

Methods of Measuring Secondary Electron Emission and Analysis of Spacecraft Charging Simulation

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Abstract

The scope of the internship project was to help the Electrostatics and Surface Physics Laboratory (ESPL) at KSC gain an understanding as to what parameters related to secondary electron emission (SEE), and electrostatic discharge (ESD) could be measured within its own facilities. As well as assistance in developing a plan for the ESPL to acquire the capabilities to measure other necessary parameters, to reduce the reliance on measurement data from facilities outside of the agency. The intern also worked closely with agency customers of the Launch Services Program (LSP) in expanding the MAPTIS database to incorporate various electrostatic and physical properties of materials used in the Gateway Program. This involved cross-center collaboration with industry and NASA contracted academia members in order to fill in the gaps of data that is missing from the database. Overall, the internship provided assistance in coordinating the approval for more materials to be added to the MAPTIS database, and continuing to assist the team at the ESPL in their consulting work for the agency through the use of various spacecraft charging and ESD simulation programs (i.e., NASCAP, NUMIT2.1). As well as assisting in the CAD design and implementation of an electrodynamic dust shield (EDS) for use in upcoming spaceflight missions. This was all done with the aim of helping the ESPL demonstrate its capabilities for the agency, and to continue expanding and localizing measurement techniques at KSC to help streamline obtaining the information NASA needs to ensure safety in current and future missions.

Introduction

Spacecraft charging is a term that refers to the charging of a spacecraft's surface, by means of collecting extra ions or electrons.¹ Differential charging on spacecraft surfaces can occur as the body is subjected to the space plasma environment. Here, various components of a spacecraft can charge to different potentials, which introduces the chance of electrostatic discharge (ESD) as the whole body tries to reach equilibrium with the space plasma environment.² This phenomenon can lead to severe damage to equipment, and cause interference in communications. Spacecraft charging has become a large concern in planning cislunar operations, and even in long-term space exploration missions.

To better understand the causes of differential charging on a spacecraft in order to prevent excessive damage and instrumentation interference, the particle interactions around the spacecraft are analyzed. There are many ways extra electrons or ions can be tossed into the particle soup of the environment local to a spacecraft in orbit, as illustrated in Figure 1. With some of the main particle interactions caused by electron emission, coming in the forms of photoelectric emission, as well as thermionic and field emissions (free electrons escaping from a metal surface that is subject to heat or an electric field respectively), as seen in Figure 2. To best

model this scenario, all possible emissions to and from the spacecraft's surface need to be considered, as the fine details of all particle interactions in this environment need to be traced in order to properly simulate and model spacecraft charging effects. One important type of emission to consider is referred to as secondary electron emission (SEE). Secondary electrons are often grouped with backscattered electrons, but have a much lower energy. Secondary electrons are defined as those emitted with an energy of less than 50 eV, making SEE very troublesome to properly detect.³

