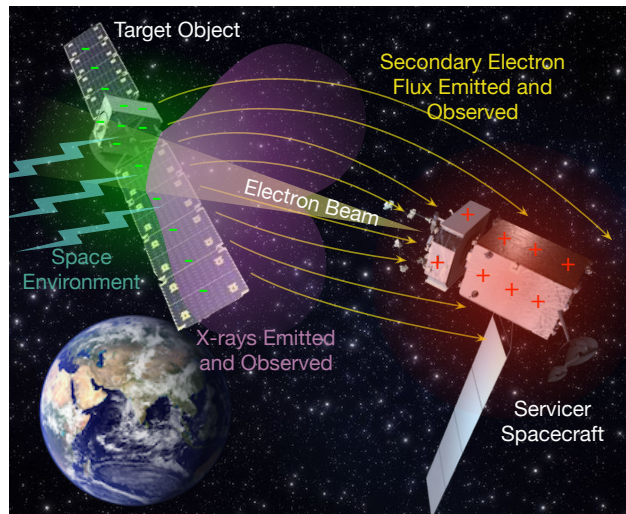


ANNUAL REPORT - 1ST PROJECT YEAR

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Touchless Charge Control of Neighboring Spacecraft in Geostationary and Cislunar Space



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Table of Contents

1	Project Overview	1
2	Related Year 1 Travel	1
3	Staffing Update	1
4	Budget Update	2
5	Accomplishments	2
6	Impacts	5
7	Changes	5
8	Schedule and Project Scope Update	5
8.1	Thrust 1: Charge Sensing While Minimally Perturbing Natural Potential of Target	6
8.1.1	Floating Potential Model and Experiments	6
8.1.2	Reducing Electron Beam Effect	7
8.1.3	Frequency Modulation	8
8.1.4	Measuring Potentials Over Time	8
8.2	Thrust 2: Environment and Open-Loop Charging Control	9
8.2.1	High Fidelity Environment Modeling	9
8.2.2	Open-Loop Charge Neutralization	11
8.3	Thrust 3: Active Charge Control	13
8.3.1	Ion Emission NASCAP Modeling	13
8.3.2	Closed-Loop Charge Control Analytic Study	13
8.3.3	Closed-Loop Charge Control Experiments	14
8.4	Associated Publications	17
8.4.1	Conference Papers	17
8.4.2	Journal Papers	18
9	Project Conclusions and Outlook	18
	References	19

1 Project Overview

This 3-year research study completed its first project year. The goal is to research active charge control of a neighboring space object in the geosynchronous and cislunar environment. To perform charge control both active and passive methods are explored. The active measures require touchless charge sensing when the target potential is changing with time and the target object could be spinning. The primary means to control charge is the use of an electron gun. The passive charge control is looking at open-loop methods, such as irradiating the servicer, the debris, or both with UV light.

Year 1 achieved some exciting research results. We have been studying the time-varying charging equations subject to a range of ambient plasma conditions. A key discovery has been that even with a single-Maxwellian plasma and an electron beam, it is possible to have multiple stable and unstable charge equilibria occur. This led to a paper on this topic and has influence the on-going work looking how more complex space environments impact the charging.

Further, we were able to do our first preliminary active charging experiments in the AVS Lab ECLIPS chamber facility. This was an exciting result that used the charge sensing techniques from a prior AFOSR grant to do our first active charge control. Much work remains to be done, including now working on numerically modeling this chamber setup to be able to analyse different charging behaviors.

Finally, good progress has been made understanding how well we can touchless measure the surface potential of time-varying charging.

The work of this project is being written up in conference papers and journal papers.

2 Related Year 1 Travel

Project related research was presented at the Applied Space Environments Conference in Huntsville, AL from October 9–13 2023. Five students travelled to Alabama to present on their spacecraft charging research. Next, two students traveled to AIAA Science and Technology Forum and Exposition (SciTech) in Orlando, Florida from Jan. 8–12, 2024 to present their written conference papers. Next, five students traveled to the bi-annual Spacecraft Charging and Technology Conference (SCTC) in Avignon, France from June 17–21, 2024. Finally, two students are set to present at the AAS Astrodynamics Specialist Conference in Broomfield, CO, Aug. 11–15, 2024, right before the project year 1 end date.

The Ph.D. student James Walker traveled twice to AFRL over the last year to make use of their JUMBO vacuum chamber to do charge control related experiments.

The conference paper list in section [8.4.1](#) shows all the conferences that were attended virtually.

3 Staffing Update

The research grant contains support for two graduate research assistants (GRAs) and 2 months of PI summer support.

The list of the students involved in this research in Aug. 15 2023 to Aug. 15 2024 is:

- Amy Haft, a Ph.D. who started in the fall of 2023. She is fully supported on this AFOSR grant. She has been supporting research on the spacecraft charging equilibria subject to complex space plasma environments.
- Andrea López, a senior Ph.D. who helped write this AFOSR proposal. She was set to support it as a GRA when she was notified in September 2023 that she won the NASA FINESST graduate fellowship. She still attends meetings and supports research and experiments based on x-ray sensing.
- Julian Hammerl, a Ph.D. student who started in the fall of 2020. He helped write this AFOSR proposal. His dissertation research is on the charged relative motion control for close proximity operations and debris mitigation. While he attended AFOSR project meetings and supported some of the proposed research, Julian has won a NASA FINESST fellowship that is financially supporting him.
- Kaylee Champion, a Ph.D. student who started at CU 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 NSF graduate fellowship and a NASA NSTGRO fellowship. Her research interests overlap with this project and she has been an active contributor. She continues to support AFOSR project related research.

- James Walker, a Ph.D. student who started in January 2022. He has supported the experimental research of the electron sensing method using a range of complex shapes, helped investigate early results with experimental pulsed charging, and helped write the AFOSR grant proposal. In summer 2023 he won the NDSEG graduate fellowship that now financially supports him. He continues to attend meetings and perform research supporting this project.
- Leya Shaw, an undergraduate researcher who supported Kaylee's research on cislunar spacecraft charging environment. She was a member of the University of Colorado Discovery Learning Apprenticeship (DLA) program
- Andrew Swackhamer, also an undergraduate DLA student who support Andrea López's research on the ambient x-ray environment for the fall semester.

As is evident from the above description, while year 1 yielded many project related research results, from a staffing perspective the project only supported a single GRA instead of two in the first project year. In the fall semester I will be fully staffed at 2 GRA's. Besides Amy being supported on this grant, the incoming Ph.D. student Ethan Webber will support this grant. Further, I am currently in the process of hiring post-doc who will start November 4, 2024. She has extensive in numerical modeling of spacecraft charging and will be able to greatly assist the many students supporting these AFOSR tasks.

4 Budget Update

The 3-year project has total funds of \$814,224. The proposal funding rate was \$263,237 for the 1st year, \$271,319 (2nd year) and \$279,668 for the third year. The cumulative year 1 budget expectations and expenses are illustrated in Figure 1.

During the first year we under-spent the project a little due to some students having partial fellowship support. However, we were able to send a lot of students to spacecraft charging related conferences which has helped advance much of the project research.

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 has left us with about \$112K in unspent funds that we plan to spend down in the 2nd year. I have been able to hire in a new Ph.D. student who will focus on this project starting fall 2024. Further, I am in discussion with a strong post-doc candidate to support this project with her advanced numerical spacecraft charging modeling skills. The roll-over funds and future PI funds will be used to support this post-doc position for the remainder of the project.

Tuition charges are expected to catch up with budgeted values now that two GRAs will be supported on this project starting fall 2024. Regarding lab supplies we didn't spend much in project year 1. We ran into several issues with the vacuum chamber losing a strong vacuum that took time to track down. In the end it was vacuum chamber seals that had to be replaced, and one of the pumps had to be serviced with new parts. Next, the x-ray sensor was not working properly for several months. This kept us from ordering the new x-ray sensor we budgeted for this project as we wanted to see first what the issue was. After many iterations with the manufacturer it was a simple cable issue. The sensor is working again properly and we are now ready to order the newer sensor model in the 2nd project year.

Looking ahead to the second project year the expenses are expected to catch up rapidly with the budgeted funds by having two graduate research assistants on this project full time, as well as hiring a new post-doc to support this project. It was very fortunate that this post-doc from the University of Sydney Physics department reached out this summer. She has strong technical skills that will greatly benefit the project. Students are expected to continue to present regularly at professional conferences and begin to publish research in journal papers.

