A Feasibility Study of the Wheel Electrostatic Spectrometer

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Abstract— Mars rover missions rely on time-consuming, power-exhausting processes to analyze the Martian regolith. A low power electrostatic sensor in the wheels of a future Mars rover could be used to quickly determine when the rover is driving over a different type of regolith. The Electrostatics and Surface Physics Laboratory at NASA's Kennedy Space Center developed the Wheel Electrostatic Spectrometer as a feasibility study to investigate this option. In this paper, we discuss recent advances in this technology to increase the repeatability of the tribocharging experiments, along with supporting data. In addition, we discuss the development of a static elimination tool optimized for Martian conditions.

I. INTRODUCTION

In order to substantially reduce the launch mass of future exploration missions, NASA is developing technologies to transform resources found on planetary bodies into consumables needed for human exploration. NASA is currently conducting research on methods to produce water and oxygen using readily available Martian resources [1]. In addition, researchers are developing additive manufacturing techniques with planetary regolith to build structures for human inhabitants and support equipment [2]. These processes are part of a larger overarching ideology known as In-Situ Resource Utilization (ISRU), or "living off the land."

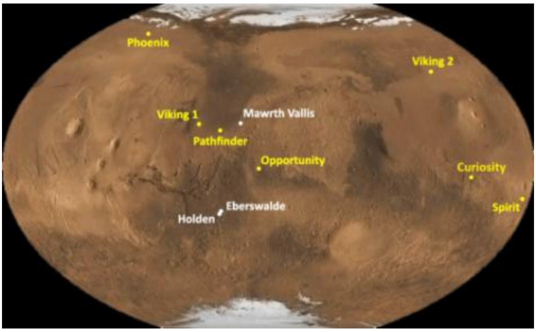
NASA must first characterize the Martian regolith in order to understand which ISRU processes are feasible for future human exploration of the Red Planet. Current Martian exploration missions require the use of time-consuming processes to identify the composition of the regolith. Wheel-based sensors could be used to determine when the rover is driving over a different material, allowing decision making algorithms to determine if the prospecting rover should stop to perform a thorough analysis of the regolith. With this type of operational structure, the mission could see a great increase in the operational efficiency of the rover in search of elements of interest [3].

The Wheel Electrostatic Spectrometer (WES) was developed to investigate the use of electrostatic wheel-based sensors on a Martian rover. The WES was derived from the Mars Environmental Compatibility Assessment (MECA) Electrometer, an electrostatic analysis instrument designed to fly on the cancelled 2001 Mars Odyssey mission [4]. Electrostatic sensors in the wheels of a Mars rover could be used as a prospecting aid by analyzing the electrostatic response with every wheel revolution

[5]. In addition, this data can be used to study how materials electrostatically respond when tribocharged against Martian regolith, a subject of great importance but not yet studied on the Martian surface.

II. PLANETARY REGOLITH AND REGOLITH SIMULANTS

The Spirit, Opportunity, and Curiosity rovers were outfitted with Alpha Particle X-ray Spectrometers (APXS) to analyze the chemical composition of the Martian regolith. Fig. 1 displays the results from these analyses [6]. The results of these tests indicate that the top layer of the Martian regolith is relatively uniform. Similar results were found during the Viking 1, Viking 2, and Pathfinder missions [7]. This global uniformity of the top layer of dust is thought to be caused by the frequent global dust storms experienced on Mars [8].



