IAC-20-E1.2.13

Lunar Dust Mitigation on Spacecraft in Low Gravity Freefall Environment

Caeden T. Dooner[a*], Shawna L. Christenson[c], Kevin L. Simmons[b]

[a*] *BLUECUBE Aerospace, 2300 Giralda Circle, Palm Beach Gardens, Florida, 33410*, cdooner12@gmail.com
[b] *BLUECUBE Aerospace, 2300 Giralda Circle, Palm Beach Gardens, Florida, 33410,* ksimmons@bluecubesat.com
[c] *Aerospace Public Policy Institute, 1303 Vision Drive, Palm Beach Gardens, Florida, 33418, schristenson@aerospace-policy.org*

Abstract

The Wolverine CubeSat Development Team (WCDT) program remains the only middle school in the United States to develop, build, test, and launch a cube-sized nanosatellite (also known as a CubeSat). Aside from satellites, the WCDT program is also focused on future lunar exploration and is developing the AMARIS lunar rover based on CubeSat technology. The goal of the AMARIS mission is to evaluate techniques for reducing the negative impacts of dust accumulation on rover solar panels and frames. Lunar dust is believed to have toxic properties that can affect people and machines. This dust adhesion problem was widely reported during the Apollo era missions and still exists today. The experiment from which this paper is based investigates how electric and magnetic fields may be used to mitigate this problem. A vacuum dust-box was designed, composed of 5 mm thick Lexan sheets in which flight-grade photovoltaic panels and anodized aluminum chassis components were subjected to regolith simulant. The goal is to determine if there is a feasible solution to mitigate the dust buildup that occurs in space. The knowledge gained from this experiment will be used in designing a team lunar rover in the near future, which will utilize CubeSat technology. Overall, this proposal uses electromagnetic and vacuum theories as a framework and seeks to further advance student understanding of the lunar environment as well as prepare the future aerospace workforce through Problem-Based Learning (PBL) and the real-world application of Physics.

Keywords: CubeSats, dust mitigation, electric fields, lunar rover, magnetic fields, regolith

Acronyms/Abbreviations

CubeSat Launch Initiative (CSLI), indium tin oxide (IDO), printed circuit board (PCB), problem-based learning (PBL), Wolverine CubeSat Development Team (WCDT)

1. Introduction

The Wolverine CubeSat Development Team (WCDT) founded in 2015, is internationally recognized for excellence in aerospace education, specifically with respect to CubeSats. The WCDT has been selected for two proposals through NASA's CubeSat Launch Initiative (CSLI). The WeissSat-1, which launched aboard a Falcon IX in 2018, and most recently, the CapSat-1, currently in design, were student-driven in both planning and development stages. Students engage regularly in problem-based learning (PBL), a teaching method in which complex real-world problems are used as the vehicle to promote student learning of concepts and principles as opposed to direct presentation of facts and concepts [1]. In their efforts to learn about how CubeSat technology might be used in different ways, members of the team are currently developing the AMARIS lunar rover to demonstrate the importance of engaging students early on in space-based research to help reinforce the academic STEM pipeline. One concern the team has is how to mitigate dust in space conditions in relation to its rover, and, research is being conducted on how best to address this issue. This paper will discuss the experiment and predicted results of lunar dust mitigation in a simulated space environment.

1.1 Dust Concerns & Need for Mitigation

Apollo 17 astronaut Gene Cernan said, "Dust is probably one of our greatest inhibitors to a nominal operation on the moon" [2]. Bombardment of micrometeoroids from glassy fragments called agglutinates cause hardware failures and are toxic to astronauts [3]. These problems were logged in the Apollo 17 mission report, which noted that "the Lunar Module pilot encountered some difficulty in operating the sun-shade of lunar extravehicular visor assembly because of lunar dust" [4]. While this has been an ongoing issue, mitigating lunar dust still has no feasible solution.

In order to utilize opportunities and lessons learned in space, and before starting the process of building and picking out the perfect, habitable planet for future settlements, researchers need to address numerous issues such as the tendency of this dust to stick to everything, and sometimes clog up airways if inhaled.

