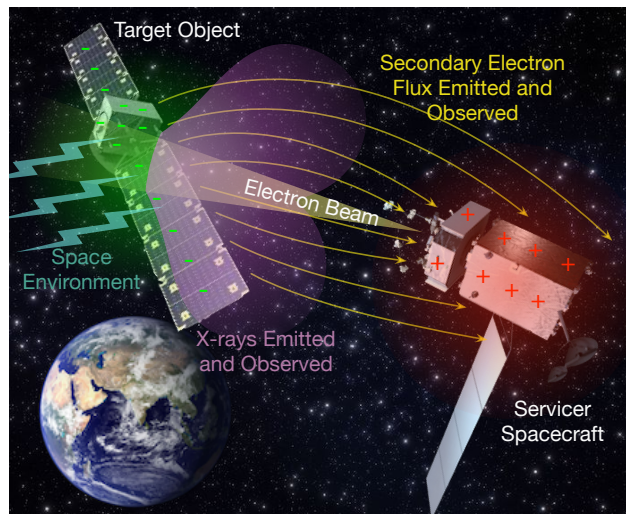


ANNUAL REPORT - 2ND PROJECT YEAR

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Touchless Sensing of Electrostatic Potential and Material Characterization Using Neighboring Spacecraft



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1 Project Overview

This 3-year research study completed its second year. The goal is to research touchless methods to sense neighboring spacecraft charge using either electron or x-ray measurements, as well as study the impact of charging on rendezvous and docking operations. The general concept is as follows. An inspector spacecraft is assumed to be station-keeping dozens of meters from a target space object and seeks to determine the relative charge of the target. This scenario is of interest to orbital inspection and servicing missions where differential charging is of concern during docking (electrostatic discharge) as well as to predict how the charged orbital perturbations impact relative motion guidance and control. The motivation for this work includes mission scenarios such as close proximity operations and vehicle inspection, servicing mission and GEO debris removal. The orbital servicing in particular is a hot topic right now with Northrop Grumman demonstrating the first autonomous docking and life-extension mission recently with the MEV-1 mission. Further, a particularly promising geosynchronous space debris mitigation method is the electrostatic tractor concept to touchlessly control relative motion or detumble an uncontrolled space object. Here touchless charge sensing has been identified as a key component of a charged relative orbit control solution to avoid bifurcations in the closed loop response. Being able to simultaneously sense the surface material property enables developing a surface charging model or making docking decisions depending on the surface composition. The target spacecraft is assumed to be flying outside the van Allen belts, such as at the geosynchronous orbit regime, where the Debye shielding effect of the ambient plasma is minimal.

The touchless charge and material property sensing methods involve both active irradiation of a conducting surface with electrons and measuring the resultant bremsstrahlung x-ray spectra or secondary electron emissions, as well as a passive sensing method using the natural space environment to stimulate these emissions. Both of these physical phenomena depend on the potential of the surface, thus the target potential can be inferred. These two methods can be used in tandem, by utilizing an x-ray spectrometer and a plasma analyzer. The 3-year project will perform both numerical and extensive experimental research to study and analyze the charging accuracy on complex shapes with multiple surface properties. Each method has its strengths that can be fused into a joint filter to create a robust sensing solution.

The second project year continued with lots of vacuum chamber experiments, new numerical simulation and analysis of the results. The pandemic had a minimal impact in 2021 as we had continued access to the lab facility and vacuum chamber. Several hardware enhancements were performed on the chamber to enable remote operation, if needed, of the experiments. This also has the benefit of now being able to run automated experiment series overnight without a graduate researcher present. The 2nd year research has focused on the charge sensing around complex three-dimensional target shapes using both the electron and x-ray sensing techniques. The chamber characterization work has been completed now and journal paper discussing this work was recently approved for publication.

The work modeling the electron beam expansion was presented virtually at the 2021 SciTech conference and has now been submitted to a journal. The broad energy electron gun was used in experiments to study the charge sensing subject to a continuum of electron energies. The charged relative motion guidance and control has been studied in multiple conference and journal papers. The new results illustrate how much the electrostatic torque impacts the relative motion control during the final docking approach phase. Further, the impact of uncertainty in the target potential knowledge, as well as the rotational motion of a three-dimensional geometry, are explored from a relative motion perspective.

New simulation tools have been developed to model the electron beam in the ECLIPS vacuum chamber to better predict what parts of a shape are being irradiated. This has greatly improved our ability to match theory and experiments as discussed in some SciTech 2022 papers on doing experimental charge sensing with a differentially charged object. A new method to sense two charged surfaces at once with the x-ray method is now being explored.

This annual report is composed as follows. Sections are included providing updates on the project travel, staffing and budget. Next a more detailed section includes a range of updates on the technical tasks. This is followed by a section listing all the associated publications. This is followed by a final section providing conclusions and outlook for the next project year.

2 Related Year 2 Travel

Many conferences trip were planned for the summer and fall of 2021, but these again all got postponed, canceled or moved to a virtual online format. The program review meeting was also held in a virtual format. Thus, travel was light this year and included. The conference paper list in section 6.1 shows all the conferences that were attended virtually. Travel charges primarily included conference registration costs.

3 Staffing Update

The research grant contains support for two graduate research assistants (GRAs). In 2021 the primary GRAs were Julian Hammerl and Álvaro Romero Calvo. Further, other new Ph.D. students Kaylee Champion, Leah Kiner (fall 2021 only) and James Walker (started January 2022) supported this project in 2020. Kaylee is fully covered with an NDSEG fellowship while Álvaro was 80% covered by the La Caixa fellowship in the spring, and then rotated to full support on the AFOSR proposal. This setup has allowed for a good overlap with the senior students and the newer students. A highlight in 2021 was Kieran Wilson earning his Ph.D. degree in May, and completing his transition of project leadership to Julian. Álvaro was very heavily involved with the AFOSR project throughout the year, but is not fully supported on another European fellowship he won for the spring 2022 semester. He is expected to defend his dissertation in May 2022. Kaylee has been working very closely with Álvaro and is learning to operate the vacuum chamber and associated experiments, as well as use his numerical simulation tools. They have made an effective team this last fall. Andrea Lopez started supporting the project in the fall of 2021 by investigating the x-ray sensing technique and seeking missions with x-ray sensors where the data might be publicly available. Her and Julian are jointly also considering the use of 2D x-ray sensors, but finding these science tools are hard to obtain and appear to be very mission specific. Leah Kiner provided simulation support in the fall of 2021 for Julian, but has not rotated off to support another research project. James deferred his Ph.D. program start date to January 2022 and is now ramping up on the software simulation tools to take on Leah's simulation support role. We are using this additional graduate student support to make the charged relative motion modeling tools available in the open-source Basilisk simulation framework.

Looking forward to 2022, the project will fund Julian, Andrea and James in the spring. Summer research opportunities are still in development, but it is expected that the three of them will support the project through most of the remaining 2022 year which will spend out our project funds.

The list of the students involved in this research is:

- Kieran Wilson, a Ph.D. student who started in the fall of 2017. He graduated in May of 2021. He is interested in the charged astrodynamics research and his dissertation is on the x-ray sensing technique of touchless charge sensing, as well as the GNC implication for rendezvous and docking. He now works with Atomos Space on relative motion guidance and control for orbital servicing mission.
- Julian Hammerl, a Ph.D. student who started in the fall of 2020. He has started working on this AFOSR project in August 2020. His dissertation research is on the charged relative motion control for close proximity operations and debris mitigation. After Kieran graduated Julian took over the general project leadership, and is the lead researchers for the x-ray charge sensing method research as well as the charged relative motion GNC work.
- Álvaro Romero Calvo, a Ph.D. student who started in the fall of 2019. His dissertation research is on the use of electrostatic and magnetic fields in space applications. He is partially supported on the La Caixa fellowship, the IAF Luigi G. Napolitano Award and partially on the AFOSR grant. After fully supporting AFOSR project in summer and fall semester of 2021, he is now supported on the Napolitano award for his last semester. He is expected to defend in May 2022.
- Kaylee Champion, a Ph.D. student who started in the fall of 2021. She came to my lab with an honors thesis on spacecraft charging from the University of Texas. She won an NDSEG graduate fellowship and has been working closely with Álvaro on this project.
- Leah Kiner, a Ph.D. student who started in the fall of 2021. She worked on this project only in the fall 2021 to help Julian charged relative motion simulation work. She has not rotated off onto another research project.

- James Walker, a Ph.D. student who started in January 2022. He is going to support the numerical simulation and experimental research for this project.
- Ryan Block, an undergraduate researcher who won an University of Colorado Discovery Learning Apprenticeship program position. This DLA program covers 1/2 of his 10 h/week appointment and the small remainder is covered by this AFOSR grant. He worked closely with Álvaro in the continued development the magnetic field control hardware setup, as well as the Lab View simulation control software. He completed his work at the end of the spring 2021 semester.

	Budget	Actual	Balance
Salaries			
Faculty Salary	\$ 58,149.00	\$ 28,644.85	\$ 29,504.15
GRA Salary	\$ 161,868.00	\$ 172,345.00	\$ (10,477.00)
Benefits	\$ 35,938.00	\$ 28,761.00	\$ 7,177.00
Salary Totals	\$ 255,955.00	\$ 229,750.85	\$ 26,204.15
Travel			
Travel Totals	\$ 20,591.00	\$ 3,755.92	\$ 16,835.08
Operating Expenses			
Printing	\$ 2,000.00	\$ 0.00	\$ 2,000.00
Cap. Eq.: Residual Gas Analyzer	\$ 5,000.00	\$ 5,071.00	\$ (71.00)
Cap. Eq.: Contactless Voltmeter	\$ 7,000.00	\$ 0.00	\$ 7,000.00
Equipment and Lab Supplies	\$ 10,000.00	\$ 26,418.85	\$ (16,418.85)
Operating Totals	\$ 24,000.00	\$ 31,489.85	\$ (7,489.85)
Tuition/Stipends			
Tuition Totals	\$ 62,723.00	\$ 80,276.00	\$ (17,553.00)
Expense Totals	\$ 363,269.00	\$ 345,272.62	\$ 17,996.38
Indirect Totals	\$ 155,815.00	\$ 140,359.83	\$ 15,455.17
Year 3 Project Budget	\$ 519,084.00	\$ 485,632.45	\$ 33,451.55

Figure 1: Comparison between budgeted and actual expenses up to project end in January 31 2022.