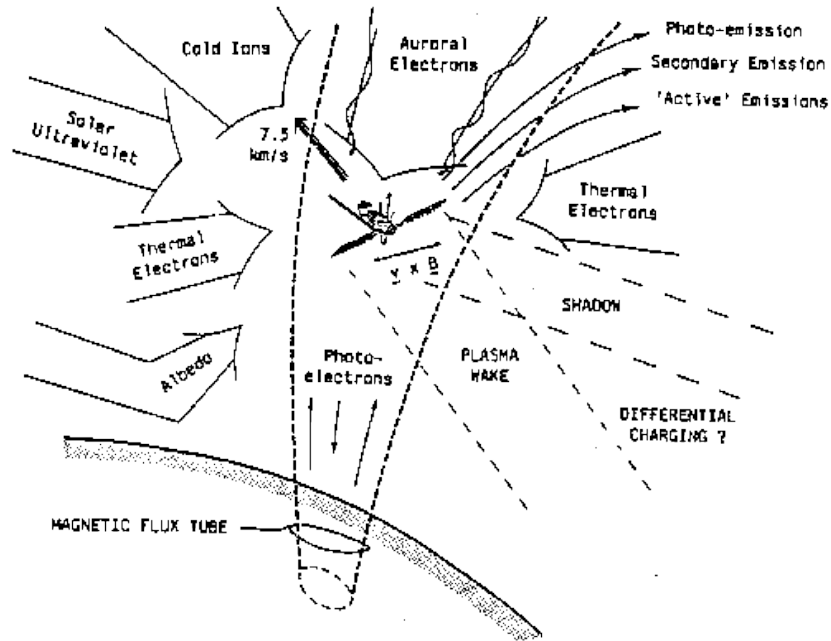


Figure 1: Particle interactions on a satellite in polar orbit

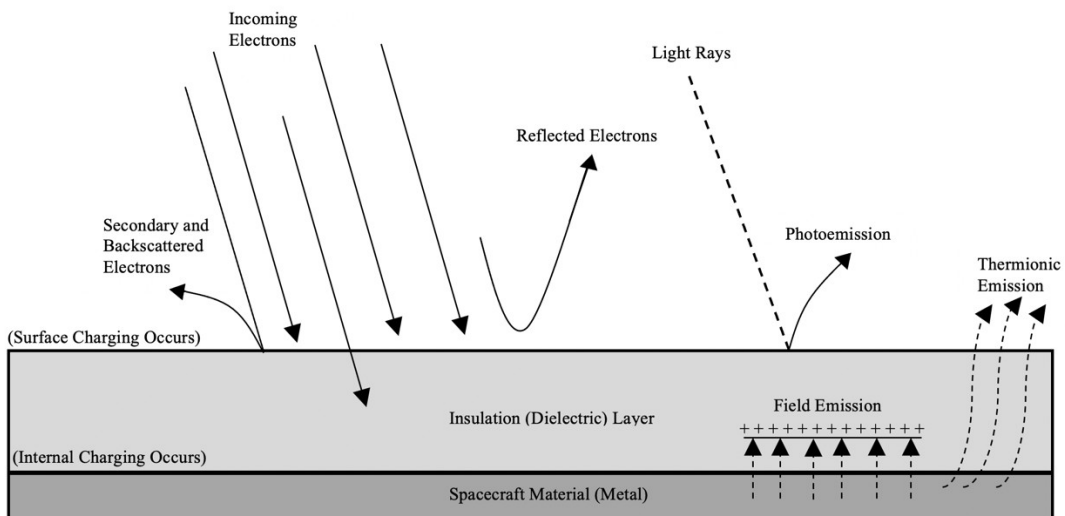


Figure 2: Closeup of spacecraft charging related particle interactions

NASA currently does not possess the capability to measure secondary electron emission (SEE) from materials without outside assistance from contracted university facilities. Because of this, KSC is in the works on developing the means to measure SEE and other ESD related parameters on numerous space materials for the LSP here within the ESPL. The ESPL had recently installed an electron gun which can be used to generate SEE, and also purchased an ion gun for use in other experimental setups. During an internship over the summer, research by an intern was needed to investigate these various SEE detection techniques, along with help in determining the best in-vacuum testing methods, instrumentation, experimental setups, and procedures needed for both the electron and ion guns in order to find the most efficient method of SEE measurement for the given application.

The work related to SEE detection and measurement led to the opportunity to help expand a material parameter database used for various spacecraft charging simulation programs around the agency. As well as the opportunity to assist the mentor in the creation of a presentation on the ESPL's lab capabilities, which will be presented at the Space Environments Virtual Seminar put on by Dr. Joe Minow from the NASA Engineering & Safety Center (NESC). The NASA database being expanded is located within the Materials and Processes Technical Information System (MAPTIS). MAPTIS is an information system from the NESC that includes NASA's Spacecraft Charging Material Properties Database (SCMD). The materials tested to date are embedded within a NASA Gateway Program document which highlights the energies, flux and test methods used to measure SEE from a variety of surfaces. However, knowledge gaps pertaining to the overall procedures used needed to be identified in order for the ESPL to begin efforts toward measuring related parameters. Part of the objective for the fall internship was to continue assisting with all of these efforts.

