Electron-beam Lunar Dust Mitigation (ELDM) Technology

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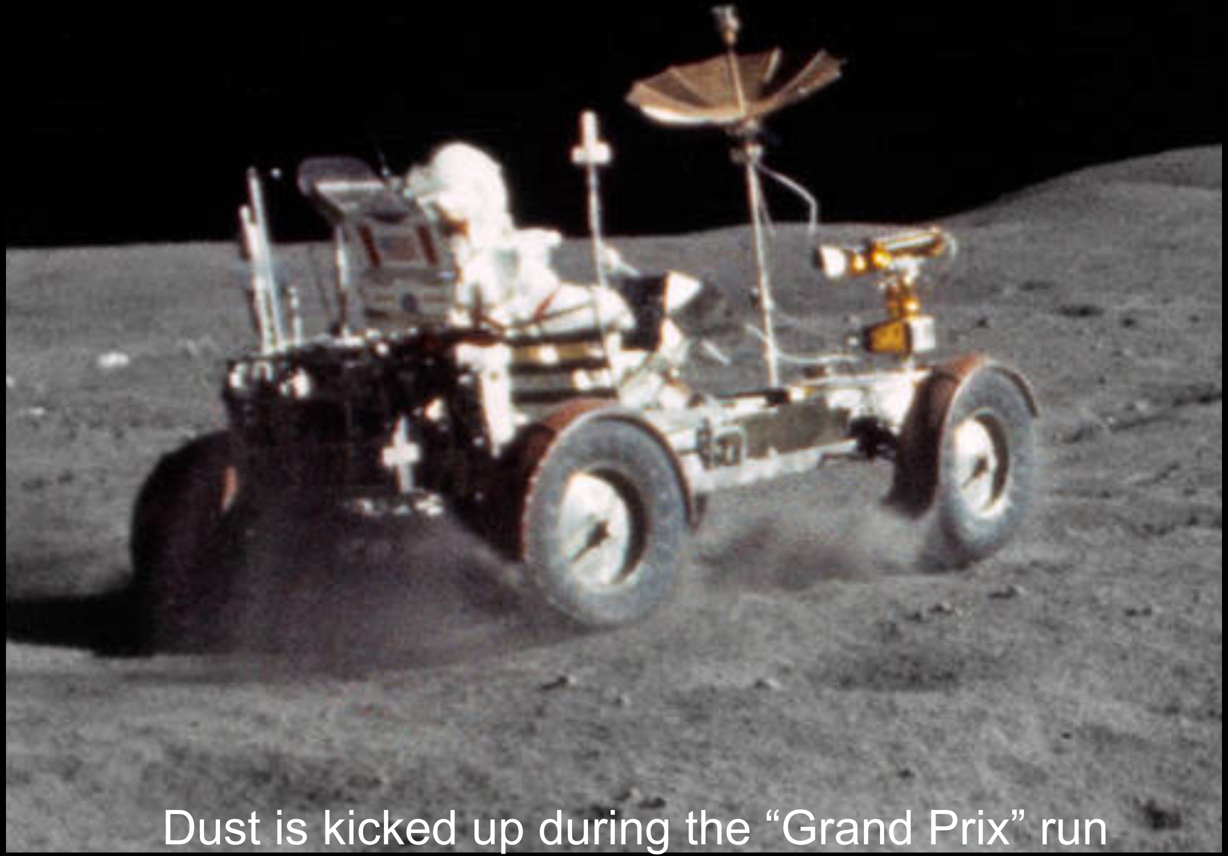
Dust Hazards during Exploration Activities

Jack Schmitt's spacesuit is covered in dust during his field investigation



Dust is kicked up during the "Grand Prix" run of the Apollo 16 Lunar Roving Vehicle (LRV)

NASA

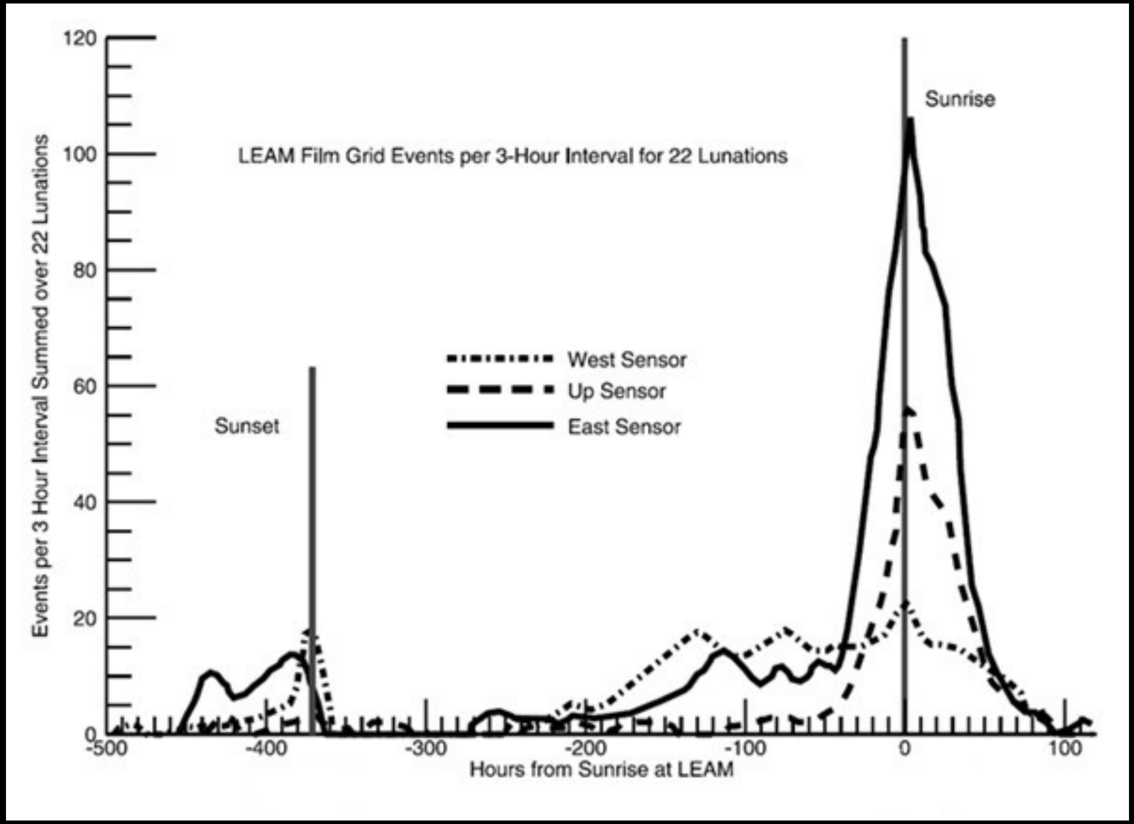
Dust Hazards due to Natural Processes
(Electrostatic dust lofting/transport)