5 Accomplishments

The current project schedule is illustrated in Figure 2. The GANTT chart lists the main research objectives. The project tasks are grouped by project thrusts and colored by their status. The 1st project year is off to a good start investigating active charge control of neighboring spacecraft. The research yielded new insight into unexpected complex charge equilibria behavior. We expected the charge modeling to yield

	Budget	Actual	Balance
Salaries			
Faculty Salary	\$ 16,256.00	\$ 0.00	\$ 16,256.00
GRA Salary	\$ 92,700.00	\$ 62,988.07	\$ 29,711.93
Benefits	\$ 15,209.00	\$ 5,983.87	\$ 9,225.13
Salary Totals	\$ 124,165.00	\$ 68,971.94	\$ 55,193.06
Travel			
Travel Totals	\$ 8,786.00	\$ 13,925.64	\$ (5,139.64)
Capital Equipment			
Upgraded X-ray sensor	\$ 9,000.00	\$ 0.00	\$ 9,000.00
Equipment Totals	\$ 9,000.00	\$ 0.00	\$ 9,000.00
Operating Expenses			
Printing	\$ 1,500.00	\$ 0.00	\$ 1,500.00
Misc. Equipment	\$ 4,500.00	\$ 205.23	\$ 4,294.77
Operating Totals	\$ 6,000.00	\$ 205.23	\$ 5,794.77
Tuition/Stipends			
Tuition Totals	\$ 36,779.00	\$ 23,274.34	\$ 13,504.66
Expense Totals	\$ 184,730.00	\$ 106,377.15	\$ 78,352.85
Indirect Totals	\$ 78,507.00	\$ 44,875.52	\$ 33,631.48
Year 1 Project Budget	\$ 263,237.00	\$ 151,252.67	\$ 111,984.33

Figure 1: Comparison between budgeted and actual expenses up to project end in January 31 2023.

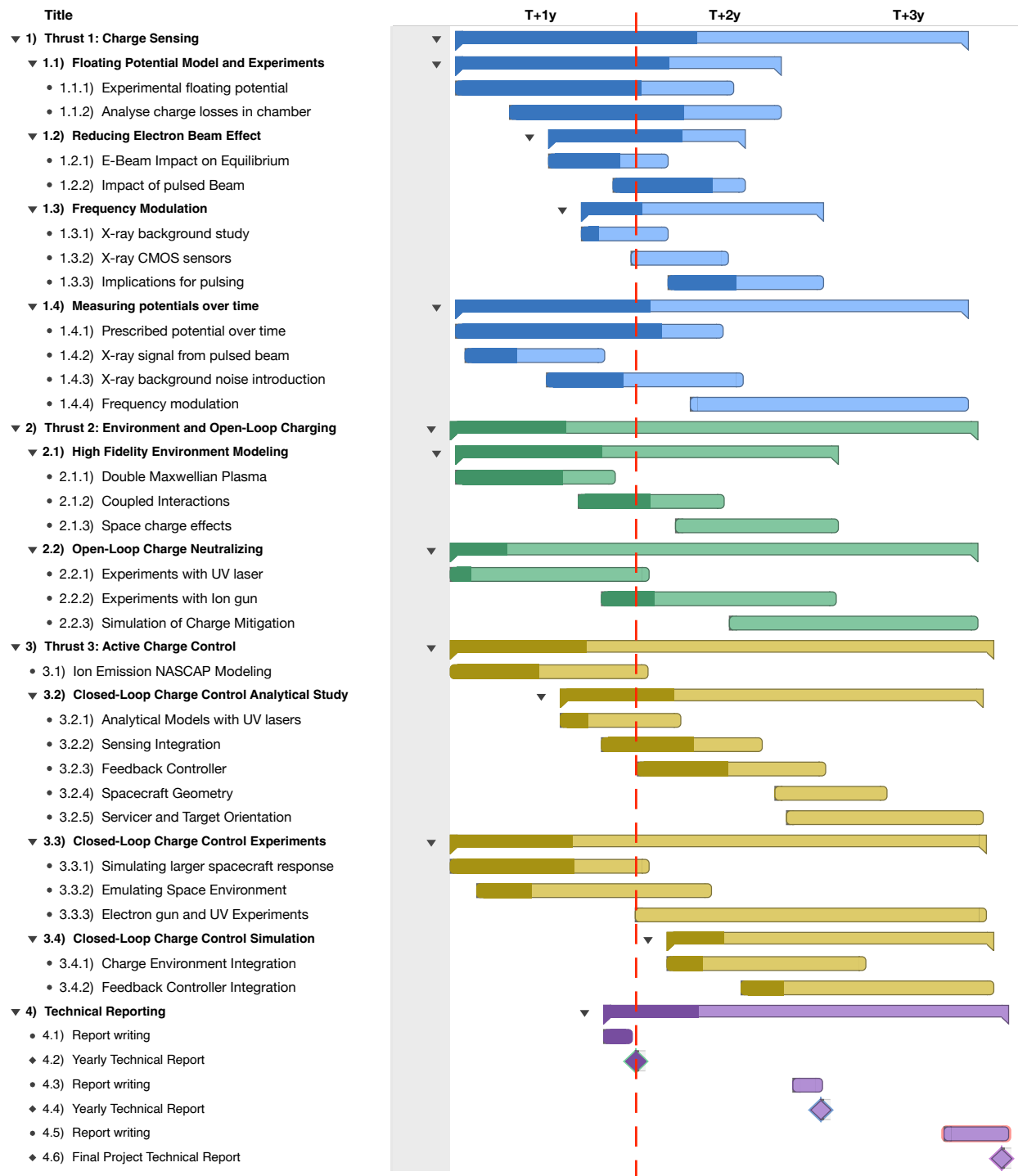


Figure 2: Current Project Schedule (darkened bar indicates degree of completion)

multiple equilibria if a multi-Maxwellian plasma was considered. However, the work has show that even with a single-Maxwellian plasma we can have multiple equilibria if the servicer electron beam is aimed at the deputy space object. The electron beam, in essence, acts as a second electron distribution. Several conference papers were written discussing these interactions. This avenue of research is turning out to be very relevant and a major focus of the second year.

Further, good progress is made numerically modeling the plasma wakes in GEO and cislunar regions. Getting these numerical solutions to work in year 1 is a strong contribution. More work remains, naturally, and the modeling work will continue through year 2. The addition of the post-doc with numerical modeling expertise will accelerate these efforts in year 2.

Another key accomplishment was demonstrating for the first time active charge control in the AVS Lab ECLIPS chamber using the electron gun and our touchless charging solution. We had to deal with several hardware challenges to get to this stage but are pleased with the first results. This work will continue and we need to now focus also on numerical modeling of these experiments to fully study them.

Finally, another year 1 accomplishment was demonstrating being able to measure the potential if the target voltage is varying with time. Prior work had focused on static potentials during the measurements. If we want to actively control a potential then measure a time varying signal is a critical component.

The research results were disseminated through conference and journal publications. The project related publications are listed in section [8.4](#).

6 Impacts

Development of the principal discipline(s) of the project:. The project year 1 period has successfully demonstrated that it is possible actively control the charge in our ECLIPS vacuum chamber. The object was electrically isolated and exposed to an electron beam. The potential was measured using our touchless charge sensing techniques.

Next, the discovery of conditions that can lead to multiple charge equilibria assuming a single-Maxwellian plasma and an electron beam, has had a big impact on the research project. We have already seen a charging experiment done at the AFRL JUMBO facility that yielded unexpected results that are explained with this new charging theory. This was an exciting discovery that is also impacting the work being done for the next two years.

7 Changes

Project year 1 started all three of the research thrusts. Some changes to the schedule were related to some experimental hardware challenges encountered with the vacuum chamber and x-ray sensors that took months to resolve. Instead other analytical and numerical tasks made good progress.

The expected year 1 hardware purchases will now occur in year 2. The new Ph.D. student joining this group will look at the x-ray sensing technique and UV charge control challenges.

There is no delay to the project timeline or expenditure. The project is making strong technical progress and we expect expenditures to catch up in year 2 with the addition of a post-doc researcher and pursuing hardware purchases.

8 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. The technical research is progressing very well. It was exciting to discover that multiple equilibria were possible with a single-Maxwellian plasma environment. This is changing some of the research direction to focus more on this component.

Further, we were successful in performing a series of vacuum chamber experiments including measuring the target potential using time-varying prescribed potentials, as well as doing some first closed-loop charge control in the AVS Lab ECLIPS chamber. Some hardware challenges did occur during year 1 that took some time to resolve, but the ECLIPS chamber is fully functioning again this summer with increased software autonomy to run a series of experiments in sequential order.

Regarding the analytical and numerical modeling, exciting initial findings were presented at several professional conferences and workshops. One journal paper studying the use of UV lasers is published and another journal paper is already submitted.

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 [8.4](#).