Other duties carried out during the internship included assisting Dr. Buhler and his colleagues at the ESPL in consulting work for various agency programs and customers. This included assistance in purchasing and gathering related industry standards and references (both internal and external to NASA) on relevant information related to the theory behind certain experimental setups and testing procedures involved in ESD and SEE measurement. The intern also assisted in contacting various companies and manufacturers in order to get technical specifications and quotes to help potentially obtain the proper equipment, instrumentation, and other necessary components needed to continue experimentation and design work at the ESPL. Some other examples of this consulting work include help in running ESD simulations alongside work done in the lab in efforts to verify/support experimental findings, along with assistance in the design and fabrication of an EDS for use in upcoming missions.

The concept of demonstrating the capabilities and usefulness of the ESPL became extremely important to emphasize early on in the internship. This is considering that during the current COVID-19 pandemic, the ability to work on-site at KSC was limited to just mission critical work, while also minimizing the number of people allowed in the lab or on site at any given time. Helping the ESPL make the most of their time in the lab by preparing outside of the lab showed to be a crucial aspect in maintaining lab operations and contributing towards mission critical objectives in current times.

Approach

To get an idea of the parameters involved in spacecraft charging and SEE, the NASA Charging Analyzer Program (NASCAP-2K) was acquired from NASA's software catalog. NASCAP is used around the agency to simulate spacecraft charging on various geometries, specifically surface charging. The program features a built-in list of 20 material variations and their associated 19 spacecraft charging parameters. The list of NASCAP's 19 parameters can be seen in Table 1 below. For a better understanding of the 19 parameters and how they are measured it was suggested to track down more materials to add into NASCAP and gain the clearance needed to access NASA's current material databases, being the Materials and Processes Technical Information System (MAPTIS).

MAPTIS is an information system from the NESC that includes the SCMD, which features the proper NASCAP parameters for a list of materials. This science-based database requires significant understanding of the field of electrodynamics, solid state, electrostatics, charging/discharging, and various material properties. As well as knowledge of SEE, photoemission and ion irradiation parameters. So, increasing the number of materials within NASCAP coincided with expanding the SCMD within MAPTIS. A meeting with Dr. Joseph Minow and his team at the NESC occurred during the process of gaining access to MAPTIS, where great interest was shown at the idea of adding more materials to the SCMD. There was also an interest in the ESPL getting started on acquiring the capability to measure some of these parameters locally at KSC.

Table 1: Standard presentation format for the list of NASCAP's 19 parameters for a material

Parameter	Value
[1] Relative dielectric constant; ϵ_r (Input as 1 for conductors)	
[2] Dielectric film thickness; d [m]	
[3] Bulk conductivity; σ_o [$\Omega^{-1} \text{m}^{-1}$] (Input as -1 for conductors)	
[4] Effective mean atomic number; Z_{eff}	
[5] Maximum SE yield for electron impact; δ_{max}	
[6] Primary electron energy for δ_{max} ; E_{max} [keV]	
[7] First coefficient for bi-exponential range law, b_1 [\AA]	
[8] First power for bi-exponential range law, n_1	
[9] Second coefficient for bi-exponential range law, b_2 [\AA]	
[10] Second power for bi-exponential range law, n_2	
[11] SE yield due to proton impact δ^H [1keV]	
[12] Incident proton energy for δ^H_{max} ; E^H_{max} [keV]	
[13] Photoelectron yield, normally incident sunlight, j_{pho} [A/m^2]	
[14] Surface resistivity; ρ_s (Input as -1 for non-conductors) [Ω/\square]	
[15] Maximum potential before discharge to space; V_{max} [V]	
[16] Maximum surface potential difference before dielectric breakdown discharge; V_{punch} [V]	
[17] Coefficient of radiation-induced conductivity, σ_r ; k [$\Omega^{-1} \text{m}^{-1}$]	
[18] Power of radiation-induced conductivity, σ_r ; Δ	
[19] Density; ρ [kg/m^3]	