The experiment, which will provide data for the construction of the future lunar rover, seeks to evaluate the effectiveness of using constant or intermittent electric or magnetic fields to repel suspended lunar dust. The value of this research is evidenced by the fact that NASA itself is currently evaluating this phenomenon [5]. Solving the problem of lunar dust adhesion to lunar spacecraft, particularly the solar arrays of surface vehicles and instruments, is of vital concern for the future of space exploration.

1.2 AMARIS Lunar Rover

The name AMARIS is of English and Hebrew origin and means “child of the moon.” Since young students are responsible for the development of this lunar rover, the name holds special meaning. Their preliminary design entails using a folded 1U CubeSat architecture, with two large drive wheels and two smaller “tail draggers” for balance. At present time, AMARIS’ intended landing site is Lacus Mortis in the lunar northern hemisphere. The rover will have a 1U footprint while in its launch phase, and once deployed, will unfold via nitinol hinges to become the size of a 2U. This small vehicle necessitates the use of redundant, yet extremely small and efficient components. The dust is a concern, in part, for the mobility of this rover design, particularly for the wheels. While it is understood that both electric and magnetic fields would have some effect on the lunar regolith, the authors are most interested in finding which field would be more beneficial by having the most impact in reducing dust to aid future missions.

1.3 Hypothesis

The student researcher hypothesized that the magnetic field would best repel dust because of its tendency to be more reactive to stationary objects. In order to test the mitigation of dust, students first had to construct a dust box to simulate space conditions.

2. **Material and Methods**

Regolith was obtained from the Exolith Lab at the University of Central Florida (UCF) in Orlando, Fl., Lexan sheets were obtained from Home Depot, and a rubber gasket, magnets, gate valves, and adhesive sealant were purchased from a local Home Depot and various online sites.

2.1 Regolith Composition & Conductivity

Lunar dust, or regolith, is a combination of a variety of particles including rock fragments, monomineralic fragments, and different types of agglutinates.

The lunar dust is made up of silicon dioxide glass, which is created by meteoroids hitting the moon [6]. The main elements found in the lunar dust are oxygen (41%-45%), silicon, aluminum, calcium, iron, magnesium, and titanium [7]. These elements make up 99% of the mass in the lunar dust.

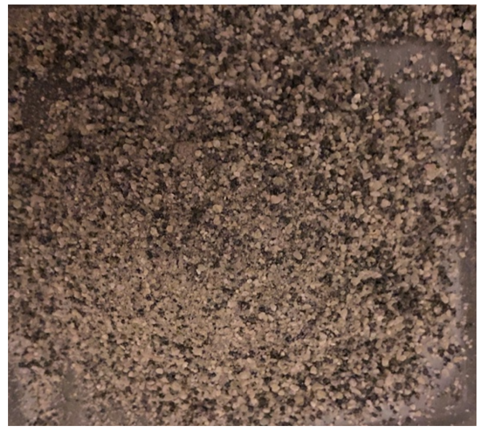

Fig.1 Exolith Lunar Simulant sample. Image Courtesy Caeden Dooner

NASA Estimates that lunar dust is ~5.1 cm thick on the lunar surface [8]. To avoid dropping into a low power mode, the AMARIS rover needs to keep clean solar panels. Smaller spacecraft have lower power budgets due to less available solar panel areas, and often less ability to optimize their angle towards the sun. It is therefore critical to mitigate that lunar dust from adhering to the panels, and from interfering with any of the rover’s drive train or other moving components. NASA also reported that when lit up from the sun’s rays, the negative charged electrons are knocked off the dust, creating a positive charge [8].The current Astrobotic mission timeline plans for eight Earth days of constant sunlight on Lacus Mortis after the landing of the Peregrine Lander. This persistent direct sunlight will cause continuously ionized regolith to hover on and above the Amaris lunar rover.

