CURRENT STATE OF THE ELECTRODYNAMIC DUST SHIELD FOR MITIGATION. C. R. Buhler[1], M. Johansen[1], M. Dupuis[1], M. Hogue[1], J. Phillips[1], J. Malissa[1], J. Wang[1] and C.I. Calle[1], [1]Electrostatics and Surface Physics Laboratory, NASA KSC, Mail code: UB-G, Kennedy Space Center, FL 32899 (Charles.r.buhler@nasa.gov).

Introduction: The Electrodynamic Dust Shield (EDS) has been developed as a means to lift, transport and remove dust from surfaces for over 18 years in the Electrostatics and Surface Physics Laboratory at NASA Kennedy Space Center. Resent advances in the technology have allowed large-scale EDSs to be fabricated using roll-to-roll techniques for quick efficient processing.

The aim of the current research is to demonstrate the 3-dimensional (3-D) version of the EDS and its applicability to various surfaces of interest throughout the Artemis program that require dust mitigation. The conventional two dimensional (2-D) EDS has been comprised of interdigitated electrodes across a surface of alternating polarity to setup non-uniform electric fields in the location of interest for which the particles need to be removed. The 2-D system can be designed to accommodate various phases. For example, the two phase EDS is comprised of two electrodes 180° out of phase, while the 3-phase EDS is 120° out of phase with the adjacent leg. 4-phase EDS configurations are also possible but for each square wave a high voltage signal is applied to each leg.

Phases: The advantages of the choice of the number of phases is determined by the user. For example, simple dust removal from the zone of interest can be accommodated with any number of phases, even 2-phases. However, if one wishes to take advantage of the traveling wave dynamics, 3 or 4-phase systems would be necessary. This would be the case for a user who wishes that the dust be deposited in a known, or controlled location. The disadvantage of the multi-phase systems is that they require more advanced circuitry and larger system electronics that may also require higher power.

Dimensionality: Users can take advantage of an additional dimensionality of the EDS. For example, most EDSs to date were comprised of electrodes placed onto a 2-D surface to generate the electric fields necessary for dust removal, as shown in the top of Figure 1. The electric field emanating from the positive (blue) electrode protrudes above and below the surface through the location of the particle to be removed and terminates at the negative (red) electrode. This spatially and time-dependent field lifts and removes the particles. A major weakness of this design is that the electric field between the traces is quite high, requiring very high dielectric breakdown strength of the materials *across* the surface. The required breakdown strength of the coating and/or adhesive thus limits the electric field (and voltage) one can apply for dust removal.

A better option is to use the 3-D version of the Electrodynamic Dust Shield shown in Figure 1 (bottom). Here the spatially dependent field is provided not by adjacent traces, but by the application of a ground layer beneath the substrate. The field needed to remove particles from the surface is still provided. Although traveling waves are not an option for the 3-D version, there are several benefits to this choice of electrode configuration such as:

1. The breakdown no longer appears across the surface, but *through* the dielectric. Not only would the base dielectric have a higher strength than an adhesive or glue, it would be much thicker and more robust. Surface breakdown is far more common than volume breakdown in materials.
2. The electrodes on the surface are all of a single polarity and can be connected electrically. Thus if an individual trace is cut, the EDS would function normally and the performance would remain unchanged.
3. The ground plane provides a “safe zone” in which the large electric fields cannot penetrate which would be used for helmets, suits, etc.. to protect the astronauts.

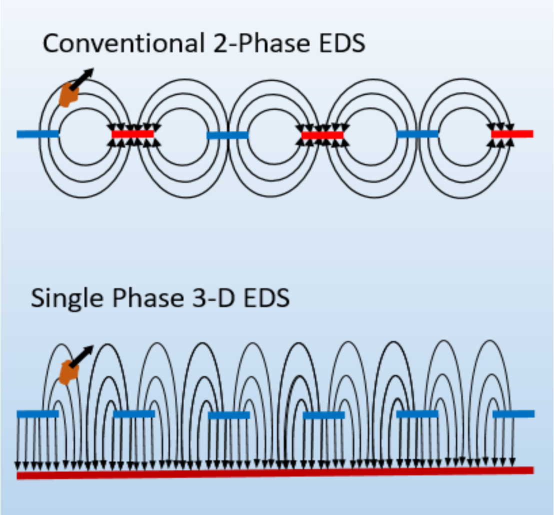

Figure 1. (top) The conventional 2-D EDS with electrodes on surface. (bottom) The 3-D version of the EDS with a ground plane beneath the electrode plane.

Examples: There are many examples of types of EDSs developed over the years. Below is a short list of applications.