To find more materials to add into MAPTIS, it was suggested to look into acquiring material data from those used in the Gateway Program from the Natural Environments Group located out of NASA's Marshall Space Flight Center (MSFC). Here, a contact was found to help out in acquiring access to the materials being used on Gateway. Another source of potential materials featured those from a revived ESPL database used to archive materials from 1986 to 2005. The database includes triboelectric charging data for over 1800 materials used in NASA projects that were once tested within the ESPL, but lacked the parameters used in NASCAP. The idea of testing these materials to measure NASCAP's 19 parameters was brought up, which led to further contact with the NESC and MSFC regarding how the Gateway materials were being tested. This led to opening a line of communication with J.R. Dennison's team at Utah State University (USU), who are involved in carrying out SEE parameter measurements on various materials for NASA/NESC under contract.

The next step involved looking into the possible methods of SEE detection, and determining the feasibility and efficiency of each method based on the application involved. The validity of the final SEE detection choice came down to the amount of accessible/relevant information on similar experimentation used in research at a few universities across the country. This included the experimental setup used within USU's facilities, considering all current Gateway material data was measured using this procedure that has been in the works for many years.

The most common setup to measure secondary electrons involves an electron beam aimed into a Faraday cup, and directed at a material sample plate inside of the cup.⁴ Also, on the cup is some sort of entrance aperture with an applied voltage to help only pass secondary electrons. This approach can be problematic as very small currents (usually picoamp levels) can be shrouded by noise and interference. Another common method used, and USU's current approach involves a setup similar to that of a retarding-grid energy analyzer. In this setup, an electron beam enters through the top of a shell covering a sample plate. Working outwards from the sample plate, emitted electrons will pass through an inner grid and a bias grid, each with their own voltage to help halt the flow of non-SE electrons. The electron beam entrance consists of a grounded tube, reaching all the way down past the inner grid. This is done to help the electron beam remain unaffected by the various potentials on the grids and collector. Electrons that pass both grids will flow upwards and gather on an inner collector shell, this is where the secondary electron yield and other parameters are measured.⁵

Near the end of the summer internship, a meeting with J.R. Dennison from USU, and Dr. Joseph Minow from NESC occurred. The objective of the meeting was to see what Gateway material data was viable and cleared for entry into MAPTIS for the first round of entry, and to check on a possible timeline of getting new materials tested such as those from the ESPL database. During the meeting, it came to be known that some of the materials within NASCAP that were shown to have inaccurate parameter data⁴ had still not been adjusted to reflect newer measurements. The result was adding around 70 new material variations to MAPTIS, along with correcting old parameters for existing materials. New materials will continue to be added as they are tested and cleared by USU in the coming months, and in for the foreseeable future considering the contract renewal that arose during these discussions. These considerations were part of what led to the opportunity to return for the fall internship, where one of the duties consisted of overseeing the addition of more materials into MAPTIS from USU's next round of testing.

Other tasks carried out during the fall internship included assisting Dr. Buhler and his colleagues at the ESPL in consulting work for various agency customers by assisting in ESD simulation alongside experimentation carried out in the lab. This was done by acquiring the internal electrostatic discharge (IESD) analysis program from NASA's Jet Propulsion Laboratory (JPL) known as NUMIT2.1. NUMIT2.1 is a numerical integration code written in FORTRAN 90. This program helps to determine the build-up of charge in a material by simulating one-dimensional internal charging, but also has a 3-D counterpart known as 3D NUMIT.