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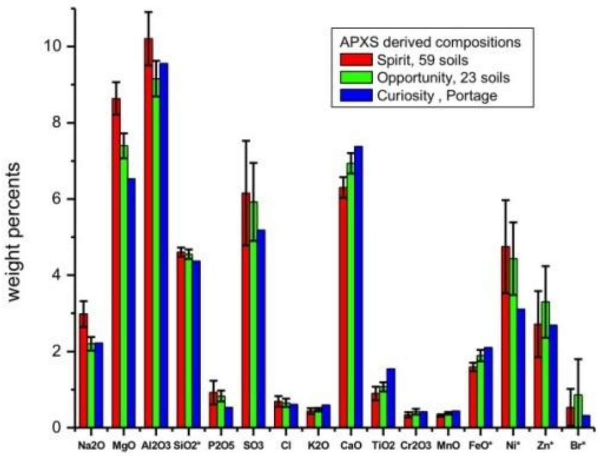
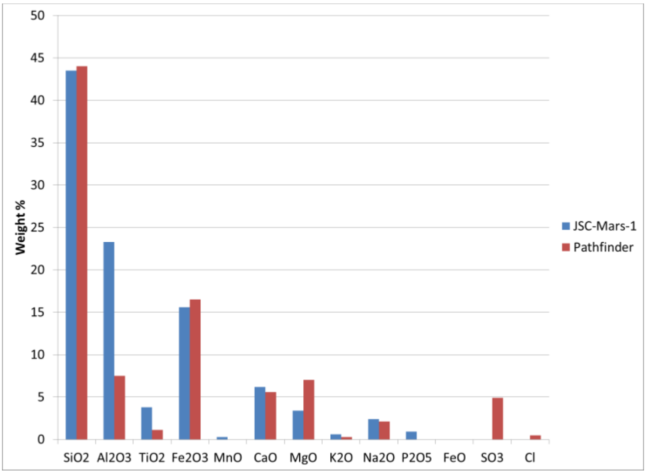


(b)

Fig. 1. (a) Landing sites of Mars missions (b) Chemical composition of Martian regolith from recent Martian sites

Although the top layer of Martian regolith has been found to be mostly uniform, the subsurface regolith may hold pockets of materials that are not dispersed evenly throughout the planet. The Mars Exploration Rover Opportunity, through an operation known as trenching, discovered dissimilarity in hematitic deposits on the surface when compared to similar samples taken from the subsurface at a depth of 8-10 cm [9]. Also, the Thermal Emission Spectrometer on board the Mars Global Surveyor found a significant variation in volcanic material in the darker colored regolith on the Red Planet [10].

NASA's Johnson Space Center has developed a Martian simulant regolith in support of research and engineering studies, known as JSC Mars-1. While not identical, this simulant roughly duplicates the chemical composition of Martian regolith. JSC Mars-1 simulant was used as one of the tested regolith simulants in this feasibility study. Fig. 2a compares the chemical composition of JSC Mars-1 simulant to results from the regolith analysis on the Pathfinder mission. JSC-1A lunar regolith simulant was also used in this study. A comparison of the two simulants is shown in Fig. 2b.



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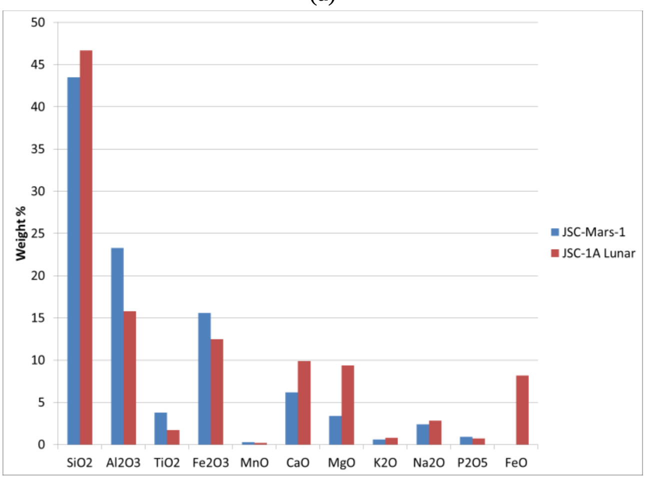

(b)

Fig. 2. Comparison of regolith simulants [11]

III. WES DESIGN AND TEST CONFIGURATION

Early WES prototypes suffered from severe slipping in regolith simulants. In order to minimize slipping, WES was outfitted with treads and weighted with two aluminum disks on the interior of the wheel. WES fully assembled weighs approximately 2.25 kg and is approximately 13 cm in diameter. The treads protrude approximately 3 mm from the surface of the wheel. The current WES prototype, shown in Fig. 3, analyzes electrostatic charge on the protruding test materials -Lucite, Teflon, G10, and Lexan.