Lunar Horizon Glow

NASA

Low-speed Dust Detection Near Terminator

by the Lunar Ejecta And Meteorites (LEAM) experiment



Berg et al., 1976

Dust Impact on Human Exploration

- Charged dust sticks to all exploration system surfaces, causing various issues:
    - Damage to spacesuits
    - Degradation of thermal radiators and optical components
    - Failure of mechanisms
    - Health risks for astronauts

- Dust mitigation is needed in a timely manner to ensure the success of Artemis missions and enable future long-term, <u>sustainable</u> human exploration on the lunar surface, as identified by the Lunar Surface Innovation Consortium (LSIC).

Current Dust Mitigation Technologies

Reviewed by Afshar-Mohajer et al., 2015

<u>Fluidal Methods</u>

Compressed gases/liquids (e.g., *Peterson & Bowers, 1990; Wood ,1991*)

<u>Mechanical Methods</u>

Brushing or vibrating (e.g., *Gaier et al., 2011a,b; Gaier et al., 2012*)

<u>Electrodynamic Dust Shield (EDS)</u>

Dust is cleaned by the traveling wave of e-field created by applying oscillating high-voltage (HV) on electrodes embedded beneath target surfaces (e.g., *Calle et al., 2006, 2009, 2011; Kawamoto & Hashime, 2018*)

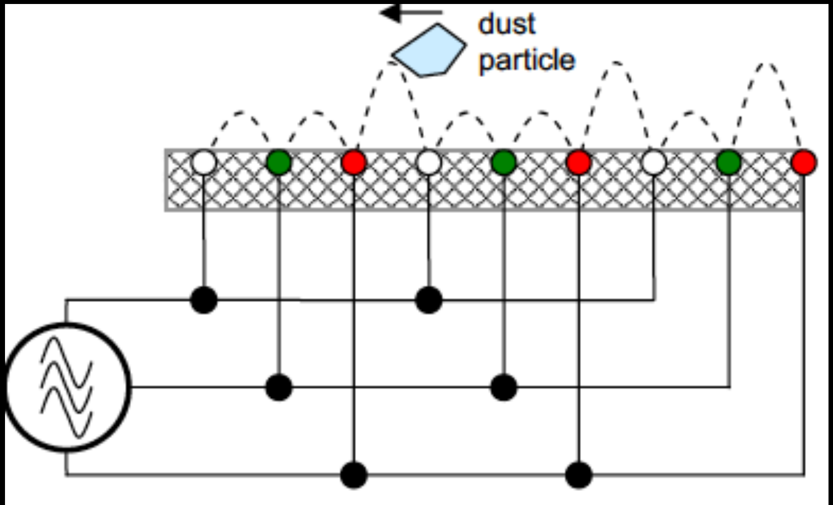
<u>Electrostatic Removal</u>

Applying DC high-voltage to remove charged dust (e.g., *Kawamoto, 2012*)

<u>Passive Methods</u>

Surface modification to reduce the dust-surface adhesion (e.g., *Gaier et al., 2011a,b; Dove et al., 2011*)

Electrodynamic Dust Shield (EDS)