A NUMIT simulation is used to calculate the internal current density, electric field, dielectric space charge density, and the replacement current density (through the back electrode) for a certain dielectric geometry.^{6,7} This is done iteratively with the use of Poisson's equation, Gauss's law, Ohm's law, and the continuity equation. The energy deposition and charge deposition profiles are also determined through the use of certain algorithms, including Tabata's algorithm.⁶ NUMIT2.1 includes the ability to simulate single and multiple dielectric layers, and can be modified in many ways in order to simulate various experimental setups and testing conditions. For instance, the input for the incident 'beam' of electrons can be altered to have either mono-energetic incident electrons, or a spectrum of incident electrons with a time-varying current density. The conductivities for each layer can also be changed with respect to time. The inputs required to run a NUMIT simulation at the most basic level (time non-varying, mono-energetic incident electrons) include a time-step, the energy and current density associated with the incident electron beam, an areal density and applied (external) voltage for the left electrode, as well as the thickness, dielectric constant (permittivity), radiation induced conductivity, dark conductivity, atomic weight, and atomic number for each dielectric layer.

Table 2: Example of Emphasized NUMIT Input Parameters

Parameter	Value
[1] Electron beam current; J_{inc} [A/m^2]	
[2] Electron beam energy; T_0 [MeV]	
[3] Dielectric thickness; d [m]	
[4] Effective atomic number of the dielectric; Z_{eff}	
[5] Effective atomic number of the dielectric; A_{eff}	
[6] Dielectric permittivity at 300 K; ϵ [F/m]	
[7] Dielectric density; ρ [g/cm^3]	
[8] Dark conductivity of dielectric; g_{dark} [$\Omega^{-1} m^{-1}$]	
[9] Radiation induced conductivity; g_{rad} [$s \cdot \Omega^{-1} m^{-1} rad^{-1}$]	

NUMIT2.1 was specifically used to assist the ESPL in consulting work done for a NASA spaceflight vehicle to determine potential ESD damage to flight cables when exposed to the space environment. The intern also helped to write an ESPL technical report on the results found from the overall electrostatic evaluation of the flight cables for agency customers.

The analysis used to determine if these flight cables were potential targets for ESD included dielectric breakdown testing and electron beam testing in the lab, along with running internal charging simulations. Here, the buildup of the electric field found from the use of simulation was considered, and compared to the dielectric strength of the material. If the simulated electric field was within an order of magnitude of the dielectric strength, then it was said that arcing could potentially occur. NASA-HDBK-4002A was also referenced in order to determine aluminum equivalent shielding and the energy stored per unit length for the cable, which can be seen below as Equation 1.

$$E_{area} = 0.5 \epsilon_r \epsilon_0 k^2 t \quad (1)$$

Where ϵ_r is the relative permittivity of the dielectric, ϵ_0 is the permittivity of free space (vacuum), k is the dielectric strength, and t is the dielectric thickness.³ The energy stored per unit length E_{area} (J/m²) was used alongside a specific given qualification energy J_{qual} (J) in order to find the maximum allowable surface area SA_{max} (m²) for the cable as seen in Equation 2. From here, the maximum allowable surface area could be back solved with the known maximum cable diameter D (m) to find the maximum allowable wire length L_{max} (m) that was associated with the energy stored per unit length, and is represented by Equation 3. This maximum cable length is the length necessary to accumulate enough electrons to discharge, and would serve as the limit for the allowable distance across the length of the cable that ESD could occur in order to meet flight qualifications.

$$SA_{max} = \frac{J_{qual}}{E_{area}} \quad (2)$$

$$L_{max} = \frac{SA_{max}}{\pi D} \quad (3)$$

The experimental setup used to test the dielectric breakdown strength of materials included the use of a Dielectric Test Unit, which is used to apply a ramping voltage from zero to breakdown at a specific AC signal in order to determine the voltage and current at the breakdown of the material. Breakdown occurs once the voltage breaks through the insulation (when the insulator becomes conductive). During the testing procedure, the test cable had one end connected to the power supply, and the other end was connected to a grounded electrode.