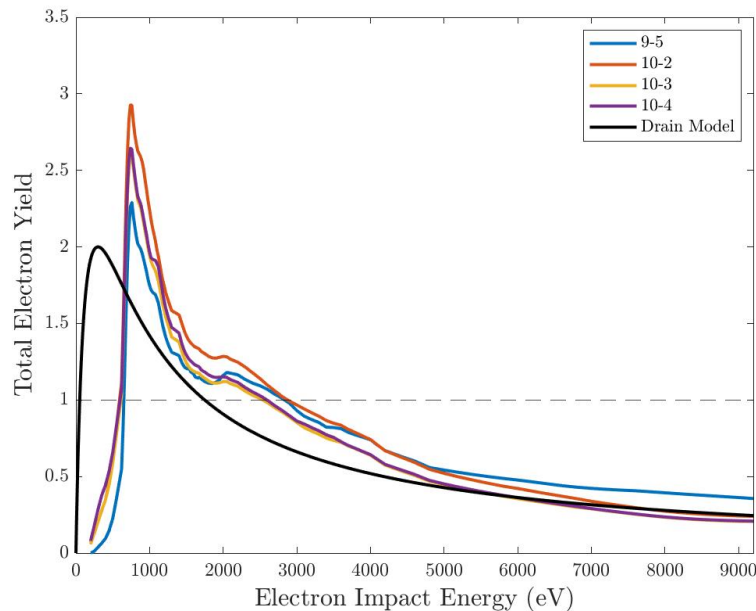


Figure 3: The measured estimations for the total electron yield of aluminum compared to the Draine model, the SEY used in out charging simulations.

8.1 Thrust 1: Charge Sensing While Minimally Perturbing Natural Potential of Target

8.1.1 Floating Potential Model and Experiments

Floating potential refers to the electrostatic potential generated on an object when it is electrically isolated and subject to external currents. In these experiments, the target is irradiated by an electron beam: the only currents acting on the target are those induced by the electron beam. The goal of these floating potential experiments is to explore the charging behavior of a target when it is not grounded or connected to a power supply and its potential can fluctuate with the electron beam. In Ref. 1, it is found that an RC circuit can be used to accurately replicate the discharging behavior a spacecraft would experience in the space environment as predicted by charging simulations. However, the experimental charging behavior did not match that of the simulations. It was determined that a significant contributing factor to this is an inaccurate total electron yield (TEY) and therefore a method for quickly and accurately determining this was developed. This technique is outlined in C-4. The idea is to measure the floating potential of a target at various beam energies, which can then be used to determine the second cross-over energy, E_2 of the TEY, the point where the number of incoming and outgoing electrons is equal.² To generate the shape of the rest of the TEY curve, the relative total electron emissions current can be measured using a Faraday cup or RPA. This is a relative current as the RPA can not capture all of the emitted electrons. A relationship between beam energy and relative total electron current can then be constructed and the result resembles a secondary electron yield curve. This is expected as the most significant contribution to TEY is secondary electrons. The difference is that the y-axis is relative current rather than electron yield. From here, it is known that, at the second cross-over energy, the yield is equal to 1. By scaling the relative yield such that the yield is 1 at the measured E_2 value, an estimation of the actual secondary electron yield is obtained. Figure 3 shows the measured TEY's compared to the SEY of the Draine model representing the ideal yield. The largest differences between the ideal model and measured yields are in the maximum yield and the energy this max occurs at. Both are larger for the experimental yields, resulting in curves that shifted up and to the right of the ideal. These trend are consistent with those of aluminum oxide, suggesting that, among other differences, there is a considerable oxidized layer on the surface of the target which will causes differences between the experimental and simulated results. It can also be seen that the exact yield varies depending

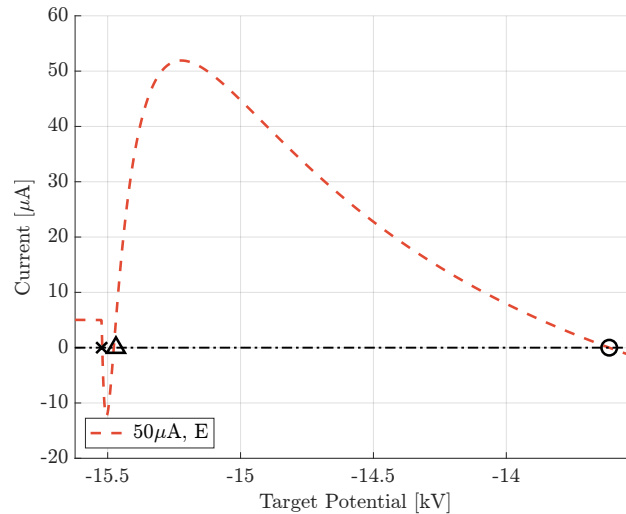


Figure 4: Multiple Equilibria: Left and right equilibria are stable, center equilibrium is unstable.

on how long the specimen has been in a vacuum chamber environment. For the most accurate results, the TEY must be calculated before each day of experiments. Further analysis of this method for estimating TEY will be conducted in year 2.

Given the opportunities that arose for experimenting with active charge control that are described in thrust 3, additional research expanding on the external circuit and floating potentials will be a focus of year 2.

8.1.2 Reducing Electron Beam Effect

The impact of the electron beam on the potential of the target is studied in detail in J-2. One of the key findings in this work is that the secondary electron emission due to electron beam impact can cause multiple equilibria to exist in a single-Maxwellian plasma. For example, multiple equilibria due to electron beam impact exist for GEO conditions with local time of 6 hours and planetary K-index of 2,³ a beam current of 50 μA , beam energy of 20 keV, and an eclipsed target. The equilibrium potential corresponds to the potential for which the total current is equal to zero. This occurs three times in Fig. 4 for the given charging model. There is a significant jump in current at the potential at which the electron beam is not energetic enough to reach the target, at about -15.5 kV in the figure (the servicer potential in this figure is $+4.5$ kV). If the total current is positive without the electron beam hitting the target, but smaller in magnitude than the electron beam current, then there is a zero crossing at this potential, corresponding to an equilibrium ($\times$). Due to the secondary electron emission, which is especially high for effective energies below approximately 1-2 keV, the total current increases again with increasing potential, resulting in another zero crossing and equilibrium (Δ). With increasing potential (increasing effective energy of the electron beam electrons), the secondary electron emission weakens, resulting in another equilibrium potential where the total current is zero ($\circ$). The left and right side equilibria are stable, while the center equilibrium is unstable.

The electron beam effects are specifically studied in J-2 for the GEO and cislunar environment. In previous charge sensing experiments, electron beam currents in the order of 10 μA were often used.⁴⁻⁷ The potential of the test object was held constant in these experiments using external power supplies. If the potential is not controlled externally, the beam charges the test object. As found in J-2, a beam current of 10 μA is enough to charge an eclipsed target to potentials close to -20 kV in GEO and cislunar space (beam energy of 20 keV). To perturb the natural potential by less than 1 V, beam currents in the order of nano-amperes are required. Such low currents may not be achievable by electron guns used for the electric potential sensing operations.

One way of reducing the current of the electron beam is to pulse the electron beam. For example, the beam can be periodically turned off and on to reduce the net current. The pulsing characteristics are described by the pulsing frequency $f = 1/T_{\text{pulse}}$ (with the period of one pulse cycle T_{pulse}), and the duty cycle $d = t_{\text{on}}/T_{\text{pulse}}$ (where t_{on} is the time that the beam is on during one cycle). This is shown in

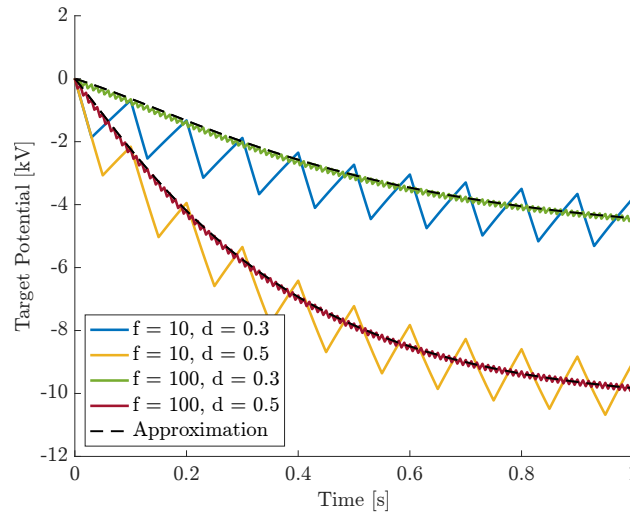


Figure 5: Pulsed Beam: Duty Cycle d and Pulsing Frequency f

Fig. 5 for different duty cycles and pulsing frequencies, and a nominal beam current of $I_{EB,0} = 10 \mu$ and beam energy $E_{EB} = 20$ keV. During the on-cycle, the beam charges the target as a continuous beam does. During the off-cycle, the beam current is zero, so the target recharges slightly towards its natural equilibrium potential. This essentially reduces the net current due to the electron beam. For on-off pulsing, the duty cycles reduces the effective beam current by approximately $I_{EB,eff} = d \cdot I_{EB,0}$ and consequently affects the obtained equilibrium potential. The frequency only determines the amplitude of the oscillations, but has no effect on what potential the target converges to. In Fig. 5, the Approximation lines correspond to a continuous beam with a current of $I_{EB} = I_{EB,eff}$. The pulsed electron beam for electric potential sensing and control is described in more detail in C-9.

