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MoonDust Characterization and Mitigation

Roman V. Kruzelecky[1], Aissa Brahim, Brian Wong, , Emile Haddad and Wes Jamroz
MPB Communications Inc., 151 Hymus Blvd., Pointe Claire, Québec, H9R 1E9

Edward Cloutis[2]
University of Winnipeg, 515 Portage Ave., Winnipeg, Manitoba, R3B 2E9

Iosif Daniel Rosca and Suong V. Hoa[3]
Concordia University, 67 1455 De Maisonneuve Blvd. W., Montreal, QC, H3G1M8

Daniel Therriault [4]
École Polytechnique de Montréal, Montreal, QC, Canada H3C 3A7

Alex Ellery[5]
Carleton University,,1125 Colonel By Drive, Ottawa. ON, K1S 5B6

and

Sylvain Martel and Xin Xiang Jiang[6]
Canadian Space Agency, John H. Chapman Space Centre, 6767 route de l"Aeroport,
Saint-Hubert, Quebec, J3Y8Y9

I.

Nomenclature/Acronyms

CNT	= Carbon Nano Tube
TEM	= Transmission Electron Microscopy
SEM	= Scanning Electron Microscopy
IR	= Infrared
LORE	= Lunar Origins and Resource Explorer
MEC	= Magneto-Electrostatic
npFe	= Single domain globules of metallic iron, 3 – 30 nm in diameter
PSD	= particle size distribution
UHV	= ultra high vacuum ($<10^{-9}$ Torr)
VUV	= Vacuum Ultraviolet

Abstract

The feasibility of extended exploration and human presence on the Moon and Mars depends critically on dealing with the environmental factors, especially the intrusive effects of dust. The prior Apollo landed missions found that the lunar dust exhibited high adherence to exposed surfaces and a restrictive friction-like action causing premature wear of the EVA suits. MoonDust is a project being performed in collaboration with the Canadian Space Agency to study the effects of lunar dust on optics and mechanics, and to develop innovative solutions to extend their operational lifetime within a lunar or Mars environment based on the unique properties of carbon nanotube

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[1] Senior Research Scientist, Space and Photonics, roman.kruzeklecky@mpbc.ca
[2] Professor, Dept. of Geography, ecloutis@uwinnipeg.ca
[3] Professor, Dept. Of Mech. and Industrial Eng, Concordia Center for Composites (CONCOM), hoasuon@alcor.concordia.ca.
[4] Professor, Dept. of Mech. Eng., daniel.therriault@polymtl.ca
[5] Professor, Dept. of Mech. & Aerospace Eng., aellery@mae.carleton.ca
[6] Sylvain.Martel@asc-csa.gc.ca; Jiang, Xin Xiangl@asc-csa.gc.ca; Jiang

(CNT) nanocomposites. To assist this work, a small lunar environment simulation vacuum chamber has been set-up at MPB Communications to enable the study of lunar dust effects on optics and rotary mechanisms at pressures to below 10^{-5} Torr. New lunar dust simulants have been developed at the University of Winnipeg, characteristic of lunar Mare (UW-M1) and highland (UW-H1) compositions, that incorporate nanophase Fe in the silica particles. This paper describes the preliminary characterization of the various available lunar dust simulants that has included IR Raman for composition, Atomic Force and SEM Microscopy for morphology, and Vibrating Sample Magnetometer (VSM) for magnetic properties. Trial CNT dust deflectors/traps were fabricated and experimentally validated for magnetic and electrostatic interactions with lunar dust simulants. Good deflection and retention of submicron dust particles for device dust protection was observed. The preliminary experimental results are discussed.

II. Introduction

The Moon, our nearest neighbor, has tremendous science significance as a repository of four billion years of solar system history, as well as providing a test-bed to validate technologies and methodologies to explore more distant asteroids and planets. The feasibility of extended exploration and human presence on the Moon (and Mars) depends critically on dealing with various environmental factors, and especially on the dust effects.

Orbital and landed lunar missions have provided us with a broad overview of lunar surface geology, and this knowledge has been augmented by returned lunar samples and recovered lunar meteorites. The lunar surface is composed of variable amounts of ilmenite ($FeTiO_3$) and related oxide minerals (e.g., ulvospinel: Fe_2TiO_4), the more abundant silicate minerals - plagioclase feldspar, pyroxene, and olivine-, and modified materials such as agglutinates (fused soil aggregates), and nanophase iron (npFe) (e.g., Taylor [1]). On the other hand, lunar regolith, or soil, is produced when micrometeorites plow into lunar rocks, and sand at high-impact velocities, fragmenting them, and melting them to create glass material. Due to a myriad of such meteorite impacts (with velocities in the range of 20 km/s), the lunar surface is covered with a thin layer of fine dust. Main factors that affect different properties of the lunar soil and/or the dust include: (i) the large lunar temperature differentials (+120° C to below –170° C), (ii) the combination of high vacuum atmosphere, and (iii) the unfiltered intense UV solar radiation. Moreover, the absence of a significant lunar natural magnetic field consequently allows charged solar wind particles to continuously hit the exposed lunar surface.

Although the lunar environment is often considered to be essentially static, it is actually known to be very electrically active. The surface of the Moon is electrically charging, following to several electrical currents which are incident on its surface, and is also exposed to a variety of different charging environments during its orbit around the Earth. The fine-grained dust is thought to be levitated by solar ultraviolet radiation during the day, and by solar wind flux during the night [2,3,4]. These processes contribute to a tenuous lunar atmosphere of moving dust particles constantly leaping up from and falling back to the Moon's surface, giving rise to a "dust atmosphere", that is hence composed of dust particles in continuous and constant motion. On the solar-illuminated day side of the Moon, the incident solar ultraviolet and X-ray radiation are sufficiently energetic to cause ionization of atoms and molecules in the lunar soil. This phenomenon is thought to result in an electrically positive charge build-up. This causes the positively-charged fine surface lunar dust to be repelled from the like-charged surface. Additional acceleration of the levitated dust in a near-surface acceleration sheath region is believed to loft the dust anywhere from meters to kilometers high distances, with the smallest/lightest particles reaching the higher altitudes. On the night side, the dust is negatively charged by electrons in the solar wind. Eventually, the levitated dust falls back towards the lunar surface under the influence of gravity and/or the oppositely charged surface, where the process is continuously repeated. On the lunar day/night terminator, there could be significant horizontal electric fields forming between the day and night areas, resulting in horizontal lunar dust transport.

The effects of lunar dust were experienced first-hand by the prior Apollo missions, between 1969 and 1972 [5]. The Apollo moonwalkers became totally covered with lunar dust, even a vacuum cleaner designed to clean off the dust jammed. The lunar dust exhibited adherence to all various exposed surfaces, as well as significant abrasiveness, partially wearing through the outer gloves of their space suits.

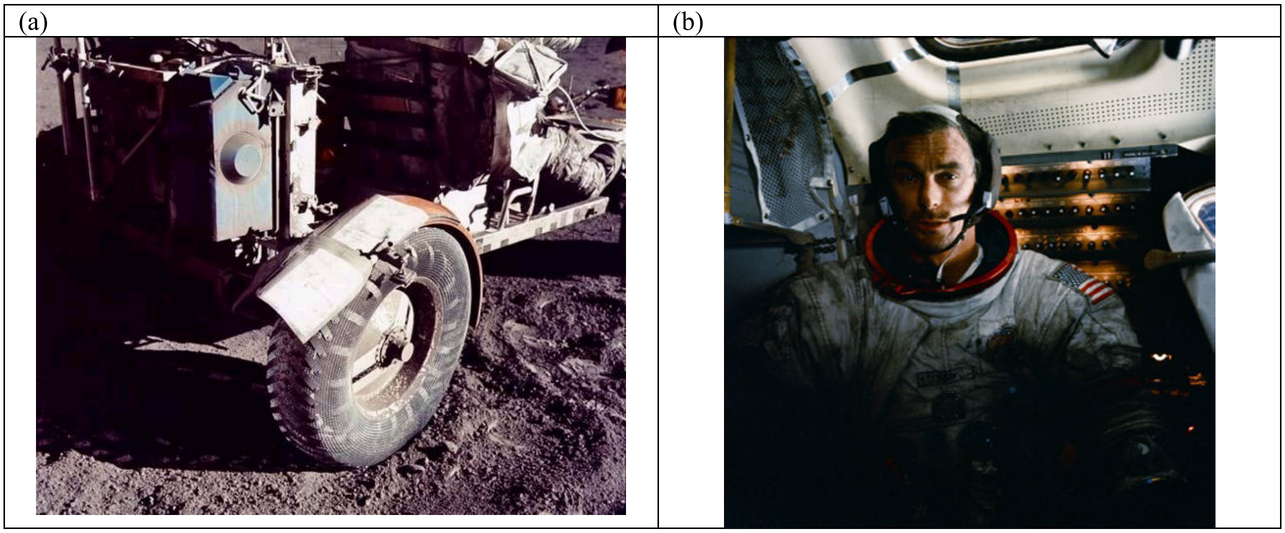
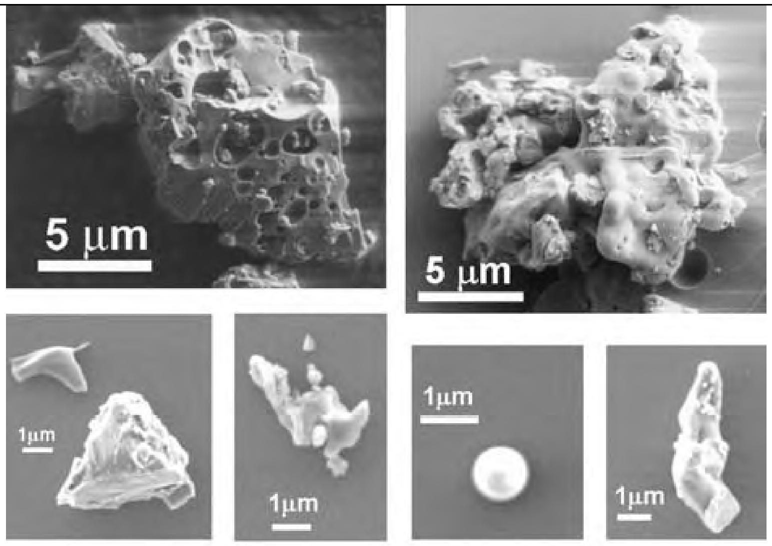


