Controlled particle removal from surfaces by electrodynamic methods for terrestrial, lunar, and Martian environmental conditions

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Abstract. An Electrodynamic Dust Shield to remove already deposited micron-size particles from surfaces and to prevent the accumulation of such particles on surfaces has been developed. In addition to terrestrial application, our NASA laboratory is adapting this technology for the dusty and harsh environments of the Moon and Mars. The Apollo missions to the moon showed that lunar dust can hamper astronaut surface activities due to its ability to cling to most surfaces. NASA’s Mars exploration landers and rovers have also shown that the problem is equally hard if not harder on Mars. In this paper, we show that an appropriate design can prevent the electrostatic breakdown at the low Martian atmospheric pressures. We are also able to show that uncharged dust can be lifted and removed from surfaces under simulated Martian environmental conditions. This technology has many potential benefits for removing dust from visors, viewports and many other surfaces as well as from solar arrays. We have also been able to develop a version of the electrodynamic dust shield working under hard vacuum conditions. This version should work well on the moon. We present data on the design and optimization of both types of dust shields as well substantial data on the clearing factors for transparent dust shields designed to protect solar panels for Martian exploration.

1. Introduction

The surfaces of Mars and the moon are covered with a layer of dust. On Mars, the fine surface material on the surface is fairly homogeneous due to the dust transport mechanism caused by the global dust storms taking place every twenty to thirty months as well as by the daily dust devils. Many of the Martian landing missions that started in the 1970s have included landers and rovers. Except for the individual dust clearing events experienced by NASA’s Spirit and Opportunity rovers—believed to have been produced by a passing dust devil—the accumulation of dust on the rover’s solar panels decreases their efficiency. This dust transport mechanism does not exist on the moon, since it has essentially no atmosphere (it has an atmospheric pressure of \(10^{12}\) mbar). However, certain observations during the Apollo missions supported the existence of dust transport on the moon [1].
horizon glow was reported by Apollo astronauts [2]. This glow has been interpreted as evidence of transient dust clouds above the lunar surface that could reach several km above the surface. Observations with the lunar Surveyor spacecraft [3] and the Lunar Ejecta and Meteorites Experiment (LEAM) on Apollo 17 indicated the presence of dust clouds [4]. Although no theoretical model satisfactorily explains the phenomenon, it has been suggested that electrostatic charging of the lunar surface due to exposure to charged particles from the solar wind as well as UV radiation could result in the levitation and transport of dust particles [5]. Even if the amount of levitated dust is negligible or nonexistent, robotic and human activities taking place during lunar exploration missions will stir up large amounts of dust, as occurred during the Apollo missions.

The development of efficient dust mitigation solutions is critical for the success of any mission to the moon and for future human missions to Mars. The Electrodynamic Dust Shield technology developed by our group is perhaps the first active method of automated dust removal from surfaces. Prototypes of the dust shield have been tested under Martian and lunar simulated environments.

2. The Electrodynamic Dust Shield.

Masuda et al showed that triboelectrified macroscopic particles can be transported by an electromagnetic traveling wave [6-9]. In the electric curtain, as they called their method, a series of parallel electrodes connected to an AC source generate a traveling wave that acts as a contactless conveyor. Particles are repelled by the electrodes used to produce the field and travel along or against the direction of the wave, depending on their polarity.

The curtain electrodes can be excited by a single-phase or a multi-phase AC voltage. In the single-phase electric curtain, parallel cylindrical electrodes connected to an AC voltage source, as shown in Fig. 1 (left), generate an electric field whose direction oscillates back and forth as the polarity of the electrodes changes. In this case, a standing wave is produced which would produce a force on any charged particle in the region of the field. A multi-phase electric curtain (Fig. 1 (right)) produces a traveling wave, since the potential at each electrode changes in steps due to the phase shift. A charged particle in this region will move with or against this wave, depending on its polarity.

