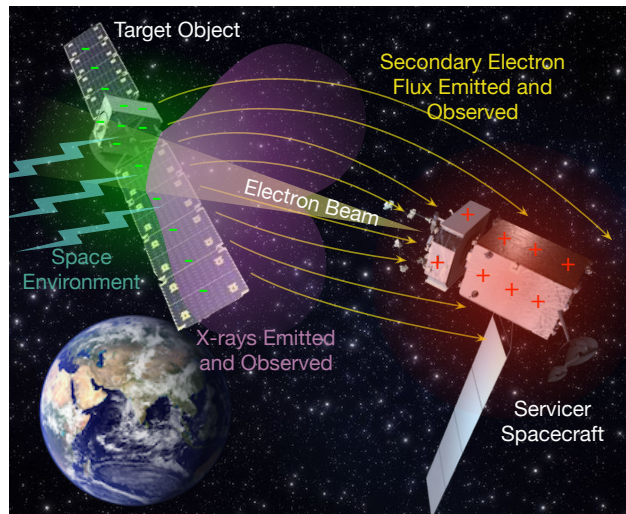


ANNUAL REPORT - 2ND PROJECT YEAR

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Touchless Charge Control of Neighboring Spacecraft in Geostationary and Cislunar Space



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1 Project Overview

This 3-year research study completed its second 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 2 achieved made strong progress with both the experimental and numerical/analytical research on active spacecraft charging. We have studied how, given a fixed amount of available power, a pulsed beam is showing promise to significantly increase the resulting electrostatic force. We have conducted active charge control experiments in our ECLIPS chamber where the potential is sensed via our secondary electron sensor and x-ray sensor. This resulted in a conference paper that is now being revised as a journal submission.

Interesting robustness results were obtained if the chamber object was exposed to a charging disturbance in the form of un-modeled photo-electron current. The basic charge control with space-suitable charge sensing worked. It will take us some more time to fully understand all results and be able to compare to numerical analytical models. The current premise is that the proposed charge control solution should use the e-beam energy as the control variable, and the resulting control exhibits some natural robustness to unmodeled charging disturbances, almost like an integral term.

A year ago we performed initial spacecraft charging experiments using the AFRL JUMBO chamber. These tests use a high-voltage trek probe to measure the potential. The near perfect voltage measurements allowed us to focus the initial tests on the charging behavior. Now, in the second year a large effort has been made to analyze the results and be able to match the behavior to numerical modeling. We are able to now numerically predict these initial chamber experiments and will expand the analysis to the more recent, and more complex, ECLIPS chamber results.

The new, more capable x-ray sensor has been received this spring and has now been fully installed and tested in the ECLIPS chamber.

Finally, the use of focused UV lights is beginning to be explored to help control the target potential. A novel idea has come up to explore using UV to enhance differential charging on a space object with non-homogenous conducting outer surface. The idea is that this could increase the electrostatic torques to reduce the times required to detumble an object.

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

2 Related Year 2 Travel

Project related research was presented at the AAS Space Flight Mechanics Meeting in Kauai, HI during January 19–23, 2024. One student traveled to this conference to present her work on pulsed spacecraft charging.

Next, two students traveled to the 9th European Conference on Space Debris in Bonn, Germany during April 1–4, 2025. This large conference is only held every 4 years. They presented their joint paper looking at field emission that can occur when large potentials are achieved with pulsing.

Finally, 4 students attended the bi-annual Applied Space Environments Conference in Toulouse, France, during May 5–8, 2025.

Two graduate students attended the annual AFOSR meeting and presented a poster on the work.

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 and researchers involved in this research in Aug. 15 2023 to Aug. 15 2025 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, as well as charging with a pulsed e-beam.

- Ethan Weber, a Ph.D. student who started in fall of 2024. He is fully supported on this AFOSR grant. He has been supporting the impact of field emission on active charge control, lead the purchase of the new x-ray sensor, and is investigating the use of focused UV lights to control the charge.
- 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. She rotated off the AFOSR grants as a GRA in summer 2025 and is supported on a NASA FINESST fellowship.
- 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. He has now graduated with his Ph.D. degree in July 2025.
- 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 in 2023–2024 academic year.
- Andrew Swackhamer, also an undergraduate DLA student in 2023–2024 academic year. He supported Andrea López's research on the ambient x-ray environment for the fall semester.
- Raaghav Lele, also an undergraduate DLA student in 2024–2025 academic year. He supported ECLIPS chamber active charging experiments and the associated numerical modeling.
- Tejaswi Shinde, hired her on as a post-doc to support this project starting Nov. 2024. Sadly, despite having a Ph.D. in numerical modeling of spacecraft charging subject to low-thrust engines using the SPIS software, she had a weak understanding of associated physics and numerical modeling. I had to let her go June 2025 after it was clear this was not a good fit.

In project year two we have supported 2 GRAs as budgeted, along with an undergraduate researcher and the a post-doc for part of the academic year. As the PI Dr. Schaub is not charging summer salary to this project at the moment, the associated funds will be used to support additional doctoral students to help with the numerical modeling of spacecraft charging.

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 2 budget expectations and expenses are illustrated in Figure 1.

The second project year supported two graduate research assistants and the new post-doc. The new post-doc was on this project from November to June before leaving the University of Colorado. As the PI became the department chair he is unable to charge his time to this project. Rather, the additional funds were used to support the post-doc. Next academic year the project will support additional graduate researchers who will support implementing our open-source Basilisk spacecraft simulation tool to include spacecraft charging related solution to give this work broader impact.

	Budget	Actual	Balance
Salaries			
Faculty Salary	\$ 37,585.00	\$ 0.00	\$ 37,585.00
GRA Salary	\$ 188,180.00	\$ 187,465.00	\$ 715.00
Benefits	\$ 32,572.00	\$ 34,522.00	\$ (1,950.00)
Salary Totals	\$ 258,337.00	\$ 221,987.00	\$ 36,350.00
Travel			
Travel Totals	\$ 17,792.00	\$ 33,482.00	\$ (15,690.00)
Capital Equipment			
Upgraded X-ray sensor	\$ 9,000.00	\$ 21,155.00	\$ (12,155.00)
Equipment Totals	\$ 9,000.00	\$ 21,155.00	\$ (12,155.00)
Operating Expenses			
Printing	\$ 3,000.00	\$ 0.00	\$ 3,000.00
Misc. Equipment	\$ 9,000.00	\$ 1,813.00	\$ 7,187.00
Operating Totals	\$ 12,000.00	\$ 1,813.00	\$ 10,187.00
Tuition/Stipends			
Tuition Totals	\$ 74,634.00	\$ 48,929.00	\$ 25,705.00
Expense Totals	\$ 371,763.00	\$ 327,366.00	\$ 44,397.00
Indirect Totals	\$ 162,793.00	\$ 157,316.91	\$ 5,476.10
Year 2 Project Budget	\$ 534,556.00	\$ 484,682.91	\$ 49,873.10

Figure 1: Comparison between budgeted and actual expenses up to year 2 end in August 15, 2025.