Figure 1: **(a) The Apollo 17 mission lunar rover's fender repaired with maps, clamps and duct tape, to try to keep dust from being kicked up while driven around the lunar surface. (b) Apollo 17 photograph showing covered in lunar dust with some dust transferred to the lander interior.**

SEM studies of dust samples returned by the Apollo 17 mission by Park *et al.*[6], as shown in figure 2, indicate that the lunar dust particles have a relatively irregular and jagged surface, with claw-like angular barbed shapes, that would allow the lunar dust to cling strongly into a porous surface. This is thought to be due to the meteorite impacts that repeatedly melted rocks into glass, and then shattered the glassy rocks into the jagged powdered glass. Moreover, those particles can exhibit submicron bubbles and a porous Swiss-cheese like structure, which increases their correspondent reactive surface area.

Figure 2: SEM images of Apollo 17 lunar dust sample 70051 (after J.S. Park *et al.* [6]).



J.S. Park *et al*. [6] estimated particle size distributions for returned lunar dust samples by dispersing an amount of 10 mg lunar dust in a 10 ml surfactant solution, which was then treated by an ultrasonic cleaner for 30 minutes (to increase the particle dispersion). A pipette was used to deposit a drop of the dispersed solution onto a cleaned Si substrate. A magnet was then applied to the back (bottom surface) of the Si sample to diminish the dust aggregation during the evaporation step. When the liquid was evaporated, the resulting lunar dust particles left behind on the silicon substrate were examined by SEM to determine their size and shape. They used commercial SCION^{TM} image processing to estimate particle areas from the SEM images. The particle diameters were determined from the estimated areas by assuming that the particles are spherical. The resulting particle size distribution (PSD) for the lunar sample 70051 is shown in figure 3a. Those results indicate that a substantial fraction of the particles are less than 1 micron in size.

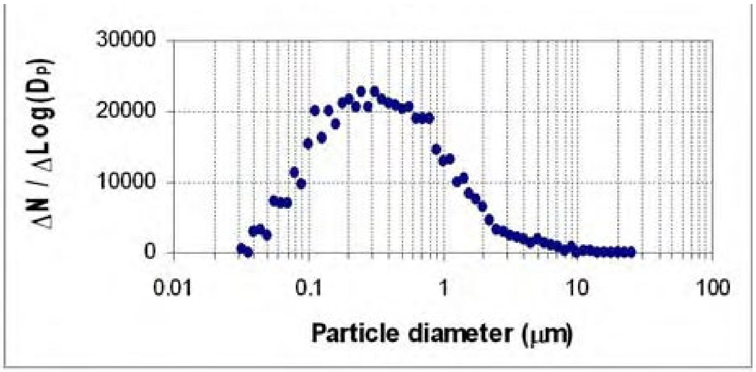


Figure 3: (a) Particle size distribution of Apollo 17 dust sample 70051 by SEM imaging (after J.S. Park, *et al.* [6]).

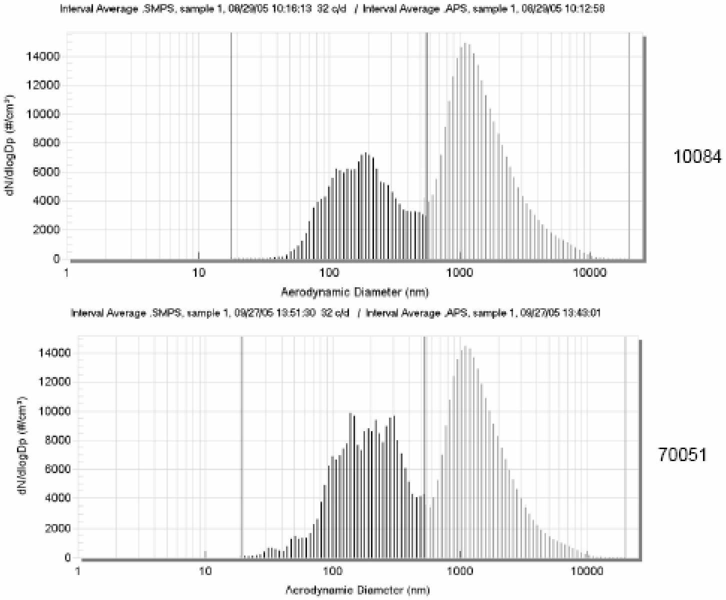


Figure 3: (b) Measured particle number density for Apollo samples 10084 and 70051 based on Aerosol techniques (after Greenberg *et al.*[8]).

Additional work on lunar dust PSD was provided by Greenberg *et al.*[8], and is summarized in figure 3b. They employed gas-phase dispersal of the lunar dust samples and aerosol diagnostic techniques. These measurements suggest the presence of some ultrafine lunar particles in the distribution (Apollo samples 10084 and 70051), with an effective diameter extending below 0.01 µm (10 nm).

Compositionally, the particle size distribution of the lunar dust has increasing abundances of agglutinate glasses and nanophase metallic iron content, with decreasing size (Gaussian average size was estimated around 3 µm) [4]. In the other hand, the Fe content can produce ferromagnetic behavior in the lunar dust, as observed by L.A. Taylor *et al.*[1] and J.S. Park *et al.* [6], causing its reaction to a magnet. In addition, there are a significant number of particles less than 2.5 µm in size, which are considered to be toxic to the human respiratory system [7].

Lunar dust is a real challenge to lunar surface operations, while also being of great scientific interest. MoonDust is a project being performed in collaboration with the Canadian Space Agency to study the effects of lunar dust on optics and mechanics, and to develop innovative solutions to extend their operational lifetime within a lunar or Mars environment. The MoonDust innovative dust mitigation solution exploits key characteristics of the lunar dust and incorporates nano-filtration technologies based on CNT and CNT/polymer nanocomposite materials. The aim is to minimize the required consumables while providing high capacity and efficiencies for the more dangerous submicron particulates. Moondust is taking a multithrust approach to lunar dust:

1. UHV grade lunar simulator chamber of relevant lunar environment conditions (VUV, dust, vacuum).

2. Development of suitable lunar dust simulants relevant to optics and mechanical joints, focusing on a suitable simulant for silica containing nano-phase Fe (as opposed to separate silica and Fe-bearing particles).
3. Development of dust deflection/trapping methods suitable for operation in vacuum environments based on polymer/carbon nanotube nanocomposites materials.

III. Review of Prior Dust Mitigation

A variety of solutions have been proposed to mitigate dust for future landed lunar missions that exploit some of the potential characteristics of lunar dust:

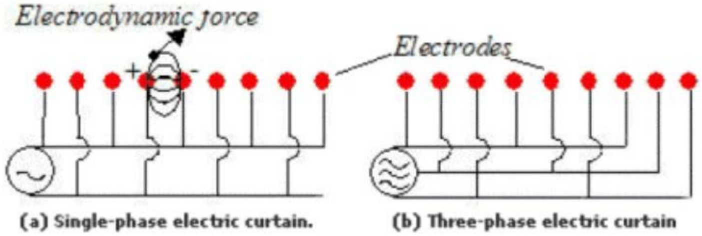
- Electrostatic curtains to repel charged dust particles, ionized by the incident solar VUV [9].
- Magnets to attract dust containing Fe.
- Use of rechargeable sticky surfaces, similar to lint rollers to remove dust [10].
- Surface treatment to reduce dust sticktion [11].
- Development of dust resistant materials and seals, to keep the dust away from critical mechanisms and spacecraft modules [12].

