Lunar Dust Mitigation and ARTEMIS Mission Operations

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Background:
Apollo 17's far Ultraviolet-Visible Spectrometer (UVS) primary objective was to measure the composition and density of the lunar atmosphere (Fastie et al. 1973). The Apollo UVS provided density measurements from 101 – 104 cm^{-3} for several elements and compounds. Interestingly, the surface concentration of H was < 10 cm^{-3} and the concentration of H^2 was < 1.2 x 104 cm^{-3}. The solar wind protons could be converted into H_2 at the lunar surface (Fastie et al. 1973), thus refining estimates on the atomic oxygen density and providing estimates for comparable O/Na ratios in the atmosphere of the Moon (Feldman and Morrison 1991). Moreover, an UVS instrument onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite, characterized the lunar exosphere by detecting (i) resonance scattering emissions of K and Na in the lunar atmosphere and (ii) scattered sunlight by suspended dust particles (Colaprete et al. 2015).

Introduction:
Each year the Moon is bombarded by about 106 kg of interplanetary micrometeoroids of cometary and asteroidal origin. Most of these projectiles range from 10 nm to about 1 mm in size and impact the Moon at 10–72 km/s speed. Much of the excavated mass returns to the lunar surface and blankets the lunar crust with a highly pulverized and ''impact gardened'' regolith of about 10 m thickness. Micron and sub-micron sized secondary particles that are ejected at speeds up to the escape speed of 2300 m/s form a perpetual dust cloud around the Moon and, upon re-impact, leave a record in the microcrater distribution [1]. The mean grain size of soil samples returned from the Apollo and Luna programs averaged between 60 and 80 mm, but it also included a significant micron and submicron population. Apollo samples revealed the presence of a variety of grain morphologies with agglutinates of irregular and sharp edges to smoother glass droplets of volcanic origins [2]. Apollo astronauts also discovered dust particles levitating over the regolith surface that caused many technological problems, compromising the performance of landing vehicles. Based on the results of these missions, it was concluded that micron- and submicron- sized dust particles levitating above the surface, posed a barely surmountable obstacle in further research and exploration of the Moon [3].

Mission	Problem
Apollo 12	Lock buttons of the equipment conveyor very hard to manipulate because of the dust accumulation in the moving parts
Apollo 15	Camera drive mechanisms got jammed with dust and prevented it from working
Apollo 16	Battery cover of radiator jammed because of dust accumulation in the mechanism
Apollo 17	Some of the moving components of the geopallet got stuck after the second EVA; the angle adjustment of some geological tools (scoop and rake) got fixed in one position which could not be changed anymore; multiple components attached to the rover jammed because of the dust exposure (e.g. bag holders, pallet locks)

Table 1. Apollo mechanisms dust-related problems based on the astronaut de-briefings [4].

Observations by the Apollo astronauts of sticking of dust to their space suits even after short extravehicular activities demonstrated the importance of control of dust contamination. Simple instruments placed on the lunar surface monitored both natural and man-made dust coverage and cleansing effects that are not fully understood [5]. Fine grains from the surface can be lofted due to human activities, but there is also an evidence that a fraction of the lunar fines is electrostatically charged and naturally transported under the influence of near surface electric fields. Conjectured resulting transport phenomena range from the levitation of micron size dust grains at low altitudes (centimeter to meter height) to the lofting of sub-micron particles to tens of kilometers. The outstanding issues of the lunar dust environment are the unambiguous detection of electrostatic lofting of dust from the lunar surface and the measurement of the impact ejecta cloud. The existing remote sensing and in-situ observations do not directly prove that the processes leading to dust charging, mobilization, liftoff and transport are active on the Moon. A series of laboratory experiments were conducted to investigate the charging and mobilization of dust under simulated conditions. While it was difficult to reproduce the variable UV and plasma environment of the Moon, the experiments provide insight into the possible physical process responsible for lunar dust transport. The levitation of dust particles in plasma sheaths, where the electrostatic forces balance the gravitational force was achieved by Sickafoose et al [6]. Dust was observed to collect charge on surfaces exposed to plasma and subsequently transported both horizontally and vertically above an electostatically biased surface that repelled electrons [7]. Dust was also observed to be transported on surfaces having different secondary electron yields in plasma with an electron beam, as a consequence of differential charging [8]. Transport by electric fields occurring at electron beam impact/shadow boundaries has been also shown to result in the formation of dust ponds (Wang et al., 2010).