Further, the second project year resulting in the purchase of the new x-ray sensor. The new model is able to handle much higher x-ray fluxes and not saturate as quickly. However, the original quote for this sensor was obtained about two years ago and we found in January 2025 that the sensor now costs about 2x as much as expected. We used some miscellaneous equipment funds and some PI support funds to cover the difference. The new x-ray sensor is now fully installed and tests.

For the 3rd year the project staffing will include 2 additional graduate researchers to support their salary, benefits, tuition, as well as their associated conference travel. The projection is that we will be spending out the project funds as budgeted by the end of the 3rd project year.

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.

5 Accomplishments

The current project schedule is illustrated in Figure 2. The GANTT chart lists the original main research objectives. The project tasks are grouped by project thrusts and colored by their status. The second project year yielded exciting results. The work studying multiple charge equilibrium was submitted to AIAA Journal of Spacecraft and Rockets and published in J-2.

Further, the work on reduced-order spacecraft charging models was published in J-3. Finally, another paper on coupled spacecraft servicer and target object charging was published in J-2.

Highlights of the research progress include a completed study on how a pulsed electron beam, subject to a fixed amount of available power, can outperform a continuous electron beam at the same power level. This work assumes the right duty cycle is used and that a high-current electron gun is available such as is being develop by a commercial company called Think Orbital. The work was presented in conference papers C-15 and C-16 and is being written up as a journal paper in J-5.

Next, exciting progress was made analyzing the AFRL Jumbo chamber charging experiments. A numerical model was developed that is able to predicted the experimental results. This work is now being written up into a journal submission in J-6. Further, ECLIPS chamber experiments were performed that include using the secondary electron emission and x-ray sensing techniques of charge sensing. Closed loop charge control has been demonstrated in these tests. The data is still being analyzed to analytically explain some of the robustness results we are seeing if a charge bias is introduced.

Finally, the new x-ray sensor was purchases, installed and tested. In addition, research has begun to explore the use of UV lights in space to control the absolute and differential charge of an object.

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 2 period has successfully demonstrated that it is possible to numerically model and predict the active charging experiments conducted at AFRL and the AVS lab.

Next, a study was completed exploring the impact of field emission on the active charging concept. The research shows that the two objects won't have any significant arcing between them with the typical 10'ish meter separation we are assuming between surfaces. Further, if high-potentials are considered, such as those that result from pulsed charging, the field emission is not a limiting factor. Rather, the feedback control will compensate for the additional charge current and still stabilize to the desired current.

7 Changes

Project year 2 saw general progress across all three of the research thrusts. While year 1 had challenges with faulty experimental equipment and computers that had to be diagnosed and fixed, year 2 was able to perform a series of experimental methods to put us back on track in a balanced manner.

In terms of research direction, the frequency modulation approach is not promising as the sensor takes too long to acquire a signal. Instead the project has expanded the work studying pulsed charging solutions which is making great progress. Further, we are looking at novel UV charge control research that will be conducted in the 3rd project year.

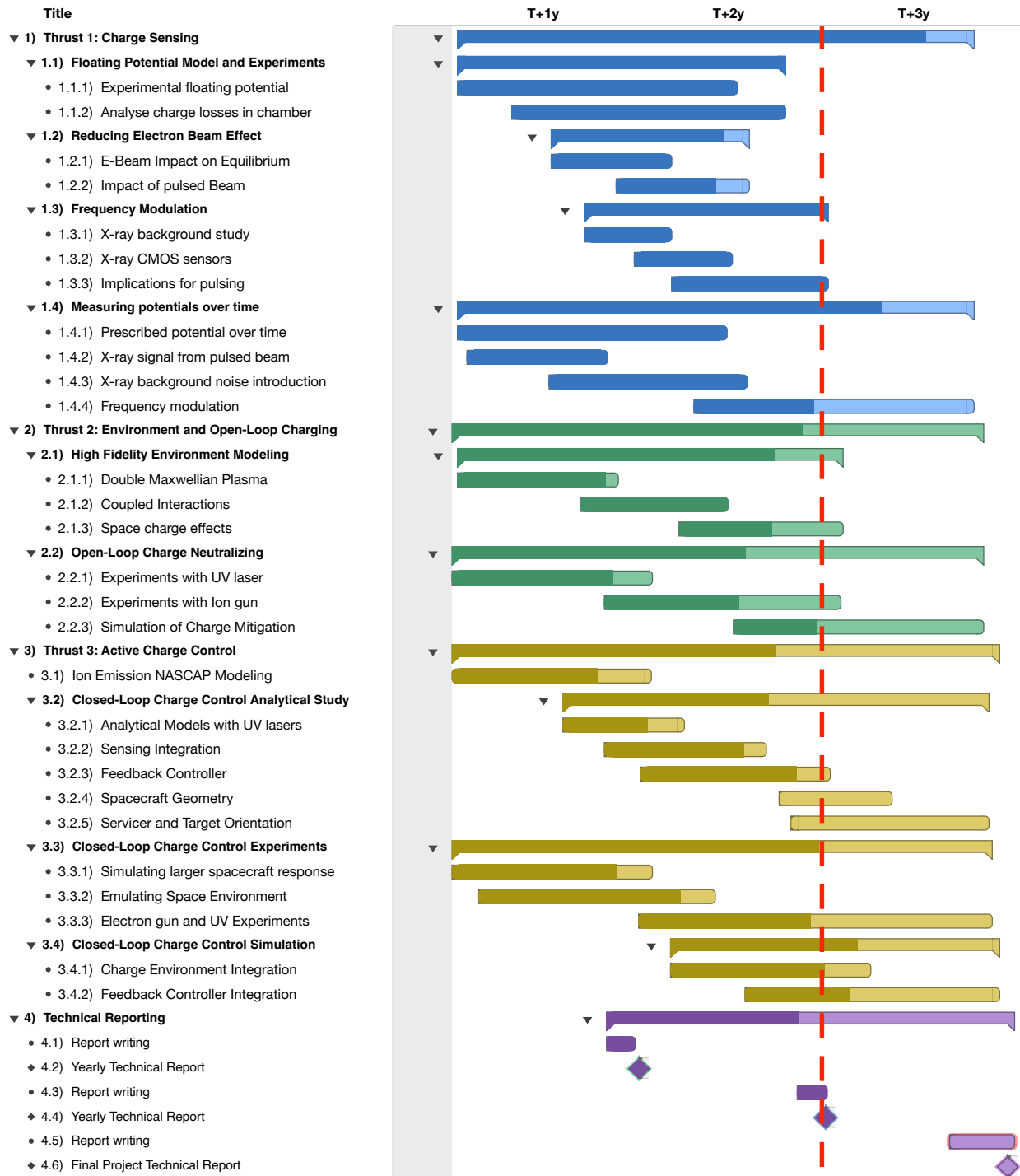


Figure 2: Current Project Schedule (darkened bar indicates degree of completion)

There is no delay to the project timeline or expenditure. The project is making strong technical progress and we expect expenditures to match the project budget by the end of year 3.