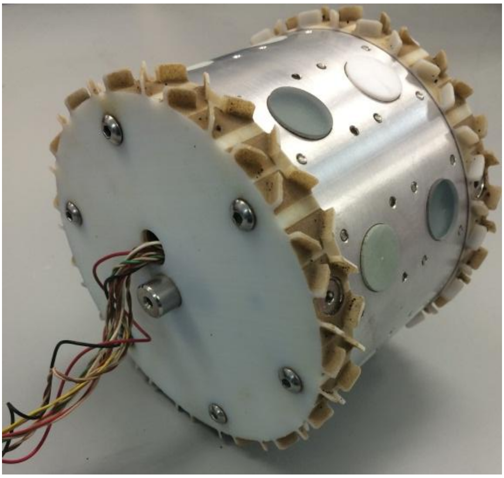

Fig. 3. Wheel Electrostatic Spectrometer second generation prototype

A precision rolling mechanism was created to roll WES repeatedly over granular materials. An acrylic tray was fabricated to house the regolith simulants to be tested and placed inside of an 80/20® extruded aluminum frame. A rolling trolley controlled by a DC motor was attached to WES. Fig. 4 displays the WES rolling mechanism.

Fig. 4. WES rolling mechanism

WES uses tribocharging sensors consisting of test materials monitored by an electrostatic induction electrode and circuit. Each induction electrode and amplification circuit is assembled on a two-layer printed circuit board, to minimize the distance the unamplified signal travels. The test materials are approximately 2 cm in diameter and protrude approximately 1 mm from the case of the wheel. The electrostatic sensor and a representation of its configuration in WES are shown in Fig. 5.

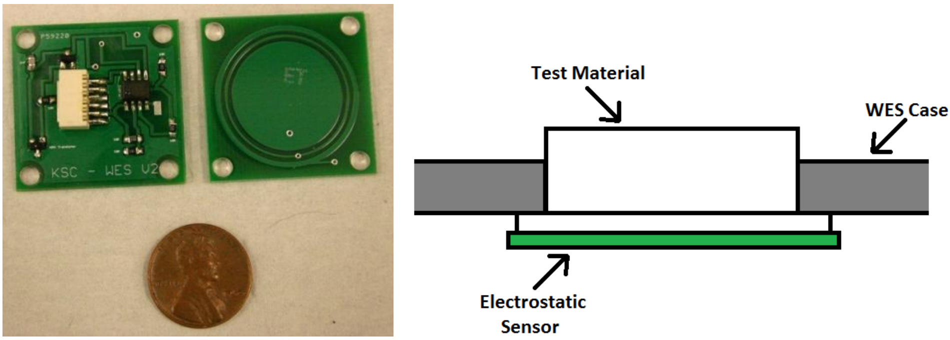

Fig. 5. Electrostatic sensor second generation prototype

As each insulator comes into contact with the regolith, an electrostatic charge exchange takes place. The test material separates from the regolith and an increased electrostatic potential develops. The electrostatic sensor output is directly proportional to the charge on the insulator. This charge (Q) is impressed on the sensing capacitor (C) in the electrometer, which generates a voltage V=Q/C. This voltage is amplified (AV) and measured as the response voltage from the electrostatic sensor. A simplified electronics diagram displaying this process is shown in Fig. 6.

