frequency broad dielectric relaxation [3]. Ilmenite concentrations of the top few meters of the lunar subsurface have been inferred from previous radar (high frequency) surveys [5]. DS will be able to detect even smaller concentrations of ilmenite, due to its larger signal at low frequencies, to depths of 10s of meters if large electrode arrays are used.

The concentration of Fe^0 increases as the lunar regolith matures. Fe^0 behaves resistively, but it should create a Maxwell-Wagner dielectric relaxation because it is surrounded by minerals that behave dielectrically. The signature of this relaxation has yet to be measured.

Applications: DS can be used to address many lunar science questions. Neutron spectroscopy has measured an increase in hydrogen concentration at the poles [6,7]. The putative signature of ice in radar scattering is controversial [8]. Near infrared spectroscopy has mapped an increase in adsorbed water near the poles [9,10]. DS can uniquely identify water ice and adsorbed water to determine if both or either are present in the polar subsurface. DS can also detect adsorbed water in the subsurface at mid-latitudes and long term studies could determine whether this subsurface adsorbed water migrates as has been observed for adsorbed water on the surface [11]. If subsurface adsorbed water is detected, it would drastically increase previous estimates of lunar water. This would provide additional constraints on the genesis of this water (cometary or solar wind derived). DS may also be able to identify layers of lunar regolith that are immature, thus identifying layers that could be sampled to determine the composition of the ancient solar wind.

DS can be used for characterize subsurface resources. This is critical before in-situ resource utilization (ISRU) is tested on the Moon. Adsorbed or frozen water is likely the most valuable resource on the Moon.

Other than water, ilmenite is the best mineral to make oxygen from. The vertical density profile determines the thickness and rippability of the lunar regolith, which can be used to determine how much feedstock is available and how easy it will be to remove.

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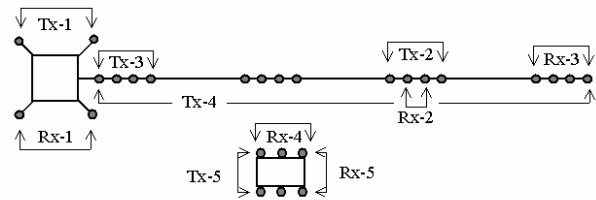


Figure 1. Alternative schematic layouts for DS electrodes. Tx = transmitter, Rx = receiver. (1) Electrodes on static lander footpads. (2) Closely spaced electrodes on ballistically deployed string for shallow subsurface investigation. (3) Widely spaced electrodes for deeper investigation. (4) Large transmitter dipole on lander and short dipole on rover (wheel base) for deep investigation. (5) Rover-only short dipoles for mobile, shallow investigation.

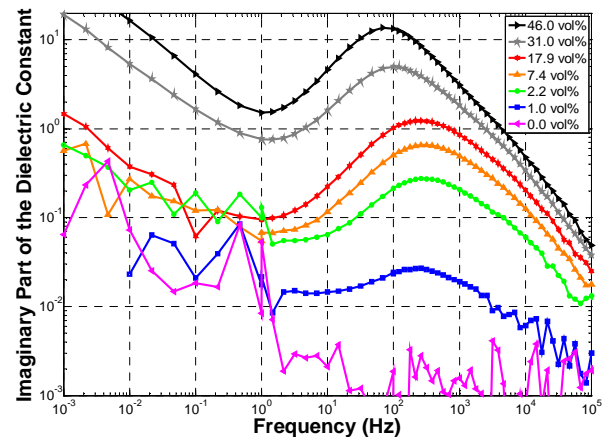


Figure 2. The dielectric response of various concentrations of ice mixed with a fine-grained sand measured in our laboratory at 181 K. The maximum near 100 Hz is the dielectric relaxation of ice. This relaxation frequency shifts to higher frequencies due to an increase in ice defects near the pore edges [2]. The low frequency relaxation of adsorbed water is represented by the decrease in imaginary part of the dielectric constant below 1 Hz. The noise floor is near 4E-3 above 1 Hz and considerable higher below 1 Hz.