DETERMINING LUNAR REGOLITH WATER CONTENT USING PERMITTIVITY MEASUREMENTS WITH THE LUNAR VOLATILES SCOUT.

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Introduction: In recent year, missions to the Moon have indicated that significant amounts of hydrogen and potentially water could be found there [1]. Especially the Lunar Crater Observation and Sensing Satellite (LCROSS) has measured a water content of 5.6±2.9 w% for the Cabeus crater [2]. Nevertheless, confirmation of these findings requires ground-truth data. The Lunar Volatiles Scout (LVS), which is currently developed at the Technical University of Munich (TUM), can potentially provide this valuable ground-truth data [3].

Lunar Volatiles Scout: The LVS is an instrumented drill designed for future mobile in-situ extraction, detection and analysis of lunar volatiles. A schematic of the instrument is given in Figure 1. By heating the regolith to high temperatures, water and other volatiles can be extracted and identified with an integrated mass spectrometer. However, accurately determining the abundance of water in the regolith remains difficult. To address this issue, a lunar regolith permittivity measurement could be added to the LVS' capabilities. In principal, the change in moisture content can be detected by comparison of the LVS' capacitance between heating rod and drill shell before and after heating the regolith. Both liquid water and water ice have a significantly higher static relative permittivity ($\varepsilon_{r,w} \approx 80$ [4]) than both lunar regolith ($\varepsilon_{r,s} \approx 5$ [5]) and vacuum ($\varepsilon_{r,v} = 1$), which results in a measureable change in capacitance when water has been extracted from the probe volume. The usage of permittivity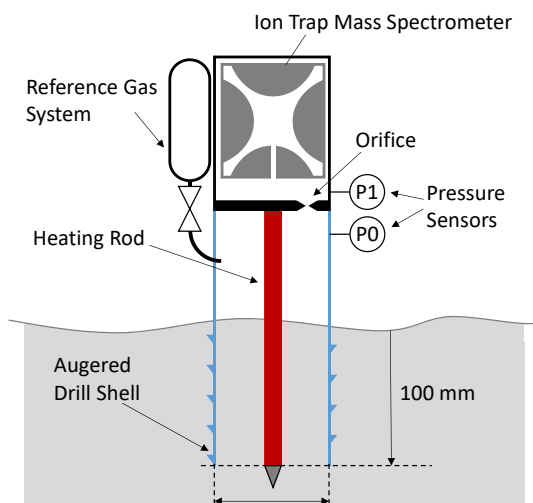 measurements to analyze water content is also included in ESA's PROSPECT instrument package [6] and has been used for various applications [7,8].

Theoretical Considerations: In this context, the LVS functions a cylindrical capacitor with the heating rod and drill shell as electrodes (see Figure 1). The capacitance of the system is proportional to the interior material's permittivity ε [9], which is a function of the interior's components individual permittivity. Multiple mixing rules for the permittivity exist [10]. For simplicity, the ideal permittivity of a mixture $\varepsilon = \sum_i \varepsilon_i \varphi_i$ was chosen with φ_i being the volume fraction of component i [11]. The capacitance C of the LVS system is then

$$C = 2\pi \frac{1}{\ln(r_O/r_I)} \left(z_s \left(\varphi_s \varepsilon_{r,s} + \varphi_w \varepsilon_{r,w} \right) + z_v \varepsilon_{r,v} \right) \text{ (1)}$$

with component height z, inner radius r_I, outer radius r_O, and s denoting sand, w denoting water and v denoting vacuum (or air). When charging the capacitive system with voltage U_0, the ideal capacitor voltage over time is described by

$$U(t) = U_0 \left(1 - e^{-t/\tau} \right) \text{ (2)}$$

with $\tau = RC$ being the time constant. Here, R is the charging resistance. The water content can then be determined by measuring the transient charging curve and using Equation 1 and 2 to calculate φ_w.

Experimental Setup: The experiment setup is depicted in Figure 2. It consists of a concentric metal tube and metal rod, which is hold in place by a non-conductive 3D-printed structure. The rod is insulated

Figure 1: LVS Schematic. Drill Shell (blue) and Heating Rod (red) form the capacitive system.