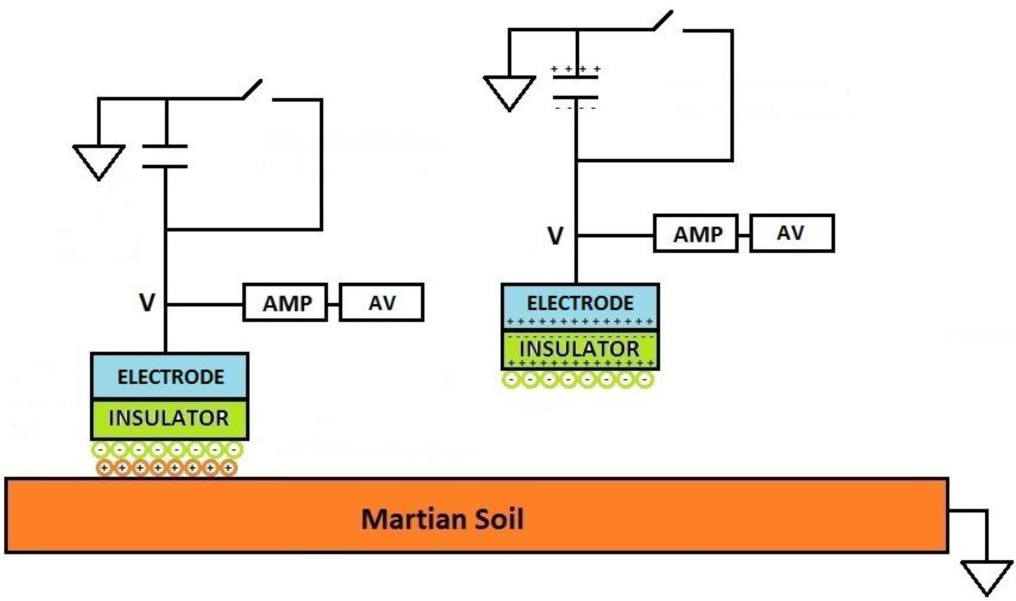

Fig. 6. Simplified electronics diagram

IV. WES TESTING

Care was taken to ensure that the WES test conditions were nearly identical for all trials. Initial tests were conducted in air at atmospheric pressure. One of the main concerns for this testing was the relative humidity (RH) prior to and during testing. The WES test apparatus was placed inside a humidity controlled chamber set to 0% RH, to mimic the extremely dry environment of Mars. The regolith and test apparatus were left to acclimate to this 0% RH environment for 12 hours. In addition, WES was rolled back and forth over the simulated Martian regolith numerous times prior to testing to ensure nearly identical simulant compactness over the many trials.

WES was rolled over each of the tested regolith simulants 25 times. At the end of each trial, the surface charge on each of the test insulators was neutralized with a fan driven AC corona static eliminator. After the surface charge was neutralized, each electrostatic sensor was zeroed. This process was adopted to increase repeatability of the tribocharging measurements based on information gained from previous testing [5]. The wheel was rolled at approximately 0.3 cm/s to approximate the average angular velocity of the current Mars Science Laboratory wheels. Fig. 7 displays the data from a typical trial.

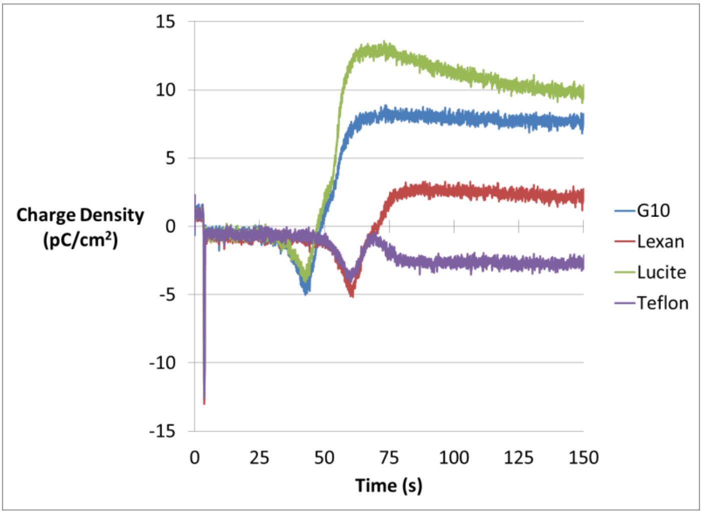

Fig. 7. WES rolled against JSC Mars-1 simulated Martian regolith

Three regolith simulants were used to analyze the electrostatic response of the test materials - Bulk Mars -1, JSC-1A >10 µm, and JSC-1A >200 µm. The data shown in Fig. 8 is the average of the peak charge density of 25 trials for each regolith type, with error bars representing the standard deviation of the peak charge for each sensor. It is apparent that the electrostatic response is different for each of the tested regolith simulants. This data indicates that a difference in grain size could be determined, in part, by the electrostatic response of materials outfitted in the wheels of a future Mars rover. These experiments also support the claim that a difference in chemical composition in Martian regolith could be sensed with wheel-based electrostatic sensors.