8.1.3 Frequency Modulation

Because of hardware issues with the current x-ray sensor, the acquisition of an improved sensor capable of obtaining measurements at higher frequencies was delayed to the 2nd project year.

8.1.4 Measuring Potentials Over Time

As space missions involving multiple spacecraft evolve in complexity, the ability to sense time-varying potentials in a touchless manner becomes vital. Prior work explored the fusion of x-ray and secondary electrons for improved robustness in touchless potential sensing of a spacecraft with a fixed electrostatic potential. This concept has been extended to time-varying potential sensing, where the target is given a prescribed potential profile C-8. Our custom built retarding potential analyzer (RPA) is used for the secondary electron method, and an x-ray spectrometer is used for the x-ray method. Figure 6 shows the setup for these experiments, where the aluminum cube is used to represent the target spacecraft.

Both instruments are utilized simultaneously to collect data while the target potential is varied following a linear or a sinusoidal profile. One key parameter for the RPA measurements is the step size. This user defined variable determines the discretization error obtained with the secondary electron method. When applied to time-varying potentials, this discretization error results in a *staircasing* effect in the estimated potentials. This undesired effect can be mitigated by using a live low pass filter.

The Kalman filter algorithm is used to estimate the potential of the target spacecraft in a dynamic scenario, using the estimates from the RPA and x-ray sensor as measured inputs. Constructing a dynamic model that accurately represents the time-varying potential of an arbitrary target object subject to the space environment and the impact of an electron gun is extremely challenging. Therefore, the state prediction equation used in the Kalman filter algorithm is greatly simplified for this study. Three different dynamic models were considered for the state prediction equation: a constant potential model (CP), a constant potential rate model (CR), and a constant potential acceleration model (CA) (see Ref. C-8 for further details). Figure 7 shows estimation results for two example target potential profiles, for the CP, CR and CA models.

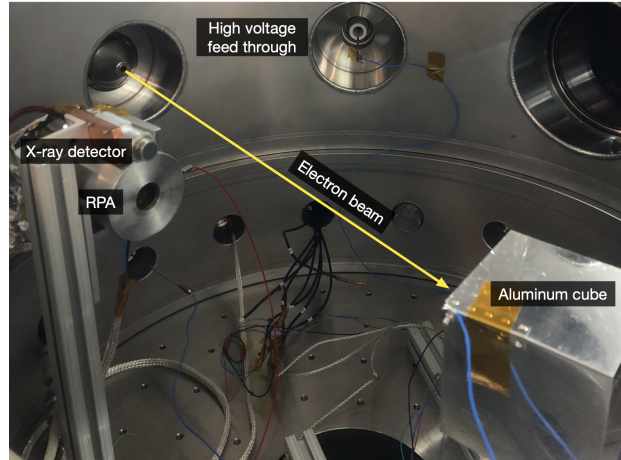


Figure 6: Vacuum chamber setup for time-varying potential experiments

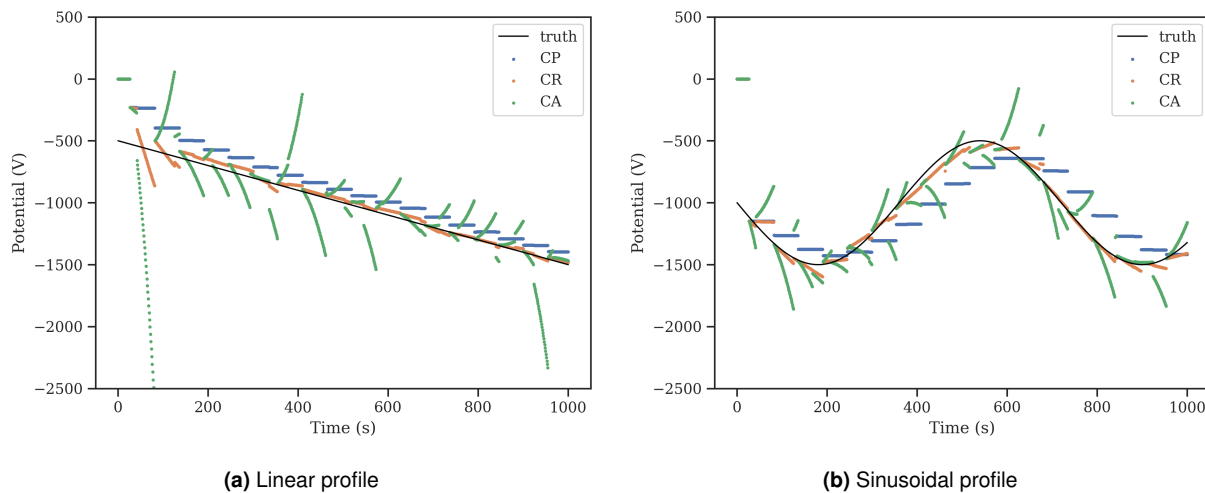


Figure 7: Potential estimation results from the Kalman filter for the three dynamical models.

The results show that, for a sufficiently smooth potential variation, the constant potential rate model outperforms the other two models in terms of potential tracking accuracy. This work also showed that the fusion of methods is robust to measurement gaps. The uncertainty in the estimation grows when secondary electron measurement gaps are present, but the x-ray measurements keep the potential estimates within reasonable bounds. This study provides valuable insights into the adaptability, accuracy and limitations of the fusion of potential estimation methods in scenarios with dynamically changing potentials.

This work will be extended in the upcoming years, adapting the existing algorithms to use frequency modulated measurements.

8.2 Thrust 2: Environment and Open-Loop Charging Control

8.2.1 High Fidelity Environment Modeling

A challenge that was highlighted in regards to charge control in GEO was the possibility for multiple floating potentials due to a bi-Maxwellian plasma. The rarified and collisionless plasma environment in GEO often becomes a combination of two plasmas during geomagnetic substorms, which inject high energy electrons and ions from the magnetotail into GEO. The resulting bi-Maxwellian plasma would result in multiple spacecraft equilibrium potentials according to the triple-root jump phenomenon.^{8,9} However, it was discovered in J-2 and discussed previously in Sec. 8.1.2 that multiple equilibria are possible even in a single-Maxwellian

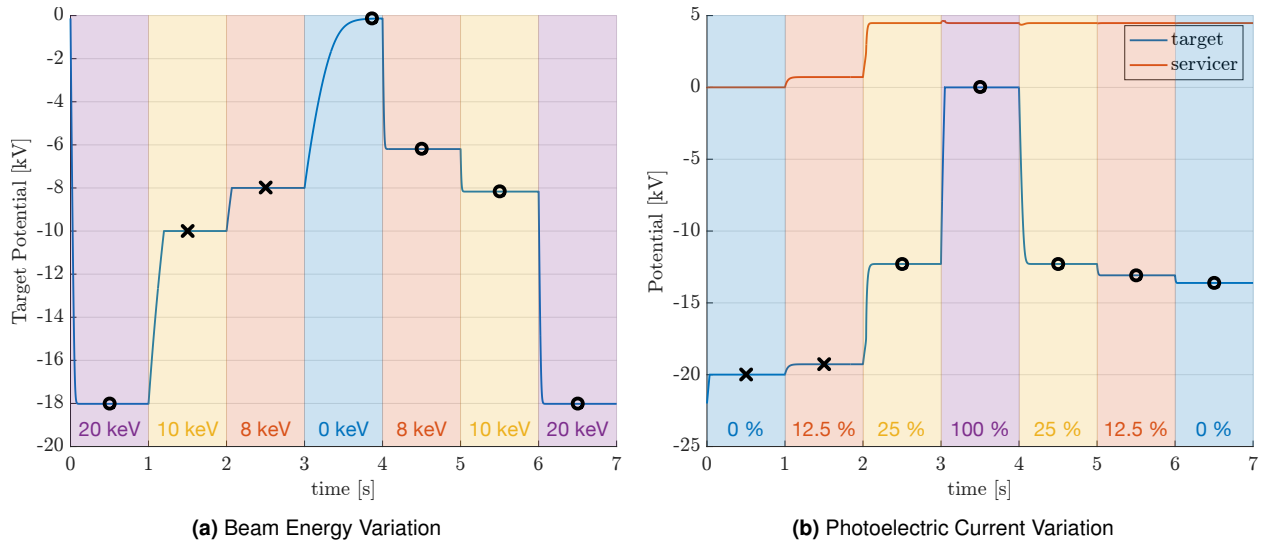


Figure 8: Change of Equilibria due to Electron Beam Energy or photoelectric Current Variation