Unlike on the surface of the moon, the sun’s rays do not knock off the electrons on the simulated lunar regolith, and instead, are not affected by the sun at all. The artificial simulant can be ionized temporarily here on the Earth’s surface by tribocharging. According to Dr. Philip Metzger, planetary physicist at UCF, the dust can be easily tribocharged by pouring the regolith over plastic blocks. However atmospheric humidity quickly neutralizes the charge imbalances in the dust normally within 25 minutes. With this information, the researchers will place lunar dust in a small plastic bag with Lego blocks, and shake the bag in order to charge the dust. In the lunar surface environment, this sharp dust sticks to everything it touches in large amounts. For this reason, NASA has recognized this issue as a top priority in its requirements for its Lunar Exploration Program. According to NASA Goddard Space Flight Center, lunar dust has an average grain size of 70 µm and has a low electrical conductivity [8].

Regolith conductivity increases with surface temperature and infrared and ultraviolet radiation. Essentially, lunar dust on its own is negatively charged; however, once solar rays shine on the dust, it becomes positively charged. This means that when the sun's light shines down on the regolith particles, electrons are knocked off, allowing the positive charge. The dust then repels against the positively charged lunar surface, creating a levitating lunar dust layer. With this problem in mind, there could be a feasible physics-related solution to the dust buildup problem, which these student authors hope to find. In short, if lunar dust is thus positively charged by solar rays in space, it may be plausible that creating a positive charge on astronauts' equipment (including rovers, gear, etc.) may repel the lunar dust, allowing for less buildup.

2.2 *Dust Box and Field Construction*

In order to test the hypothesis, an investigation of the effects of electric and magnetic fields was conducted by individually varying both fields in a dust box containing a solar panel. It was crucial that the dust box be sealed to better simulate the airless lunar environment. The dust box was a rectangular solid composed of six Lexan sheets of 4 mm thickness, with dimensions of 25 cm x 25 cm x 10 cm on the +z face was placed a hinge for access and a gate valve for pulling the vacuum.

A 25 cm^2 5 Volt max single junction solar panel was placed at 90 degree angle to direct sunlight on a cloudless day, and the voltage was recorded. The magnetic field used to test the ability to impact regolith adhesion to the printed circuit board (PCB) mounted solar arrays was provided by a 1 Tesla (10,000 Gauss or 50 pound strength) neodymium magnet. The electric field was provided by a direct current power supply, with a tunable range between 0.0 and 30.0 Volts. The electric field around the PCB mounted solar array was provided by two thin polyethylene sheets coated on one side with a transparent, but conductive coating of indium tin oxide (ITO) mounted parallel 5 cm above and below the solar panel in the dust box.

2.3. Preliminary Experiment Design

The researcher expected that the simulated dust could be easily ionized by exposing the dust to sunlight. To test this idea, a small amount of lunar regolith simulant was ionized in sunlight for 30 minutes. This is so that the electrons are knocked off by the sun's rays, which should create a positive charge. The solar panel is also exposed to the sun with the idea that it gains voltage. The dust box was then agitated to disperse the dust. Immediately after dispersing the dust, voltage data was recorded as a function of time as well as the resulting voltage drop. This test was repeated with electric and magnetic fields of various strengths applied to the immediate volume around the solar panel.

3.Theory and calculations

3.1 Law of Electrostatics (Newton)

Newton's laws of electrostatics are a vital component of this experiment. It is the quantized nature of the atom which requires a precise frequency of radiation to ionize a molecule through the absorption of a precise frequency/wavelength of a photon and subsequently eject an electron. This is the cause of the charged lunar dust particles [9].

The law of electrostatics states that like charges will repel and opposite charges will attract. Charged particles are likewise affected by electric and magnetic fields [10]. Depending on the orientation of the field lines and direction, a charged particle will be accelerated in an electric or magnetic field. Knowing the dust is negatively charged, the use of Coulombs Law allows one to calculate the force experienced by the charged dust in an electric field. Calculating electric field strength ($F=kq_1q_2/r^2$) and measuring subsequent PV outputs serves as a basis of evaluation and comparison of electric and magnetic fields. Similarly, the magnetic field produced by passing a current through a coiled wired is calculated as ($B = \mu_0 I2\pi r$) [9]. Electric and magnetic field investigations can also simulate the movement of particles as they either repel or attract. An electrical field creates a force that accelerates the charged particle, and depending on the charge of the particle, it will either decelerate or accelerate. Also, if the charged particle is moving between electric plates, it will be deflected toward the plate with the opposite charge as the particle. This suggests that if the dust is positively charged, then an electric field will help repel the dust. The strength of the electric field can be calculated using kxq/d2 or Force/Charge [9].