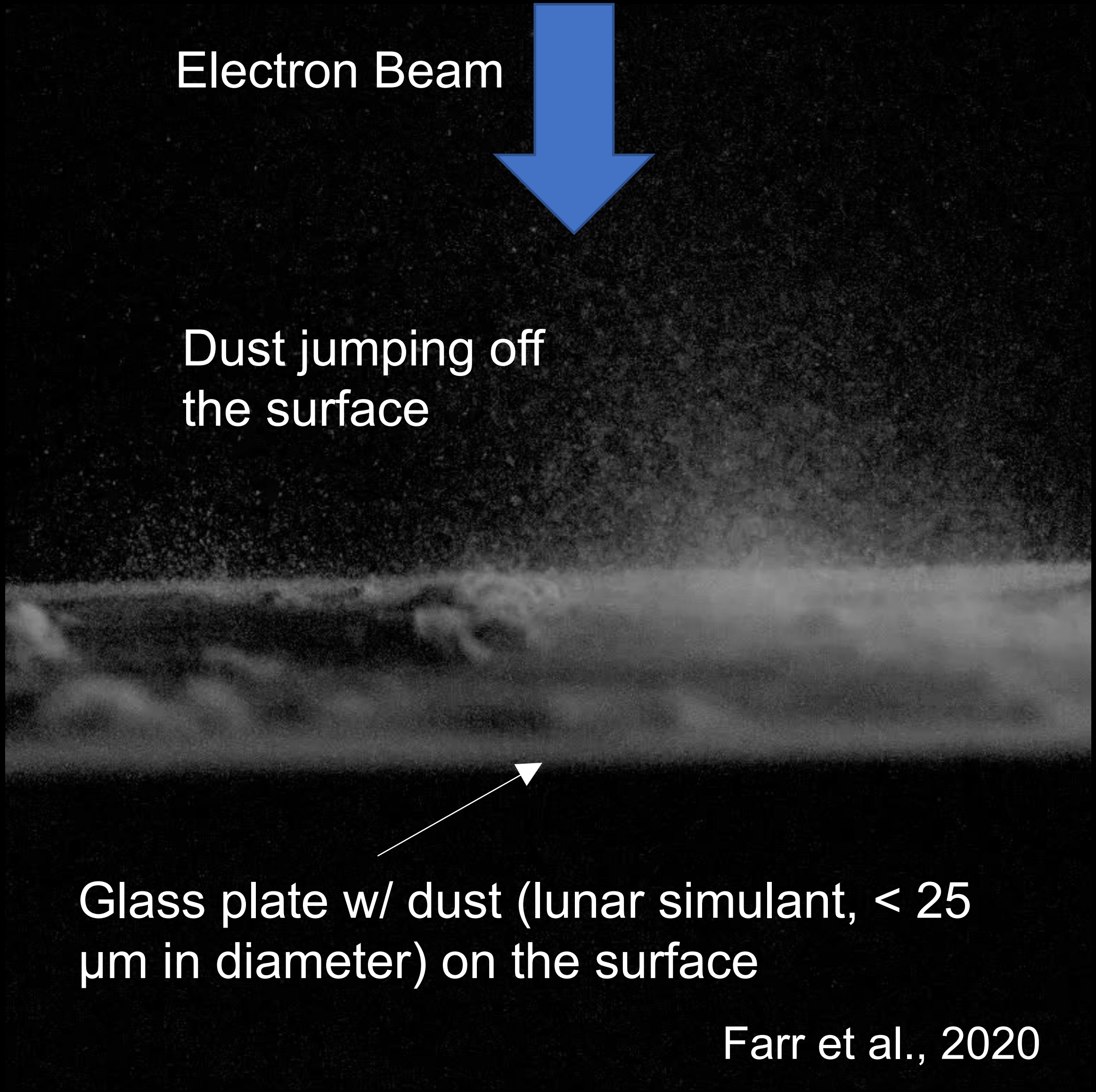


Calle et al., 2011

Current technologies all have advantages and <u>disadvantages</u> including low efficiency, prefabrication, HV safety issues, surface damage, or using consumables.

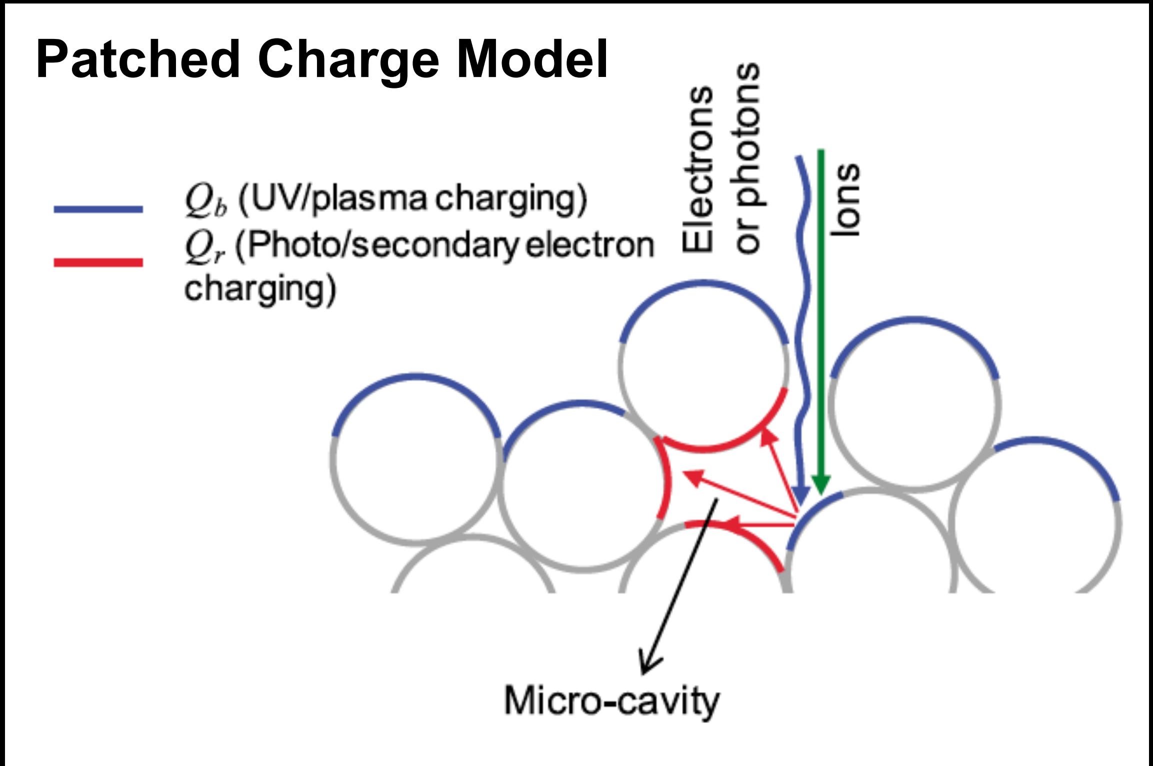
Novel Technologies are needed.