4 Budget Update

The 3-year project has total funds of \$777,667. The proposal funding rate was \$267,524 (1st year), \$251,560 (2nd year) and \$258,583 for the third year. The cumulative year 2 budget expenses are illustrated in Figure 1 and discussed below.

During the first year we underspend the project a little due to some students having partial fellowship support and due to not having the expected in person conference and annual review meetings. The rollover

funds were used in the 2nd year to hire on additional graduate researcher support. Conferences continued to be virtual in 2021 and the funds were used instead for several vacuum chamber enhancements to further automate the test, and make it possible to operate and monitor experiments remotely if needed. Fortunately we never lost general access to the research lab in 2021 due to Covid restrictions. But, these enhancements have made running experiments even more efficient.

The staffing section discusses which students were supported in what semester, and to what degree. The PI, Dr. Schaub, ended up not charging any of his summer time to the AFOSR project. This left us with about \$30K to roll over into the final year. This will be used to support a 3rd Ph.D. student in the spring, and then either in the summer of fall semester.

The tuition charged were a higher than budgeted as students as the project supported more than the equivalent of 2 students each semester. This was intentional to spend down the year 1 roll over funds. I'm pleased to report that I was able to hire not just 1, but 2 new female graduate students to the lab who supported the AFOSR project in the fall of 2021. The roll over funds were very helpful in making early offers. Kaylee later on won the NDSEG fellowship, allowing me to make another offer to Leah who also accepted.

Looking forward to the third and final project year, we are on track to complete the tasks on time and on budget. We are expecting in person conferences to resume. For example, both Julian and Álvaro presented in-person related work at the January 2022 SciTech conference. However, these travel charges have not hit the project yet and don't show up in Figure 1. We are doing to present papers at the spring spacecraft charging conference, and plan to attend a series of summer and fall conferences. The additional GRA support has been very helpful to expanded on the proposed research, as well as taking on the additional effort to convert the research code of simulating charged astrodynamics and make it available to the community through the open-source Basilisk astrodynamics simulation framework.¹

5 Schedule and Project Scope Update

The current project schedule is illustrated in Figure 2. The Proposal tasks are grouped by project thrusts and colored by their status. All of the year 2 tasks have been completed. A few of the 3rd year tasks have been begun as well. This is due to the additional GRA support allowing some more in depth investigations and alternate approaches to be explored. Overall the students are very familiar now with working under Covid restrictions (masks, etc.). By the summer 2021 the university of Colorado lifted all social distancing restrictions and mask requirements. However, the mask requirement was re-instated in the fall of 2021 and has remained in effect since then. The original proposal discussed looking at Auger electrons. However, by the end of year 1 we determined this approach was not a good way to go. This work has not been replaced with new studies of using a pulsed charging solution, as well as studying using a UV laser to excite electrons and control better the target charging. The GANTT chart reflects these changes.

The following sections provide executive summary style discussions on each research thrust area. Where appropriate, we point to the full papers that have been written on this research and are available as downloadable PDF links in Project Publication section 6.

5.1 Thrust 1: Electron Based Sensing

5.1.1 Complex Shapes with Heterogeneous Surface

A previous AFOSR grant focused on the development of the Multi Spheres Method (MSM) to model the electric field around a complex spacecraft body. The MSM approach has been extensively used in this work, and is applied in J-3 to show how concave geometries and internal corners focus the flux of secondary electrons, while convex surfaces and external corners have the opposite effect. These preliminary results have motivated the development of an advanced SIMION-based numerical simulation framework that not only computes the trajectory of secondaries, but also couples the dynamics of the electron beam and the Retarding Potential Analyzer (RPA).

This software suite, that has been made publicly available through J-9, has been employed to address the detectability of spacecraft potentials using the secondary electron method and study the coupling between electron beam propagation and secondary electron generation processes. Moreover, particle tracing frameworks like ours enhance our visualization capabilities, leading to simulations where the intersection between the electron beam and the target object can be immediately addressed, as shown in Fig. 3. Our

¹<https://hanspeterschaub.info/basilisk>

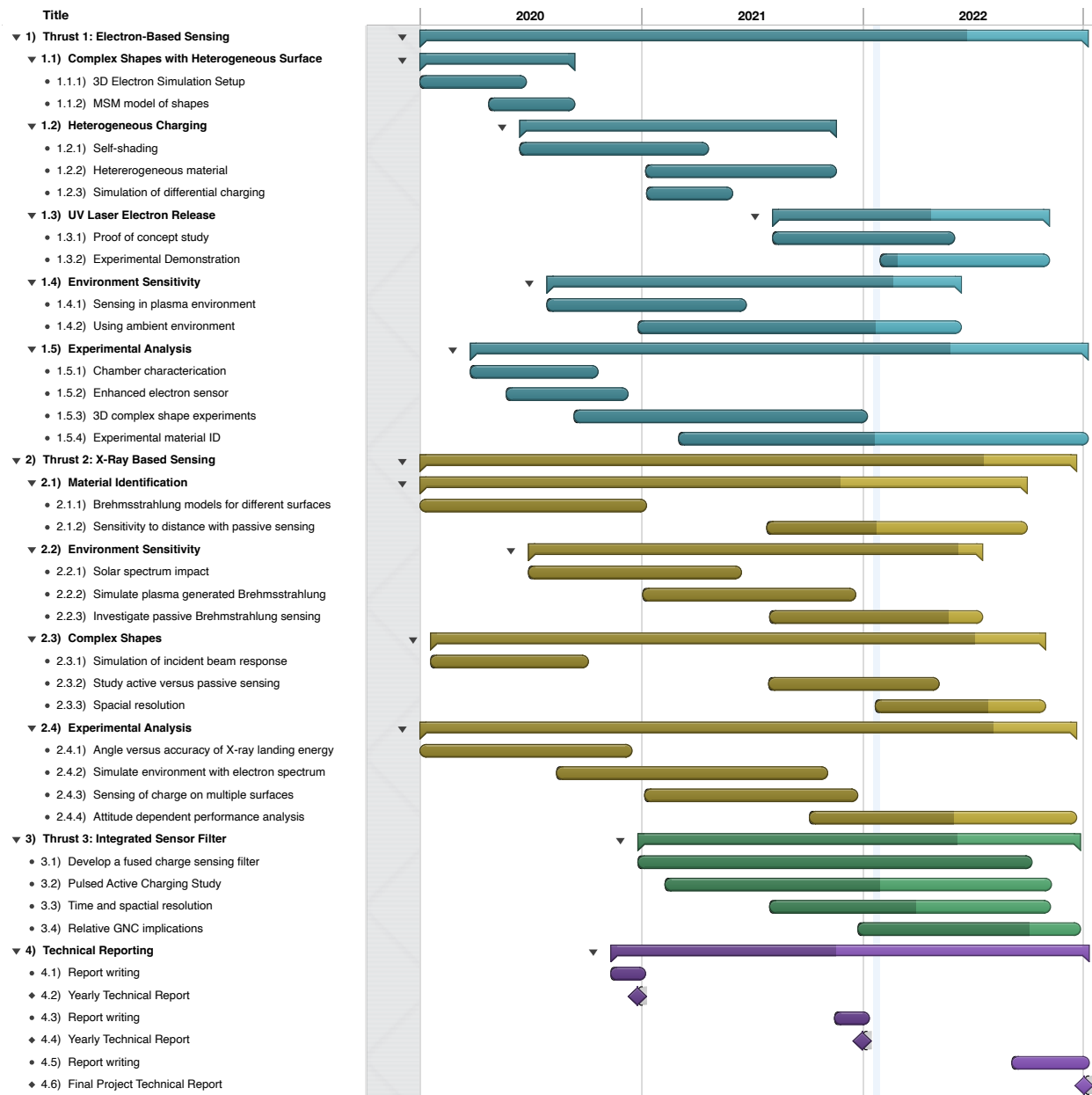


Figure 2: Current Project Schedule (darkened bar indicates degree of completion)

results, validated with experiments at the ECLIPS facility (see [J-7](#)), show that an efficient computational approach that neglects space-charge effects can be applied to the study of electron-based sensing. The detectability of a given target can thus be addressed with a minimum computational effort, which opens the door to new on-board flight algorithms.

5.1.2 Heterogeneous Charging

The presence of differential charging (i.e. multiple potentials in the same spacecraft body) can significantly alter the trajectories of all particles involved in the electron sensing process; in particular, those of secondary electrons. Although modern design best practices recommend all exterior surfaces to be connected to a common ground,¹ this is often hard to achieve in the daily practice, ultimately leading to arcing events.²⁻⁵ On one hand, a differentially-charged body steers the electrons in different directions with respect to the uniform potential scenario. On the other, their observability may be severely compromised due to the generation of

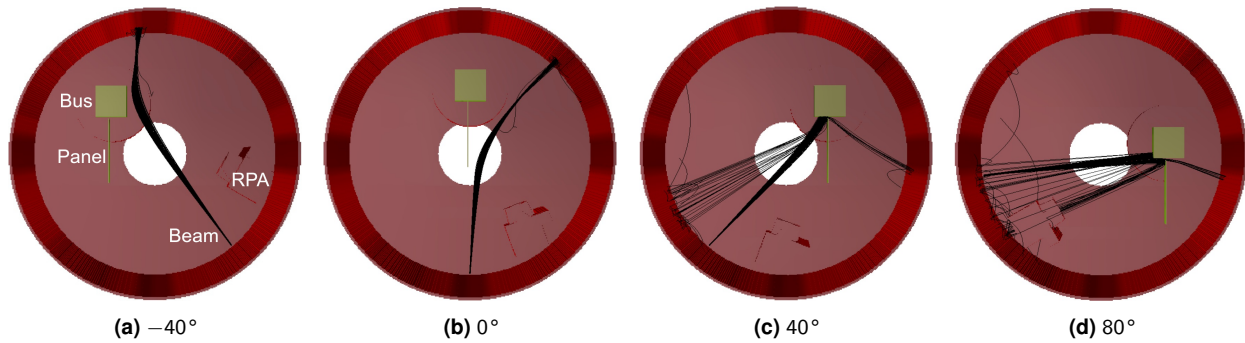


Figure 3: Electron beam trajectory for different electrode heading angles α at the ECLIPS facility