Figure 2: Experimental Setup: LVS system connected to read-out electronics and on precision scale. Quartz sand and distilled water in the background.
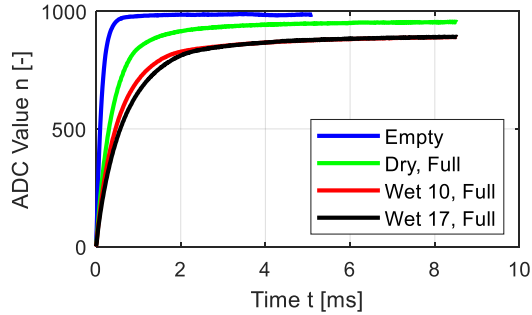
Figure 3: Preliminary Results: Charging Curves. ADC read-out over time of the LVS system for different materials. 'Empty' and 'Full' refers to sand filling, 'Dry' and 'Wet' to its water content with the numbers indicating water content.

Table 1: Experiment data: Measured sand mass m_s and water content φ_s. Measured (τ_m) and calculated (τ_c) time constant for experiments depicted in Figure 3.

Case	m_s [g]	φ_w [%]	τ_m [μs]	τ_c [μs]
Empty	0	0	134±3	43
Dry	154	0	426±1	345
Wet 10	154	10	582±5	499
Wet 17	154	17	719±3	624

towards the interior to prevent parasitic currents. The interior of the tube can be filled with material of interest. For simplicity and better availability, we used quartz sand as analogue material for the pretests and tracked the amount of water in the probe with a precision scale. Water content was chosen to be in the same magnitude as the LCROSS measurements (see Table 1, [2]). Experiments with lunar regolith simulants are planed.

The electronics consist of a commercial microcontroller charging the system with 3.3 V and reading a buffered 10-bit analog input, which returns ADC values n. We used a 5.0 MΩ charging resistance.

Experiments were conducted where the LVS system was filled with different components. Four cases have been selected to demonstrate functionality: (1) empty, (2) filled with dry sand and (3) filled with wet sand. For each experiment, ten measurements were made. Figure 3 shows mean charging curves of the system resembling the LVS. Additionally, exponential curves of form $n(t) = n_0(1 - \exp(-t/\tau))$ have been fitted to the data using a Nonlinear Least Square method to get the time constants of the system.

Results: Mean values and standard deviations for the time constants from selected experiments are given in Table 1, alongside analytically calculated values. Time constant correlates with both more mass and higher water content. The experiments' charging curves also display distinct differences (see Figure 3). A linear fit to measured over calculated time constants returns a nearly unity slope and an offset of around 80 μs, possibly due to the measurement technique. The linear dependency clarifies that the geometry of the LVS can be adapted to function as capacitive system with a dependency of the time constant to the capacitance of the contained material. This should in principal hold true for moist lunar regolith. By measuring relative change in capacitance instead of absolute values, the system is also quite insensitive to external disturbances and uncertainties, such as geometric misalignments due to launch.

Additionally to measuring the water content, the capacitance of the empty LVS system could be used to determine the amount of regolith in the LVS. Regolith and vacuum themselves have different permittivities which result in different capacities for different filling heights. Experiments investigating this correlation show promising results, while this relevant property is otherwise hard to determine.

In general, the experiments show that the investigated method works and that it can be applied to the LVS. By measuring the permittivity before and after the heating process, the LVS is able to determine the amount of water in lunar regolith.

Additional Investigations: Nevertheless, there are still major issues with the system, which are currently being analyzed with experiments and simulations. Firstly, proper integration of in the LVS is being investigated. Secondly, precise calibration of the system with internal parasitic resistances and initial conditions under thermal vacuum conditions can yield better insight. The current read-out electronics are neither flight ready nor capable of frequency dependent permittivity measurements. Including analyses of frequency behavior could also increase the science yield of the instrument. Finally, the selection of the mixing rules, especially with water ice, should be revised and a reliable model for the permittivity of lunar regolith are being developed to ease result interpretation.

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