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, power-constrained pulsed charging research is becoming a very promising direction of this projection that was not originally envisioned.

Further, we continued to use the ECLIPS chamber to do a range of charge control related experiments including active charge control of an electrically isolated object in the chamber that was also subjected to a charging bias through the photo-electron stimulator in ECLIPS. No significant hardware challenges occurred in the 2nd project year.

Regarding the analytical and numerical modeling, strong progress has been made matching up the numerical models with the JUMBO charging experiments from the last year, and we have started to analyze the more recent ECLIPS chamber experiments where touchless charge sensing and photo-electron disturbances are being considered.

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.

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

8.1.1 Floating Potential Model and Experiments

A central requirement for experimental validation of pulsed electron beam interactions is the creation of a floating potential target inside the vacuum chamber. Unlike a grounded or high-voltage-controlled target, a floating object responds passively to incident beam currents, thereby more accurately mirroring the charging behavior of a charged spacecraft in orbit. However, due to the small self-capacitance of the test object (in our experiments an aluminum cube or sphere whose capacitance is on the order of tens of picofarads), the native charging time is too short (on the order of microseconds) to allow transient potential dynamics to be captured.

To address this, a passive external circuit is connected to the floating target outside the vacuum chamber via a high-voltage feedthrough. The key design goal of this circuit is to artificially increase the effective capacitance of the system, thereby extending the time constant of the charging and discharging behavior and enabling measurement of transient charging behavior.

A circuit model that maps the physical spacecraft charging environment to an RC analog has been developed as part of a previous AFOSR grant.¹ In that work, the spacecraft is modeled as a capacitor subject to various space current sources (plasma electrons and ions, photoelectrons, secondary electron emission, etc.). The circuit adds a resistor and capacitor in parallel and measures the discharge current over a 1 GΩ resistor. Additionally, a relationship between the components of the RC circuit and properties of the space environment was derived and to used map experimental circuit elements to space environment parameters:

$$C = C_{SC} \quad (1)$$

$$R^{-1} = \frac{Aqn_i\omega_i}{4T_i} + \frac{Aqn_e\omega_e}{4T_e}e^{\phi_N/T_e}, \quad (2)$$

While this RC model captures discharging behavior well and matches experimental results, it did not extend charging times. In the traditional RC circuit, the charging time constant is inherently limited by the small capacitance of the test object and the incident electron beam current. A collaboration with the Air Force Research Labs and the specialized equipment they have allowed for a more thorough investigation into this research. To delay this charging, the circuit was adjusted with a new resistor R_1 on the incoming beam path, limiting the rate of current flow into the capacitor (see Fig. 3) and recreate a standard RC charging circuit. To still be able to measure the charging behavior directly from the circuit, a bleed circuit to ground (now using a voltage divider) was kept in place in addition to the RC charging circuit. The voltage divider allows for the measurement of a small voltage drop with an oscilloscope which has a much higher time resolution than a picoammeter used for the bleed current measurement.

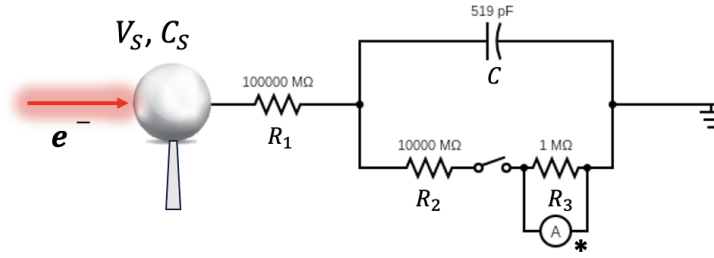


Figure 3: Schematic of the proposed RC charging and discharging circuit.

However, this configuration introduces new complications: the added resistor effectively decouples the capacitance of the sphere from the external capacitor, rendering the system inconsistent with the single-capacitor RC assumption used in the derivation for the discharging behavior. Mathematically, the system evolves as a set of coupled differential equations with voltages across both the sphere and the capacitor evolving independently (the final voltages remain coupled, however):

$$C_S \frac{dV_S}{dt} = I_{EB} - \left(\frac{V_S - V_C}{R_1} \right), \quad (3)$$

$$C_C \frac{dV_C}{dt} = \frac{V_S - V_C}{R_1} - \frac{V_C}{R_2 + R_3}, \quad (4)$$

where V_S is the potential of the sphere, V_C is the potential across the external capacitor, and R_1 only affects the charging leg, while $R_2 + R_3$ governs discharging. I_{EB} is the electron beam current which is the nominal emission during the charging process and zero while discharging. These equations have been validated with experiments shown in Fig. 4.