Dust Mitigation Utilizing an Electron Beam



Farr et al., 2020

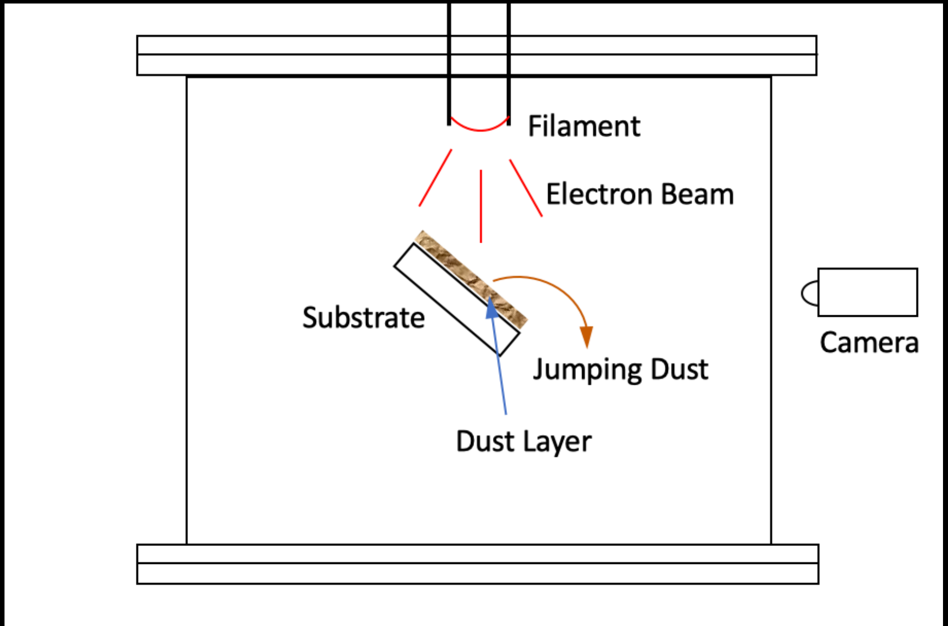
Dust Charging and Release Mechanism



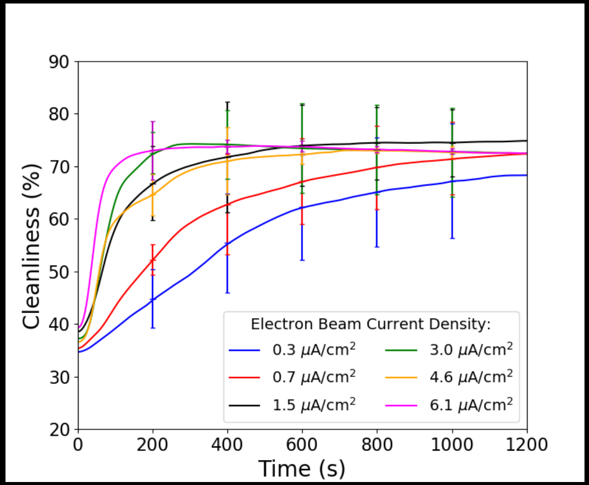
Wang et al., 2016

Secondary electrons absorbed inside microcavities result in a buildup of substantial negative charges on the surrounding dust particles, and repulsive forces cause them to be released from the surface.

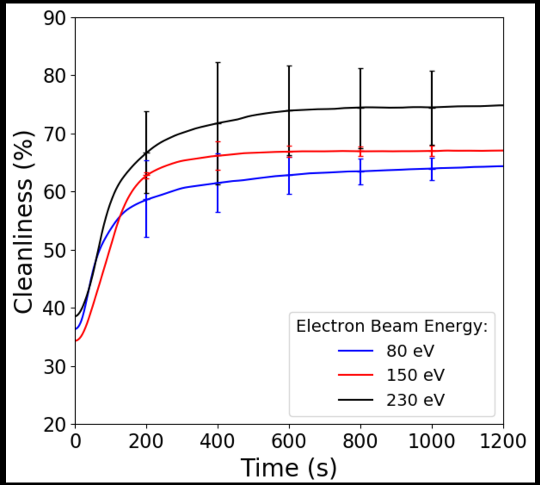
I. Fixed Beam Angle to the Sample Surface



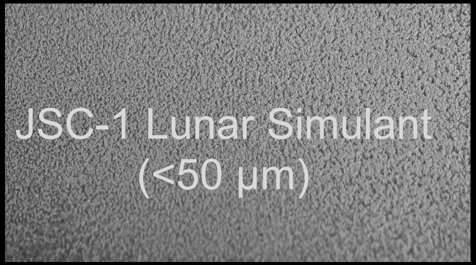
Beam Current Density



Beam Energy



Before



After

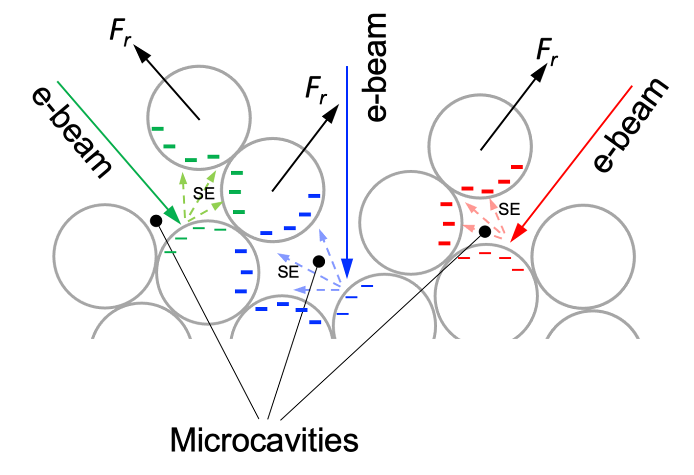
Glass Sample

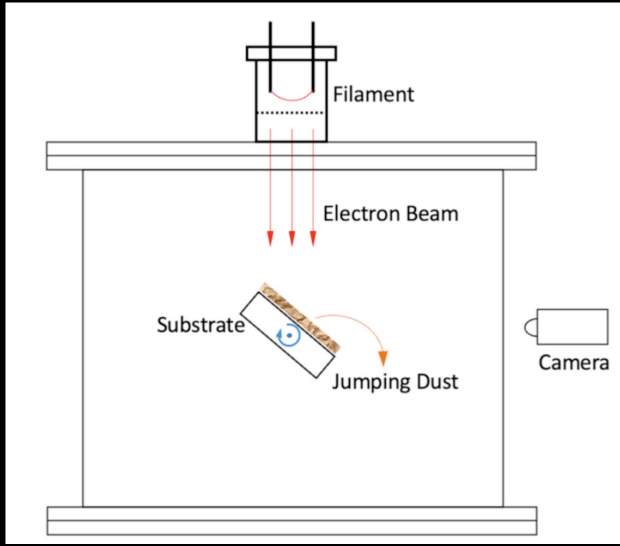
- Dust with the size <50 μm in diameter is used, which is most difficult to be cleaned due to strong adhesive forces.
- Optimized electron beam parameters: ~230 eV with a minimum current density between 1.5 and 3 $\mu A/cm^2$.
- The cleanliness reaches ~75% on the timescale of ~100 s for the glass and spacesuit samples.