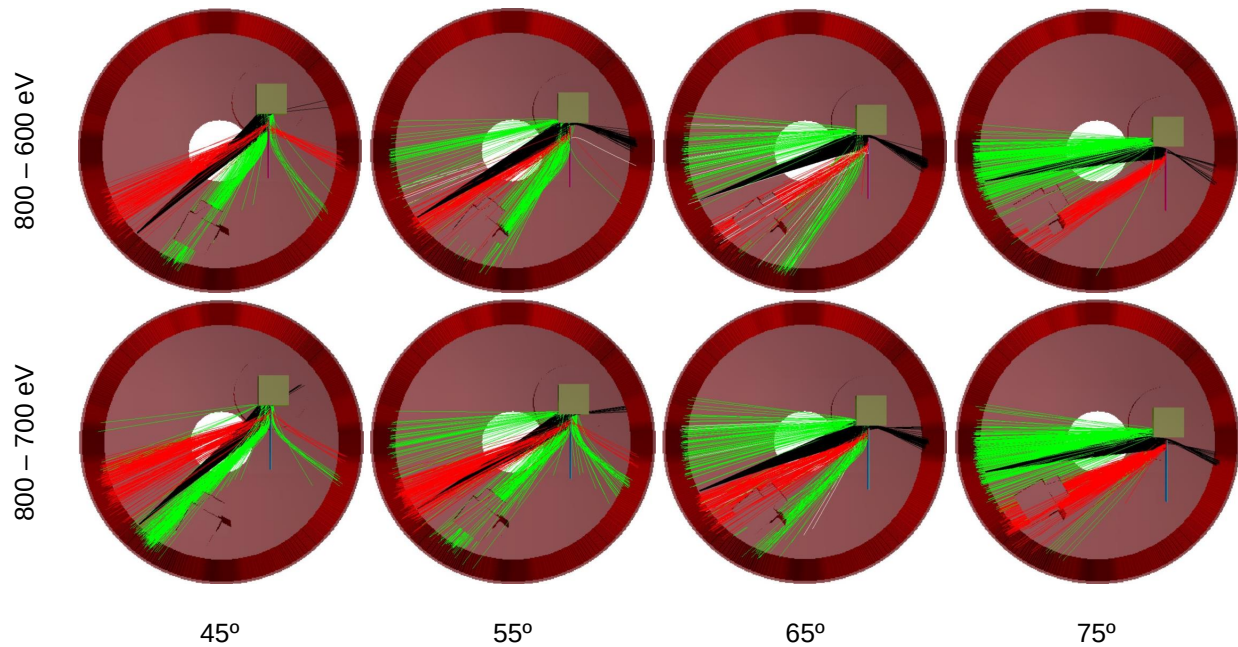


Figure 4: Secondary electron trajectories in the ECLIPS system as a function of the electrode assembly heading angle and its configuration of potentials

potential traps.⁶

Preliminary analyses of the secondary electron steering induced by differential charging were presented in J-3. This year, the particle tracing framework introduced in Sec. 5.1.1 has been extended in J-9 to the study of differential charging. The results match the experimental measurements taken at the ECLIPS chamber for the geometrical configuration depicted in Fig. 3, where a bus and panel are charged independently and combined to create a spacecraft-like assembly. The assembly is rotated while irradiated by an electron beam, and the resulting flux of secondaries is measured. Figure 4 show the beam (black) and the trajectories of secondary electrons from the bus (green) and panel (red) when the bus is charged to -800 V and the panel is charged to -600 and -700 V. As it can be observed, the RPA, located at the bottom left corner of the image, detects one, both, or none of the fluxes depending on the charging state and the relative orientation.

The full observability space of the experimental setup is finally presented in Fig. 5 for electrode potentials ranging from -500 V to -800 V, heading angles from 0° to 80°, and the electron beam configuration depicted in Fig. 4. The incoming electron current from the bus and panel is quantified for each electrode energy range. Not surprisingly, the observable states conform a small subset of the search space, restricted mostly to the 50° to 80° range. Equipotential surfaces are generally easier to observe, as they avoid the generation

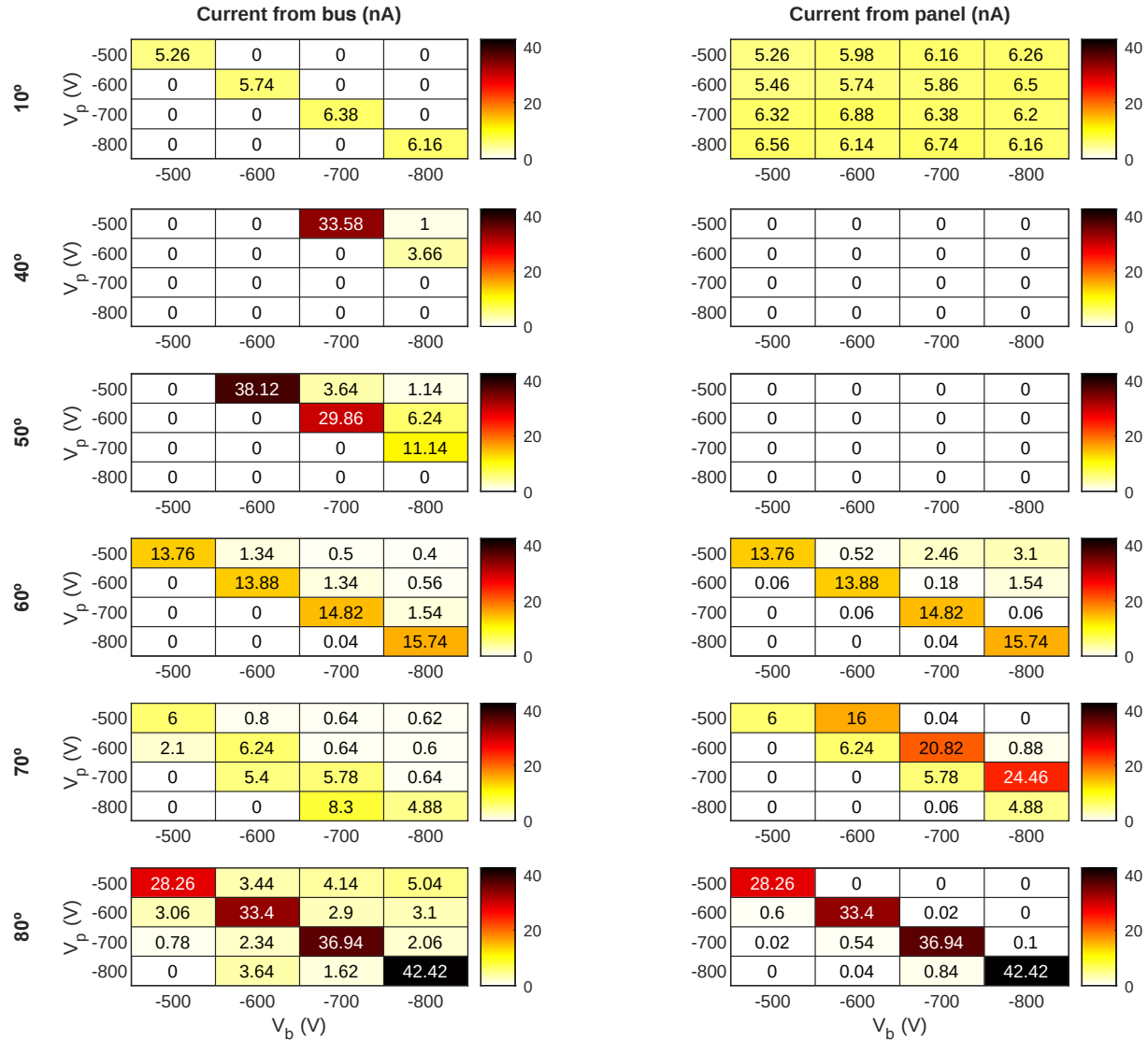


Figure 5: Observability matrix of the ECLIPS system for different heading angles and panel-bus potentials. Missing angles are not observable.

of electron traps between the electrodes, increasing the effective secondary emission area. For those cases where the equipotential state is observable (60° to 80°), the current (or, equivalently, the trajectories of the secondaries) becomes remarkably stable with the applied voltage. Since secondary electrons are created with small initial energies, the beginning of their trajectories closely follows the electrostatic field lines, which determine their future evolution far away from the assembly. Thus, for a sufficiently large electrode potential, the resulting trajectories and measured current will behave as noted. Further details on this evaluation and its experimental validation can be consulted in [J-9](#).

5.1.3 Material Identification (now UV laser charging)

Our original proposal raised the possibility of using Auger electron spectroscopy (AES) to identify surface materials. Auger electrons manifest as tiny characteristic peaks between 50 eV and 3 keV in the energy spectrum of a sample irradiated by photons or electron beams.⁷ Since the energy of auger electrons is very small, their mean free path in the solid is limited to 3-10 nm. Therefore, AES is a surface characterization technique that usually requires careful sample preparation. This can be particularly problematic in highly

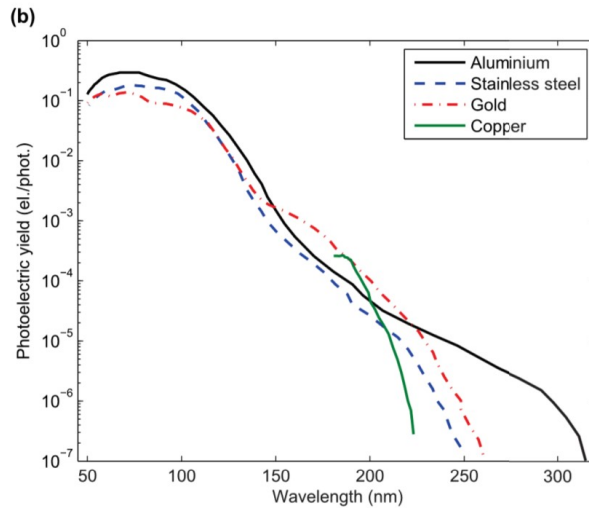


Figure 6: Various Materials Photoelectric Yield Versus Wavelength¹¹

reactive samples with thick surface oxide layers.⁷ Spacecraft surfaces in high Earth orbits are exposed to the continuous bombardment of solar wind, composed of protons, electrons, and traces of atomic oxygen and other heavy ions.⁸ Therefore, these surfaces experience significant degradation of their mechanical, optical, and electrical properties during the mission.^{9,10} In other words, a potential application of AES to a remote spacecraft surface is not likely to produce any technically useful result. Given this combination of factors, we decided to focus our efforts on more promising lines of work.