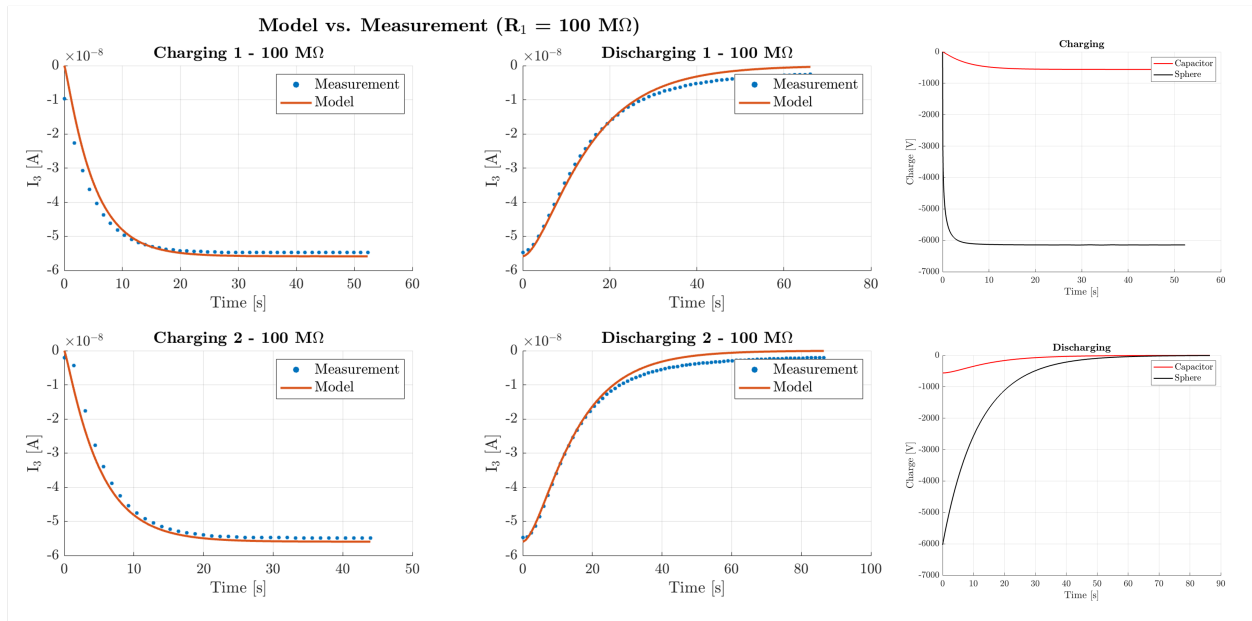


Figure 4: Comparison of the coupled differential equation charging model with experiments. Given that $R_1 = 100 \text{ M}\Omega$.

If $C_S \approx 0$, the equations simplify into one single differential equation. However, this equation only describes the capacitor charge and mathematically converts the sphere into a current source, which is not the case. Moreover, based on capacitance values from our experimental setup in the JUMBO vacuum

chamber at Air Force Research Laboratory (AFRL), the measured the capacitance of the sphere is relevant compared to the capacitor.

- Sphere to chamber (ground): 26.3 pF
- Sphere + cable to ground: 102.9 pF
- External capacitor: 519 pF
- Combined Capacitors (parallel): ~ 620 pF
- Combined Capacitors (series): ~ 102 pF

This implies that in the worst case (series connection), the sphere still dominates the system response, making direct potential modeling difficult unless R_1 is large and $C_S \rightarrow 0$.

An alternative configuration explored involves just attaching a capacitor in series with the target; no resistor. Preliminary experiments shown in Fig. 5 demonstrate that the charging of the target is significantly slowed down. With just the external capacitor, the system acts as a large spacecraft. However, because there is no resistor, or other component, this system can not simulate a space environment.

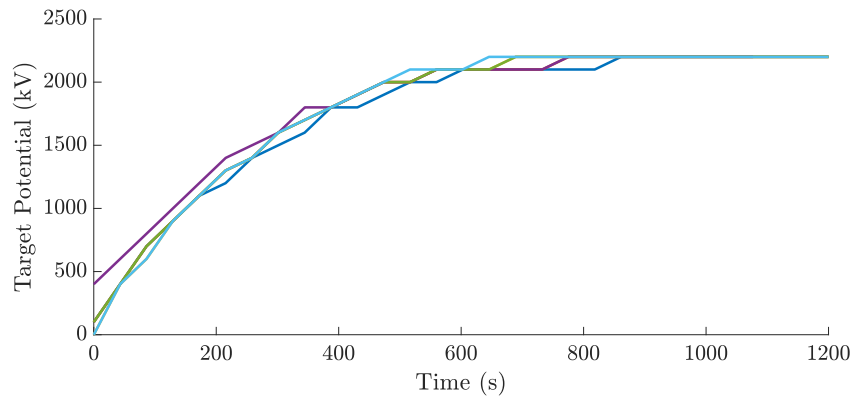


Figure 5: Slowed down charging behavior achieved by attaching just a capacitor to the target object.

This work is on going and additional resistor configurations will be explored in Year 3. However, the major goal of this section was to increase the charging time of the target in order to see transient behaviors and simulate large objects with a small target in a vacuum chamber. This goal has been achieved and can now be used to further charging research, such as active charge control and beam enhancements via pulsing. The secondary goal of simulating a space environment will be explored in year 3.

8.1.2 Reducing Electron Beam Effect

The impact of the electron beam on the equilibrium potential of a floating object was studied in detail in J-2, where a key finding was that secondary electron emission (SEE) due to beam impact can result in multiple equilibrium potentials in space environments such as GEO and cislunar orbit. For instance, a 20 keV, $50\mu\text{A}$ electron beam targeting an eclipsed spacecraft can lead to three distinct equilibrium potentials, two of which are stable. This nonlinearity is primarily driven by the strong SEE at low effective electron energies.

To minimize perturbation of the natural potential during charge sensing operations, the study proposed pulsing the electron beam to reduce the net delivered current. Theoretical modeling shows that pulsing, which is characterized by frequency and duty cycle, can effectively lower the average beam current (by a factor of the duty cycle), thereby allowing potential measurements with reduced disturbance. Importantly, beam pulsing changes the charging dynamics but not the final equilibrium potential, enabling more accurate sensing if properly configured. The theoretical part of this part of the project is considered complete.

The goal of characterizing the effect of the electron beam on a target and developing methods for mitigating these effects are considered complete. Reference J-2 thoroughly characterizes the coupled

charging behavior using a continuous electron beam and Ref. 2 describes using a pulsed beam to minimally charge the target object while still enabling sensing.

8.1.3 Frequency Modulation

To support frequency modulation experiments, an Amptek FAST SDD x-ray sensor was acquired early in Year 2. This sensor uses a silicon drift detector with an improved peaking time and x-ray count rate compared to the previously used Si-PIN detector and is among the fastest commercially available x-ray detectors. It was selected over the originally proposed CMOS-based x-ray detector due to its easier integration with the existing vacuum chamber set up while still enabling high-speed measurements.

Since its acquisition, the sensor has been calibrated and used in spacecraft charging experiments. However, initial testing and calibration showed that even with the improved sensor, signal acquisition rates remained too slow for the intended frequency modulation techniques. As a result, research focus has shifted away from frequency modulation and toward pulsed charging and UV charge control. The acquired FAST SDD will continue to support these and other experimental efforts relevant to the project.

8.1.4 Measuring Potentials over time

With the transition away from frequency modulation, previous plans to adapt the time varying potential estimation techniques developed in C-8 for use with frequency modulation are no longer being pursued. Still, the broader objective of measuring spacecraft potentials over time remains a major research focus through its application to closed-loop active charge control.