environment with the addition of an electron beam current. Moreover, J-2 demonstrates that it is possible to jump from one stable equilibrium, through an unstable middle root, to another stable equilibrium due to variations in electron beam energy or photoelectric current, as seen in Fig. 8. In the following discussion, the "left-side" equilibrium refers to the most negative equilibrium potential that results when the electron beam is initially not energetic enough to impact the target. The "right-side" equilibrium refers to the least negative equilibrium potential that is the result of the electron beam impact and the following secondary and backscattered electron currents. In Fig. 8, convergence to a left- or right-side equilibria are denoted using $\times$ or $\bullet$, respectively. It was found that changes in the electron beam energy can cause the equilibrium to jump in two directions: right-to-left or left-to-right. When the target is initially uncharged, the electron beam with energy 20 keV is able to impact the target and a right-side equilibrium at -18 kV results. When the beam energy is reduced to 10 keV, it can no longer impact the target due to its severe negative charging and the potential converges to a left-side equilibrium at -10 kV. Should the electron beam energy then be increased back to 20 keV, the target would again be easily impacted by the electron beam and converge to a right-side equilibrium. On the contrary, changes in the photoelectric current can only cause equilibrium jumps in one direction: left-to-right. This is because changing the target orientation and thus the photoelectric current enforces the right-side equilibrium, thereby eliminating the left-side equilibrium altogether.

With the knowledge that equilibrium jumps are possible in the single-Maxwellian plasma with an electron beam and naturally in the bi-Maxwellian plasma, it became of interest to determine how the equilibrium potential would behave in a bi-Maxwellian environment with an electron beam (See C-7 and C-12). First, the properties of the natural potential jump in the bi-Maxwellian plasma were investigated. The flux in a bi-Maxwellian plasma is governed primarily by 4 parameters: the electron density of population 1 (n_1), electron density of population 2 (n_2), the electron temperature of population 1 (T_1), and the electron temperature of population 2 (T_2). The electron densities can be represented by the ratio $\alpha = n_1/n_2$. It was found that variations in the environment do not dictate whether the spacecraft converges to the left- or right-side equilibrium, but do determine whether a left-side equilibrium will exist. Moreover, while the initial target potential governs the value of the equilibrium potential, changes in the environment do not affect this result. At a particular T_1 and T_2 , variations in α can cause the electric potential of the target to jump to a positive potential.

The inclusion of the electron beam expands on these conclusions. The results of active charging in a bi-Maxwellian plasma can be visualized in Fig. 9, where Fig. 9a gives a complete picture of active charging by showing the total current as a function of the spacecraft potential ϕ and α , and Fig. 9b shows the target potential over time. Here, T_1 and T_2 are held constant while α varies from 0.1 to 10. It was found that jumps in the equilibrium potential due to perturbations in α are critical when α is small, and the equilibrium potential converges to a particular value as $\alpha \rightarrow \infty$. It was also found that jumps to positive potentials are

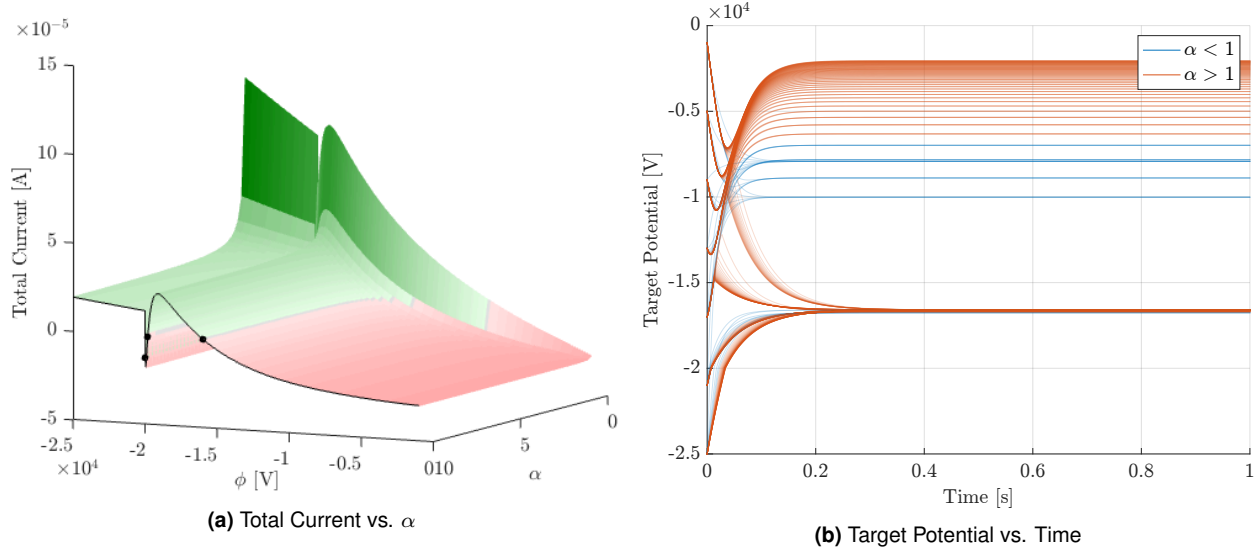


Figure 9: Active Charging in a Bi-Maxwellian Environment

possible in extreme environments even with the electron beam current included at $I_{\text{beam}} = 50 \mu\text{A}$. However, the force analysis showed that the force between the target and servicer remains attractive for most cases due to induced charging effects from the servicer's relatively significant electric field. The coupled charging effects can be observed in Fig. 9b. For the right-side equilibrium cases, the initial impact of the electron beam causes sudden negative charging. However, as the positive potential on the servicer builds, electrons are attracted back, thus abating the effect of the electron beam current on the target. This explains the following positive charging before converging to equilibrium.

The bi-Maxwellian distribution function is not the only distribution function that may represent the plasma environment at GEO. In quiet periods or periods of direct exposure to the solar wind, a kappa function represents the plasma distribution. Additionally, a combination of a cool single-Maxwellian plasma and a hot kappa plasma may exist. The flux distributions of these are

$$f(E) = n \left(\frac{q_0}{2\pi\kappa T m} \right)^{1/2} \frac{E}{\kappa T} \left(\frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \right) \left(1 + \frac{E}{\kappa T} \right)^{-\kappa-1} \quad (1)$$

and

$$f(E) = f_1(E) + f_2(E) \quad (2a)$$

$$f_1(E) = n_1 \left(\frac{q_0}{2\pi m T_1} \right)^{1/2} \frac{E}{T_1} \exp \left(-\frac{E}{T_1} \right) \quad (2b)$$

$$f_2(E) = n_2 \left(\frac{q_0}{2\pi\kappa T_2 m} \right)^{1/2} \frac{E}{\kappa T_2} \left(\frac{\Gamma(\kappa + 1)}{\Gamma(\kappa - 1/2)} \right) \left(1 + \frac{E}{\kappa T_2} \right)^{-\kappa-1} \quad (2c)$$

respectively, where $\Gamma(x)$ is the Gamma function and κ is the spectral index, which must be greater than 1. It was found that varying κ can change whether the target will converge to the left- or right- side equilibrium. In some cases, it may even be possible to create a left-side equilibrium in an environment where there was not one previously. It was also observed that greater suprathermal tails (smaller values of κ) change the equilibrium potential, while as $\kappa \rightarrow \infty$, the function converges to a Maxwellian for the kappa distribution or bi-Maxwellian for the Maxwellian and kappa summed distribution.

8.2.2 Open-Loop Charge Neutralization

Decreasing the magnitude of a satellite's charge allows for dangerous arc discharges to be avoided and can minimize electrostatic forces and torques between two charged spacecraft during proximity operations. Performing charge neutralization without knowledge of a spacecraft's potential allows for the dangers associated with spacecraft charging to be avoided without involving potential sensing techniques. This is

referred to as open-loop charge neutralization. Two methods are investigated: using VUV lasers to excite photoemissions from a servicer or target and using an ion gun to impose positive currents on a target.