Photoemission currents are being explored as an alternate method for material identification. As shown in Fig. 6, the photoelectric yield in electrons per photon is dependent on the surface material. More specifically, the wavelength at which photoelectrons are initially emitted is dependent on the material. To take advantage of this, UV light sources with varying wavelengths may be used to actively emit photoelectrons. The wavelength of the UV light source, or sources, can be incrementally decreased until photoemissions are sensed. The wavelength at which these initial photoemissions occur may then be used to determine the identity of the material being impacted by the UV light source.

5.1.4 Environmental Sensitivity

The environmental sensitivity has been addressed in J-1 and also as part of J-9. Therefore, this task is considered completed.

5.1.5 Experimental Analysis

5.1.5.1 Chamber Characterization

The characterization of the ECLIPS vacuum chamber facility has been thoroughly addressed in J-7. The paper includes information on the sources of the facility, including the electron gun, ion gun, vacuum ultra-violet light, broad spectrum electron gun, and magnetic control system; probes, including the RPA, x-ray spectrometer, and multimeters; and ancillary equipment, including the pressure gauges, residual gas analyzer, bakeout system, magnetometer, motion stages, power systems, and Labview VI interface. Most of the hardware work during 2021 has focused on replacing the external lift mechanism, finishing the design and installation of the coils for magnetic environment control, and installing a new bakeout system that enables higher quality vacuum conditions. These last two subsystems are depicted in Fig. 7. At the time being, the facility has reached a level of maturity that allows performing spacecraft charging experiments on a regular basis.

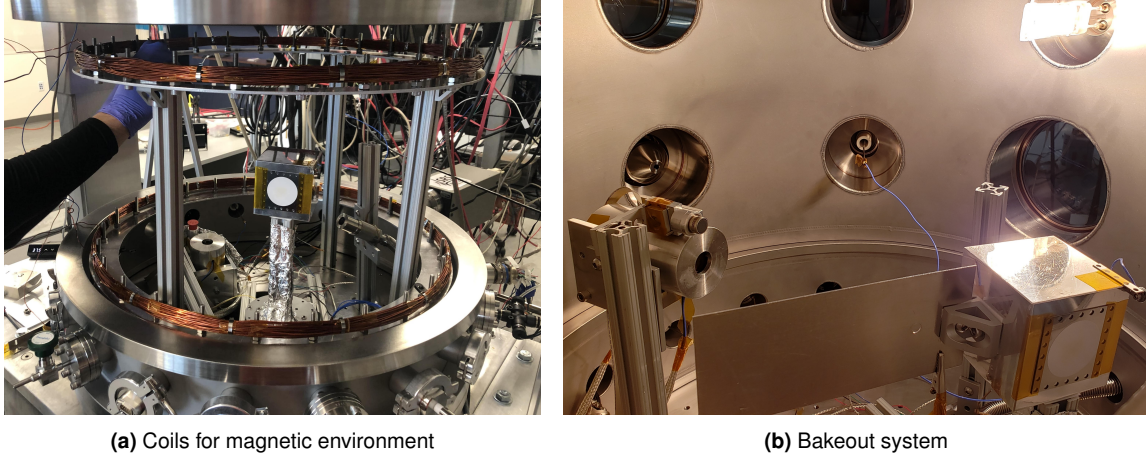


Figure 7: Electron beam trajectory for different electrode heading angles α at the ECLIPS facility

5.1.5.2 Enhanced Electron Sensor

The electron sensor development and design was completed in 2020 as has been shown to work well for this project. The chamber characterization paper at [J-7](#) provides more details on its function. This task is considered completed.

5.1.5.3 3D Complex Shape Experiments

An extensive experimental campaign has been carried out in [J-9](#) to validate the numerical simulations from Sec. [5.1.1](#). The experimental setup depicted in Fig. [8](#) was employed for that purpose, and is designed to measure the energy spectrum of electrons arriving at the RPA for a given bus and panel electrode potentials and assembly rotation angle. A 3.8 cm diameter Kimball Physics Rugged Phosphor Screen is employed to set the unperturbed electron beam configuration and provide a known initial condition for the numerical simulation. The beam reaches both electrodes with a ~ 2.5 cm final beam diameter. Secondary electrons are thus generated over both surfaces, enabling the study of differential charging problems. Further details can be found in [J-9](#).

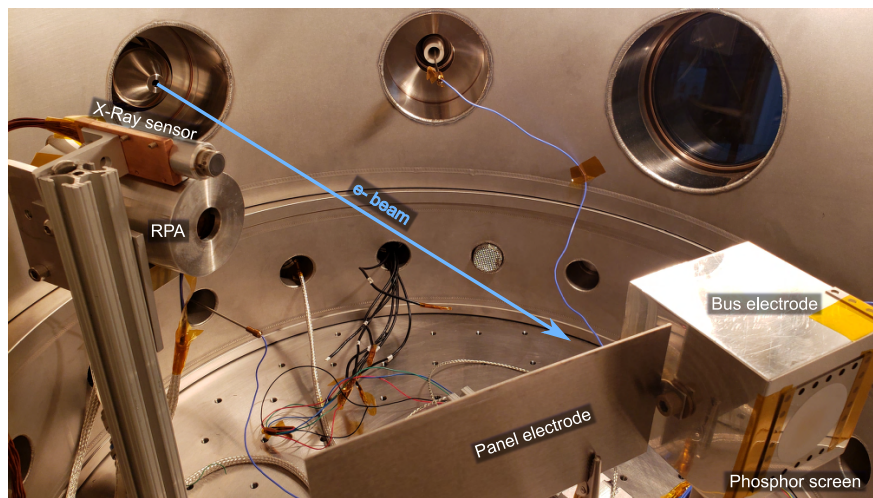


Figure 8: Experimental setup for complex shapes and differential charging experiments

5.1.5.4 Experimental Material Identification

The ideas discussed in Sec. 5.1.3 require a set of dedicated experiments and hardware, and therefore fall beyond the scope of this project. However, experiments analogous to those conducted in Sec. 5.1.1 are being carried out in 2022 using an UV source. The goal of this ongoing experimental campaign is to build a database that will be used to validate new multi-particle simulation frameworks where both the UV photons and the secondary electrons will be considered. The simulation of photons involves numerous coupled physical mechanisms that require special attention. As usual, the goal is to find the balance between computational efficiency and physical accuracy that will enable new applications.

5.1.6 New Developments

As described in Sec. 5.1.3 and 5.1.5.4, photoemission currents are being explored as an alternate method for material determination, and also to estimate potentials.

5.2 Thrust 2: X-Ray Based Sensing

5.2.1 Material Identification

5.2.1.1 Bremsstrahlung models for various materials

The Bremsstrahlung models have been discussed in the previous annual report and also in C-1 and J-10. This task is considered complete.

5.2.1.2 Sensitivity to Distance with passive sensing

The sensitivity to distance with passive sensing for debris sensing and space situational awareness applications has been addressed in the previous annual report and also in C-1 and J-11. The sensitivity of the passive x-ray method in terms of material identification will be investigated in the 3rd project year.

5.2.2 Environmental Sensitivity

The environmental sensitivity has been investigated thoroughly in the previous year. For Solar spectrum impact, see C-1 and J-11. The simulation of plasma generated Bremsstrahlung and the theory of the passive x-ray method are discussed in C-1. For the experimental validation of the passive x-ray method, see Sec. 5.2.4.2.

5.2.3 Complex Shapes

5.2.3.1 Simulation of incident beam response

The electron beam expansion and deflection for spacecraft charging applications have been discussed in the previous annual report as well as in C-4 and J-5. The SIMION particle tracing software framework (see Sec. 5.1.1) is used to verify the electron beam trajectory in the vacuum chamber during our experiments. This is especially helpful for experiments with complex shapes, as the landing location of the electron beam on the target object is non-trivial due to the complex electric field, as discussed in Sec. 5.2.4.3. The response of the electric potential of the target object to the incident beam is discussed in Sec. 5.3.3. This task is considered completed.

5.2.3.2 Active vs passive sensing summary

The active x-ray sensing method requires an electron gun on the servicing spacecraft that is aimed at the target object and excites x-rays. This method utilizes the fact that x-rays are only excited with energies up to the landing energy of the incident electrons. By finding the maximum energy of the x-ray spectrum, one can estimate the landing energy of the electrons and infer the electric potential of the target object if the potential of the servicing craft is known. The passive x-ray method uses the x-rays excited by the ambient plasma environment to estimate the electric potential of the target object. By measuring the electron energies at the servicing spacecraft, one can compute a theoretical x-ray spectrum and compare the number of photons with the actually detected number of photons to infer the electric potential. While the active method requires an electron beam, the passive method requires means to measure the electron population. Due to the

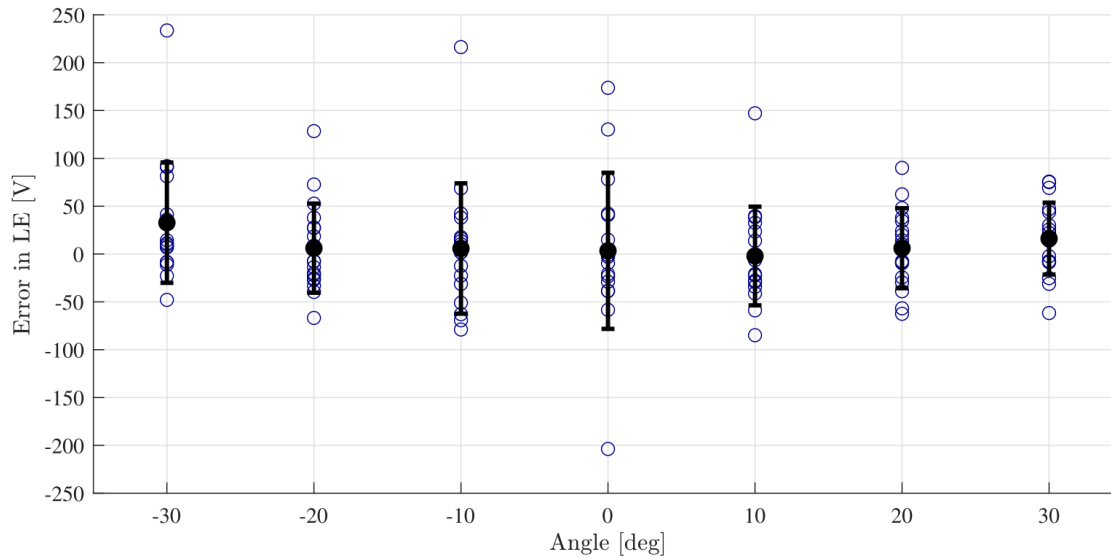


Figure 9: Landing energy errors vs detector-beam separation angle

significantly higher current of the electron beam compared to the ambient plasma currents, the ambient plasma does not infer with the active method (see previous annual report and [C-1](#), [J-11](#)).