A current research direction related to this objective involves the sensing of differential charging on a rotating spacecraft. In addition to differential charging being time varying, the ability to sense individual components depends on the time-varying orientation of the target. This leads to a complex, time-varying, charge sensing problem that requires novel sensing techniques. To address this, research into the application of the UV laser charge sensing method, established and demonstrated in J-1, to targeted sensing of differentially charged spacecraft has begun, and experiments exploring this method will begin in early Year 3.

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. In a bi-Maxwellian plasma, changes in the plasma parameters can trigger a sudden jump in the spacecraft potential from thousands of volts negative to a few volts positive, and vice versa. This phenomenon is known as the triple-root jump, which was first proposed in 1965³ and confirmed experimentally in 1988.⁴ The mechanism of the triple-root jump is explained in detail in Ref. [5, Chapter 5]. As environmental parameters continue to change in one direction over time, the spacecraft potential roots of the total flux equation coalesce and eventually disappear together, causing the spacecraft potential to jump from a stable equilibrium potential to another stable equilibrium potential of opposite polarity through an unstable third root.

In previous bi-Maxwellian plasma simulations, the trigger for the potential jump was not entirely clear. However, recent work brings to light the significance of the total backscattered and secondary electron yield in predicting potential jumps. Whether a spacecraft charges to a positive or negative potential is governed by the total secondary and backscattered electron yield, $\delta + \eta$, where δ is the secondary electron yield and η is the backscattered electron yield. When the total yield is less than 1, the spacecraft charges negatively. When the total yield is greater than 1, the spacecraft charges positively. This concept can be used to determine when a jump will occur for an initially uncharged spacecraft in a bi-Maxwellian plasma by applying it to the current balance equation:

$$\frac{\int_0^\infty f(E)[\delta(E) + \eta(E)]dE}{\int_0^\infty f(E)dE} = \langle \delta(E) + \eta(E) \rangle \quad (5)$$

Using Eq. (5), we can predict that the spacecraft will charge positively when $\langle \delta(E) + \eta(E) \rangle > 1$ and negatively when $\langle \delta(E) + \eta(E) \rangle < 1$. In the case where $\langle \delta(E) + \eta(E) \rangle = 1$, the net incoming or outgoing flux is zero.

Ref. 6 explains that negative charging at the threshold occurs as a sudden jump when $T_A < T_1 < T^* < T_2$ where T_A and T^* are the anti-critical and critical temperatures of the spacecraft material.

Eq. (5) is valid for the natural charging case. However, the implementation of the electron beam affects the individual secondary and backscattered electron yield. With the electron beam, Eq. (5) becomes

$$\frac{\int_0^\infty f(E)[\delta(E) + \eta(E)]dE + f_{\text{beam}}[\delta(E_{\text{beam}}) + \eta(E_{\text{beam}})]}{\int_0^\infty f(E)dE + f_{\text{beam}}} = \langle \delta(E) + \eta(E) \rangle \quad (6)$$

This equation can be used to predict the plasma environment at which the triple root jump will occur with the addition of the electron beam. Because the secondary and backscattered electron yield models vary, year 3 work will include comparisons of common models to show how the charging of the electrostatic tractor changes depending on the secondary and backscattered electron yield model.

When the spacecraft is not initially uncharged, the condition at which sudden jumps in potential occur becomes more complicated. If a spacecraft is charged to a potential ϕ_0 , then it must be a stable root of the current balance equation $I_{\text{net}} = 0$. This means that a small perturbation in the spacecraft $\delta\phi$ diminishes over time, which requires that

$$\frac{dI_{\text{net}}(\phi_0)}{d\phi} < 0 \quad (7)$$

Thus, assuming the existence of multiple roots, the spacecraft will experience a potential jump to another stable root if the following three scenarios occur:⁷

$$\frac{dI_{\text{net}}(\phi_0)}{d\phi} > 0 \quad (8a)$$

$$\frac{dI_{\text{net}}(\phi_0^-)}{d\phi} > 0 \text{ and } \frac{dI_{\text{net}}(\phi_0^+)}{d\phi} < 0 \quad (8b)$$

$$\frac{dI_{\text{net}}(\phi_0^+)}{d\phi} > 0 \text{ and } \frac{dI_{\text{net}}(\phi_0^-)}{d\phi} < 0 \quad (8c)$$

In the case of Eqs. (8b) and (8c), the potential will jump in the positive direction or negative direction, respectively. New simulations show that there is an even more specific method to the potential jump. For scenarios in which there are three roots, the spacecraft will jump to the negative root if ϕ is less than the unstable root and to the positive root if ϕ is greater than the unstable root. Thus, if a perturbation $\delta\phi$ occurs such that $\phi = \phi_0 + \delta\phi$ moves the opposite side of the unstable root, a potential jump to the next stable root will occur.

The bi-Maxwellian plasma environment also brings about unique challenges not considered in previous studies that consider only one plasma population.^{8,9} During quiet times, the plasmopause can extend out as far as $L = 7$, fully encompassing GEO at $L = 6.6$. This exposes GEO satellites to cold plasmasphere particles than can hinder active charging effects. Previous studies introduce the idea of the pulsed electron beam as a method of increasing the electrostatic force.⁹ New research shows that it is possible to maximize the electrostatic force between spacecraft by finding an optimal duty cycle discussed in J-5 and C-15. It was found that in an active GEO plasma environment in eclipse, the pulsed beam reduced the re-orbit time to a graveyard orbit from 93 days to only 5 days. The massive increase in the electrostatic force is the result of the spacecraft charging to very high potentials; the target charges to over -150kV in this example. Figure 6 illustrates how optimizing the duty cycle results in a peak force by maximizing the magnitudes of target and servicer potentials. During quiet times, the target does not charge to such high potentials, but the pulsed beam still helps overcome charge neutralization from the colder ambient plasma.

The exploration of the pulsed electron beam as a method to overcome quiet times also led to the investigation of field emission as a result of charging to high potentials. It was originally of concern that the field emission would occur rapidly at a very high charge concentration, which would lead to arcing between the target and servicer. The threshold at which this would happen was studied in COMSOL, a physics-based finite element solver C-16. It was assumed that arcing would occur at the vacuum breakdown limit for current density at the cathode, 10^{12} A/m². However, these simulations were not time dependent. Field emission was then included in the AVS time-dependent MATLAB charging program discussed in J-5 and C-16. These