The same process happens with a magnetic field as well. Magnetic fields are created by magnetized areas and by moving electric charges. According to Samuel Ling, "A charged particle moving in a [magnetic] field experiences a sideways force that is proportional to the strength of the magnetic field" [10]. Once the magnetic field is created, it will magnetize the lunar dust and thus the dust will rotate and form the lines of the magnetic field. This will show where the magnetic field lines are, what they look like, and most importantly, will repel lunar dust away from the solar panels. The strength of the magnetic field can be calculated using the magnetic field strength equation: $B=\mu_0 NI/L$.

3.2 Vacuum Theory

In order to create a vacuum-like environment, all air and other gases need to be removed; this is called the vacuum theory. According to Tungsten.com, there is roughly one particle per cubic centimeter of space [11]. In order to simulate how a dust particle would react to electric and magnetic fields in space, researchers must simulate a space-like environment. Vacuum theory states that depending on the size of a container, the pressure will either increase or decrease depending on whether the container is sealed and is expanding in volume [12]. The vacuum theory involves three main types of flow in a vacuum: continuum, molecular, and Knudsen. According to Vac Aero, a company that manufactures vacuums, molecular flow is seen at pressures below .001 mbar, which is the high and ultra-high vacuum range. The intermolecular collisions in this level are less frequent meaning molecules are free to move in multiple directions.

While molecular flow involves molecules moving in multiple directions, continuum involves the molecules moving in straight lines through a pipe. This can be found in the low vacuum range. Knudsen flow describes the movement of fluids with high Knudsen numbers [13]. This means that the characteristic length in the flow space is of the same or smaller order of magnitude as the mean free path. For this experiment, in order to create a vacuum in the dust box, researchers will use a vacuum pump and a gate valve to suck air out of the box using a continuum flow for roughly twenty seconds. The continuum flow should seal the lid to the box and should get majority of the molecules out of the box. However, a vacuum pump cannot achieve the same vacuum as space, meaning there will be higher levels of molecules still in the box, which will be more of an effect on the simulated dust.

4. Results

The first tests conducted involved the voltage drop off of the solar panels when using ITO plates vs without. The chart below shows the percentage drop off from the DC power supply to the ITO plates.

Table1. Solar Panel Voltage loss with ITO panel

Applied Voltage	Measured Voltage	% Difference
5V	4.5V	~10%
10V	9.8V	~2%
15V	12.6V	~16%
20V	19.8V	~1%
25V	24.7V	~1.2%
30V	29.9V	~.3%

The transparent conductive ITO plates proved that there was a 2% drop off of voltage through the ITO plates and without. This shows that the ITO plates would have little effect on the results in the experiment.

The electric and magnetic field strengths were calculated using their own respected equations. Using the magnetic field strength equation, the strength was determined to be 7.11x10^-5 T. This shows that the 1 Tesla magnet would have that much of an effect on the dust. Similarly, the electric field strength was calculated to be 3000VPM which was then used to find the point of charge, which was 3.34x10^-5 C. When tested using the lunar dust, neither the electric nor magnetic field produced significant effects on the particle motion of the dust. Once researched more in depth, it was discovered that simulated lunar dust needed to be tribocharged rather than exposed to sunlight. However, the student researcher learned that the dust can be easily tribocharged by pouring it over plastic blocks. This method will be tested and the experiment will be completed at a later date.