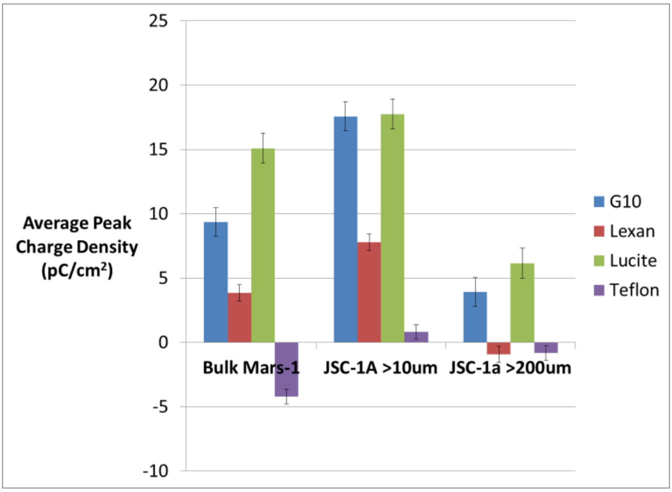

Fig. 8. WES test results

At first glance it appears that Teflon charges very little against the regolith simulants. However, contact and separation must occur for the electrostatic sensor to indicate a charge on the tested insulator material. A significant amount of dust adhesion on Teflon was noted during a majority of the trials, explaining Teflon's masked net surface charge. The regolith simulant is most likely charged positively and the Teflon negatively, which results in the dust charge partially cancelling the perceived Teflon charge. It is hypothesized that strong electrostatic forces prevented the regolith simulant from separating from the Teflon test material due to Teflon's ability to hold charge. Fig. 9 shows the electrostatic dust clinging of JSC Mars-1 simulant on Teflon, while simultaneously demonstrating the absence of this effect on G10. This suggests that future Mars missions should minimize the use of Teflon in favor of other materials that may have similar properties without the unwanted electrostatic dust clinging tendency.

Fig. 9. Dust clinging electrostatically to Teflon (top center) and G10 (bottom center)

V. MARTIAN PRESSURE STATIC ELIMINATION TOOL

As determined in previous research, the surface charge of each of the test insulators must be neutralized in order to obtain repeatable results [5]. Another portion of this feasibility study provided a proof-of-concept demonstration that a static charge eliminator could be developed for Martian atmospheric conditions. The Martian atmosphere is comprised of mostly carbon dioxide at 9 mbar, making it inherently difficult to reach the voltages used in terrestrial high voltage static eliminators. In addition, at this gas pressure, gas breakdown often results in a large volume glow discharge instead of corona discharge.

The Electrostatics and Surface Physics Laboratory at NASA's Kennedy Space Center relied on its expertise in using high voltage equipment in Martian atmospheric conditions to develop the Martian Pressure Static Elimination Tool. The static eliminator electrode geometry consisted of a central high voltage needle point encircled by a grounded electrode approximately 2.5 cm in diameter, as shown in Fig. 10.

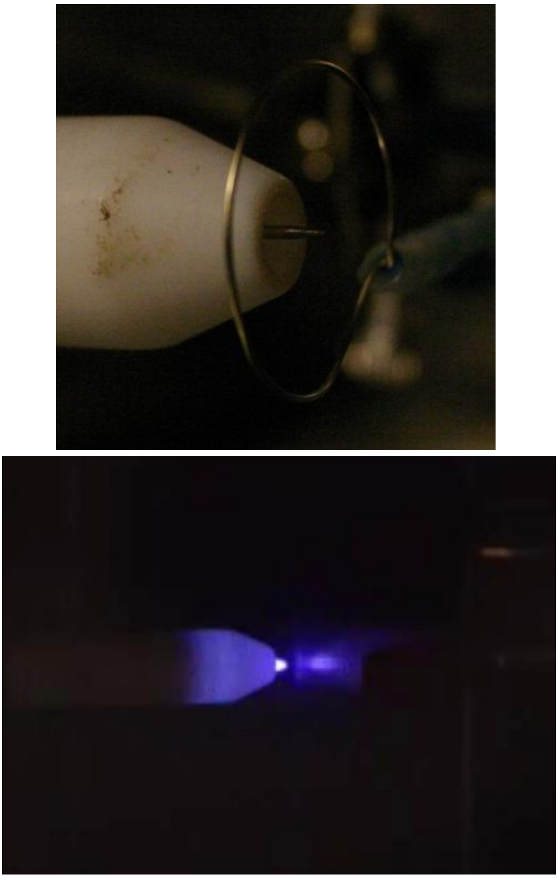

Fig. 10. Static eliminator geometry (Top), Static eliminator corona/glow discharge in a simulated Martian atmosphere (bottom)

The first prototype of the static eliminator did not have the ring ground electrode. In this case, a glow discharge formed between the high voltage needle and the test capacitor. The ions in the glow discharge left the capacitor in a charged state with a substantial residual voltage. This problem was remedied by the addition of the circular ground electrode, which limited the glow discharge to the region between the needle and ring. In this case, the electric field from the charged capacitor could extract opposite polarity ions from the glow discharge region.