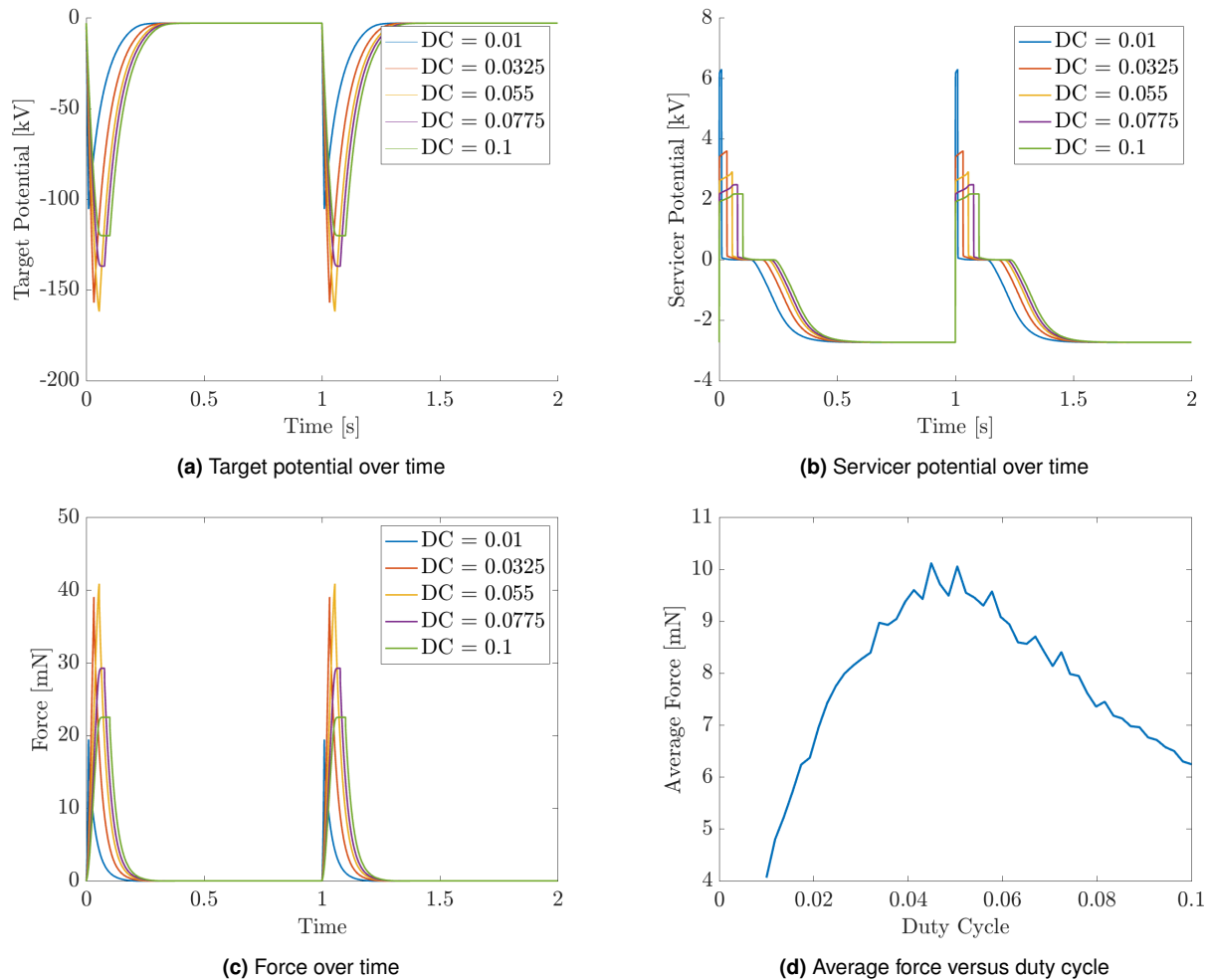


Figure 6: Coupled effects of the pulsed electron beam for duty cycles ranging from 1% to 10%

simulations showed that arcing was highly unlikely to occur between spacecraft because the current density at which field emission begins does not exceed 10^{-11} A/m². Instead, field emission is a significant limiter of the potential to which the spacecraft can charge depending on the emitting tip size. Field emission was simulated for tip radii from 1 μm to 50 μm with the pulsed beam at a duty cycle of 5%, shown in Figure 7. It was found that at 50 μm , field emission is negligible. However, as the tip radius decreases, the emitted current increases and the potential of the spacecraft decreases. At 1 μm , the spacecraft charges to only -6.4 kV, compared to -165 kV without field emission.

8.2.1.1 Particle-In-Cell Simulations

High fidelity Particle-In-Cell (PIC) simulations of the electrostatic tractor in a single Maxwellian GEO environment were begun in Spacecraft Plasma Interaction Software (SPIS). Several parameters were varied to determine their influence on electrostatic tractor performance including sun direction, separation distance, spacecraft size and electron gun parameters.

Initial results indicate that if the electron gun current is larger than the photoelectron current, the sun direction and resulting photoelectron current has minimal influence on the spacecraft potentials. More significantly, as the separation distance between the spacecraft increases and the beam current increases, the divergence of the beam also increases. This makes the outer regions of the beam more susceptible to perturbations due to the electric field about the spacecraft, even results in some of the beam being drawn