The experimental setup used for electron beam testing was assembled inside a high vacuum chamber pumped down to around 10⁻⁶ Torr, and consisted of an electron beam to emit unwanted electrons towards the test cable, along with a Faraday Cup to verify the electron beam current density. The electron beam was mounted to a flange at the top of the vacuum, and aimed downwards towards the Faraday Cup, which was mounted on a linear translation stage. Electron

beam testing was used to see if the breakdown characterized earlier could be met during flight when the cables were exposed to space environment conditions, and to determine if the energies involved were below what was needed to meet qualifications. During the testing procedure, the cable was mounted within the vacuum with the electron beam above.

Another moment during the internship was the opportunity to help the ESPL in their collaboration with Embry Riddle Aeronautical University's EagleCam CubeSat project. Where the task was to assist in the implementation of an EDS to protect camera lenses onboard a CubeSat. Embry Riddle's EagleCam CubeSat will be part of the payload on Intuitive Machines' Nova-C Lunar Lander, which will land on the surface of the Moon in the near future (scheduled for the fall of 2021).⁸ During the mission, the CubeSat will separate from the lander as it approaches the surface of the Moon in order to record the landing. This will be the first ever third-person footage of a lunar landing as seen from the lunar surface, as well as the first implementation of Wi-Fi to transmit data on the surface of the Moon. Considering that the CubeSat will make contact with the lunar surface, dust mitigation plays a crucial role in ensuring success during the mission. The camera lenses will also be one of the prime targets for lunar dust adhesion and buildup, so impact with the lunar surface will present one of the worst-case scenarios for dust's interference on equipment used on the Moon.

Considerations for the implementation of EDS technology on the EagleCam CubeSat include the placement of the EDS on the outer surface, and the power supply within the interior assembly of the CubeSat. For the EDS power supply, it is important to choose the placement to best reduce action about the axis of rotation of the CubeSat in order to provide stable camera footage during the descent. The EDS power supply also has to be in a location within the inner assembly of the CubeSat that helps to reduce interference with other nearby electronic components. For the EDS electrodes, optimizing their placement is done to maximize the effects that the generated electric field has on dust clearance, and the effectiveness varies with the geometries used in the design of the EDS.

The cameras onboard the CubeSat that will be used to observe the lunar landing feature spherical lenses that will need be covered by an EDS, meaning that the overall shape and structure of the EDS can have an impact on the captured footage by altering the camera's field of view. Current EDS technology provides solutions that are flat (2-D, or have no curve), and usually feature glass panels. If the camera lens was to protrude from the surface of the CubeSat's outer assembly, the EDS would have to sit on a mount connected to the outer structure which would be positioned over the opening for the lens. Or, the EDS would have to sit flush with the CubeSat's outer surface assembly, and the camera lens would not be allowed to protrude from the assembly. Either way, the field of view of the spherical lens would be reduced. With these considerations and historical implications of the mission objective, the fabrication and design of a curved EDS is being considered.

A curved EDS will eliminate the possibility of having the reduce the overall field of view of the camera, as the lens would be able to protrude from the surface of the CubeSat's outer assembly as the EDS sits flush over the lens in its identical shape. Some of the challenges that come with a curved EDS include the material selection, as well as the fabrication of reliable curved surfaces and flexible circuits, and placement of electrodes throughout the curved surface. This will also bring new complexities to associated modeling and design techniques. If a curved EDS can be

implemented properly on the finished EagleCam CubeSat flight model, it will be the first of its kind used in any space related mission.