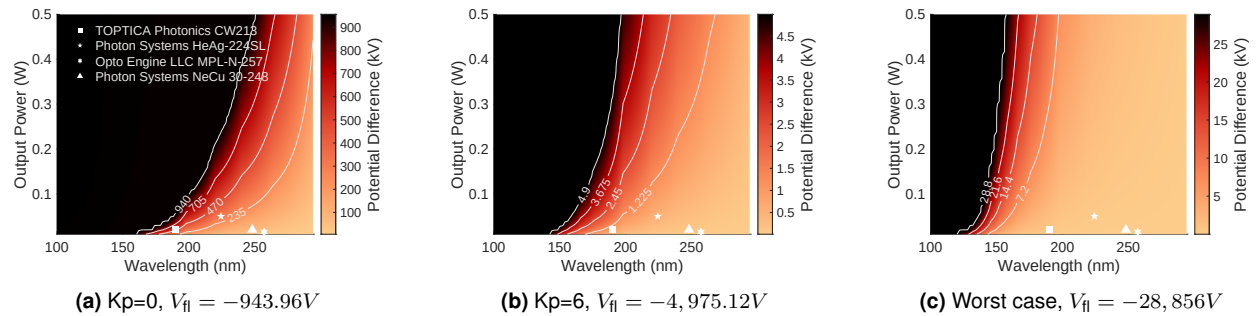


Figure 10: Change in floating potential of a 0.75 m radius spherical spacecraft in various GEO eclipse environments as a function of UV laser wavelength and output power. Commercial-off-the-shelf UV lasers are scattered for comparison.

Initial computations show that photoelectron emissions from UV lasers can be used to neutralize spacecraft potentials in various GEO environments. Figure 10 shows the change in spacecraft potential as a function of UV laser wavelength and output power. The black region indicates when the spacecraft potential is approximately zero. It is also shown that open loop charge neutralization using photo emissions is more efficient in calmer environments, as the ambient electron current is lower. These findings and other work related to touchless potential sensing using photo emissions is published in J-1. Experiments in J-1 also show that photo emissions occur when a UV laser is aimed at a target, and the magnitude of these photo emissions can be accurately simulated. Experiments using a VUV lamp to apply a positive current to a target is also discussed in Section 8.3.3.

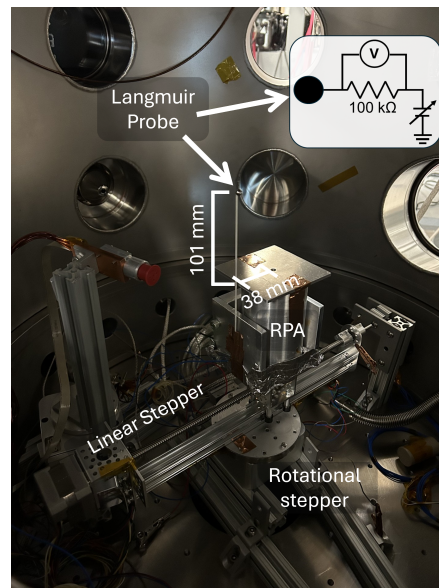


Figure 11: Ion beam mapping sensor package

As mentioned, open loop charge neutralization may also be done with an ion gun. In this case, a servicer aims its ion gun at a target to apply a positive current and decrease the potential magnitude of the target. This can again be investigated using computational and experimental techniques. The ECLIPS vacuum chamber has a Nonsequitur Technologies 1402 Ion Gun installed that emits Ar^+ ions up to 3keV. The ion gun has not been used in charging experiments, thus it was necessary to characterize the emitted ion beam. This was done using a spherical Langmuir probe and RPA mounted 359 and 460 mm from the ion gun exit,

respectively. The two sensors are placed on a linear and stepper motor, allowing them to travel almost the entire floor of the chamber (see Fig. 11). As a result, a current density map of the ion gun is generated and shown in Fig. 12. The beam is not perfectly symmetric, but the highest current density region may be considered approximately circular. The beam radius is 3.84 cm as measured by the RPA and 3.15 cm as measured by the Langmuir probe. Based on this, and assuming an initial radius of 1 mm at the ion gun exit, the half angle of the beam may be estimated to be $\approx 4.9^\circ$. More information regarding recent work with the ion gun can be found in C-10.

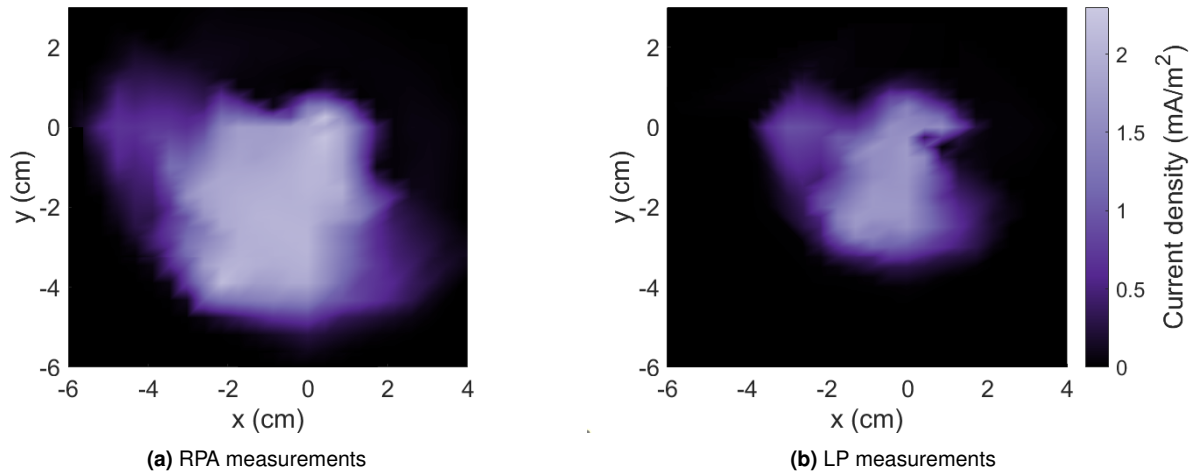


Figure 12: Current density map of the unaltered ion gun emissions measured by the RPA and Langmuir Probe

8.3 Thrust 3: Active Charge Control

8.3.1 Ion Emission NASCAP Modeling

In order for an electron beam emissions to reach a target, the electron beam must have an energy greater than the difference between the servicer and target potential ($E_{EB} > \phi_S - \phi_T$). Otherwise, the electron beam will be attracted back towards the servicer and miss the target. If the servicer is significantly smaller than the target, it will saturate to a positive potential and attract the electron gun away from the target before the desired target potential is achieved.¹⁰ To account for this, ion gun emissions may be used to emit positive current from the target and limit its potential growth.

Ion emissions are heavier than electrons, imparting a non-negligible momentum transfer on the servicer. In addition, emitted ions may be attracted back towards a negative servicer, negating the positive emitted current and imparting more momentum transfer. Thus, this complex problem is investigated with spacecraft-plasma interaction tools, like NASCAP-2k and Spacecraft Plasma Interaction Software (SPIS).

Initial simulations are done in NASCAP-2k Version 4.4. NASCAP-2k has a built in function to model charged particle emissions with its *emitter* tool. However, simulating the charging behavior of two nearby spacecraft is non-trivial and requires trial and error to ensure the simulations are accurate and appropriately converge. So, a spherical target and servicer are modeled, and only the electron gun emission is included initially. The setup and some of the initial results are shown in Fig. 13. The charging behaviors were presented at the 2023 Applied Space Environments Conference in associated presentation C-2. Future work will include the ion gun as well to simulate the entire electrostatic tractor setup.

8.3.2 Closed-Loop Charge Control Analytic Study

Active charge control refers to the use of one or more controlled currents which, when applied to a target, influence its electric potential. In this case, the currents being considered are a negative current generated by an electron gun and a positive current generated by UV lights. To implement closed-loop charge control, a measurement of the target's electric potential is required. This measurement is then fed into a feedback control, allowing the applied current and resulting target potential to be adjusted.