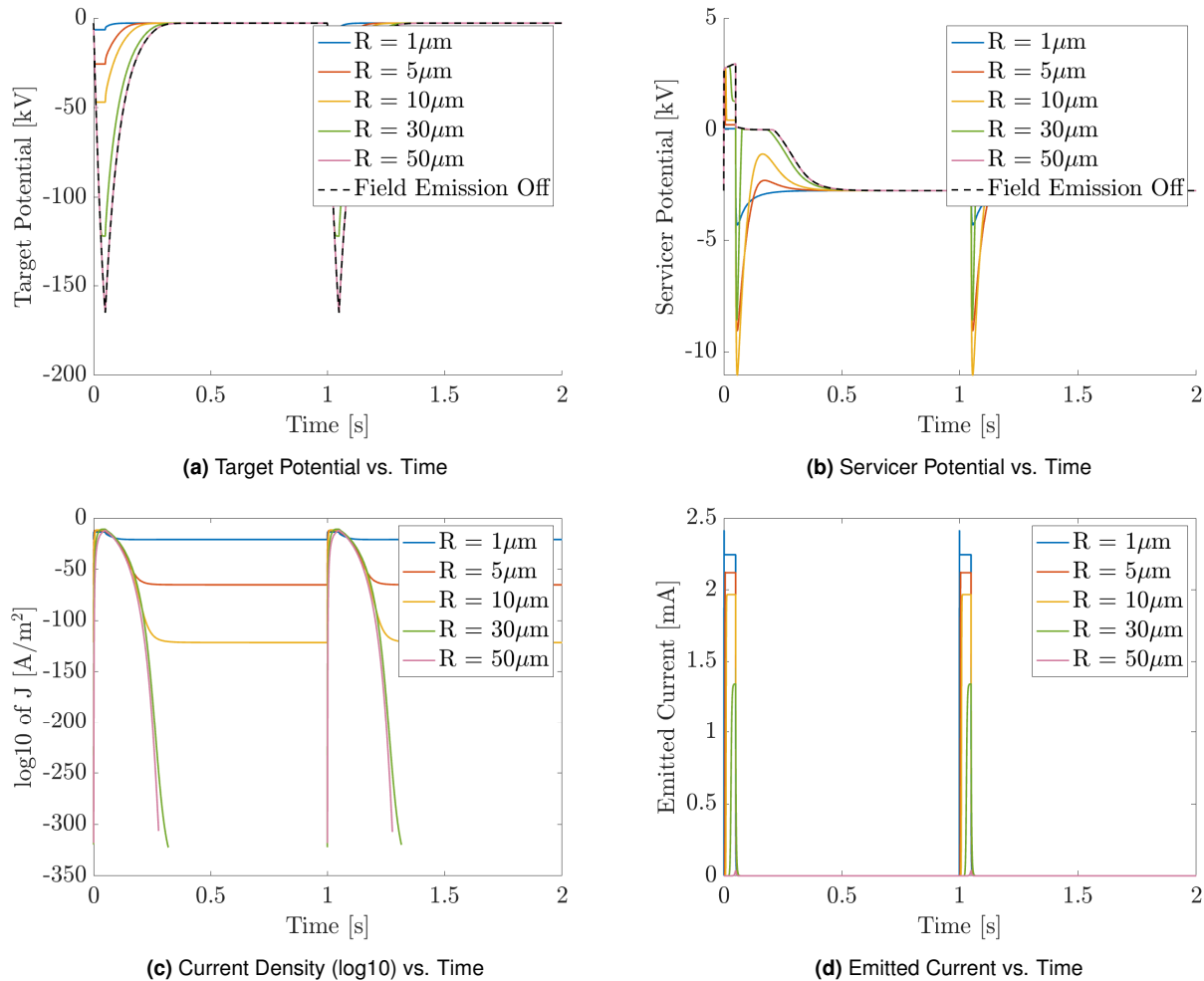


Figure 7: Coupled pulsed-beam charging results with field emission at duty cycle 5%

back toward the servicer. The validity of these results are currently being tested to ensure that this does not occur as a result of the simulation parameters.

8.2.2 Open-Loop Charge Neutralization

Open-loop charge neutralization refers to driving an uncontrolled target's electric potential to 0 V without measuring the target's potential. Hazardous electrostatic discharges (ESDs) can occur during docking operation when the electric potentials of the two spacecraft are different. Active charge control, outlined in Sec. 8.3, requires a measurement of the target's potential but can impart a wide range of electric potentials on the target. However, if just a 0 V is desired, a measurement of the target's potential is not necessarily required. Using a VUV lamp, photo-electron emissions can be excited from a target and drive its potential to 0 V. As long as a sufficiently strong VUV lamp is used, this can be achieved without remotely sensing the potential of target. This work has been explored extensively in J-1 and is considered complete (as it pertains to this project). Additional experiments were completed and shown in Fig. 8. These experiments start by using an electron to achieve a -1.5 kV potential on the target with a $13 \mu\text{A}$ current, then, without any measurement, the VUV lamps are activated and a 0 V potential is maintained on the target.

Open-loop charge control was also discussed using an ion gun to apply the positive current instead of VUV lamps. However, it has been determined that this is not realistic and that a measurement of the target's potential would be required for implementing charge control with an ion gun.

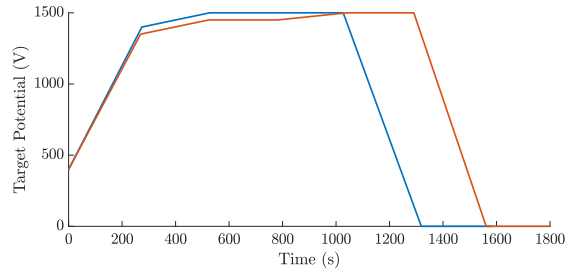


Figure 8: Two separate trials demonstrating open-loop charge control using a VUV lamp.

8.3 Thrust 3: Active Charge Control

8.3.1 Ion Emission NASCAP Modeling

The electron beam must have an energy greater than the difference between the servicer and target potential ($E_{EB} > \phi_S - \phi_T$) during electrostatic tractor operations. Otherwise, the electron beam will be attracted back towards the servicer and miss the target (see J-2). 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 mitigate this, ion gun emissions may be used to emit positive current from the servicer and limit its potential growth.

We are currently modeling charging behavior for spacecraft equipped with an electron gun in Nascap-2k and SPIS. An outline of the SPIS results is given in Section 8.2.1.1. Initial simulations are conducted with an electron gun to ensure the simulations converge and are representative of realistic charging behavior. Once the simulations with an electron gun are validated, an ion gun will be added to investigate the difference in servicer charging behavior.

8.3.2 Closed-Loop Charge Control Analytic Study

Active charge control (ACC) refers to the use of one or more controlled currents which, when applied to a target, influence its electric potential. Throughout this research, the currents being applied have been a negative current generated by an electron gun and a positive current generated by UV lights. In contrast to previous research where the potential of a controlled spacecraft was controlled, the closed-loop active charge control here is touchlessly applied to an uncontrolled target object. 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. In year 1, preliminary experiments were conducted demonstrating two potential methods for touchless ACC. Results of this work are presented in C-6 and C-11. Year 2 has continued this work with a focus on analyzing these methods analytically. The work presented in this section can also be found in J-6

Two methods of touchless ACC of a target have been explored: current active charge control (CACC) and energy active charge control (EACC). Both methods use a high energy electron beam to irradiate the target with negatively charge particles. Each method deals with a different aspect of the electron beam; CACC influences the current emitted from the electron beam while EACC controls the energy of the emitted electrons. The goal of both these methods is to achieve a net current of 0 A on the target surface when the potential of the target reaches the desired value. The numeric simulation frame work for both these methods was developed for a single spacecraft in a vacuum environment irradiated by an electron beam and VUV lamp. For CACC differential equation that governs the active charging behavior is given by

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\phi}_T \\ \dot{I}_{EB} \end{bmatrix} = \begin{bmatrix} \frac{I_{EB}}{C_{sc}} \left(c \left[\exp\left(\frac{-(E_{EB} + \phi_T)}{a}\right) - \exp\left(\frac{-(E_{EB} + \phi_T)}{b}\right) \right] + A - B \exp(-C(E_{EB} + \phi_T)) - 1 \right) + I_{ph} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ u \end{bmatrix} \quad (9)$$

Here, u is the applied control and, for these studies, both a proportional (P) and proportional/derivative

(PD) controller were developed. Other than I_{EB} and ϕ_T , all the variables in Eq. (9) are material or beam properties that are constant for the scenario.