Optical Systems: The transparent version of the EDS makes use of Indium Tin Oxide (ITO) electrodes on 2-D surfaces. The TRL for this technology is quite high at TRL 8, with versions of this currently flying as part of the MISSE-11 payload on the ISS. The ITO electrodes on glass with a glass top-layer has been shown to remove more than 98% of dust under high vacuum conditions [1]. Tests using Apollo samples under simulated lunar gravity were shown to exhibit this clearing efficiency as well [2]. These glass systems are ideal for camera lenses and laser cover glass systems. Past and current projects include the RASSOR rover lenses, RESOLVE cameras, and camera lenses for future CLIPS missions.

Photovoltaic Systems: EDSs comprised of ITO coated polyethylene terephthalate (PET) have been made to cover commercial solar photovoltaic (PV) panels and can be made as large as 152 cm × 101 cm using roll-to-roll processing. The substrate is acrylic which is flexible, durable, as well as lightweight. Current efforts are underway to incorporate EDS technology within solar cells themselves. KSC is working with the Glenn Research Center to imbed EDS electrodes into the fabrication of solar cells in FY2020.

Thermal Radiators: The ESPL has developed 3-D versions of the EDS for thermal radiator paint systems such as AZ-93 and A276 thermal paints as well as 3-D and 2-D versions of the EDS using reflective surfaces such as the aluminum-coated fluorinated ethylene propylene (FEP) first and second surface mirrors [1]. A key takeaway from the development of the EDS is that its versatility allows the devices to be fabricated using the materials that are common to that system. Here, aluminum is the electrode material but is also inherent to the radiator itself. Thus the addition of new materials or components is minimized when incorporating an EDS into an existing system.

Fabrics: EDS's have been formed from fabrics as well. A fabric that contains conductive elements can be "turned into" a dust removal system. For example, an electrostatically dissipative fabric used for clean rooms usually contains conductive threads woven into small patterns. If one energizes the threads and provides a metallic grounded layer the inside the suit, dust removal can be achieved removing lunar simulant. An astronaut suit would contain at least one if not many (MLI) conductive ground layers to protect the astronaut which could safely contain the field from the energized threads on the outside. The ESPL has shown this to be possible and New Technology Reports have been written [3].

Power Supply Requirements: The current power supplies for the EDS require approximately 2-4 Watts of power regardless of the size of the EDS. The volume of the MISSE power supply is currently 5 cm × 10 cm × 13 cm = 666 cm^3 and is in the process of being miniaturized with the goal of it being no larger than a pack of gum. This is possible since the power needed to remove the dust on an EDS (displacement current only) is on the order of a few mW ideally (~μA·kV), thus most of the power used in the current configuration is due to the supply itself.

EMI/EMC: The EDS and its high voltage power supply have been tested for EMI/EMC per ISS Standard 30238 [4] and have passed the Radiated Emission requirements [see 5-6] for use on the MISSE carrier and are not a significant source of noise.

Modes of Operation: The user has the ability to operate the EDS in two modes: continuous or intermittent. The choice depends on the dust loading and clearing requirements for each system. For example, surfaces requiring stringent cleaning may want to operate in continuous mode to keep particles from contacting the surface. This non-contact eliminates the well-known Van der Waals force of adhesion which is difficult to overcome. Other systems that can handle moderate amounts of fine dusting may consider EDS operation intermittently to save power.

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References: [1] Calle, C. I., C. R. Buhler, M. R. Johansen, M. D. Hogue, and S. J. Snyder. "Active dust control and mitigation technology for lunar and Martian exploration." *Acta Astronautica* 69, no. 11-12 :1082-1088. (2011). [2] Calle, C.I. et al., "Reduced gravity flight demonstration of the dust shield technology for optical systems". In *2009 IEEE Aerospace conference* (1-10). (2009). [3] Manyapu, Kavya K., Peltz L., de Leon P., Gaier J.R., Tsentalovich D., Calle C. and Mackey, P., "Investigating the Feasibility of Utilizing Carbon Nanotube Fibers for Spacesuit Dust Mitigation." 46th International Conference on Environmental Systems, (2016). [4] Space Station Electromagnetic Techniques, SSP 30238 Revision D (1998). [5] Carmody, Lynne M., and Carl B. Boyette. "EMC Test Report Electrodynamic Dust Shield." EML-0069-REF (May 2, 2014). [6] Carmody, Lynne M., Birr, R.B., and Carl B. Boyette. "EMC Test Report Electrodynamic Dust Shield (EDS) High Voltage Power Supply (HVPS)" EML-0204-REF (March 20, 2018).