High voltage positive and negative DC pulses were applied to the static eliminator point electrode. A duty cycle of 10%, amplitude of ±1.2 kV, and frequency of 10-100 Hz were used for all testing. Two large brass sheets were used to fabricate a parallel-plate high-voltage capacitor with a measured capacitance of 180 pF. One of the brass plates was connected to ground. A brass sphere was connected to the other capacitor plate and used as a contact electrode when charging the capacitor (see Fig. 11). A translating high voltage (HV) contact was used to charge the capacitor while under Martian atmospheric conditions by moving it until it made contact with the sphere. The HV contact was retracted from the sphere once the capacitor was charged. A non-contact electrostatic voltmeter was used to read the voltage on the sphere during testing. The voltage on the capacitor was monitored prior to testing to ensure that the observed voltage reduction was a result of the static eliminator and not charge loss due to a leakage path. The static eliminator was placed in a vacuum chamber on a translating mechanism to vary the distance between the HV plate of the capacitor and the static eliminator.

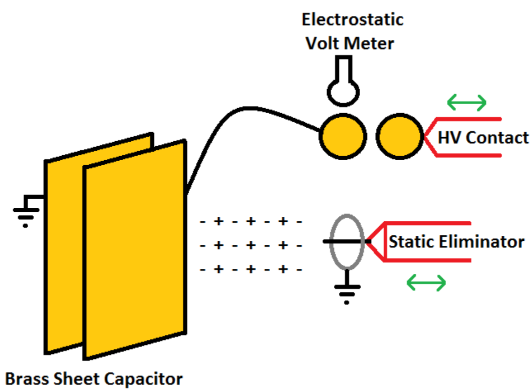

Fig. 11. Static eliminator test configuration

To test the effectiveness of the Martian Pressure Static Eliminator, the frequency was varied between 10 and 100 Hz and the distance between the static eliminator and the target capacitor was varied between 5 and 25 cm under Martian atmospheric conditions. It was discovered that increasing the frequency and decreasing the distance lowered the time needed for static elimination. However, even at a distance of 25 cm the static eliminator was able to reduce the capacitor voltage to less than 20% of the initial voltage in less than one second. A sample of the results from these tests is shown in Fig. 12.

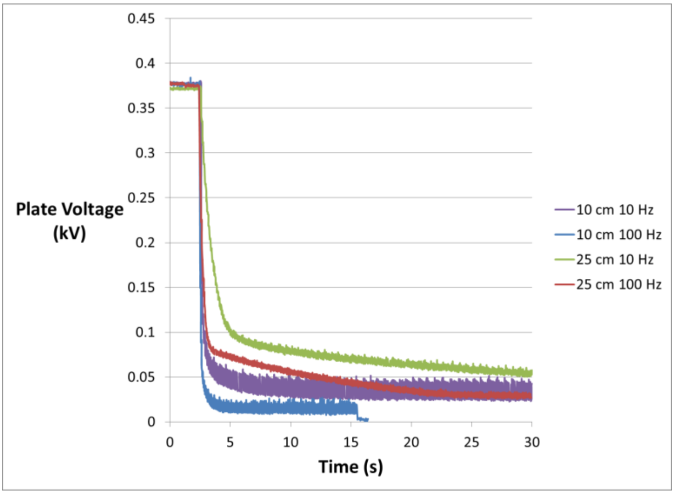

Fig. 12. Discharging a 180 pF capacitor in a simulated Martian atmosphere using two static eliminator waveform frequencies and two distances of the eliminator

An experiment similar to the previously described test was performed with the WES geometry. To create a parallel-plate capacitor that would match the capacitance of the WES sensor geometry, copper tape was placed on the top of the WES Teflon insulator and on the back of the electrostatic sensor. The same method for charging the capacitor in the previous experiment was also used for this capacitor. The static eliminator was placed approximately 10 cm from the test sensor capacitor. Fig. 13 shows the test configuration for this experiment.