![Figure 1](image)

Although the forces responsible for the levitation of the particles are highly dependent on their charge, uncharged particles can ultimately be removed from the curtain as well. It has been well documented that polarizable particles can be levitated using these techniques [10]. Since many larger neutral particles contain nearly equal amounts of positive and negative charges on their surface, these particles possess an extrinsic electric dipole moment. If this dipole moment is exposed to a spatially non-uniform electric field, the particles will experience a force. Likewise, particles with intrinsic electric dipole moments or containing polar materials like water will also experience a force. The movement of particles with internal electric dipole moments in a non-uniform electric field is called the dielectrophoretic force [11]. All that is required for levitation is that the particles have a different dielectric constant than that of the surrounding medium.

An Electrodynamic Dust Shield has been developed that can remove dust from surfaces and prevent dust accumulation [12-15]. This technology is based on Masuda’s electric curtain method. Two types of screens were designed and built. Opaque shields, with thin cylindrical copper electrodes on a circuit board substrate and transparent shields using indium tin oxide (ITO) electrodes on a polyester substrate. The shields are coated with a transparent dielectric to decrease their breakdown potential.
3. Experiments

Experiments at ambient conditions, at simulated Martian and lunar conditions were performed. The dust simulants used for the testing was Mars JSC-1 simulant [16], JSC-1a Lunar Simulant, and Minnesota lunar simulant. The Mars JSC-1 simulant was sieved into different size bins.

To quantify the behavior of screens, a clearing factor CF was defined in the following way.

\[
CF = \frac{(\text{Initial Dust} + \text{Screen}) - (\text{Final Dust} + \text{Screen})}{(\text{Initial Dust} + \text{Screen}) - (\text{Screen})}
\]

CF can be used to judge the performance of the screen while changing peak voltage, operating frequency, pulse pattern, coating thickness, line spacing, line width, atmosphere (terrestrial, Martian, lunar) [21]. For all experiments reported here, the clearing factor was measured after 100 cycles of the waveform.

3.1. Ambient Conditions

Experiments with opaque and transparent screens were performed at ambient conditions. Figure 5 shows an example of 0.02 g of Mars JSC-1 simulant evenly spread in the middle of a screen. After energizing the shield, the simulant is cleared to the edge of the board.

Figure 2 (left) shows an example of a transparent screen with Mars JSC-1 simulant spread over its entire surface. Figure 2 (right) shows the same screen after energizing. About 80% of the dust was cleared, revealing the solar panel underneath. A small portion of dust remains on the right side of the screen directly over a dead trace in the ITO (That trace had been damaged in handling during repeated experiments). In damage-free portions of the screen, there is very little difference in performance between the copper screens and the ITO screens.

Figure 2 (Left). Transparent screen covered with Mars JSC-1 simulant. (Right) Transparent screen after energizing. The solar panel below the screen is revealed.

Figure 3. CF vs. trace spacing in air at STP. Figure 4. CF vs. frequency in air at STP.
The next set of figures shows the result of experiments of clearing factor while varying different parameters. Figure 3 and 4 show clearing factor vs. parameter for Mars JSC-1 simulant in air at standard temperature and pressure (STP). Some of the behavior at ambient conditions can be applied to the Martian and lunar environments, but there are a few, nontrivial differences in parameter choice for optimum CF with changing atmosphere. Each point in these graphs represents the average of 10 trials. The error bars represent the standard deviation of those 10 trials. Overall, smaller trace spacing results in better CF.

The operating frequency of the screen has almost no effect on CF at 1500 V, presumably because the particles travel many grid spacings and have a large momentum (Fig. 10). At lower voltages, there is weak frequency dependence. Note that the drop at 20 Hz is real and repeatable.

3.2. Simulated Martian Conditions

Tests were performed with several shields with 0.5 mm trace spacing. The Martian simulant was kept in a vacuum oven at temperatures above 120°C and atmospheric pressures of about 1 kPa for several days to obtain a relatively high degree of dryness in the simulant.

In an effort to neutralize any possible charge accumulation on their insulating coatings, the shields were exposed to an ionizer prior to dust loading. The shields were run with a complex waveform consisting of alternating Moesner and Higuschi and sine waveforms at 10 Hz with an amplitude of 400 V. The shields were repeatedly activated for about one minute followed by a five-minute deactivation period. Figure 5 shows the shields before and after activation.