The Apollo 17 astronauts used duct tape to help cope with the lunar dust [10]. One proposed approach is a rechargeable sticky roller to remove dust from surfaces.

C.J. Wohl et al. are considering topographical alterations of the surface of materials to reduce the surface energy for stiction, either via a sprayed-on coating or by laser ablation of the surface [11]. They have found that laser ablation of polyimide substrates can reduce the surface sticktion as measured by the contact angle of water droplets.

L. Taylor [12] at the University of Tennessee suggests using moderate-power microwaves to melt the surface lunar dust to provide a protective surface for lunar operations. This lunar *in situ* paving would be useful to minimize dust disturbances by surface operations near a lunar base.

In the 1960's [9], preliminary concepts were developed for a dust electric curtain, based on the Apollo mission experiences. This was furthered in the early 1970s by Prof. Senichi Masuda (University of Tokyo) [13]. His work was related to the development of a traveling wave ‟electric curtain”, as an air-pollution filter, to deal with charged smog particulates. His electric curtain employed a series of parallel electrodes consisting of thin wires, spaced roughly a centimeter apart. An alternating voltage was applied to the electrodes, as shown in figure 4.



(a) Single-phase electric curtain.

(b) Three-phase electric curtain

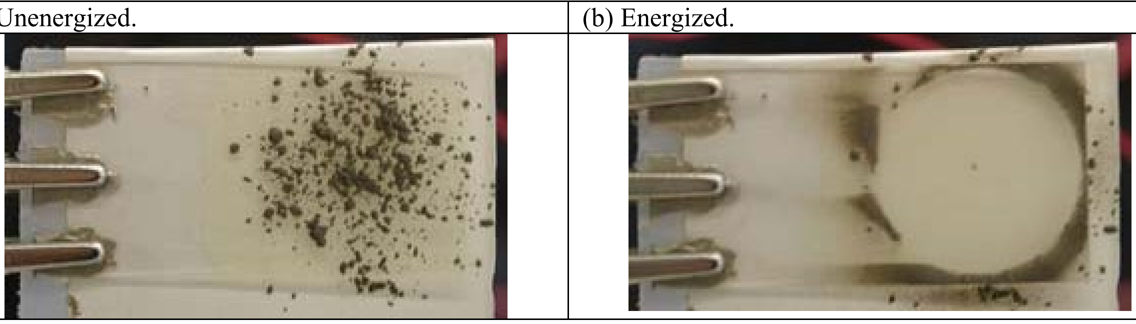
Figure 4: Diagram of the original ‟electric curtain” (after S. Masuda *et al.*[13]).

Instead of providing the same alternating current to all the parallel electrodes at the same time, Masuda slightly delayed the onset of the current to each successive electrode. This results in an electromagnetic field of each electrode that has to be out of phase with its nearest neighbors, creating thereby an electromagnetic wave that rapidly traveled horizontally across the surface on which the electrodes lay. Any charged particles lying on the electrodes surfaces got lifted and moved by that traveling electromagnetic wave, as if they were surfers being pushed along by an ocean wave.

NASA has an active dust mitigation program that is currently studying possible dust mitigation technologies for large optics elements, such as solar cells. The Electrostatics and Surface Physics Laboratory at the Kennedy Space Center (C.J. Calle *et al.* [14]), in collaboration with several universities, is evolving the electric curtain approach for a ‟dust shield”. The ‟dust shield” is based on transparent and electrically-conductive indium titanium oxide (ITO) electrodes. The mesh of electrodes is usually covered with a thin insulating layer to increase the breakdown voltage. The electrode spacing for the preliminary samples was ranged from 0.48 to 0.67 mm. Two different approaches are being studied, where the curtain electrodes can be excited by a single-phase and/or a multi-phase alternative current/voltage.

In the single-phase electric curtain, parallel cylindrical electrodes connected to a common alternative voltage source 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 generate a force on any charged particle in the region of the field. However, the multi-phase electric curtain 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 in the same and/or the opposite direction to the generated electromagnetic wave, depending on its polarity.



(a) Unenergized.

(b) Energized.

Figure 5: Transparent screen coated with a transparent ITO three-phase spiral pattern. (Left) The electrode area is covered with JSC-1A lunar simulant. (Right) Electrode area after its energizing. (after Calle *et al.* [14]).

When the transparent dust shield was covered with simulated lunar or Martian dust, and was put in a vacuum chamber that was then pumped down to the rarefied atmospheric pressure of Mars or the Moon, most of the dust was thrown off to the side in seconds (see figure 5) after application of the ac voltage. The electric curtain approach requires an ac voltage source and use of relatively high voltages (>500 V) to provide the required ac electric field.

IV. MoonDust CNT nanoComposite Dust Mitigation

MoonDust is a project being performed in collaboration with the Canadian Space Agency, to study the effects of lunar dust on optics and mechanics elements, and to develop innovative micro/nano-filtration solutions to extend their operational lifetime within a lunar environment.

To assist this work, a small lunar environment simulation vacuum chamber is being set-up to enable the study of lunar dust effects on optics and rotary mechanisms. The simulation chamber includes filtered, oil-free vacuum pumping to below 10^{-6} Torr, an injection system for lunar dust simulants, UV source for vacuum UV (VUV), and diagnostic ports for relevant optical and electrical measurements.

Samples of actual lunar dust, as returned by the prior NASA Apollo missions, are being studied under controlled conditions, to develop the detailed requirements for suitable lunar dust simulants, in terms of nano-phase Fe content, particle size distributions and shapes, relevant optical and mechanical characteristics. This is being used to assist the formulation of suitable simulants for optics and mechanics elements.

The MoonDust mitigation solution exploits key characteristics of the lunar dust, the electric charging and ferromagnetism properties, and incorporates nano-filtration based on carbon nanotube technologies. The aim is to minimize the required consumables and voltages (i.e., low power requirements, and ideally, to avoid completely the need of any external energies sources), while providing high capacity and high efficiencies for filtering and trapping the particles, especially the more dangerous submicron ones.

Carbon nanotubes are tiny tubes made exclusively with carbon atoms. When they are properly formed and lined up, they can provide a considerable electrical and thermal conductivities, and very high mechanical strength. They can also provide a huge porous volume for trapping micro/nanoparticles and/or even bacteria. Carbon nanotubes can be aligned to provide a filter membrane [15], with attainable pore sizes below 20 nm. The exceptional thermal and mechanical stability of carbon nanotubes, their high surface area for trapping dust, and relatively controlled fabrication processes make this technology very attractive for dust deflection and/or filtration. The selected approach uses carbon nanotubes embedded in a second polymer medium (i.e., the host matrix) with a larger pore size, to provide a nanocomposite structure. These can be fabricated optically opaque or relatively transparent for optical aperture dust protection, depending on the selected CNT content and matrix. This will be discussed in a future paper.

Terrestrial filtration is usually based on forced air or liquid flow through the filter medium. The MoonDust innovative solution exploits key characteristics of the lunar dust: electrostatic charging due to photoemission caused by the intense incident solar UV light, and the ferromagnetism property associated with nanophase Fe in the lunar dust, to facilitate filtration in a vacuum environment.

On the lunar surface there is an almost infinite source of the levitated dust. Therefore, the preferred approach is to deflect incident levitated dust away from critical apertures and mechanical joints. As shown in figure 6, a combination of magnetic and electrostatic attraction can be used to deflect levitated dust away from the desired optics or mechanical parts. The 3-D structured CNT nanocomposite acts as the electrode for the dust deflection. It can also be used as a dust trap with a high capacity for particles from the micron to submicron particle size to immobilize the dust and render it harmless within structures and manned habitats.

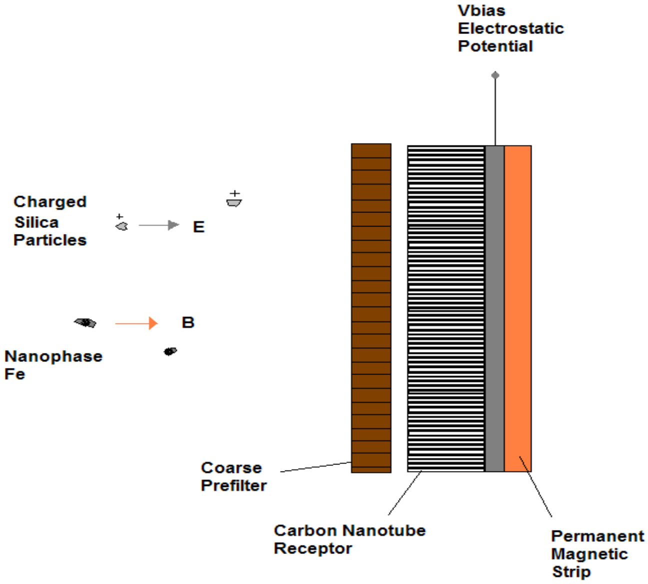


Figure 6: Schematic of MoonDust MEC magneto-electrostatic dust nanofilter.