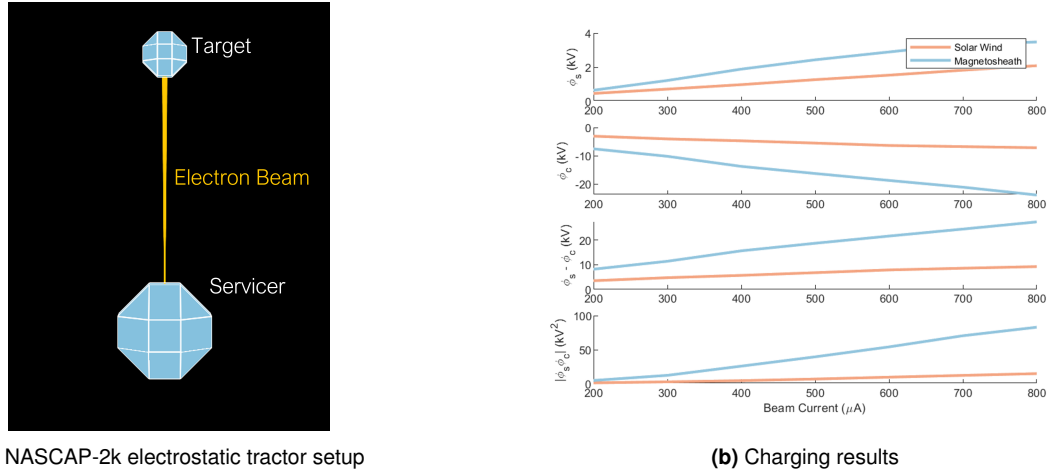


Figure 13: Electrostatic tractor setup and charging results in the cislunar environment as a function of beam current for a beam energy of 40 keV.

An analytic study of the building blocks for the feedback controller was outlined in the original proposal. This included developing a simulated feedback controller which could then be used to compute the electron beam and UV lamp parameters necessary to achieve the control as well performing a comparison of the secondary electron and x-ray methods in terms of speed and accuracy. These methods would be explored as the current facilities in the AVS lab did yet not allow for active charge control experiments. However, a collaboration with the Air Force Research Lab at Kirtland Air-force Base allowed for novel experimental research into active charge control. As such, the Closed-Loop Charge Control Analytic Study will be merged with the Closed-Loop Charge Control Simulation.

The modeling with UV lasers will be explored after the charge control simulation framework is developed, but the sensing integration and feedback controller were developed as part of the Closed-Loop Charge Control Experiments. An in-depth explanation of these elements is given in the following section.

8.3.3 Closed-Loop Charge Control Experiments

The Electrostatic Tractor (ET) is a novel method for active debris removal in geostationary orbits that utilizes electrostatic forces.^{11,12} Equipped with a high energy electron gun, a servicing spacecraft directs a beam of electrons at the target, imparting a negative current and decreasing the potential on the target.¹² Because the servicing craft is losing electrons, it experiences a positive current and an increasing potential.¹² This leads to opposing electric potentials on the spacecraft and an attractive Coulomb force generated between them, which allows for contactless manipulation of the target.¹² Closed-Loop Charge Control is required to maintain a desired electric potential on the target and therefore control the attractive force between the two spacecraft.

For year 1, the focus was proposed to be the simulation of large spacecraft responses and emulation of the space environment. However, these aspects are strongly coupled with the floating potential experiments in Sec. 8.1.1 and as such have also been pushed to year 2. These research objectives were shifted in favor of electron gun and UV experiments, which were slated for years 2 and 3. This adjustment was made possible by a collaboration with the SCICL lab at AFRL. Using their electron gun control and electrostatic voltmeter (as well as the other facilities) facilitated active charge control research.

Active charge control of a target is first explored experimentally in C-6. By controlling the voltage on the internal grid of the electron beam, the current emitted from the beam can be controlled. This controlled negative current is applied in tandem with a positive current generated by vacuum ultraviolet (VUV) lamps. The output of the VUV lamps cannot be controlled by the computer and therefore simply applies a constant positive current I_{ph} . Because the target is being irradiated by an electron beam, secondary I_{se} and backscattered I_{be} electrons will also be generated on the surface of the target, applying a positive current. Balancing these currents is the key to controlling the potential of the target

$$I_{net}(\theta_T) = -I_{EB}(\theta_T) + I_{se}(\theta_T) + I_{be}(\theta_T) + I_{ph}(\theta_T) = 0. \quad (3)$$

The goal is to adjust the electron beam current, I_{EB} , such that the net current, I_{net} , is zero when the target potential, θ_T , is equal to the desired potential. In other words, the electron beam current is adjusted such that floating potential of the target is equal to the desired potential.

A proportional and derivative feedback controller is developed for controlling the grid of the electron gun. The proportional control is

$$\delta\theta_P = K_P(\theta_F - \theta_T) \quad (4)$$

The change applied to the grid potential, $\delta\theta_P$, is proportional to the difference between the goal potential θ_F and the actual potential θ_T , where K_P is the proportional gain. The derivative control is defined similarly, except the applied change is proportional to the rate of change of the error ($\theta_F - \theta_T$).

The experimental setup for this paper shown in Fig. 14 includes a Faraday cup, UV detector, electrostatic voltmeter (Trek Probe), and a 4 in diameter gold-plated copper disk. With this, the electron current impacting the target and the target's electric potential is continuously measured.

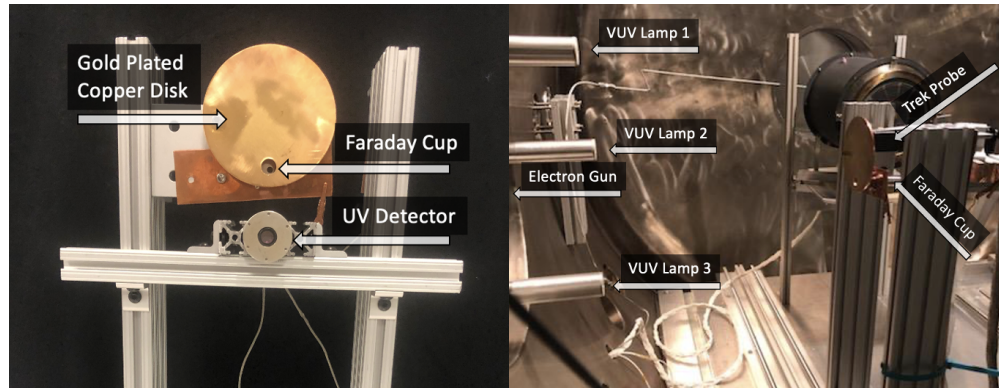
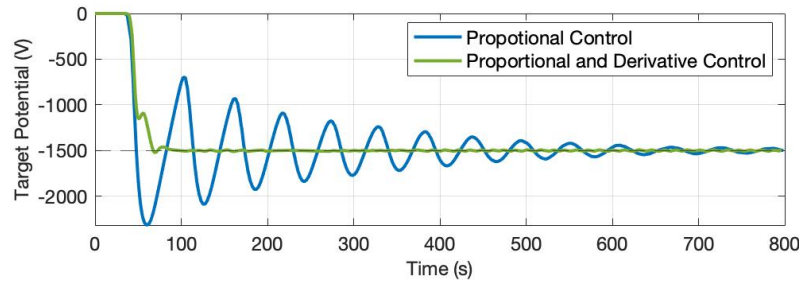


Figure 14: The experimental setup used for active charge control with current control

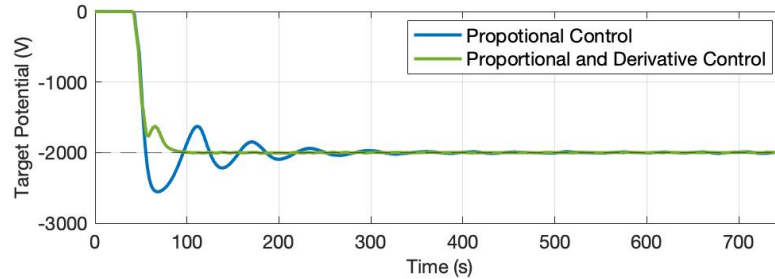
The control is implemented for a variety of charging scenarios including for beam energies of 8 keV, 10 keV, and 12 keV and goal potentials ranging from -500 V to -4000 V. Some of the results are shown here; a full analysis of the results is given in C-6.

For both the P and PD control, the electron beam is able to drive the target to the goal potential. Using only the proportional control, the behavior is extremely under-damped; however, it still achieves the control in a reasonable amount of time. Using the derivative control as well yields much faster convergence, with the goal potential being achieved in under 100 s in both cases. In all of the explored cases, by controlling the emitted current from the electron beam, the electric potential of the target can be controlled to an error of ± 20 V. This is the first example of contactless active charge control of an uncontrolled target. Throughout this entire paper, VUV lamps apply a constant positive photoelectric current. This allows the target to discharge when the electric potential is more negative than the goal. Without the lamps, the only mechanisms for discharging are ambient losses such as field emission or leakage currents, which cause the rate of discharge to become far too slow for realistic operations. It is shown that, with the photo-electric current of the VUV lamps, the target can be discharged 4000 V in under 150 s. With just the ambient electron losses, the same discharge takes on the order of hours, demonstrating the need for these VUV lamps.