![Figure 5 (Left). Dust shield covered with Martian simulant dust in vacuum chamber at 7 torr. A halogen lamp shines on the shield, which sits on a solar panel. The potential of the solar panel is monitored. (Right) Dust shield in vacuum chamber at 7-torr CO$_2$ after shield operation.](image)

In an effort to determine if glow discharges occur at the low limiting potentials at Martian environmental conditions, we measured the currents for a shield driven by sine and square waveforms at a frequency of 10 Hz with an amplitude of 400 V. These currents were of the order of 15 μA for the sine wave and 70 μA for the square wave signal.

3.3. Simulated Lunar Conditions

Preliminary experiments with JSC 1a simulant were performed in a vacuum chamber at 10$^{-6}$ kPa. As was done for the Mars tests, the lunar simulant was kept in a vacuum for several days. The shields were driven with a Mosener and Higuchi waveform with a maximum amplitude of 1,200 V (higher potentials result in electrical breakdown through the substrate or the coatings). The shields used in these runs had trace spacings of 0.5 to 1.0 mm. Aerosolized simulant dust (<20 μm) was deposited on the shields under very low relative humidity conditions (Fig. 6).
The potential generated by a halogen lamp shining on a solar panel placed under the shield was monitored and the data was recorded. The voltage generated by a reference solar panel covered with a clean screen placed in the chamber alongside the screen was also monitored. These voltages were used to quantify the shield performance. Figure 16 shows the shield after activation. Solar panel generated voltages were measured for two different shields with 0.76 mm trace spacing. A shield clearing efficiency of 71% was measured.

At lunar pressures, the breakdown voltage is very high; therefore, it is possible to run the screen without an insulating layer. Figure 7 shows CF of Minnesota lunar simulant vs. voltage at 10⁻⁶ kPa, simulating lunar pressure. Again, the CF increases with increasing voltage. It is interesting to note that at 400 V there was no motion of the lunar simulant, resulting in a clearing factor of zero. Figure 8 shows CF vs. trace spacing at 10⁻⁶ kPa. The data are somewhat sparse to draw definitive conclusions, but the overall trend of decreasing CF with increasing spacing is evident.

4. Discussion
For operation in air at STP, clearing factors of 95% or greater were achieved, and performance was not heavily dependent on screen parameters. In the Martian atmosphere, peak voltage is limited to 400 V due to Paschen breakdown. With correct parameterization of the screen, 90% clearing factor can be obtained. To further quantify the shields operating under Martian environmental conditions, the potentials generated by a halogen lamp shining through the semitransparent boards of the shields onto a solar panel were monitored. These potentials were measured relative to the potential of a shield covered with simulant prior to shield activation. Operation of the shields at simulated Martian
conditions is more problematic due to Paschen breakdown that limits the maximum applied potentials running the shields to 400 V. These relatively low potentials clearly provide less energy to transport the particles than the 1,200 to 1,500 V permitted at ambient conditions. A combined Moesner and Higuchi-sine waveform was used to drive shields at Martian simulated conditions. Clearing efficiencies improved considerably. The values of the electric currents measured for the sine and square waveforms driving the shields suggest that there is some power loss due to glow discharge. A 10% increase in current drawn for a given shield at Martian pressures compared to ambient atmospheric pressure.

5. Conclusions
Electrodynamic dust shields have been designed and constructed to effectively remove already deposited dust from surface or to prevent the accumulation of dust. This shields, based on the electric curtain concept, are activated by three-phase power supplies providing a Moesner and Higuchi square wave based signal combined with a simple sine waveform. We have been able to optimize the shields in terms of electrode width and separation, driving frequency and maximum amplitude, and dielectric coating for three specific environments: terrestrial at ambient conditions, a Mars simulated atmospheric environment, and a lunar simulated environment. Applications to instrument viewports for lunar in situ resource utilization processes are currently being investigated.

6. References
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