Farr et al., 2020

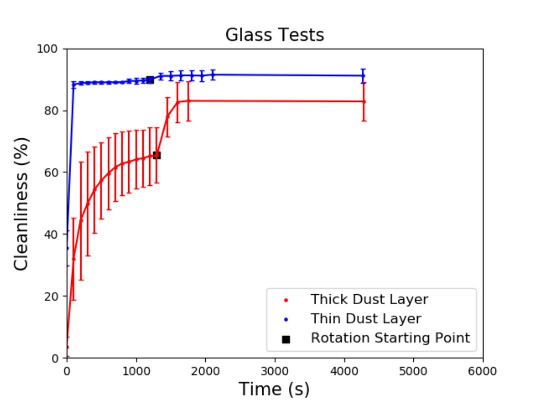
II. Varying Beam Angle to the Sample Surface

Patched Charge Model w/ microcavities exposed to beams at different angles

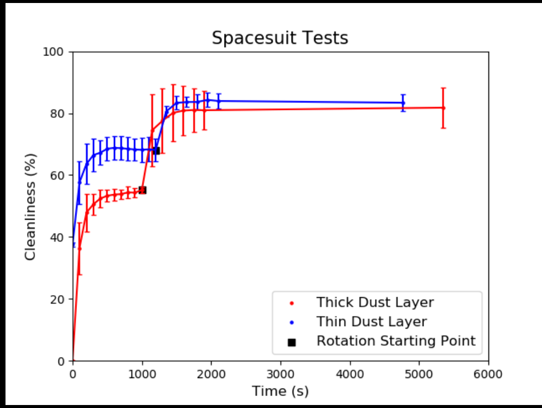




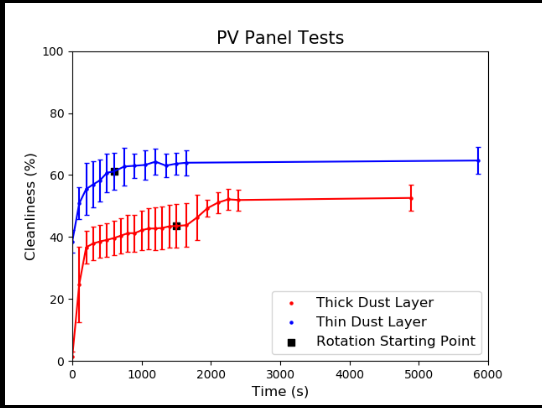
Glass



Spacesuit



PV Panel



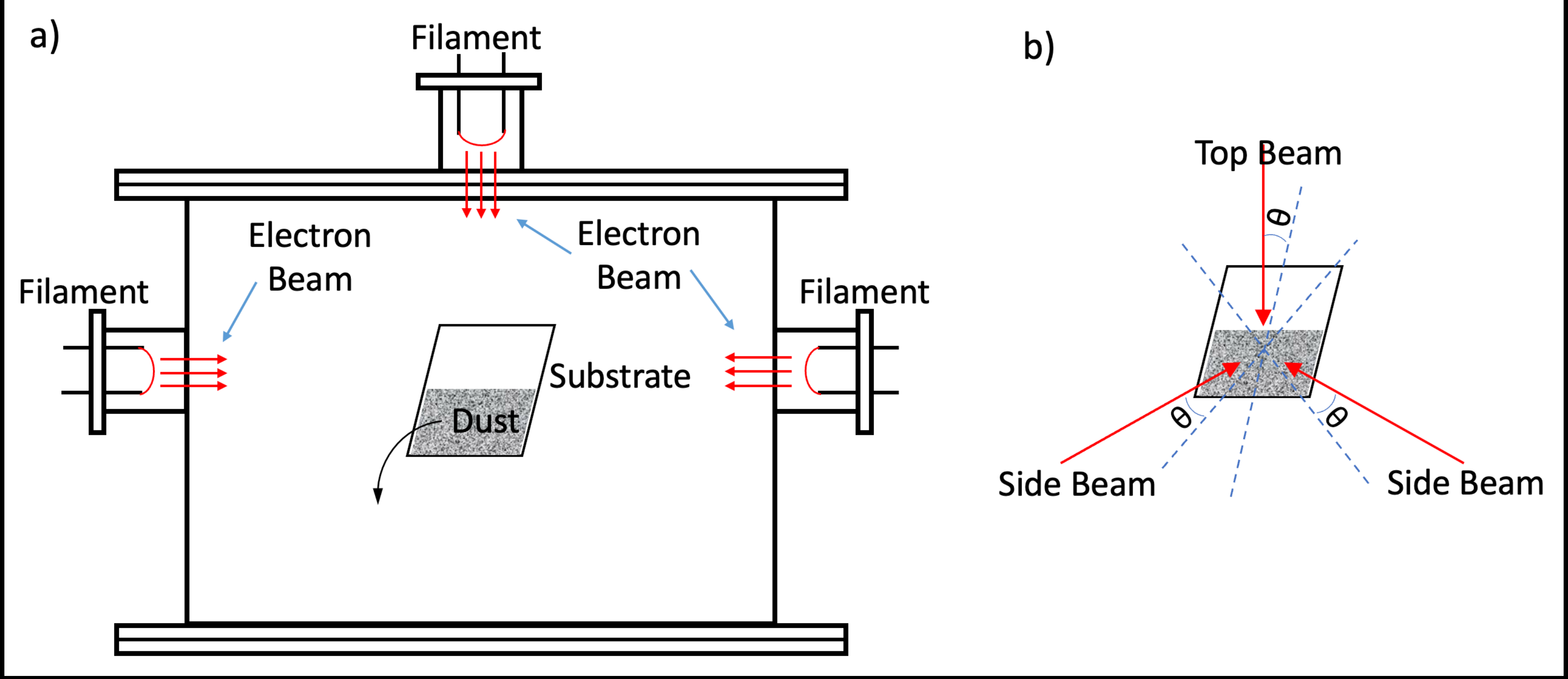
- Varying beam incident angle by rotating the surface causes more microcavities to be exposed and subsequently more dust to be charged and released from the surface.