5. Discussion

5.1 Future Investigations

Though the experiment was inconclusive as far as determining whether the dust could be mitigated using the magnetic and electric field and the impact of the two fields on the dust, the researcher still learned a lot about what works and what needs to be worked on. As next steps, the student researcher will be using the tribocharging method to ionize the dust for the electric field. Once the researcher can find an appropriate method to pour the dust repeatedly over the plastic blocks, then the electric field will be tested. With regards to the magnetic field, it was discovered after talking to Dr. Metzger that the simulated dust is unable to be magnetically charged. The student researcher, instead, will try to use a Vandegraff generator to test whether the dust would be attracted or repelled from the generator. Once that test is concluded, the researcher will try to magnetically charge the dust using that same method, long enough to complete the experiment.

5.2 Experimental Difficulties

There were many original ideas that did not pan out over the course of the experiment. Originally, the strength of the electric and magnetic fields were to be calculated using a coded Arduino. While there are codes specifically for calculating flux density of a magnetic field and the strength of an electric field, the researchers were unable to find a way to make the Arduino work properly. It is possible, and probably easier, to use a coded Arduino for the calculations of the strength of the two fields, but an acceptable alternative would be to calculated by hand using the two field equations.

Another major problem involved the simulated dust. When conducting an experiment involving real lunar regolith, it is difficult to simulate dust that would respond the same way as it would on the lunar surface. While UCF's Lunar Highlands Simulant is a satisfactory alternative, its properties are not completely identical to actual lunar regolith. For example, the ionization and magnetically charging of the dust. As discussed earlier, the dust did not respond to the electric or the magnetic field. The researcher first tried to charge the dust using the sun's rays. It was incorrectly assumed that since lunar dust can be positively charged, then the simulated dust could do the same. The researcher then attempted to ionize the dust via tribocharging, which involves pouring the simulated dust in this case on plastic blocks for a period of time (which is dependent on the particular need). In order to maximize dust exposure to the blocks the researcher placed 4 plastic blocks (2 cm x .7 cm x 1 cm) into 0.9 L Zip-lock bag along with ~10 grams of dust and shook by hand for five minutes.

The researcher tested to see if the dust was ionized by placing small cut-up pieces of paper around the dust to see if it would attract. It was determined that the dust did not react to that method. The researcher tried again, this time creating a funnel where the dust could be poured on top of the plastic blocks and fall into a bowl to collect the dust and be repeated as necessary. This test was also conducted outside in sunlight so that dust could make contact with the air and sunlight to see if that had any effect on the dust. This process was done multiple times and the test still showed no effect on the dust. If the experiment is to be replicated, ionizing the dust using this method is possible, but there needs to be a proper way to make the simulated dust hit and fall the blocks repeatedly for a long period of time.

For the amount of time the student researcher had with the experiment, the constructed dust box was a simple method to hold the dust, however, if replicated, the dust box should have more durable and superior materials. There was a lot of difficulty in constructing the dust box due to the fact that it was constructed using rudimentary and basic materials. There were many patches and cracks from which air could escape, and the researcher did not have a lot of workspace and design knowledge with which to work. A possible design alteration, which could make accessing the box easier is if a researcher could reach inside the box with gloves so that the dust could be touched and stirred easily without allowing air to escape.

5.3 Results for AMARIS

Though the experiment has not been fully completed, there is still beneficial information that can be explored for future rover design. In the beginning, student researchers were thinking of proficient ways to mitigate the dust. The electric and magnetic field tests were conducted with the intent of using one specific field for the rover, however, after conducting this experiment, both fields would be beneficial in their own ways. The electric field is more beneficial for when stationary, and the magnetic field is more beneficial when moving [14]. Since AMARIS will not be stationary at points and moving slowly at other points, both fields would have their own benefits.