5.2.3.3 Spatial resolution

The spatial resolution for complex shapes is discussed in Sec. [5.2.4.3](#).

5.2.4 Experimental Analysis

5.2.4.1 Angle versus accuracy of X-ray Landing Energy

Two different sets of experiments were performed. For the first one, the target object orientation is fixed, while the angle between the electron beam and the detector is varied. The purpose of this analysis is to find out if the x-ray detector could be mounted on the same spacecraft as the electron gun (resulting in a small angle between electron beam and detector), or if the x-ray detector needs to be attached to another co-orbiting spacecraft to increase the angle between electron beam and detector. No statistically significant relation is found between angle of the detector and landing energy estimation error, using a Kruskal–Wallis test for analysis of variance of the data shown in Fig. 9. This is an interesting finding, as the directional nature of bremsstrahlung radiation is well established in the literature. However, much prior work has focused on thin films of material, where incident electrons experience only one interaction with the material prior to exiting the film. In contrast, our work focuses on comparatively thick samples, on the order of 1 mm or more, where the electron will be fully stopped in the material.

For the second set of experiments, the detector remains fixed, while the orientation of the target object (a titanium plate) is varied. This corresponds to a more flight-like scenario, such as a tumbling target spacecraft. While the x-ray spectrum is not expected to evolve with angle, at grazing incidence angles the electron beam may miss the bulk of the plate and instead deliver significant current to the chamber walls. While the chamber is well grounded and the μA -level beam currents are unlikely to have any impact on the chamber potential, the resultant x-ray spectrum will be generated from a grounded target rather than the potential controlled plate. The spectra resulting from these interactions will be a combination of x-rays emitted from the potential controlled plate and the grounded chamber walls, encompassing multiple potentials that the methods presented here cannot account for. Additionally, for some orientations (especially for complex-shaped objects), the target object itself can prevent x-rays from reaching the detector, resulting in a loss of signal (see [5.2.4.3](#)). Much like the case with the rotating detector, an ANOVA regression did not find any statistically significant relation between angle and landing energy estimation error, supporting the

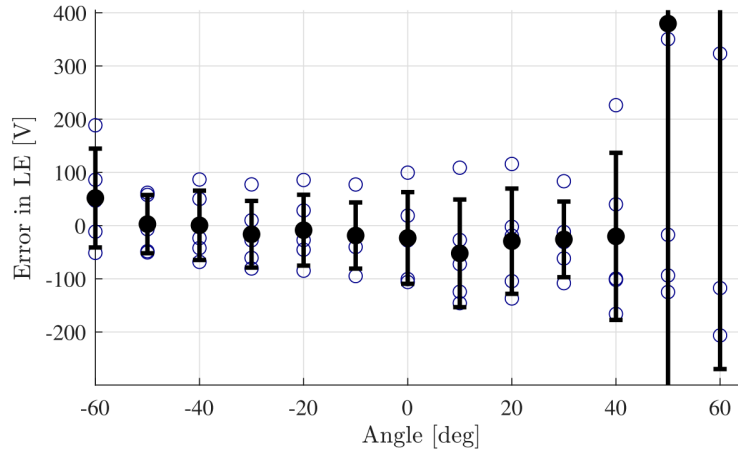


Figure 10: Landing energy errors vs target plate angle. The 0° reference is perpendicular to the incident beam; interference with the chamber wall occurs at $> 40^\circ$

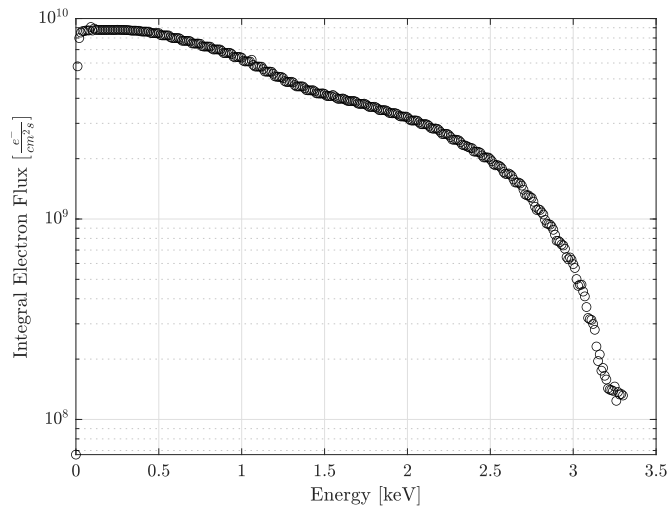


Figure 11: Integral electron flux of the broad-spectrum electron gun up to 3.3 keV, measured by the retarding potential analyzer

null hypothesis that there should be no dependence (Fig. 10).

This task is considered completed.

5.2.4.2 Simulate environment experimentally

The theory of the passive x-ray sensing method, which uses the ambient plasma environment instead of an active electron beam, has been discussed in the previous annual report and in C-1. A negatively charged spacecraft effectively shifts the energy of the incident electrons. A spacecraft charged to -10kV, for example, will repel any incident electrons with less than 10 keV. Therefore, the electron spectrum will be shifted by 10 keV, and the resulting x-ray spectrum changes accordingly. If the servicing craft can measure the local electron population, then the potential of the target can be inferred by examining the reduction in x-ray emission.

A number of experiments have been performed to validate this method experimentally with a broad-spectrum electron gun. In contrast to a mono-energetic electron gun, which emits electrons only with a single energy, a broad-spectrum electron gun simultaneously emits electrons with a wide range of energies,

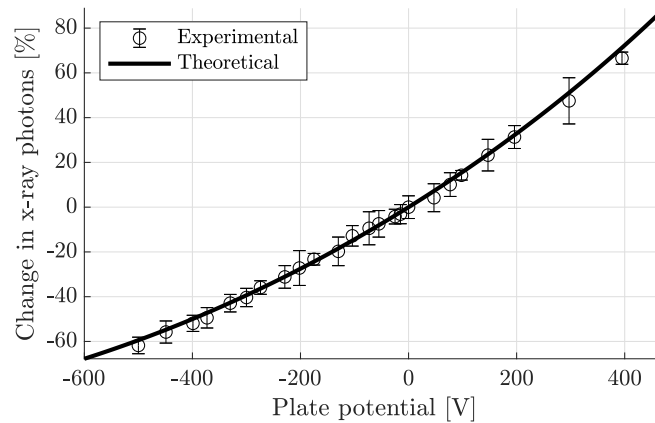


Figure 12: Change in characteristic x-ray photon emission due to ambient plasma as a function of plate potential

as shown in Fig. 11. This allows us to simulate the space environment, where electrons and ions have a wide range of energies as well. The active x-ray method uses the maximum energy of the bremsstrahlung spectrum to infer the landing energy of the electrons and the electric potential. This is not possible for electrons with a broad spectrum of energies. Instead, the measured electron flux is used to compute a theoretical x-ray spectrum. For a negatively charged object, the total number of photons decreases. By shifting the electron spectrum and recomputing the theoretical x-ray spectrum for several target object potentials, the theoretical change in number of x-ray photons as a function of target potential is obtained, as shown in Fig. 12. The actual number of photons detected during the experiment is then compared with the theoretical number of photons, which allows us to determine the electric potential of the target object. This is shown in Fig. 12.

5.2.4.3 Sensing of charge on multiple surfaces

The estimation of electric potentials of complex-shaped differentially charged objects has been investigated in C-11. A set of experiments was performed charging the two components (panel and bus) of the test object at different potentials (see Sec. 5.1.1 and Fig. 8). The particle tracing software SIMION was used to support the analysis by verifying the electron beam landing spot.

Using a narrow electron beam with a focused landing spot allows for exciting x-rays from only one component at the time. Which component's potential is estimated depends on the landing location of the beam, which is highly dependent on the orientation of the test object and the deflection of the beam caused by the electric field. For such configuration of electron beam and a non-rotating object, multiple x-ray spectra taken from different landing spots are required to measure the potentials of different components. The results of these experiments are shown in Fig. 13. This figure highlights the effect of the orientation of the target object on the measured potential due to the varying deflection of the beam. If the Ground potential of 0 V is measured, then the beam is deflected so much that it hits the grounded chamber wall instead of the target. At an angle of 10° , the beam impacts the panel on one side, while the x-ray detector (16° away from the electron beam) is located on the other side. Thus, no x-rays are detected, and no potential is estimated due to the loss of signal.

To estimate potentials of multiple components simultaneously, the beam must hit these different components during the collection time of the detector. A new method is proposed in C-11 that uses the principle of superposition of individual x-ray spectra and theoretical x-ray models to measure multiple potentials simultaneously using a single recorded x-ray spectrum. The idea is that the individual spectra from each component are super-imposed to make up the total spectrum. By estimating one potential, one can compute a theoretical spectrum for the corresponding estimated landing energy. This theoretical spectrum deviates from the actually measured spectrum due to the presence of another potential. By looking at the residual spectrum (the difference between measured and theoretical spectrum), one can then estimate the