In C-11, this research is expanded by developing a control that manipulates the energy of the electron beam and incorporates remote sensing methods into the feedback control. Experiments were conducted in the ECLIPS vacuum chamber using the same setup depicted in Fig. 6. While performing the experiments in C-6, it is found that the electron beam could be used to drive the target to less negative potentials and effectively discharge the target by adjusting the beam energy. Implementing control with the electron beam energy would allow the target to be discharged without the additional VUV lamps, and this is shown in the results of C-11. The same current balance as C-6 is being performed, except now there is no photo-electric current and the beam energy is being manipulated rather than the current. Also, rather than using an electrostatic voltmeter to measure the target's potential like in C-6, the secondary electron method (SEM) is implemented in C-11. The secondary electron method is a novel technique for remotely measuring a



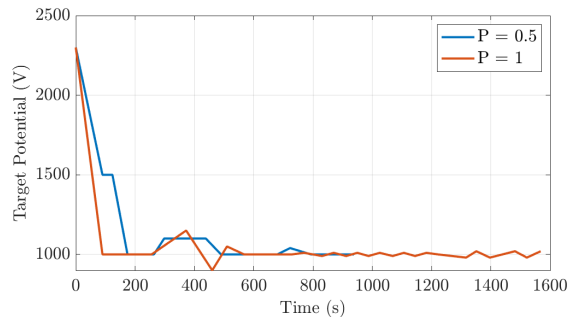
(a) Achieving a goal potential of -1500 V.



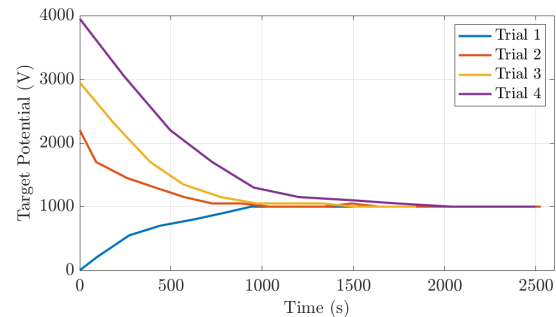
(b) Achieving a goal potential of -2000 V.

Figure 15: The charging behavior when using both the proportional and derivative controller with a 10 keV beam.

target's electric potential. An important aspect of the SEM is a voltage sweep on applied to the grid of the RPA while continuously measuring the current. Because of this, two methods of applying the voltage are tested with the control: a constant voltage sweep (Fig. 16b) and a continually adjusting sweep (Fig. 16a). The chosen sweep method does change the speed and accuracy of the control, but does not affect that ability of it to converge. By using remote sensing techniques in the feedback controller, a more realistic charging scenario is explored. Some of these results are given here. The same proportional controller as C-6 is used in C-11, except the $\delta\theta_P$ is applied to the beam energy instead of the electron beam grid. It is shown in C-6 that derivative control is unnecessary for these experiments.



(a) Achieving a goal potential using multiple gains and an adjusted secondary electron method voltage sweep.



(b) Achieving a goal potential using various initial energies and a constant secondary electron method voltage sweep.

Figure 16: The charging behavior when using proportional energy control to achieve a -1000 V target potential.

For gains ranging from 0.2 - 2, the controller converges to a variety of goal potentials with a resolution of at least 50 V. For gains less than 1, a resolution of 20 V is achieved. In each case, the control converged in a reasonable amount of time, however the exact convergence time depends on multiple factors. From these results, it is shown that remote sensing techniques can be incorporated into the active charge control of a target's potential in a vacuum chamber environment. Additionally, it is shown that, using energy control, the potential of a target can be driven to a desired goal potential without additional VUV lamps.

In C-11 and C-6, active charge control of a target is shown by controlling the beam current and energy. Each method has trade offs. Therefore, an in-depth comparison of the two techniques must be conducted: evaluating sensitivity, uncertainty, and the response to a non-vacuum chamber environment. Recently, a second collaboration with the AFRL allowed both the current and energy control to be conducted in the JUMBO chamber. The results of both forms of control using the same facilities and experimental setup (very similar to the setup shown by Fig. 14) will be used to preform this comparison. This work will extend into years 2 and 3.

8.4 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.

8.4.1 Conference Papers

- C-1 A. López and **H. Schaub**, "Relative Orbit Estimation with Wide Field of View Binary X-ray Sensing," AMOS, Maui, Hawaii, Sept. 19–22, 2023.
- C-2 K. Champion and **H. Schaub**, "Impacts of Cislunar Plasma on Electrostatic Tractor Potentials," Applied Space Environments Conference, Huntsville, AL, October 9–13 2023.
- C-3 J. Hammerl, A. Haft and **H. Schaub**, "Neighboring Spacecraft Charging due to Continuous Electron Beam Emission and Impact," Applied Space Environments Conference, Huntsville, AL, October 9–13 2023.
- C-4 J. D. Walker, J. Hammerl and **H. Schaub**, "Experimentally Estimating Secondary Electron Yield," Applied Space Environments Conference, Huntsville, AL, October 9–13 2023.
- C-5 K. Champion and **H. Schaub**, "Electron Beam Properties for Touchless Potential Sensing of Complex Geometry Spacecraft," AIAA Science and Technology Forum and Exposition (SciTech), Orlando, Florida, Jan. 8–12, 2024.
doi:[10.2514/6.2024-1064](https://doi.org/10.2514/6.2024-1064)
- C-6 J. D. Walker and **H. Schaub**, "Active Charge Control Using an Electron Beam and Ultraviolet Light Source," AIAA Science and Technology Forum and Exposition (SciTech), Orlando, Florida, Jan. 8–12, 2024.
doi:[10.2514/6.2024-2691](https://doi.org/10.2514/6.2024-2691)
- C-7 A. Haft and **H. Schaub**, "Effects of the Double-Maxwellian Plasma on Continuous Spacecraft Charging in GEO," Spacecraft Charging and Technology Conference, Avignon, France, June 17–21, 2024.
- C-8 A. López and **H. Schaub**, "Touchless Time-Varying Electrostatic Potential Sensing in Orbit: Fusion of X-ray and Electron Methods," Spacecraft Charging and Technology Conference, Avignon, France, June 17–21, 2024.
- C-9 J. Hammerl and **H. Schaub**, "Pulsed Electron Beam For Electric Potential Sensing And Control," Spacecraft Charging and Technology Conference, Avignon, France, June 17–21, 2024.
- C-10 K. Champion and **H. Schaub**, "Ion Optics for Laboratory Spacecraft Wake Generation," Spacecraft Charging and Technology Conference, Avignon, France, June 17–21, 2024.
- C-11 J. D. Walker and **H. Schaub**, "Development of Experimental Methods for Active Charge Control using Remote Sensing Methods Techniques," Spacecraft Charging and Technology Conference, Avignon, France, June 17–21, 2024.
- C-12 A. Haft and **H. Schaub**, "Electrostatic Tractor Effectiveness in a Non-Maxwellian GEO Plasma Environment," AAS Astrodynamics Specialist Conference, Broomfield, CO, Aug. 11–15 2024.
- C-13 J. D. Walker and **H. Schaub**, "Reaction Wheel Momentum Control While Electrostatically Tugging Tumbling Space Object," AAS Astrodynamics Specialist Conference, Broomfield, CO, Aug. 11–15 2024.

8.4.2 Journal Papers

- J-1 Á. Romero Calvo, K. Champion and **H. Schaub**, "Enabling Ultraviolet Lasers for Touchless Spacecraft Potential Sensing," *IEEE Transactions on Plasma Science*, Vol. 51, No. 9, Sept. 2023, pp. 2468–2481.
doi:[10.1109/TPS.2023.3264914](https://doi.org/10.1109/TPS.2023.3264914)
- J-2 J. Hammerl and **H. Schaub**, "Coupled Spacecraft Charging Due to Continuous Electron Beam Emission and Impact," *Journal of Spacecraft and Rockets*, published online July 2, 2024.
doi:[10.2514/1.A36010](https://doi.org/10.2514/1.A36010)
- J-3 J. Hammerl and **H. Schaub**, "Reduced Order Spacecraft Charging Models for Electrostatic Proximity Operations," *IEEE Transactions on Plasma Science*, submitted.

9 Project Conclusions and Outlook

The project completed on schedule and budget. We completed the expect work and were able to do some exploratory follow-on research studying pulsed charging, the use of UV diodes for secondary electron emission, as well as demonstrating that it is possible to floating potential experiments in the ECLIPS chamber. Here we are using the electron gun to charge a spacecraft shape inside the chamber instead of controlling the potential through an external electrostatic power supply. The project supported a large number of graduate students with 3 completed Ph.D. and 4 in progress. Further, the 3 year project was presented in 23 conference papers and presentations, and published in 13 journal papers.

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