This is being used to address the dust mitigation needs of the potential LORE science payload for JAXA's Selene-2 lunar lander/rover mission, as well as future manned lunar and Mars mission requirements.

V. Lunar Dust Simulation

One of the major issues facing the development of mitigation strategies for lunar dust contamination (broadly defined), is that the formation conditions associated with lunar dust are unique to the lunar surface environment, and such conditions are not present on the Earth's surface. Extensive efforts to identify or develop realistic lunar dust and soil simulants have been ineffective to date. Commonly available lunar soil simulants, such as Johnson Space Centre (JSC-1) and Minnesota Lunar Simulant (MLS-1) only reproduce some aspects of lunar soils [1,6,18]. Such materials are supplemented by a variety of synthetic materials that simulate other aspects of the lunar soil.

The existing simulants provide excellent reproducibility of selected properties of lunar soils, and hence they should not be dismissed out of hand as being inferior. It is also worth mentioning that the use of a variety of different simulants enables researchers to better isolate selected properties of interest. Thus, existing and new simulants are complementary for many applications:

1. CHENOBI and OB-1 [19]. These two materials are designed to simulate lunar highland soils. Both CHENOBI and OB-1 use the Shawmere anorthosite (a high-purity anorthosite from Ontario) as the base material. To produce CHENOBI, a portion of the Shawmere anorthosite was melted and quick-cooled to produce an anorthositic glass. By contrast, the glass in OB-1 is an iron-rich steel mill slag. This material has been roughly ground to produce a range of grain sizes. CHENOBI provides superior reproducibility of lunar highland spectral and physical properties, but its magnetic properties are not well matched (due to the lack of nanophase iron).

2. JAXA simulants. Collaborators at JAXA recently provided us with both a mare and lunar simulant that were produced by Shimizu Corp. for testing of the JAXA Selene-2 instrument. Little information is as yet available on the composition of these materials (probably for proprietary reasons). The mare simulant is apparently derived from glassy basalts-andesites from Mt. Fuji, and the composition of the highland simulant is not yet known. Spectrally, these materials provide reasonable but not high-quality matches to lunar spectra - they lack the red slope of lunar spectra that is attributable to nanophase iron. Both materials are finely powdered, suggesting that they are probably good matches to lunar soil mechanical properties.

3. NASA JSC-1A [20]. NASA JSC-1A is a widely used lunar mare simulant. It was derived from a basaltic cone in Arizona and it provides a reasonable compositional match to lunar mare soil. It also contains a few tens of percent of glass, suggesting that it also provides a reasonable mechanical lunar soil analogue. This material has not been processed subsequent to its extraction from the mine site, and is only sieved to provide samples with a grain size of <1 mm. Spectrally it provides a reasonable match to lunar mare spectra, with the exception of the red slope in lunar spectra that is attributable to nanophase iron.

4. Chinese Academy of Sciences mare simulant. We are awaiting delivery of a sample of NAO-1, a new lunar mare simulant developed by researchers at the Chinese Academy of Sciences. This material is presumably derived from basalt lava flows in western China, but little information on this new simulant has been acquired at this point.

Production of more realistic lunar soil simulants likely requires extensive laboratory modifications of either naturally occurring terrestrial geological materials, or synthetic materials. We are developing a range of “simulants”, that collectively will allow us to simulate nearly all the characteristics of lunar soils, albeit with relevant properties scattered among different “simulants”.

By utilizing a range of such simulants, we expect to be able to examine carefully the effects of key lunar soil properties, on mechanical systems and optical components. Key lunar soil properties that we expect to simulate include composition of mare and highland soils and dust, electrostatic properties, particle angularity, glass/agglutinates, grain size distribution, and nanophase iron. To meet these requirements, two new simulants are being developed at the University of Winnipeg, UW-1M and UW-1H, in small quantities. The UW simulants are compositionally very close to lunar soils in all important respects:

- Mineral abundances
- Mineral composition
- Nanophase abundances and size
- Angularity of glassy component
- Grain size distribution

UW-1M is designed to reproduce the characteristics of lunar mare soils. To this end, we are using constituent minerals that are both spectral and compositional analogues of lunar minerals, and we have found such materials for lunar olivine, orthopyroxene, clinopyroxene, plagioclase feldspar, and ilmenite. These materials are mixed in the same proportions as common lunar mare, although it should be noted that there is no one "typical" lunar mare composition - it varies somewhat from place to place on the Moon. However, we have adopted an average "global" mare composition for UW-1M. These minerals are then combined with appropriate amounts of basaltic glass, ground diatomite, and our silica gel-nanophase iron complex. All of these materials are ground prior to mixing to enhance the proportion of fine-grained (<1 micron) particles to better match the lunar soil and dust.

UWM1 – Mare simulant:

- Made from lunar-like pyroxene, ilmenite, plagioclase, and nanophase iron-impregnated silica gel (glass/agglutinate simulant).
- Nanophase iron reproduces its abundance in lunar mare and larger particle size
- End member abundances simulate “average” lunar mare

UW-1H is designed to reproduce the characteristics of lunar highland soils. Lunar highland soils are also somewhat variable in composition, but we have again adopted a "global" highland soil average composition. The production of UW-1H differs somewhat from UW-1M. For UW-1H we use the CHENOBI simulant which contains both crystalline and glassy anorthosite. The lunar highlands, being older than the mare, contain a greater proportion of anorthosite glass. This material is then mixed with appropriate amounts of ilmenite, ground diatomite, and our silica gel-nanophase iron complex. All of these materials are ground prior to mixing to enhance the proportion of fine-grained (<1 micron) particles to better match lunar soil and dust.

UWH1 – Highland simulant:

- Made from lunar-like pyroxene, ilmenite, plagioclase, and nanophase iron-impregnated silica gel (glass/agglutinate simulant).
- Nanophase iron reproduces its abundance in lunar highlands and larger particle size
- End member abundances simulate "average" lunar highland

These materials are being used to examine how various dust properties affect mechanical and optical components, utilizing an appropriate environment chamber. By using a suitable combination of the various available simulants, it should be possible to provide a relatively good overall simulation of the different effects of lunar dust.

VI. Dust Characterization

In our experiments, we used a permanent magnet to attract lunar dust (as well as similarly sized lunar simulants) to a magnet. The magnetic field was measured with a DC gaussmeter, and the amount of soil attracted to the magnet was visually estimated from repeat observations. The strength of the magnetic field at the point of contact with the sample was 0.2 Tesla. The amount of sample attracted to and retained by the magnet for various materials is provided in **Table 1** below.

Table 1. Results of magnetic attraction experiments on Apollo soil samples and lunar regolith analogues.

Material	**Grain size**	**Amount of sample attracted and retained by magnet (%)**
Apollo soil 15041.71	<1 mm	80%
Apollo soil 15041.64	<1 mm	90%
Terrestrial plagioclase feldspar (PLG108)*	<90 μm	<5%
Terrestrial clinopyroxene (PYX016)*	<90 μm	<5%
Synthetic ilmenite (ILM201)*	<45 μm	90%
JSC-1A lunar mare simulant (PSA003)	<1 mm	95%
FJS-1 lunar mare simulant	<1 mm	95%
Shimizu HS lunar highland simulant	<1 mm	90%
CHENOBI lunar highland simulant (PSA001)	<1 mm	85%
UWM1 lunar mare simulant	< 500 μm	90%
UWH1 lunar highland simulant	<500 μm	90%
UWH1P lunar highland simulant with no nanophase iron	<500 μm	5%
UWM1P lunar mare simulant with no nanophase iron	<500 μm	5%

These results provide some useful insights and cautionary notes concerning appropriate lunar regolith analogues:

- Many of the widely used and newly created lunar simulants exhibit magnetic properties (at least as far as the extent of this experiment is concerned) that are equivalent to lunar soil samples
- The magnetic portion of lunar soils is concentrated in both ilmenite and nanophase iron-bearing particles
- The presence of nanophase iron seems to make a large fraction of a fine-grained sample magnetic; this is likely due to agglomeration of particles in a fine-grained mixture
- While magnetic properties are broadly similar for the lunar soil samples and many of the analogues, the nature of the magnetic fractions is known to be different between lunar samples and the naturally occurring terrestrial analogues.

A detailed EDX (energy dispersive x-ray) characterization on the various Moondust was used provide an accurate Idea about the atomic composition and metallic content of each powder. The results are summarized in figure 7.