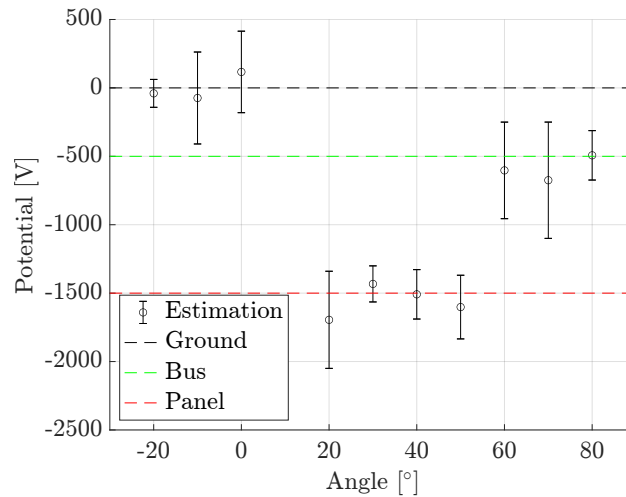


Figure 13: Complex Shape and Differential Charging: Narrow Beam results

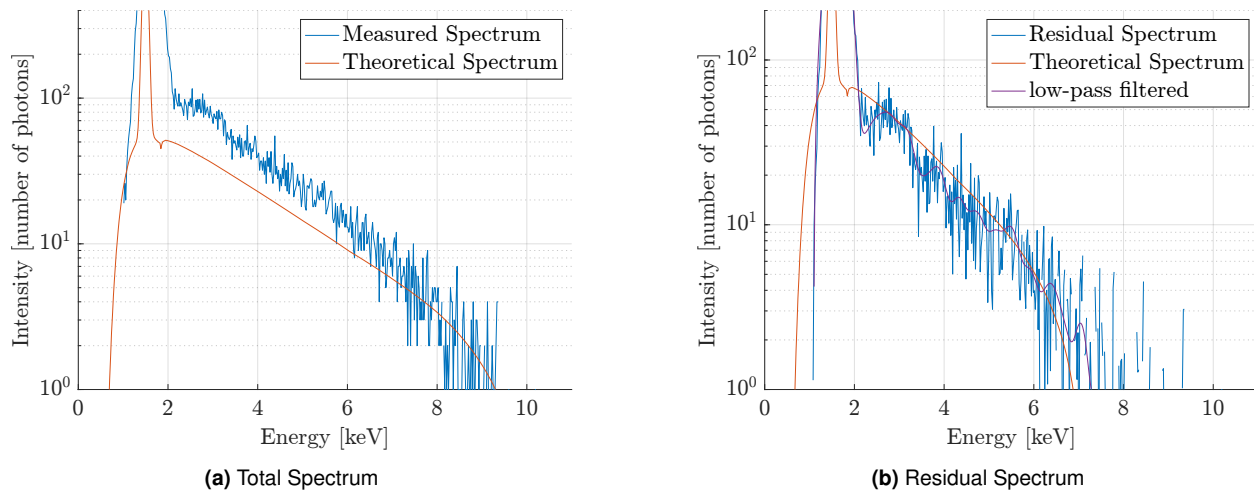


Figure 14: Measuring multiple components simultaneously: Beam energy of 10 keV, $\Phi_B = 0$ V, $\Phi_P = -3$ kV

potential of the other component. Experiments were conducted with a wide electron beam able to excite x-rays from multiple components at the same time, demonstrating the viability of the proposed method. Figure 14 shows a sample result from these experiments.

5.2.4.4 Attitude Dependent performance analysis

When sensing the potential of different components, the landing spot of the electron beam determines where the x-rays are obtained from, and thus which component's potential is estimated. The landing spot width can be modified by adjusting the focus of the electron gun. The landing spot location depends on the orientation of the target object with respect to the servicer, and on the deflection of the beam caused by the interaction of the electron beam with the electric field between these objects. For certain geometrical configurations of the experiment, the orientation of the test object is such that the target itself blocks the x-rays from reaching the detector. As seen in C-11, for some experimental configurations the electron beam deflection is significant enough to cause the beam to miss the target, which for an in-orbit scenario would result in a loss of signal.

Dynamic experiments are planned for simultaneous estimation of potentials of different components, where the target object rotates during the x-ray collection time: with the electron beam hitting different

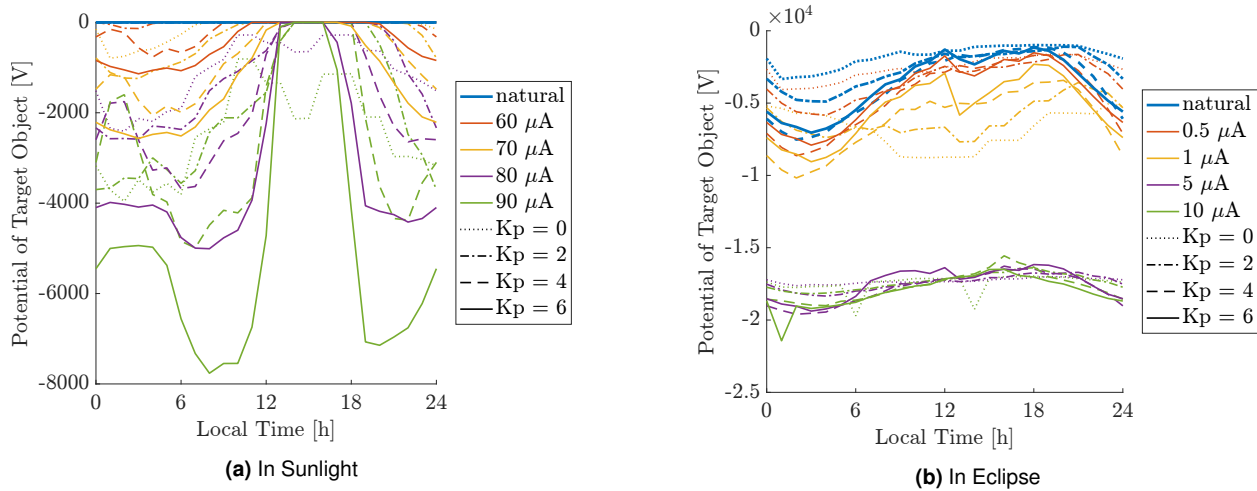


Figure 15: Continuous Beam: Equilibrium potential of target spacecraft for various electron beam currents and different space weather scenarios

components during the 20 second time frame, the total recorded x-ray spectrum is a superposition of multiple individual spectra by each component, and the potential of each component could be estimated.

5.2.5 New Developments

Other approaches for potential sensing of differentially charged objects are being investigated: the use of a 2D x-ray imager and the use of a cluster of x-ray sensors. For the former, potential sensing using the passive method described in Section 5.2.4.2 is being implemented on x-ray data of celestial objects from in-orbit x-ray observatories. For the latter, the aim is to have a wide field of view of overlapping sensors, in order to gain an understanding of the heading of the object generating the signal, particularly relevant for the passive method.

5.3 Thrust 3: Integrated Sensor Filter

5.3.1 Develop Fused Charge Sensing Filter

The study of a fused charge sensing method combining secondary electrons and x-rays has been discussed in J-6. This task is considered completed.

5.3.2 Develop a Fused Material ID Algorithm

This task will be investigated later in the 3rd project year. It is dependent on how the UV laser electron emission approach works out.

5.3.3 Time and Spatial Resolution

Dynamic experiments with complex-shaped and differentially charged target objects are planned for the 3rd project year using the x-ray method, where the target object is rotating during the 20s x-ray accumulation time frame.

Another interesting research direction was found that deals with the response of the electric potential of the target object to the incident electrons. Figure 15 shows the equilibrium potential of the target spacecraft in response to the electron beam for various electron beam currents and planetary indices K_p , as a function of the spacecraft local time in GEO. In sunlight, beam currents up to $50\mu A$ can be used without changing the potential of the object. This is relatively large compared to the $10\mu A$ current that is used in most of our experiments. However, in eclipse, where no photoelectric current is present, even small beam currents of less than $1\mu A$ change the potential of the target. While solar eclipses are rare in GEO, it is possible that the target spacecraft is eclipsed by the servicing spacecraft. While sensing electric potentials, it is desired not to change the potential of the target object.

One approach to prevent charging while sensing is to use a pulsed electron beam. By periodically turning the beam on and off, one can reduce the beam current to a fraction of the continuous beam. The

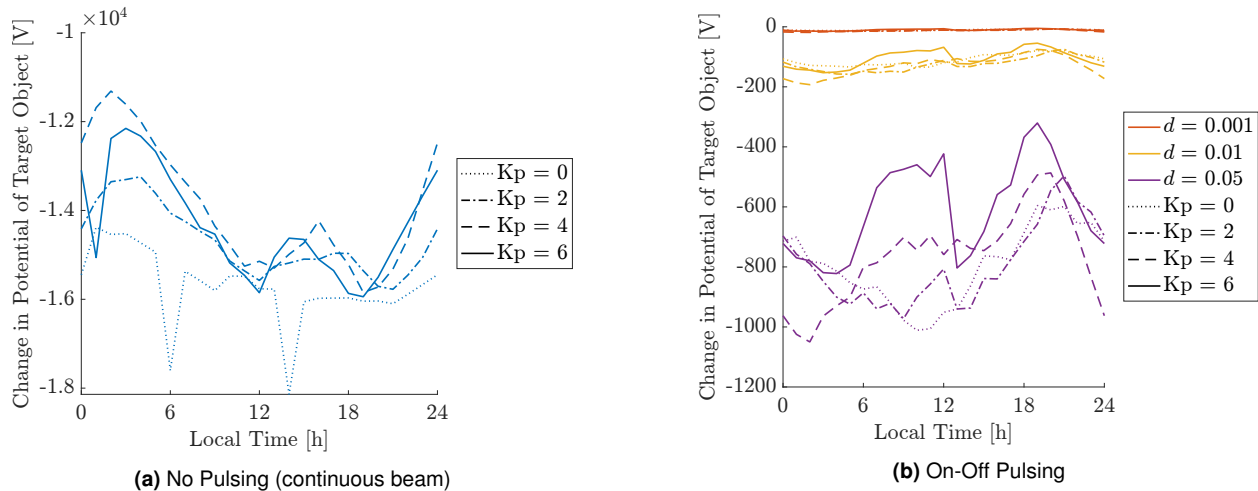


Figure 16: Equilibrium potential of target spacecraft for various electron beam duty cycles and different space weather scenarios, in eclipse

smallest possible continuous electron beam current is limited by the minimum beam current of an electron gun. Using a pulsed beam allows us to reduce the net current even further, thus preventing charging. This is shown in Fig. 16.

A pulsed beam could also be advantageous in terms of signal-processing, because the x-rays are emitted at a known frequency. Additionally, a pulsed beam could be used for active-charge control (where the potential of a neighboring object is to be controlled) by controlling the duty cycle depending on the potential of the object. This work was presented at the virtual Applied Space Environments Conference, Nov. 1-5, 2021.

5.3.4 Relative GNC Implications

5.3.4.1 Electrostatic Tractor

The Electrostatic Tractor is an Active Debris Removal method that aims at relocating retired satellites from geostationary orbit to a graveyard orbit using electrostatic forces. Since the proposed relative motion control feeds forward the estimated electrostatic force, a good estimate of the electric potential of the debris is required. Figure 17 shows the equilibrium separation distance between the servicer and the debris as a function of the electric potential estimation error ΔV . If the estimation error exceeds the critical point ΔV^* , there is only one possible equilibrium location at the other side of the debris. To reach this position, the servicer would have to move through the debris, which would cause a collision. Thus, the critical point ΔV^* is the maximum allowable estimation error. Figure 18 shows that this maximum allowable estimation error decreases significantly for some debris orientations, especially if a protruding structure of the debris is pointing toward the servicer (e.g. at $\alpha = 0^\circ$, $\beta = -90^\circ$, the solar panel of the debris is pointing toward the servicer). For this work, see C-8 and J-4.