- The overall cleanliness increases 10-25% from the fixed beam angle.

- The ultimate cleanliness reaches 83–92 % for the glass and spacesuit samples. The PV panel is shown to be more adhesive to the dust with the maximum cleanliness of 50–63 %.

Farr et al., 2021

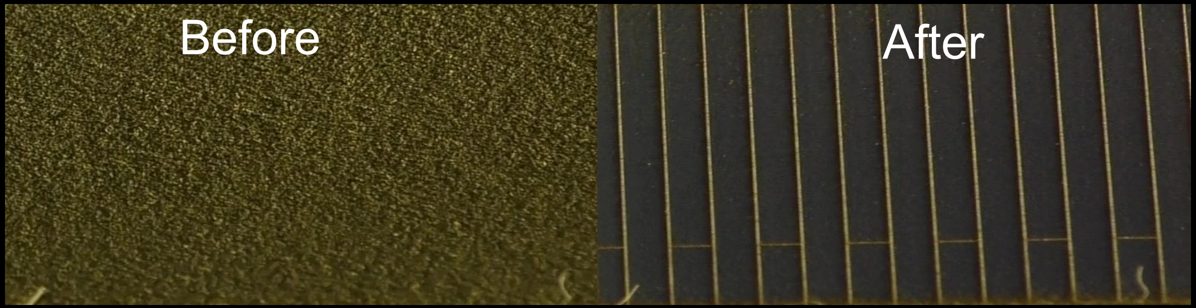
III. Multiple Beams at Different Angles to the Sample Surface
(An alternative configuration to varying beam angle)