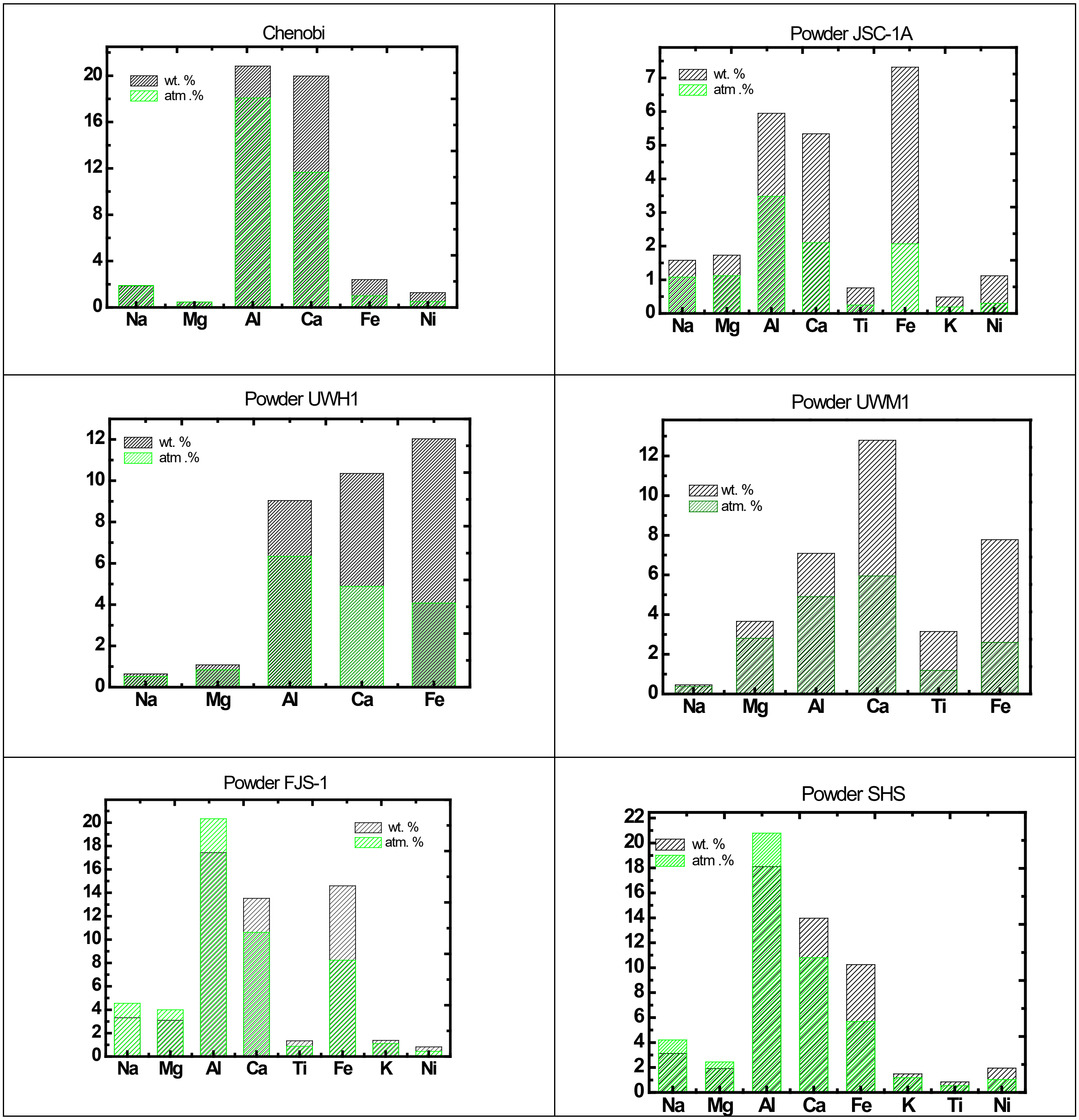
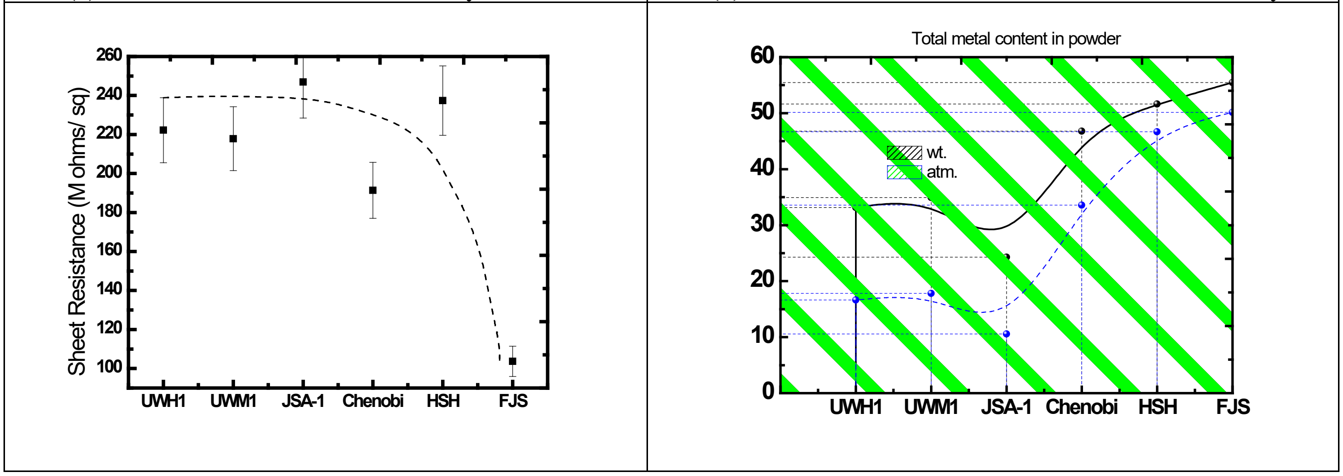


Figure 7: Summary of the composition of several of the different lunar dust simulants as measured by energy dispersive X-ray spectroscopy.



(a) Dust Simulant Sheet Resistivity

(b) Simulant % metallic content from EDX Analysis

Figure 8: Summary of the (a) resistivity and (b) % metallic composition of the lunar dust simulants.

The sheet resistivity of the lunar dust sample was measured using coplanar electroded, as summarized in figure 8a. It was found that there is an excellent correlation between the electrical conductivity, the magnetic susceptibility and the metallic content of the lunar simulant powders:

Metal load increasing= less resistive dust= more magnetic dust = more deflection efficiency.

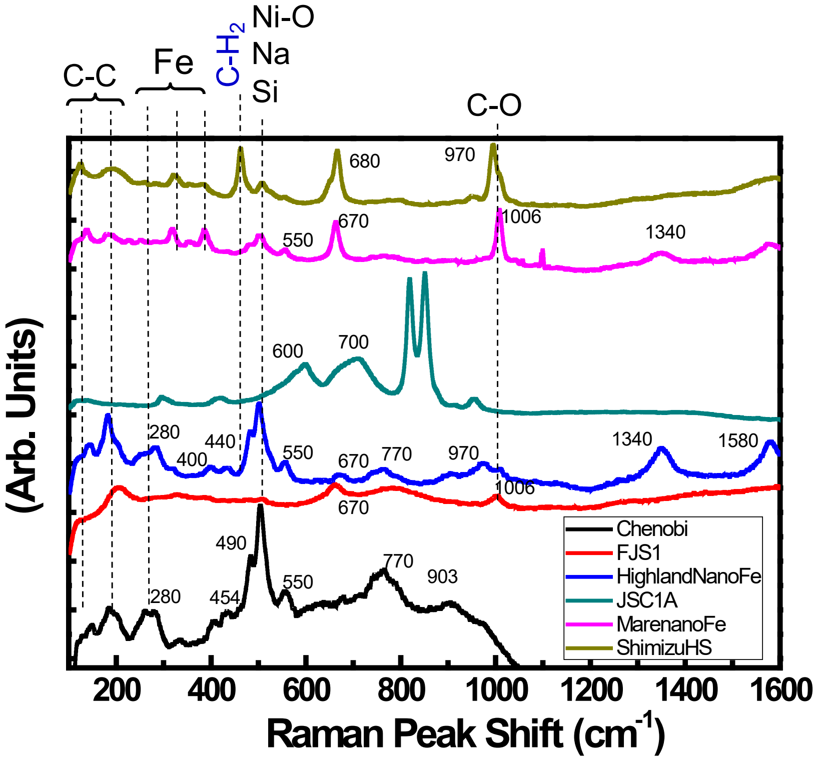


Figure 9: Summary Raman spectral measurements using 532 nm excitation.

Raman spectra of the various available lunar dust simulants were accumulated using 532 nm CW laser excitation to provide additional information on the dust stimulant molecular structures and compositions. The different lunar dust simulants exhibit distinctive, characteristic Raman spectra, as summarized in figure 9. The Raman spectroscopy is a very useful tool to differentiate the various simulants.