Additional work in C-9 considered the effects of the debris attitude on the performance of the Electrostatic Tractor during the reorbit process. The results show that the reorbit time is reduced if a protruding structure of the debris is pointing towards the servicer, as this increases the electrostatic force between the two craft. It was also found that, for a tumbling debris, the effects of potential estimation errors (as described above) on the stability of the relative motion control are reduced but not eliminated.

5.3.4.2 Constrained Guidance for Spacecraft Proximity Operations Under Electrostatic Perturbations

Our previous AFOSR report explored the importance of electrostatic perturbations on the dynamics of close-proximity GEO spacecraft. We have now shown that such perturbations can induce torque levels exceeding 5 mN-m during severe charging events, imparting $1^\circ/\text{s}$ rotational rates to uncontrolled bodies like

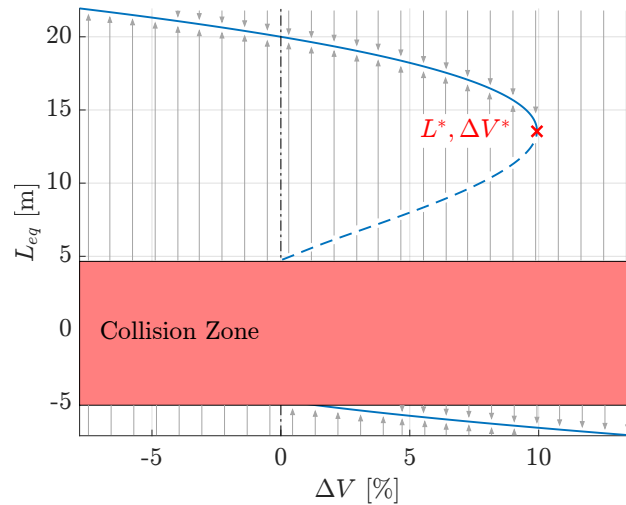


Figure 17: Equilibrium locations L_{eq} of the closed-loop response for potential estimation error ΔV

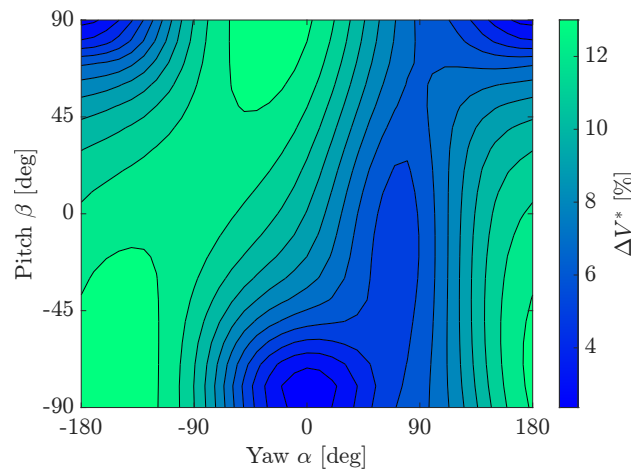


Figure 18: Attitude effects on the critical potential estimation error ΔV^*

debris or servicing clients. Our goal for 2021 was to develop new guidance algorithms to account for this effect. The result can be found in J-8 and is subsequently summarized.

First, a sub optimal but deterministic and computationally efficient sampling-based method is developed to minimize the impact of electrostatic torques during rendezvous, combining the MSM framework and the touchless potential sensing technologies explored in this work. This approach is applied to a simulated servicing scenario and found to reduce the accumulated rotational rates of the target by over 50%, yielding significant improvements in control effort, and potential improvements in safety. Figure 19 illustrates a straight line rendezvous perturbed by electrostatic interactions, using a guidance policy that does not account for those electrostatic perturbations. The dashed line illustrates the trajectory unperturbed by electrostatics. Qualitatively, the iterative guidance approach to minimize imparted torques shown in Fig. 20 experiences far less perturbation from the nominal, straight line trajectory shown in Fig. 19. These simulations are performed with 80 sphere models for the target and 92 spheres for the servicer, and 10 kV potentials on each. This is a severe charging event only relatively infrequently at GEO, but is reasonable to anticipate in a spacecraft lifetime. This scenario therefore offers a plausible instance of significant electrostatic perturbations due to space weather interactions.

Secondly, an optimized strategy to minimize final rotational rate of a target using a pseudospectral collocation-based method is explored. The same trajectory is optimized with a fifth order polynomial approximation using Matlab's `fminsearch` unconstrained optimization function. This method returns a final

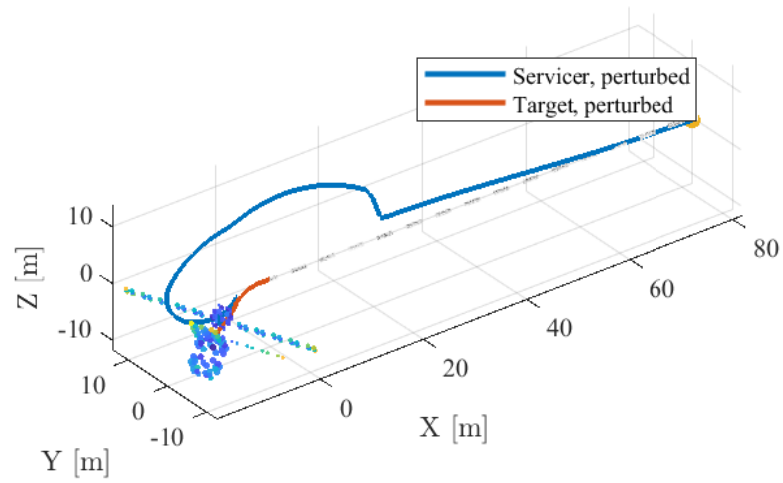


Figure 19: Rendezvous trajectory perturbed by 10 kV electrostatic potential on each spacecraft, with no guidance accounting for electrostatic interactions.

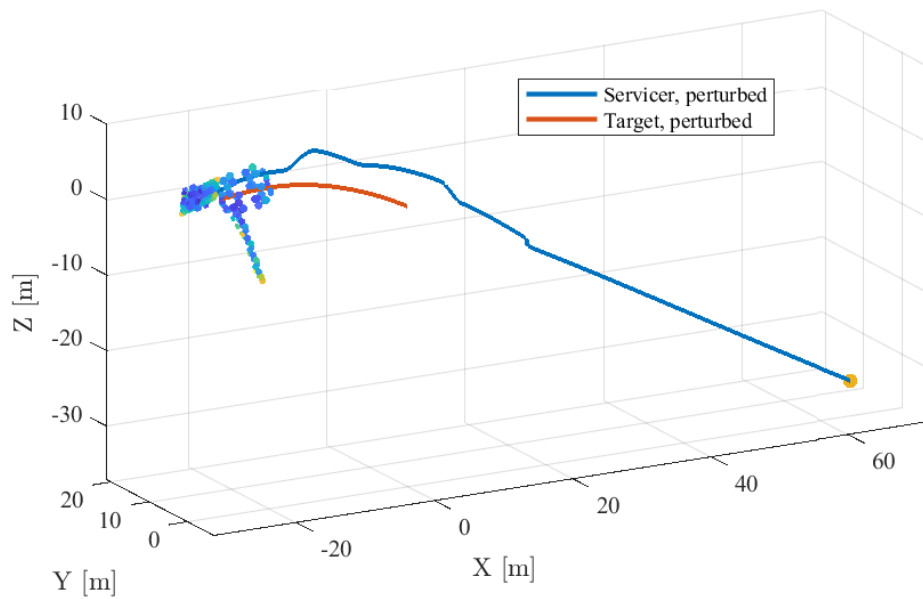


Figure 20: Rendezvous trajectory perturbed by 10kV electrostatic potential on each spacecraft, with guidance accounting for electrostatic interactions.

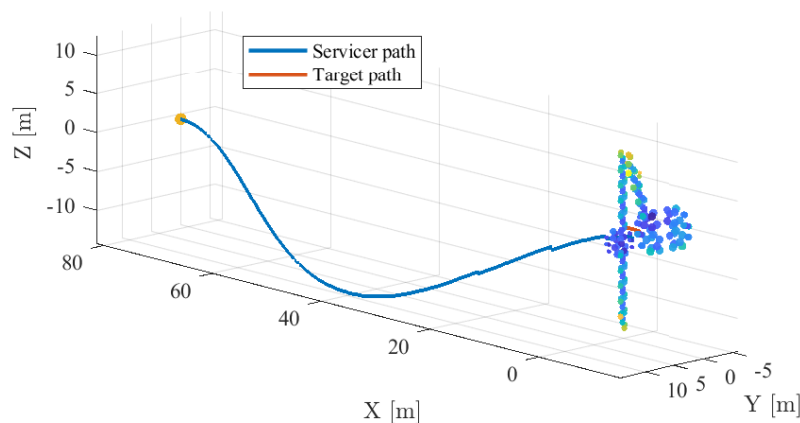


Figure 21: Pre-computed optimal trajectory, final result.

target rotational rate of just 0.006° (in contrast to the $0.01^\circ/s$ to $0.25^\circ/s$ of the sampling-based algorithm) when subject to 10 kV potential levels and SRP. The optimal trajectory is shown in Fig. 21. These results present a significant improvement in final rotational rate, but at dramatically increased computational cost. While the sampling-based approach could compute a desired approach vector and attitude in ~ 0.1 seconds, the `fminsearch` optimizer required $\sim 10^4$ times longer and thousands of iterations to converge, with each requiring integration for a full trajectory. Such high computation times occurred despite having just 6 total tuning parameters. Increasing the search space with higher fidelity polynomials comes with an accompanying increase in computational time. Therefore, although the sampling approach provides a sub-optimal solution to the trajectory, it has benefits in computational burden, enabling on-orbit recomputation as potential estimates evolve.

The globally optimized approach requires a priori knowledge of both spacecraft potentials throughout the approximation, which limits its applicability in practice. However, it is found to be robust to moderate mis-estimates in potentials. Further details can be found in J-8.