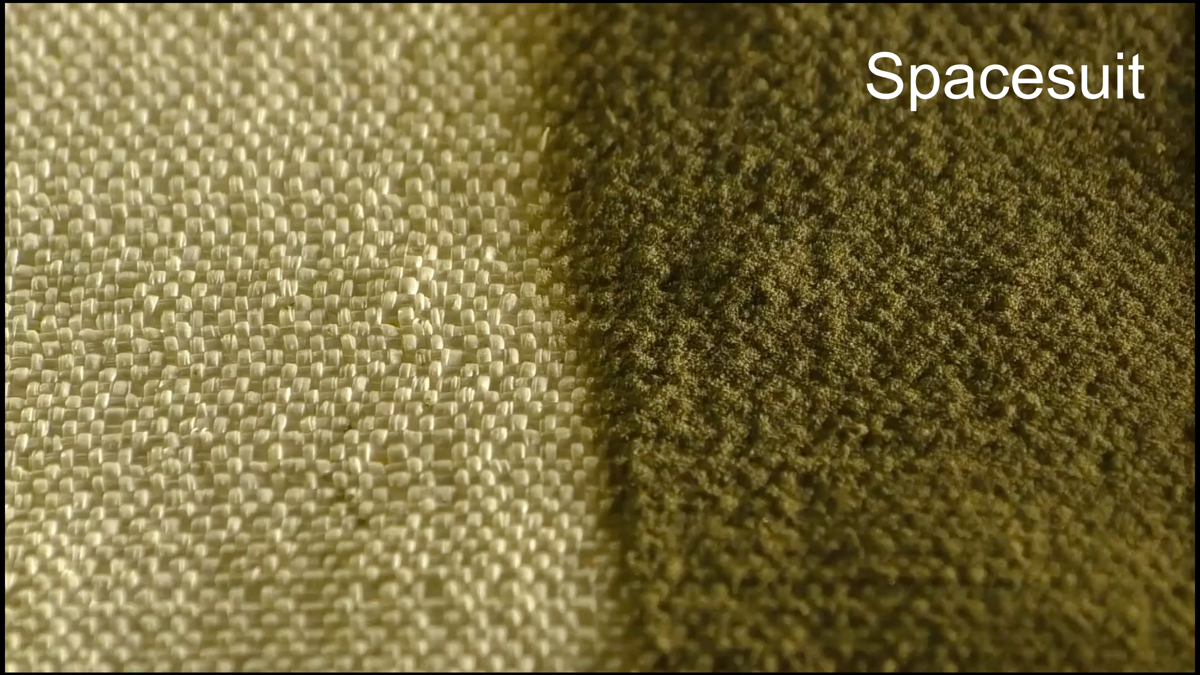


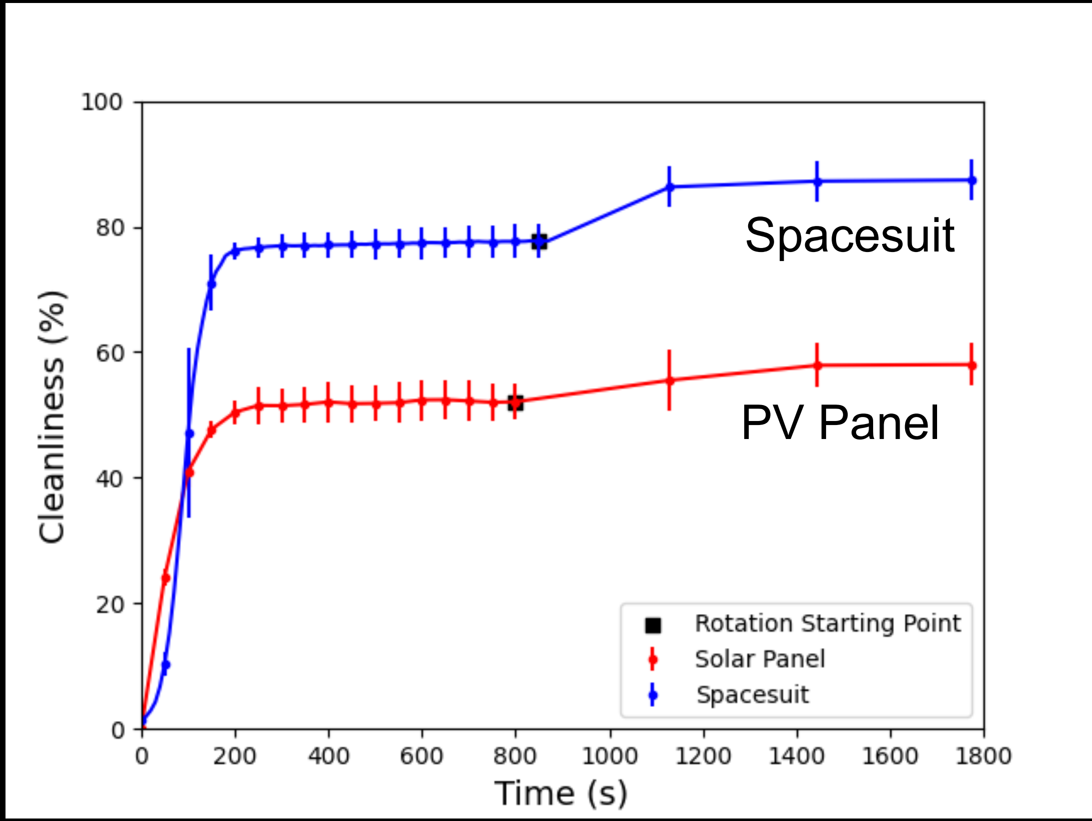
Farr et al., 2022

III. Multiple Beams at Different Angles to the Sample Surface

PV Panel



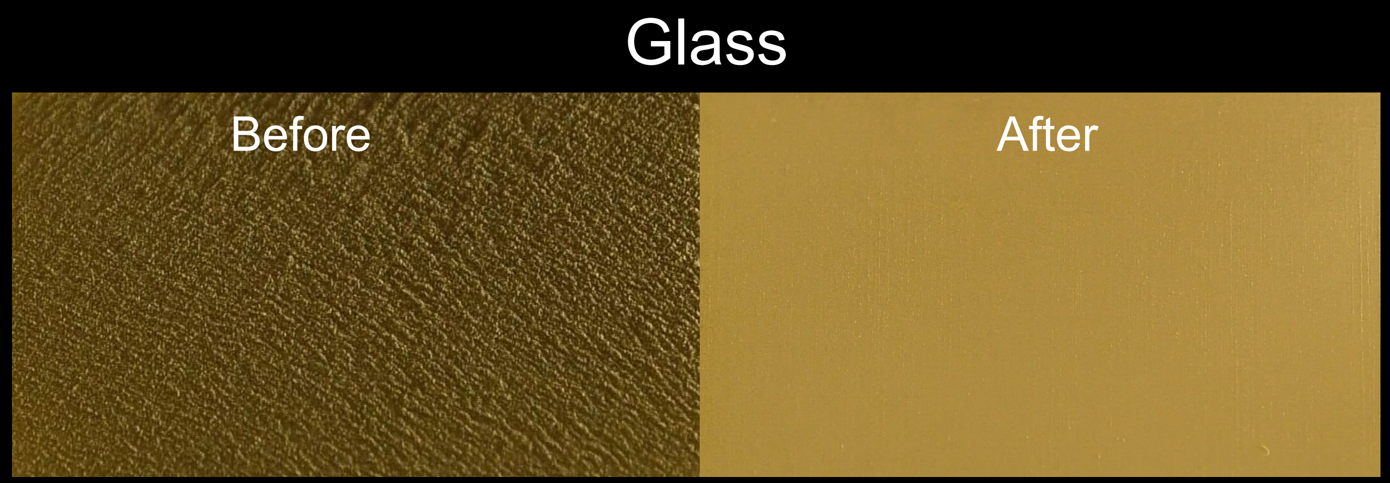


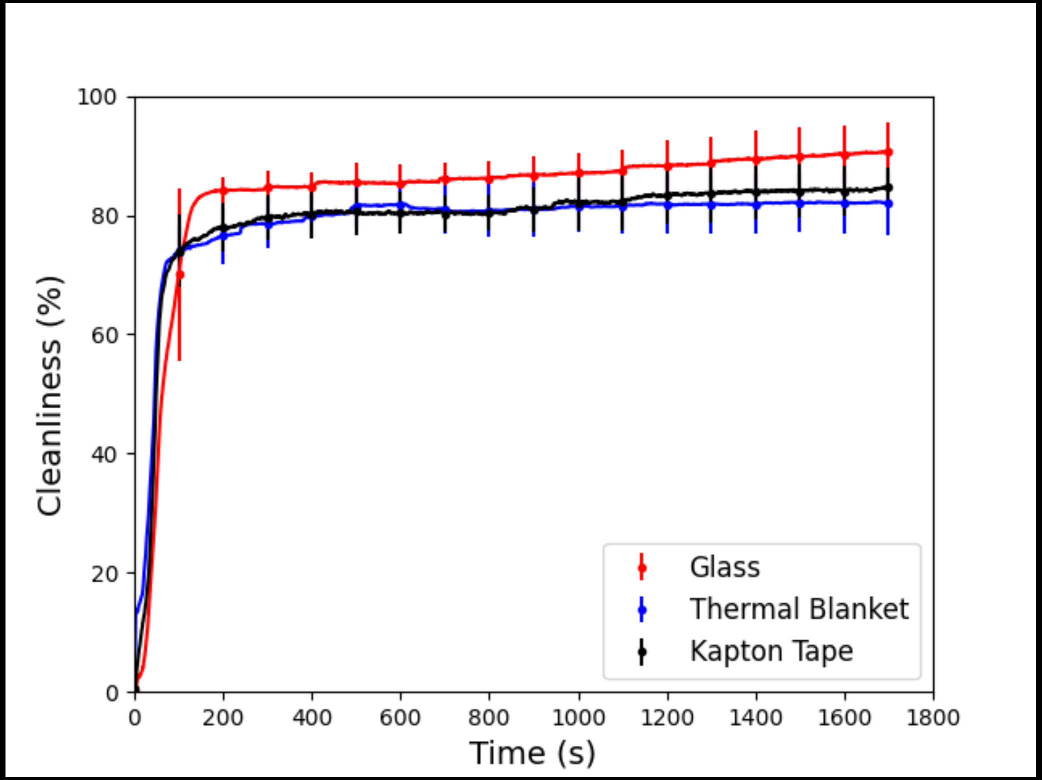


- Spacesuit cleanliness reaches 80% and additional rotation increases the cleanliness to ~92%.
- PV panel is shown to be more adhesive to the dust with the maximum cleanliness of ~60 %.