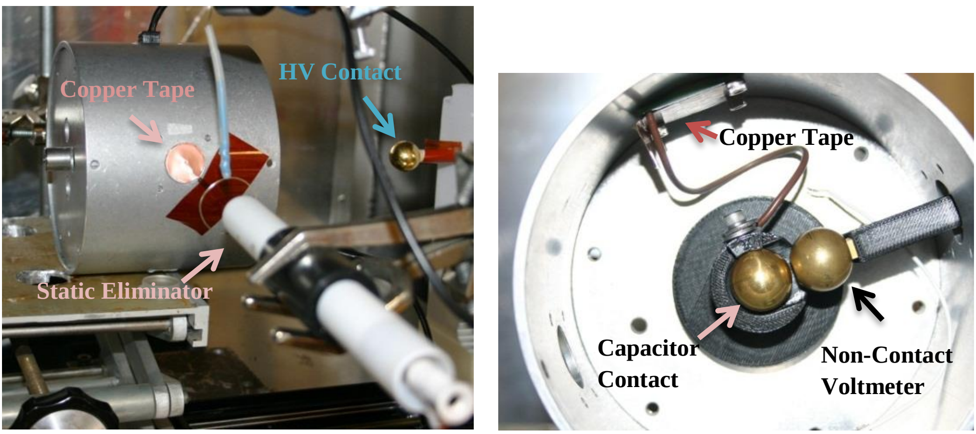

Fig. 13. Experimental setup for testing for the WES sensor geometry

The WES sensor-based capacitor was charged to approximately 360 volts and monitored for several minutes to verify minimal charge loss. Fig. 14 displays the data from this testing. In one trial, the capacitor was charged with positive voltage. In a second trial, the capacitor was charged with negative voltage. The positively charged capacitor’s voltage decreased to less than 10% of the original voltage within 0.04 seconds. For the negative voltage trial, the capacitor voltage dropped below 10% within 0.3 seconds. The results indicate that in this geometry, a static eliminator with the proper electrode geometry and waveform can be used to rapidly and substantially remove static charge built up on a surface in a Martian atmosphere, even when the surface has some capacitive coupling to ground.

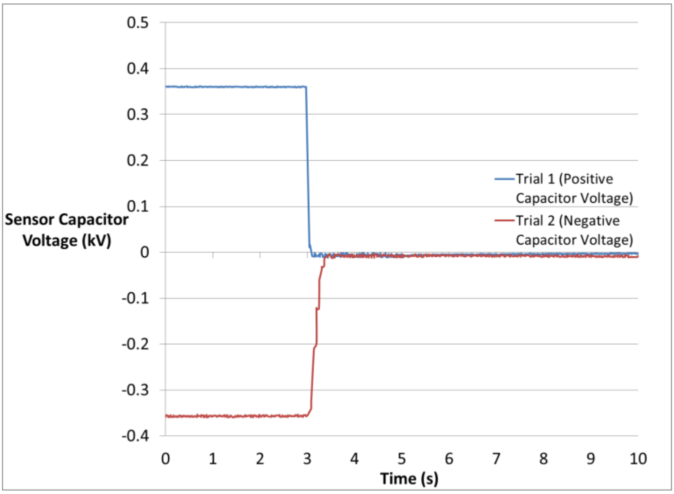

Fig. 14. Static elimination testing on WES sensor based capacitor in a simulated Martian atmosphere

VI. CONCLUSIONS

The tests discussed in this paper demonstrate the feasibility of wheel based electrostatic sensors to act as a prospecting aid on the Martian surface. A difference in electrostatic response was demonstrated when rolling against different regolith simulants and grain sizes in a well-controlled environment, indicating that WES has potential to drastically increase the efficiency in searching for materials with certain properties. While this instrument is not designed to replace any existing equipment, as the information retrieved from current analysis tools is far superior to that of the developed electrostatic sensor array, it may alert mission scientists when the rover is rolling on a different type of material. In addition, a proof of concept Martian pressure static eliminator was developed. This device is an enabling technology for wheel based electrostatic sensors.

Future work will focus on experiments with regolith simulants that have been doped with materials of interest for ISRU processes. To further test the feasibility of WES, this instrument should be incorporated into an existing field demonstration rover to better understand how the electrostatic responses of the test materials change in an operational environment, where key variables will be less controllable. Ideally, these tests would be conducted under low ambient humidity.

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