5.3.5 New Developments

The pulsed electron beam (see Sec. 5.3.3) as a method to prevent charging while sensing electric potential was not part of the initial proposal, but was found to be an interesting new direction of research for this project.

6 Associated Publications

The following comprehensive list contains the research grant related papers that have been created thus far, or are in progress. When available, the paper title links directly to a public PDF of this paper, and the DOI number is a hyperlink to the publisher web page.

6.1 Conference Papers

- C-1 K. Wilson and H. Schaub, "[Environmental X-Ray Considerations For Bremsstrahlung-Based Surface Potential Determination](#)," AIAA SciTech Forum, Orlando, Florida, Jan. 6–10, 2020, *AIAA Atmospheric and Space Environments Best Paper Award winner*
doi:[10.2514/6.2020-0049](https://doi.org/10.2514/6.2020-0049)
- C-2 K. Wilson, M. Bengtson and H. Schaub, "[Hybrid Method of Remote Sensing of Electrostatic Potential for Proximity Operations](#)," IEEE Aerospace Engineering Conference, Big Sky, Montana, March 7–14, 2020
- C-3 K. T. Wilson and H. Schaub, "[Impact Of Electrostatic Perturbations On Proximity Operations In High Earth Orbits](#)," AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, Aug. 9–13, 2020.

- C-4 Á. Romero Calvo, G. Cano Gómez and H. Schaub, "[Electron Beam Expansion And Deflection Uncertainty For Active Charging Applications](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1540](#)
- C-5 M. T. Bengtson, K. T. Wilson and H. Schaub, "[Broad-Spectrum Electron Gun for Laboratory Simulation of Orbital Environments](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1539](#)
- C-6 K. T. Wilson, M. T. Bengtson, J. Maxwell, Á. Romero Calvo and H. Schaub, "[Characterization of the ECLIPS Space Environments Simulation Facility](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1538](#)
- C-7 K. T. Wilson and H. Schaub, "[Constrained Guidance For Spacecraft Proximity Operations Under Electrostatic Perturbations](#)" IEEE Aerospace Engineering Conference, Big Sky, Montana, March 6–13, 2021
- C-8 J. Hammerl and H. Schaub, "[Effects of Electric Potential Uncertainty on Electrostatic Tractor Relative Motion Control](#)," 8th European Conference on Space Debris, Darmstadt, Germany, April 20–23, 2021
- C-9 J. Hammerl and H. Schaub, "[Debris Attitude Effects on Electrostatic Tractor Relative Motion Control Performance](#)," AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, August 8–12, 2021
- C-10 Á. Romero Calvo, J. Hammerl, and H. Schaub, "[Touchless Potential Sensing Of Complex Differentially-Charged Shapes Using Secondary Electrons](#)," AIAA SciTech Forum, San Diego, CA, January 3-7, 2022.
doi:[10.2514/6.2022-2311](#)
- C-11 J. Hammerl, Á. Romero Calvo, A. López, and H. Schaub, "[Touchless Potential Sensing Of Complex Differentially-Charged Shapes Using X-Rays](#)," AIAA SciTech Forum, San Diego, CA, January 3-7, 2022.
doi:[10.2514/6.2022-2312](#)
- C-12 J. Hammerl and H. Schaub, "Uncertainty Analysis of the Electrostatic Tractor Control Performance," AAS Guidance and Control Conference, Breckenridge, CO, Feb. 3–9, 2022

6.2 Journal Papers

- J-1 M. Bengtson, J. Hughes and H. Schaub, "Prospects and Challenges for Touchless Sensing of Spacecraft Electrostatic Potential Using Electrons," IEEE Transactions on Plasma Science, Vol. 47, No. 8, 2019, pp. 3858–3866.
doi:[10.1109/TPS.2019.2912057](#)
- J-2 K. T. Wilson and H. Schaub, "Impact of Electrostatic Perturbations on Proximity Operations in High Earth Orbits," *Journal of Spacecraft and Rockets*, Vol. 58, No. 5, Sept-Oct 2021, pp. 1293-1302,
doi:[10.2514/1.A35039](#)
- J-3 M. Bengtson and H. Schaub, "Electron-Based Touchless Potential Sensing of Shape Primitives and Differentially-Charged Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 58, No. 6, Nov.-Dec. 2021, pp. 1847-1857,
doi:[10.2514/1.A35086](#)
- J-4 J. Hammerl and H. Schaub, "Effects of Electric Potential Uncertainty on Electrostatic Tractor Relative Motion Control Equilibria," *Journal of Spacecraft and Rockets*, 2021,
doi:[10.2514/1.A35165](#), *in press*
- J-5 Á. Romero-Calvo and H. Schaub, "Simulation and Uncertainty Quantification of Electron Beams in Active Spacecraft Charging Scenarios," *Journal of Spacecraft and Rockets*, 2021,
doi:[10.2514/1.A35190](#), *in press*

- J-6 K. T. Wilson, M. Bengtson and H. Schaub, "Remote Electrostatic Potential Sensing for Proximity Operations: Comparison and Fusion of Methods," Submitted to *AIAA Journal of Spacecraft and Rockets*.
- J-7 K. T. Wilson, Á. Romero-Calvo, M. Bengtson, J. Hammerl, J. Maxwell, and H. Schaub, "Development and Characterization of the ECLIPS Space Environments Simulation Facility," Accepted to *Acta Astronautica*
- J-8 K. T. Wilson, Á. Romero-Calvo, and H. Schaub, "Constrained Guidance for Spacecraft Proximity Operations Under Electrostatic Perturbations," Submitted to *Journal of Spacecraft and Rockets*
- J-9 Á. Romero-Calvo, J. Hammerl, and H. Schaub, "Touchless Potential Sensing of Differentially-Charged Spacecraft Using Secondary Electrons," Submitted to *Journal of Spacecraft and Rockets*
- J-10 K. T. Wilson, J. Hammerl, H. Schaub, "Using Plasma-Induced X-ray Emission to Estimate Electrostatic Potentials on Nearby Space Objects," Submitted to *Journal of Spacecraft and Rockets*
- J-11 K. T. Wilson, H. Schaub, "High earth orbit x-ray environment impact on remote electrostatic potential sensing," Submitted to *Space Weather*

7 Project Conclusions and Outlook

I'm excited with the progress during the second project year. We now have a much better ability to model charge sensing around complex shapes through improved numerical simulations validated with chamber experiments. The latest research results is looking at novel modifications to the x-ray sensing method that might allow for multiple potentials to be measured at the same time. The concept discussed in C-11 will be explored further in the final project year. The chamber setup has also made nice improvements this year to make us more robust to pandemic related laboratory shut-downs. As a result we can now remotely control several aspects of the experiments without having to be physically present. Further, the impact of the active electron beam on the target vehicle potential shows encouraging results in sun-lit conditions, illustrating that the impact is small in this situation. In the shaded region of GEO, however, the active beam can drastically change the target potential. For this scenario we are exploring the concept of a pulsed electron beam and early results illustrate that the target charging will be significantly less. Lastly, the students have begun to explore using a UV laser to emit the electrons. Compared to the electron beam method, the UV laser thus creates a positive current onto the target which could be exploited.

The graduate researchers are excited to return to in-person conferences. Sadly the long post-poned spacecraft charging conference in spring was recently decided to be virtual only. But, we are expecting other conferences to be in person. Funding wise we are doing well. The small remaining funds will be used to continue the additional 3rd graduate researcher support over the last project year.

References

- [1] Garrett, H. B. and Whittlesey, A. C., "[Spacecraft Design Guidelines](#)," *Guide to Mitigating Spacecraft Charging Effects*, chap. 3, John Wiley & Sons, Ltd, 2012, pp. 26–61, doi:10.1002/9781118241400.ch3.
- [2] Olsen, R. C., McIlwain, C. E., and Whipple Jr., E. C., "[Observations of differential charging effects on ATS 6](#)," *Journal of Geophysical Research: Space Physics*, Vol. 86, No. A8, 1981, pp. 6809–6819, doi:10.1029/JA086iA08p06809.
- [3] Grard, R., Knott, K., and Pedersen, "[Spacecraft charging effects](#)," *Space Science Reviews*, Vol. 34, No. 3, Mar 1983, pp. 289–304, doi:10.1007/BF00175284.
- [4] Roeder, J. L. and Fennell, J. F., "[Differential Charging of Satellite Surface Materials](#)," *IEEE Transactions on Plasma Science*, Vol. 37, No. 1, 2009, pp. 281–289, doi:10.1109/TPS.2008.2004765.
- [5] Ferguson, D., White, S., Rast, R., and Holeman, E., "[The Case for Global Positioning System Arcing and High Satellite Arc Rates](#)," *IEEE Transactions on Plasma Science*, Vol. 47, No. 8, 2019, pp. 3834–3841, doi:10.1109/TPS.2019.2922556.

- [6] Lai, S. T., *Fundamentals of Spacecraft Charging: Spacecraft Interactions with Space Plasmas*, Princeton University Press, 2012.
- [7] E. Davis, L., MacDonald, N. C., Palmberg, P. W., Riach, G. E., and Weber, R. E., "Handbook of Auger Electron Spectroscopy," Tech. report, Physical Electronics Division, Perkin-Elmer Corporation, 1976.
- [8] Schmelz, J., Reames, D., von Steiger, R., and Basu, S., "Composition of the Solar Corona, Solar Wind, and Solar Energetic Particles," *The Astrophysical Journal*, Vol. 755, No. 33, 2012.
- [9] Vest, C. E., "The effects of the space environment on spacecraft surfaces," *John Hopkins APL Technical Digest*, Vol. 12, No. 1, 1991.
- [10] Reyes, J. A., Fulford, K. W., Plis, E. A., Hoffmann, R. C., Murray, V. J., Cowardin, H. M., Cone, D., Ferguson, D. C., Bengtson, M. T., Shah, J. R., and Engelhart, D. P., "[Spectroscopic behavior of various materials in a GEO simulated environment](#)," *Acta Astronautica*, Vol. 189, 2021, pp. 576–583, doi:10.1016/j.actaastro.2021.09.014.
- [11] Laulainen, J., Kalvas, T., Koivisto, H., Komppula, J., and Tarvainen, O., "Photoelectron emission from metal surfaces induced by VUV-emission of filament driven hydrogen arc discharge plasma," *AIP Conference Proceedings*, Vol. 1655, AIP Publishing LLC, 2015, p. 020007.