VII. MoonDust Vacuum Simulator Facility

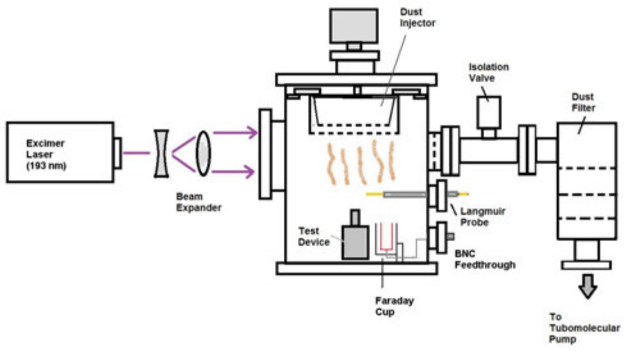
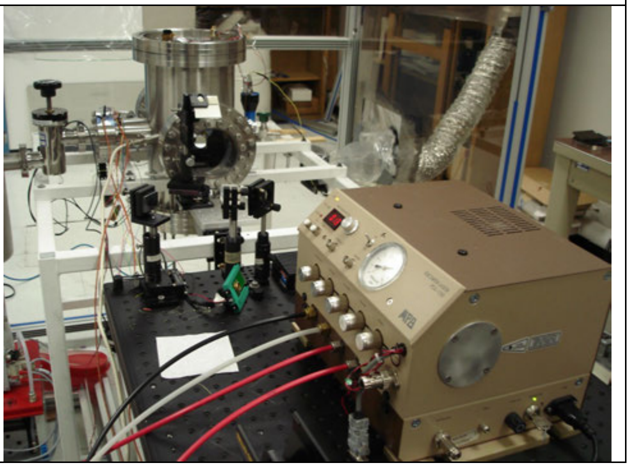
(a) Schematic of the MoonDust lunar simulator vacuum chamber.	**(b) Photograph of the main chamber showing a UV fused silica window for dust UV irradiation using a MPB excimer laser operating at 193 nm. Additional optical ports enable spectral measurements of the levitated dust.**
	

Figure 10: MoonDust Lunar dust simulator vacuum chamber at MPBC.

The MoonDust lunar surface simulator facility at MPB Communications (see figure 10) builds upon the expertise gained with an existing lunar sample environment chamber located at the University of Winnipeg. It features all stainless-steel construction using UHV-grade conflat flanges. Oil-free pumping is provided using a turbomolecular pump, backed by a molecular drag pump. A high through-put fine particulate filter is fitted between the chamber and the pumping system. Moreover, a bellows-sealed valve can be used to isolate the simulator chamber when dust is being injected, to further protect the pumping system.

The lunar dust simulator chamber features an internal 3" O.D. sieve dust shaker to provide a stream of fine dust particles onto the test device. Different sieve apertures can be selected in the micron range to assess the corresponding effects on small optics elements and mechanical joints.

One of the optical ports is used for the UV excimer laser source, operated at an emission wavelength of 193 nm, to provide VUV excitation and charging of the lunar dust as it falls onto the test device. Additional ports facilitate spectral measurements of the dust and charge measurements using a biased Faraday cup.

The test device is mounted to fixtures in the bottom flange. There are additional electrical feedthroughs to operate vacuum compatible motors, and for the readout of additional sensors to probe accurately the amount of accumulated dust, optics/ mechanics temperatures, etc.

The most critical system in terms of simulating the lunar environment is the dust dispensing system. This system works in conjunction with the rotational input to deliver regolith simulant to the system undergoing testing. The dust dispensing system consists of a stainless steel sieve mounted in a dispensing cup. The cup and sieve, held by springs, is free to move and is jolted by a small solenoid actuator. The entire dispensing system is exposed to high vacuum, and so must be filled adequately before the chamber is sealed and testing commenced.

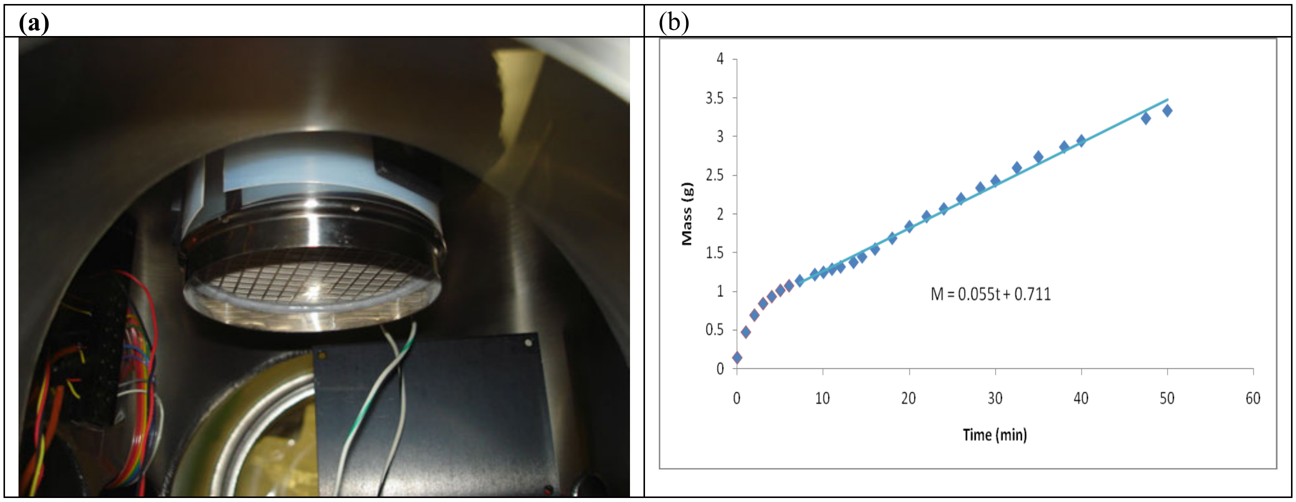


Figure 12: (a) Internal view of 75 mm O.D. programmable dust dispensing system and (b) cumulative dust mass provided by dust Shaker at 2 Hz agitation.

In summary, the MoonDust lunar simulation chamber provides a relatively large internal working volume and allows the simulation of what are felt to be the most important lunar surface conditions. It offers a direct way for examining the effects of dust exposure on both the performance of components intended for the lunar surface, mechanical or optical, and the effectiveness of various dust mitigation strategies to extend this performance over the required mission duration.

VIII. Preliminary Testing

The lunar dust simulator facilities at MPB and University of Winnipeg were used to study the effects of dust simulants on relevant mechanical joints and on optics.

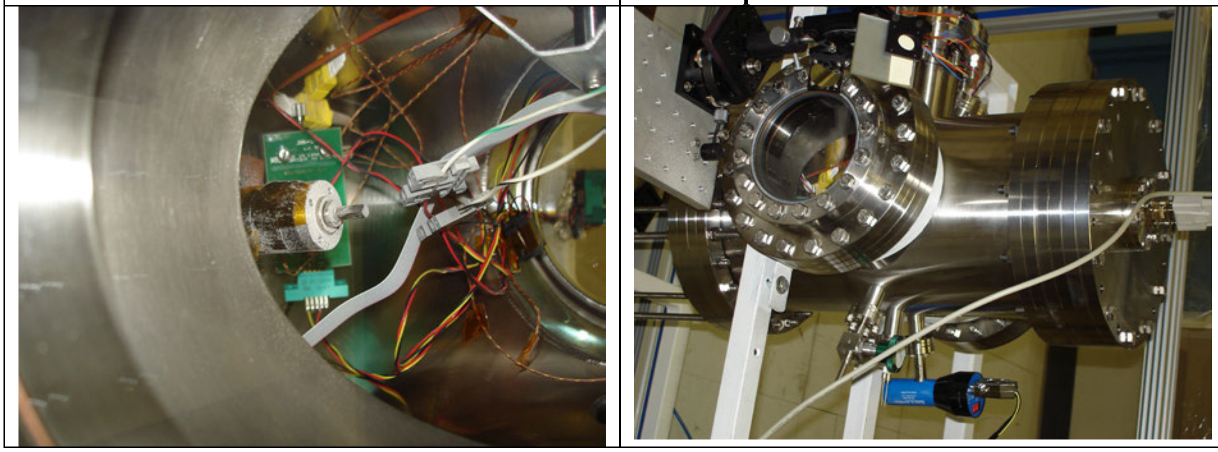
Preliminary protection of a 20 mm diameter optical aperture using the CNT nanocomposite dust trap/deflector was investigated under several conditions:

1. **UV 3-D photoexcitation of the levitated dust using a ring of UV LEDs**
2. **Vacuum photoexcitation using a 193 nm laser source with beam expanded to about 40 mm**
3. **Vacuum levitated dust with no applied photoexcitation**

A. Dust Effects on Mechanics

The introduction of dust into a motor, gear, or rotary joint can be harmful to its function; however, since rotary joints require the motion of a rotor relative to a stator, absolute sealing is impossible. Some methods of shielding rotary joints against dust include: tight running fits between shafts, with dry (e.g. Teflon or Vespel) or wet (e.g. grease) lubrication between them; the use of double shielded ball bearings to keep dust away from moving parts; the use of brushes or felt as a low-friction means of permitting relative motion but rejecting the ingress of dust; and the use of various elastomer seals such as radial shaft seals, mechanical seals, v-ring seals and axial clamp seals.