Farr et al., 2022

III. Multiple Beams at Different Angles to the Sample Surface



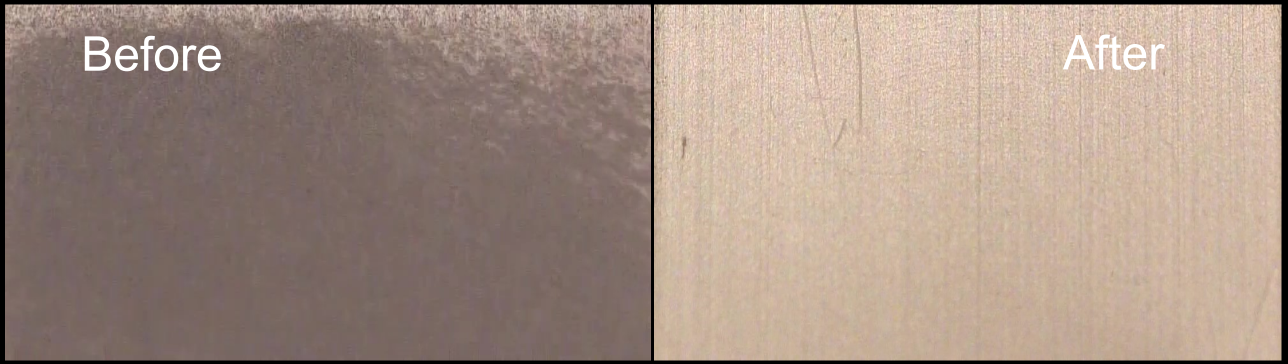


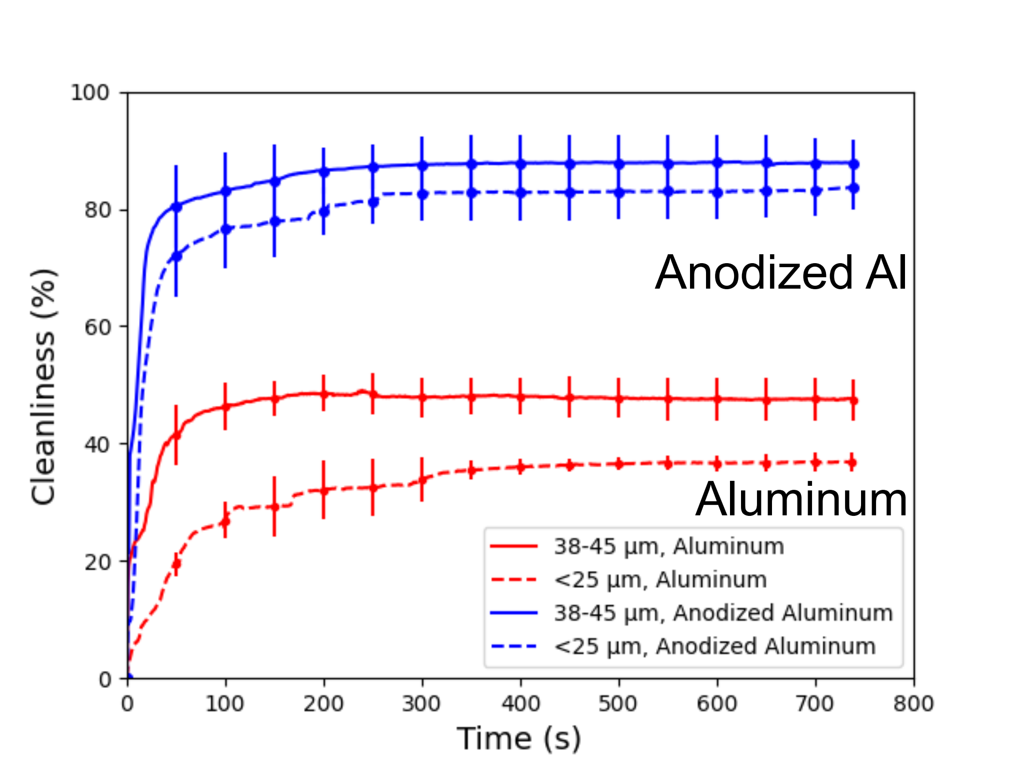
Glass, thermal blanket and Kapton tape reach the 80-90% cleanliness

Farr et al., 2022

III. Multiple Beams at Different Angles to the Sample Surface

Anodized Aluminum





- Aluminum shows poor cleaning efficiency. It is likely that image forces of charged dust on a conducting surface tend to attract the dust, making them harder to be removed.
- Anodized Aluminum shows good cleaning efficiency due to the thick oxide layer.

Farr et al., 2022

Summary and Future Work

- A novel E-beam Lunar Dust Mitigation (ELDM) technology is developed and demonstrated in the laboratory for sustainable lunar surface exploration.

- A variety of samples were tested, showing ELDM is efficient for most of insulating materials with the overall cleanliness reaching as high as 92% on the timescale of 2-3 minutes. No Electrostatic Discharge (ESD) events were observed in all tests.

- Various beam configurations were tested, showing exposure of the samples at different beam angles results in the best performance.

- ELDM devices will be developed and tested on the lunar surface.