More tasks during the course of the internship included gathering references/resources on various subject matter, including literature on SEE measurement, photovoltaic dust removal/charging, and more. Some important topics included methods of capacitance and permittivity (dielectric constant) measurement that could be performed on an EDS, along with help in understanding the impact that the resistivity of dust has on an EDS in order to help optimize its polarization times. Another task included starting to find NASCAP parameters for lunar dust grains, in efforts to better simulate surface charging on dusty spacecraft surfaces.⁹ Standards were also gathered and purchased in efforts to provide the mentor with the proper reference materials to help create NASA's Dust Standards document. Purchasing and gathering relevant ASTM, ISO, and NASA standards to help increase the ESPL's understanding on how to properly facilitate testing of materials for measuring permittivity (dielectric constant) and other parameters related to ESD, SEE, and spacecraft charging. All of these tasks helped to shed some light on the innerworkings of the agency, and give exposure to the day-to-day work environment of NASA employees. Getting necessary data into the hands of scientists and engineers throughout the agency with ease is incredibly important to increasing NASA's overall work efficiency.

Conclusions

Overall, the internship provided assistance in determining proper methods to measure SEE, along with the parameters associated with plasma, ions and electric fields that are seen in experiments at the ESPL. Other tasks were to acquire standards along with other relevant reference material, oversee the addition of material parameters to the MAPTIS database, and provide assistance in consulting work alongside the ESPL for agency customers. Some notable moments included utilizing NUMIT to assess possible discharge damage to cables, and assisting in the design and fabrication of an EDS for the EagleCam CubeSat project in ESPL's collaboration with Embry Riddle Aeronautical University. Measurement techniques, equipment, and experimental setups were also analyzed to help the ESPL determine how to proceed in filling the gaps formed by this missing Gateway Program data and measuring other related parameters not found in current databases.

The outcome of the project was helping to increase the number of materials and associated parameters in the SCMD for usage in various spacecraft charging modeling software (i.e., NASCAP, NUMIT), and other applications related to current NASA missions. Expanding the ESPL's measurement capabilities was done with the aim of having the means to replicate/verify data from outside sources locally at NASA, and continue to test new materials to further populate the SCMD. Streamlining the access and broadening the scope of material information available throughout the agency will continue to be a crucial aspect in ensuring safety and success in all future missions. It will be crucial in the coming years to make measurements to characterize the space plasma environment, in efforts to better understand space weather conditions through various means of modeling and simulation.

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A big thank you to Dr. Daoru Han for kickstarting this whole pursuit, and being a great mentor (and friend) along the way. As well as a thank you to Dr. Han's team at the Gas and Plasma Dynamics Lab. Also, to the NASA-Missouri Space Grant Consortium for the initial consideration, past support, and decision to fund this internship during these current times. Lastly, a big thanks to Dr. Charles Buhler for considering me to fulfill the role of these internships, and further introducing me to this fascinating field. It has been an honor getting to observe and participate in the day-to-day experiences around the lab with you and your colleagues in the ESPL and around the agency. The inclusion over the last 6 months has been an extraordinarily eye-opening experience to say the least. Never have I met a group like you all, but it's safe to say I found my people, and I am looking forward to collaborating with you all in the future.

Biography

Joey Faudel from Kansas City, Missouri is a Mechanical Engineering student currently in the final semester of his Senior year at MS&T. After discovering his passion for astronomy and space exploration, he got his GED and dove head first into college in efforts of one day working for NASA. After receiving the MAE Department's Distinguished Research Fellowship in Summer 2019 under Dr. Daoru Han, he continued to work with Dr. Han's graduate students in the Gas and Plasma Dynamics Laboratory as an undergraduate research assistant until the Summer of 2020. Work with Dr. Han's team in the lab led to the opportunity to participate in NASA internships for the ESPL at Kennedy Space Center in the Summer and Fall of 2020 under the mentorship of Dr. Charles Buhler. All of these experiences have led to an interest in participating in research regarding the lunar surface environment and dust mitigation, in efforts to assist in future missions on the Moon and other upcoming cislunar operations.

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