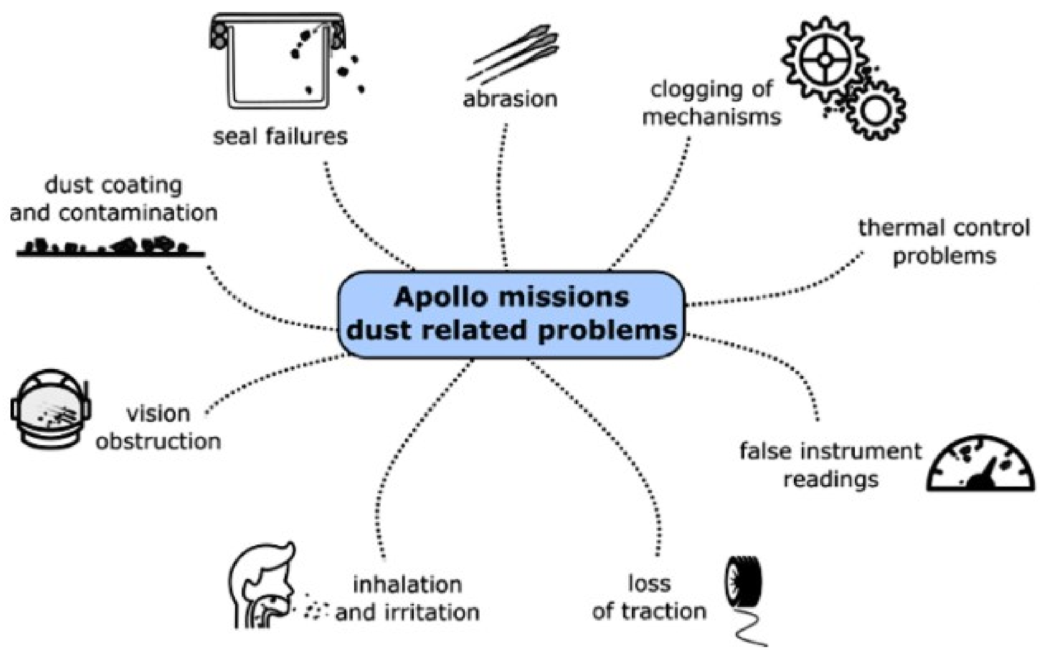
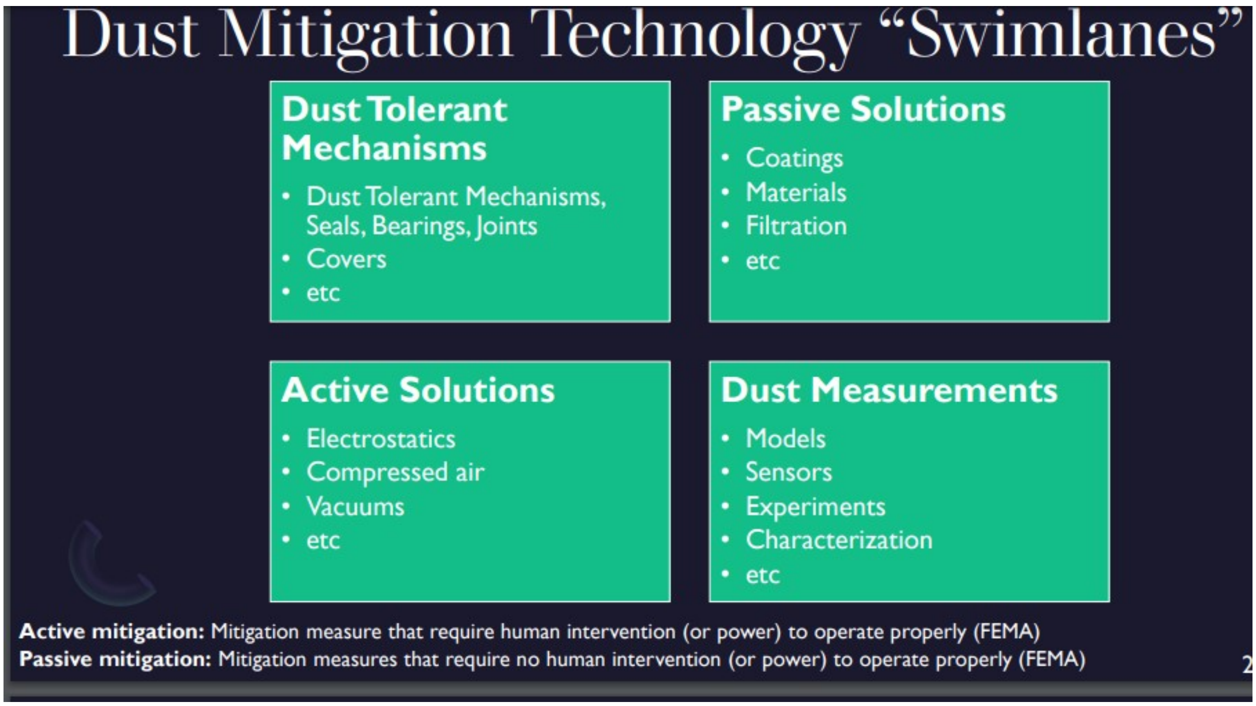


Figure. Apollo dust related problems chart, based on categorization [9].