The trial testing was conducted over a period of several days using a selected vacuum grade motor similar to those previously used successfully for the Spirit and opportunity Mars rovers. The purpose was to established an initial baseline for the motor performance in a lunar dust simulant vacuum environment without any additional dust protection.

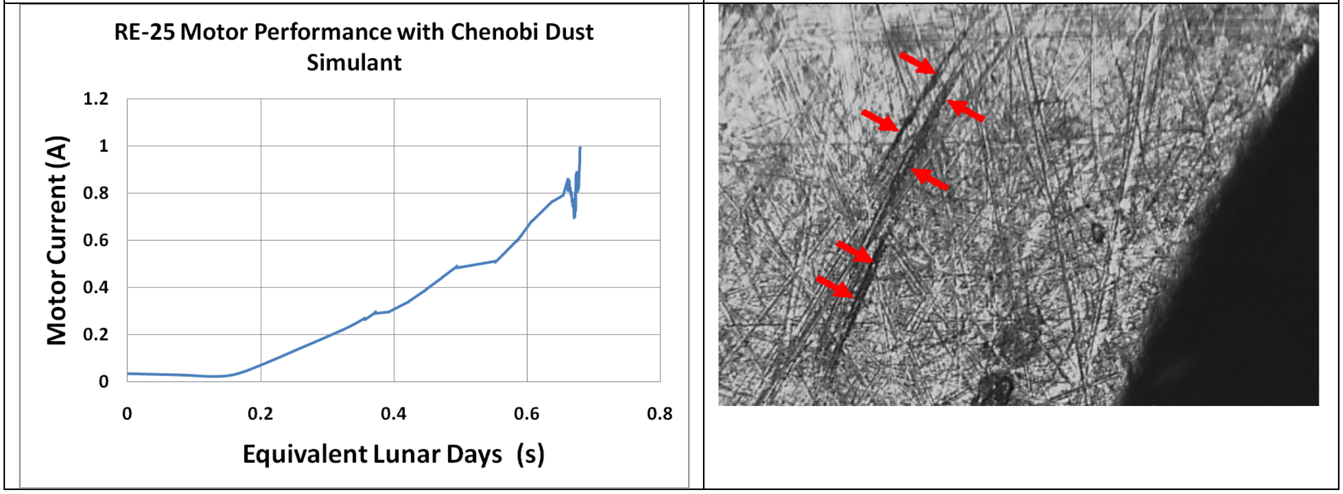


(a) Maxon RE25 motor mounted onto MoodDust chamber base.

(b) motor ongoing vacuum testing at about 60 rpm.

Figure 13: Photographs of preliminary rotary motor vacuum test set-up.

The motor rotation was set at a relatively low rate of 60 rpm to prevent overheating in the vacuum environment. The motor current and temperature were monitored periodically. Temperature monitoring using a thermocouple proved too noisy and this needs to be improved. The motor seized after the equivalent of 0.7 lunar days operation in the levitated dust (see figure 14a).



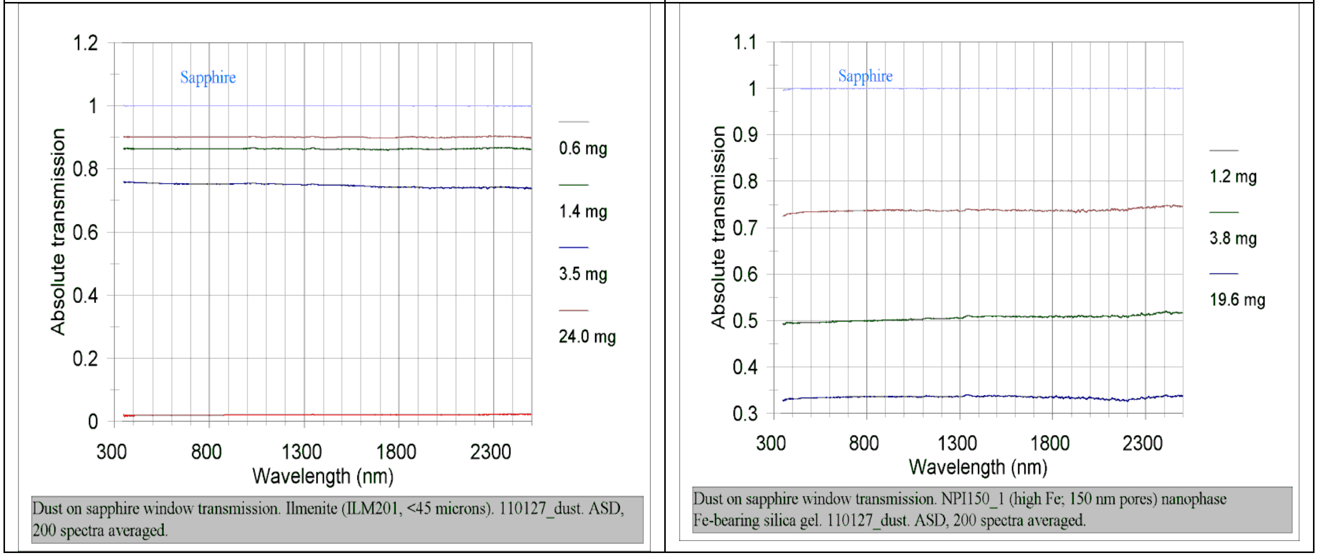
(a) Motor current variation with vacuum dust exposure (60 rpm constant rotation).

(b) RE25 sealed inner bearing mechanical wear by Chenobi lunar dust simulant after 0.7 equivalent lunar days exposure using the MoonDust simulator chamber.

Figure 14: Experimentally measured diagnosis of a vacuum-grade Maxon RE25 motor after exposure to a low flux of Chenobi lunar dust simulant at 0.1 mTorr in the MPBC MoonDust vacuum simulator.

The motor was dismantled for diagnosis. Despite the basic seals and minimal agitation of the dust, the dust stimulant was able to penetrate into the inner bearings. There was visible mechanical wear, as noted in figure 14b. The results indicate that dust mitigation is critical to extend operations over a full lunar day.

B. Dust Effects on Optics



(a) Ilmenite dust on 25 mm O.D. sapphire window.

Dust on sapphire window transmission. Ilmenite (ILM201, <45 microns). 110127_dust. ASD, 200 spectra averaged.

(b) Silica with nanophase Fe on 25 mm O.D. sapphire window.

Dust on sapphire window transmission. NPI150_1 (high Fe; 150 nm pores) nanophase Fe-bearing silica gel. 110127_dust. ASD, 200 spectra averaged.

Figure 15: Experimentally measured lunar dust simulant degradation of optics.

The effects of lunar dust simulants on optics was studied using the simulator facility at the University of Winnipeg. The experimental data indicate that the dust coating does not introduce spectral signatures that can obscure measurements. However, the optics coating by lunar dust, either silica or Fe-bearing oxides, will significantly increase the UV optical absorption, that can lead to optics heating, as well as to reduce the overall spectral transmittance to affect signal throughput for optical measurements. This will be of particular concern for solar panels.

C. CNT nanocomposite Deflector/Trap Dust mitigation

Experimental validation of the CNT nanocomposite dust deflector.trap approach was provided using the MoonDust simulator at a vacuum lever of about 0.1 mTorr. The test set-up is shown schematically in figure 16. This represents a worst case scenario as the dust deflection needs to operate against Earth's gravitational attraction.