6. Conclusions

Lunar dust continues to be a problem for astronauts and for equipment. In order to keep astronauts safe and equipment free from damage, researchers need to find an acceptable solution to mitigating lunar dust. A possible solution to this problem is to repel the dust using electric and magnetic fields since lunar dust, when exposed to sunlight, is positively charged. The researchers hoped to test this solution using simulated lunar dust from UCF's Exolith Lab, however, due to the properties of the simulated dust, the experiment was inconclusive and is still in the process of alternate testing. While the experiment is inconclusive, researchers have learned much through Problem-Based Learning, and have made progress in their future design. In the beginning of the AMARIS project, student researchers had no idea of where to start or what the necessary steps were to design a rover; however, now, foundation is more clear. By working on real-world STEM experiments, more students identify themselves as future engineers. PBL, such as constructing spacecraft, allows students to explore difficult problems in STEM and feel as though they are contributing to future solutions.

Acknowledgements

The authors wish to thank UCF Exolith Lab in Orlando, Fl for the lunar dust simulant and, Dr. Philip Metzger in particular for his guidance during the experiment process.

References

[1] Illinois CITL, Problem-Based Learning; Teaching Strategies N.D. https://citl.illinois.edu/citl-101/teaching-learning/resources/teaching-strategies/problem-based-learning-(pbl), (accessed 07.15.20)

[2] J. McClain, Dust is Far from the least of our worries as we plan to colonize Mars, 5 October 2018,https://www.wm.edu/news/stories/2018/book-dust-is-far-from-the-least-of-our-worries-as-we-plan-to-colonize-mars.php,(accessed 07.12.20)

[3] C. Cross, V. Cross, C. Dooner, 33Rd Annual Small Satellite Conference: AMARIS Lunar Rover Evaluation, 7 August, 2019

[4] O. Morris, Apollo 17 Mission Report, March 1973, https://history.nasa.gov/alsj/a17/A17_MissionReport.pdf, , (accessed 06.20.20)

[5] L. Keesey, NASA's Coating Technology Could Help Resolve Lunar Dust Challenge 5 November 2019,https://www.nasa.gov/feature/goddard/2019/nasa-s-coating-technology-could-help-resolve-lunar-dust-challenge (accessed 07.14.20)

[6] T. Phillips, Apollo Chronicles: The Mysterious Smell of Moondust, 1 January 2006 https://www.nasa.gov/exploration/home/30jan_smellofmoondust.html#:~:text=Almost%20half%20is%20silicon%20dioxide,such%20as%20olivine%20and%20pyroxene. (accessed 07.13.20)

[7] R. Korotev, The Chemical Composition of Lunar Soil, N.D., https://sites.wustl.edu/meteoritesite/items/the-chemical-composition-of-lunar-soil/ (accessed 07.13.20)

[8] L. Keesey, NASA's Coating Technology Could Help Resolve Lunar Dust Challenge 5 November 2019,https://www.nasa.gov/feature/goddard/2019/nasa-s-coating-technology-could-help-resolve-lunar-dust-challenge (accessed 07.14.20)

[9] P. Zitzewitz, *et al.* lMcGraw-Hill-Education, Physics Principles and Problems, Glencoe Sciences, 2005

[10] S. Ling, W. Moebs,J. Sanny, Motion of a Charged Particle in a Magnetic Field 26 July 2019, https://opentextbc.ca/universityphysicsv2openstax/chapter/motion-of-a-charged-particle-in-a-magnetic-field/#:~:text=A%20charged%20particle%20experiences%20a%20force%20when%20moving%20through%20a%20magnetic%20field.&text=Since%20the%20magnetic%20force%20is,it%20forms%20a%20complete%20circle. (accessed, 07.10.20)

[11] Midwest Tungsten Service, Basic Vacuum Theory, N.D. https://www.tungsten.com/tips/basic-vacuum-theory/ (accessed 07.13.20)

[12] VAC Aero International, The Fundamentals of Vacuum Theory, 10 August 2018 https://vacaero.com/information-resources/vac-aero-training/170466-the-fundamentals-of-vacuum-theory.html (accessed 07.13.20)

[13] Pfeiffer Vacuum, Types of Flow in a Vacuum, N.D. https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/types-of-flow/ (accessed 07.13.20)

[14] K.Stenhouse, J. Hanania, J. Donev, Energy Education; Electric Field, 28 April 2020,https://energyeducation.ca/encyclopedia/Electric_field (accessed 07.16.20)