Problems with Apollo surface equipment that suffered from dust damage developed as rigid-body mechanisms. Rigid-body mechanisms consisted of stiff elements connected by kinematic pairs (hinges, sliders etc.), such as an opening mechanism of a sample container with a hinge attached to the lid. The process of dust related damage propagation for such mechanisms starts with the contamination. The dust particles enter the backlashes (gaps) in the mechanism, increasing the friction in the mechanism and, therefore, the energy required for operations. Prolonged accumulation of dust further increases the friction in the mechanism, which ultimately leads to jamming. Some examples of dust-related damage of mechanisms mentioned in the Apollo de-briefing reports and discussed in the literature are presented in Table 1. The common cause of these problems is the exposure of the gaps between adjacent sliding or rolling elements in the mechanisms to move above the lunar surface, dust protection by exposure avoidance is challenging. The lack of inter-element gaps makes compliant mechanisms resilient to jamming caused by lunar dust: this approach can be categorized as an implicit dust mitigation technology complementary to already well established active and passive dust mitigation technologies [10]..It is important to note that there is no single dust mitigation technology that can solve all dust induced problems [11].

NASA's Artemis missions will be challenged by the abrasiveness, thermal and optical properties, and electrostatic charging of lunar dust, which will wear on spacesuits, seals, air filtration systems, and static structures like solar arrays and thermal radiators just as it did throughout the Apollo missions. Several ongoing research endeavors throughout the industry evaluate passive coatings for dust mitigation. However, passive solutions have some key challenges to overcome. Passive solutions must compete with an electrically charged lunar regolith which can change charge based upon the lunar cycle, exposure to radiation, and solar winds. Dust will also be charged, transported, and deposited on thermal radiators due to plume surface interactions. Surface treatments and coatings have historically shown unforeseen impacts on thermal performance. At least one active dust mitigation strategy will be necessary for long-term human inhabitancy of the Moon.



Typical implementations of Electrodynamic Dust Shielding (EDS) involve electrodes embedded in a surface that function as an interdigitated capacitor and uncharged particles using forces generated by fringing electric fields. In particle size regimes of 20 to 500 µm, Coulombic forces dominate over other forces, such as adhesive and gravitational forces [12]. Thus, an EDS can successfully remove and transport particles within this regime. EDS systems are designed to work on small scale particles [13]. In earth's atmosphere, Guo et al. showed that EDS can clear up to 90 % of dust from solar panels, on timescales of around 30 seconds [14].Similar experiments were conducted using a lunar dust simulant, JSC-1A, where 20 mg of dust was deposited on solar panels with various electrode configurations. The solar panels operated at 20 % capacity of the panel's original output voltage without any dust mitigation, but after two minutes of EDS activation, the capacity returned to 90 %. After 30 minutes, the capacity of the solar panels reached 98 % of the original voltage output [15]. EDS has also been tested in various reduced gravity and vacuum environments. As an active mitigation strategy, current electrodynamic dust shielding (EDS) actuations require very high voltages (in the thousands of volts) to operate and effectively repel dust particles. The high voltage necessitates additional electronics to convert the supply power from typical avionics (in the tens of volts) to the EDS panels. The integration of the EDS into a surface is a complex process, which requires design considerations during the radiator design process so as to not affect radiator performance while still allowing good dust mitigation. There is little doubt that there will be systems or subsystems which cannot utilize the integrated EDS solution [16].

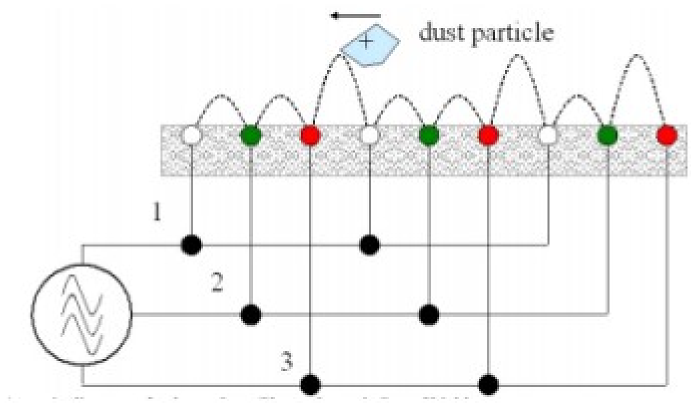


Figure . Schematic showing the electrostatic dust shield (EDS) working to move charged dust particles [17].

Problem:
Simple instruments placed on the lunar surface monitored both natural and man-made dust coverage and cleansing effects that were not fully understood [18]. Apollo astronauts observed dust sticking to their spacesuits even after short EVAs, demonstrating the need for control of dust contamination. The short-duration Apollo missions suggested lunar dust may critically affect future technical systems with mission timelines spanning months, years, or even decades [19].

Purpose:
Although active dust removal is a viable mitigating strategy, this paper aims to explore passive dust mitigation strategies because spacecraft and surface systems are often energy limited. Passive dust management minimizes adhesion-enabled electrostatic forces between the surface and the dust [20].

Method and Results (TBD):
Several ongoing research programs from a literature review will be evaluated per passive coatings for dust mitigation. However, passive solutions compete with a variable electrically charged lunar regolith. Early work suggesting active dust mitigation management necessary for long-term human inhabitancy of the Moon, will be explored [21].

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