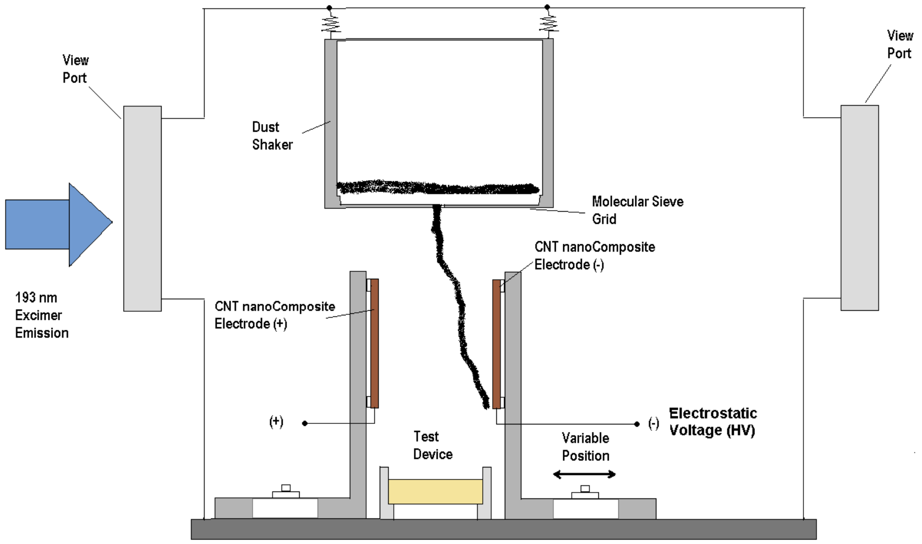
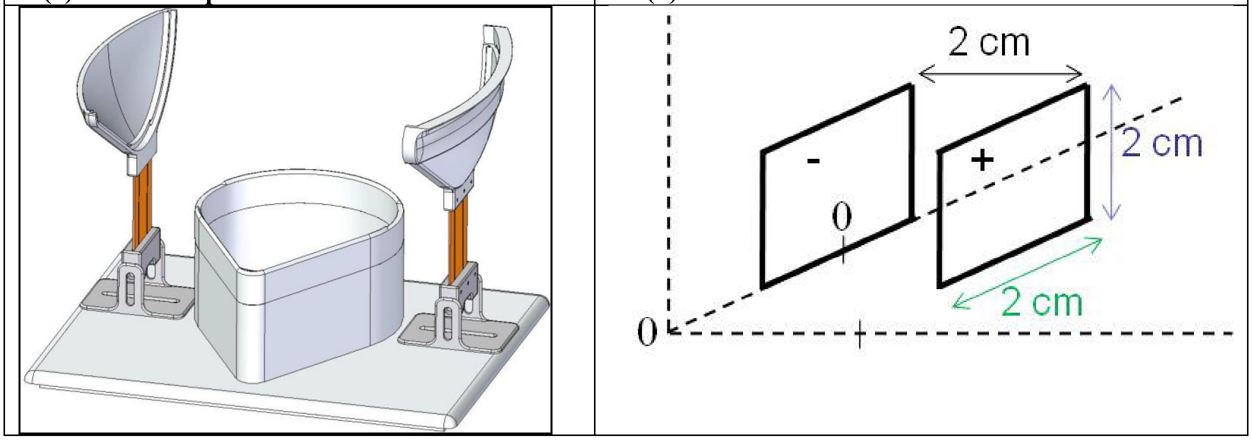


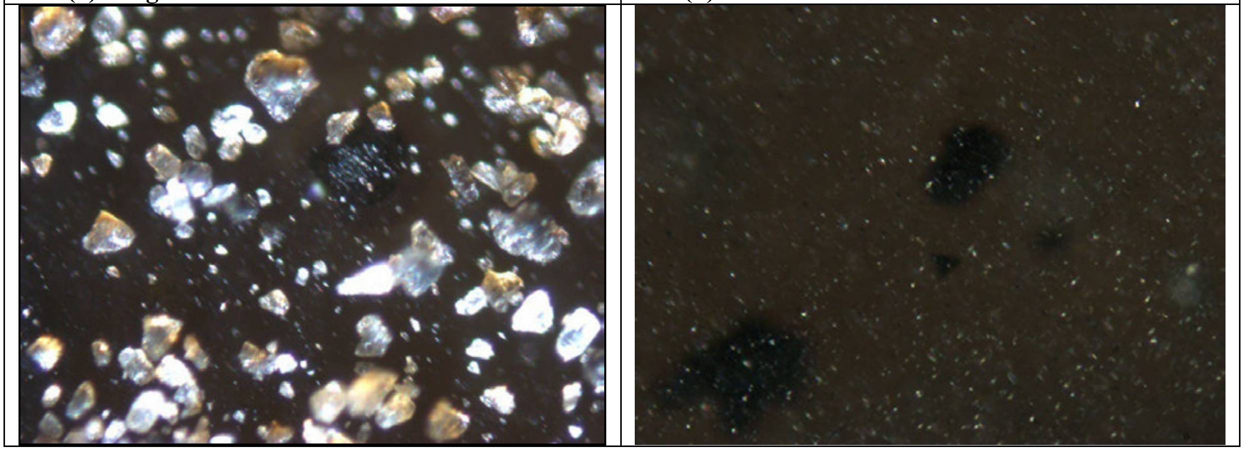
Figure 16: Schematic of the MoonDust Vacuum Chamber Test Set-up.

A parallel plate architecture made by CNT and CNT/polymer nanocomposite material was adopted for the Moondust trial electrostatic deflection in vacuum, as shown in figure 17. The CNT nanocomposite solution can function both as a protective shutter and as the dust deflection electrodes. The preliminary testing was conducted using an applied DC bias of 1000 V between the two electrodes. Gravity was perpendicular to the CNT electrodes, towards the optic device.


(a) Test Set-up

(b) Electrostatic Simulation Model

Figure 17: Schematic of vacuum test set-up.



(a) Negative CNT Electrode

(b) Positive CNT Electrode

Figure 18: VUV biased dust deflection and capture on the negative and positice CNT nanocomposite electrodes under vacuum conditions.

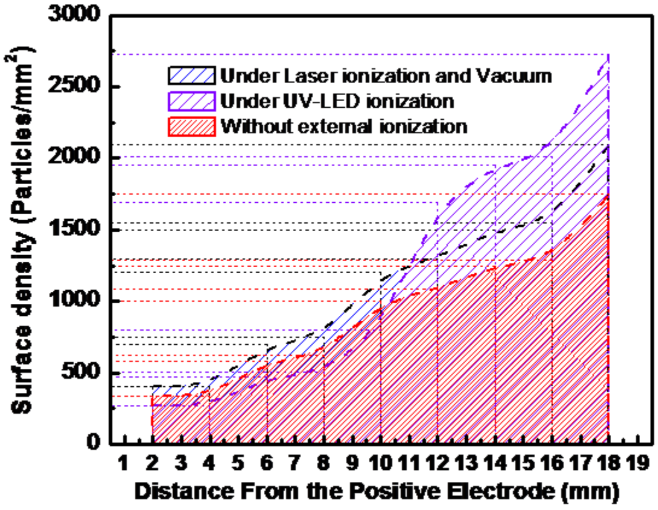
Experimentally it was found that there was almost no dust accumulation on the positively bias CNT electrode (see figure 18b). There was considerable deflection of the dust onto the negatively biased electrode (see figure 18 a) spaced 20 mm away, even in the presence of 1 g gravity perpendicular to the electrodes to attract the dust towards the optical aperture.

IX. Discussion and Conclusions

Lunar dust is a real challenge to lunar surface operations, while also being of great scientific interest. The lunar surface provides an almost infinite source of dust. Lunar surface operations will most likely require a combination dust mitigation strategies; from minimization of agitation of the dust, to local protection of devices and personnel.

Preliminary experimental testing using the MPBC MoonDust lunar simulator facility and relevant dust simulants indicate that optics and sealed vacuum-grade motors similar to those used on the Mars Spirit and Opportunity rovers can show some degradation effects after only a fraction of a lunar day. The results indicate that dust mitigation is critical to extend operations over a full lunar day.

Figure 19: Comparison between the UV LED ring light photo excitation, 193 nm excimer laser excitation with un-ionized dust deflection results from positive electrode at 1000 V using inter-digitized nanocomposite filter.



The cumulative quantities of the deflected trapped dust were compared between the two ionization-methods, and with non ionized particles. The results are summarized in figure 19. The preliminary results indicate that even non-excited dust can be electrostatically deflected. Additional UV photoexcitation assists the dust deflection, most likely due to the added dust photoionization and charging. In this respect the UV LED ring source was the most effective since it provides a 3-D volumetric excitation of the injected dust. The required dust deflection voltage can be under 1000 V. Using the selected approach, it should be possible to extend the usable lifetime of optics and mechanics on the lunar surface by a factor of 10 or more.

The dust mitigation is being applied to the protection of optical elements and rotary mechanical joints. Scale up of the approach to the dust protection of larger structures such as solar panels is being considered. The ultimate goal is to develop methodologies that do not require, ideally, any external power for their functional operation. Potential near-term applications include the protection of optics devices and mechanisms for the LORE science payload for potential inclusion on JAXA's Selene-2 landed lunar mission.

The significant advantages of the selected CNT nanocomposite approach include:

- 3-D highly porous structure with variable pore size
- Electrically-conductive to function as both the dust trap and deflector electrode
- Filtration or trapping of particulates to nm in size
- Operation in vacuum via dust electrostatic and/or magnetic deflection
- Can be scaled to protect larger devices
- Light-weight structure for minimal added mass
- Vacuum compatible materials
- Can be suitable for lunar temperature extremes of 120 K to 400 K

Acknowledgments

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