In order to discuss the stability of this control, Eq. (9) must be linearized about an equilibrium point and the eigenvalue of the resulting control matrix analyzed. This analysis has only been conducted for the proportional controller. Performing this stability analysis and linearize about the goal target potential gives the resulting stability requirement for CACC:

$$0 \leq K_P \leq 4.01 * 10^{-9} \quad (10)$$

Selecting a proportional gain that satisfies this constraint will result in a stable control for small deviations about the equilibrium point. Further numerical analysis is needed to validate this stability condition.

The second method of active charge control, EACC, applies control to the beam energy. The differential equation that governs this behavior is given by

$$\dot{x} = \begin{bmatrix} \dot{\phi_T} \\ \dot{E_{EB}} \end{bmatrix} = \begin{bmatrix} \frac{I_{EB}}{C_{sc}} \left(c \left[\exp\left(\frac{-(E_{EB} + \phi_T)}{a}\right) - \exp\left(\frac{-(E_{EB} + \phi_T)}{b}\right) \right] + A - B \exp(-C(E_{EB} + \phi_T)) - 1 \right) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ u \end{bmatrix}. \quad (11)$$

Except for the state vector x , Eqs. (9) and (11) are the same because only difference is what component the control is being applied to. Again, a P and PD controller were developed, but, through experimental investigations, it was determined that derivative control is not required and as such is excluded from the analytic study. To analyze the stability of the system, Eq. (11) is linearized and discretized. For CACC, the system was not discretized as the time for the charging dynamics is comparable to the control times. This is the not case for EACC: the target charges significantly faster than the control is applied. Analysing the eigenvalues of the linearized discrete system for results in the gain condition of

$$0 \leq K_P \leq 2. \quad (12)$$

Using any proportional gain that satisfies this condition results in a stable control for small deviations about the equilibrium point.

Two stable touchless active charge control feedback controllers have been developed and analytically proven to be stable for small deviations from the equilibrium charging point for select gains in a vacuum chamber environment. Year 3 will focus on incorporating the space environment into the charging equations and re-evaluating the stability conditions.

Thus far, analytical studies have focused on the use of broad beamed UV lamps rather than focused lasers, and both an analytical UV lamp model and a UV lamp MATLAB simulation model have been implemented as part of task 2.2.1. Now as the project reaches its final year, new and growing research directions have prompted the need for a dedicated analytical UV laser model. During year 2, the topic of UV charge sensing and control for differentially charged spacecraft has gained momentum, prompting a need for UV laser models that allow for targeted charge sensing and control. As discussed in J-1, the use of UV laser based methods overcomes multiple technical challenges faced by electron-beam methods, the most important being the effect of the electrostatic environment on the electron beam trajectory. By using a focused UV laser, individual components of a differentially charged spacecraft can be directly sensed, allowing for the differential charging of to be precisely mapped. Furthermore, using a UV laser alongside an electron beam for targeted active charge control enables techniques for mitigating or actively controlling the differential charging of such a spacecraft for applications like docking or de-tumbling. For these reasons, the addition of an analytical UV laser model will be a priority in year 3.

8.3.3 Closed-Loop Charge Control Experiments

Experiments were conducted in tandem with the development of numeric active charge control simulations. Year 1 had a focus on demonstrating the possibility of active charge control in a vacuum chamber environment, both with ideal sensing and more realistic remote sensing. These experiments and their results are described in C-6 and C-11.

This past year (year 2) focused more on performing more useful experiments. The first set of experiments were performed in collaboration with the Air Force Research Laboratory (AFRL) in their JUMBO

vacuum chamber and were used to validate the numeric simulations. These experiments are outlined in J-6. Both experiments for CACC and EACC were conducted; however, further analysis demonstrated that, while it is an effective method for touchlessly controlling the potential of target in a vacuum chamber environment, the current method of CACC is not applicable to a realistic charging with multiple spacecraft and the space environment. Fig. 9 shows how that increasing the beam current does not exclusively decrease the target potential. Beam current and target potential do not have a monotonic relationship in a realistic charging scenario; therefore, the linear PD controller would not be feasible for CACC as it is possible to end up in a region where increasing/decreasing the beam current does not drive the target to the desired equilibrium. A more complex, nonlinear control must be developed for CACC to be a viable method of touchless ACC in situ, but this is not necessary. Figure 9 shows that beam energy and target potential do have a monotonically increasing relationship and as such, the P controller should achieve the desired control in a realistic charging scenario. As such EACC is now the focus of the closed-loop charge control work.

Using the experiments conducted with AFRL and the numerical charging model described in Sec. 8.3.4, a comparison between the two was conducted in order to validate the charging simulations. Figure 10 shows this comparison for three charging scenarios.

Each scenario has an initial potential of -0.4 kV and a goal potential of -2 kV. The proportional gains (K_P) are $K_P = 0.6$, $K_P = 1$, and $K_P = 0.1$ to represent a slightly underdamped, overdamped, and underdamped scenario, respectively. In each case, the numerical simulations show the same overall behavior as the experiments. The slightly underdamped trial is the most similar with both lines being nearly on top of each other while the other two deviate slightly more but are still very similar. These inconsistencies are likely due to the inaccurate total electron yield (TEY) model used in the numeric simulations. If a more accurate TEY is developed, it can be incorporated into the numeric model, but, even with the slightly inaccurate model, the experimental results match the numeric results well, validating the EACC model for a vacuum chamber environment. With the numeric charging model validated, it can be used to explore realistic charging scenarios with a higher degree of confidence. Additional experiments were conducted using both energy and current control that are not shown here.

The experiments conducted at AFRL allowed for EACC and CACC to be explored with idealized sensing. Using an electrostatic voltmeter, accurate measurements of the target's potential were fed into feedback controller ever ≈ 1 s; however, this is not realistic for in situ applications. Because of this, remote sensing techniques were integrated into preliminary vacuum chamber experiments in C-11 during year 1. This allowed for active charge control to be explored in the ECLIPS vacuum chamber. In C-11, two methods for utilizing the secondary electron method (SEM) for remotely sensing a target's potential: the constant SEM (CSEM) and dynamic SEM (DSEM). For the CSEM, no additional control is required: the instrument searches the entire measurement space with a high accuracy. In contrast, the DSEM initially measures the entire measurement space with a low accuracy and as the control progresses, refines the measurement space and increases the accuracy. Both methods were shown to allow for EACC and were further explored in year 2. Building on this work from year 1, EACC is explored with an additional external bias of a photoelectron current and a simplified dynamic environment using remote sensing methods.

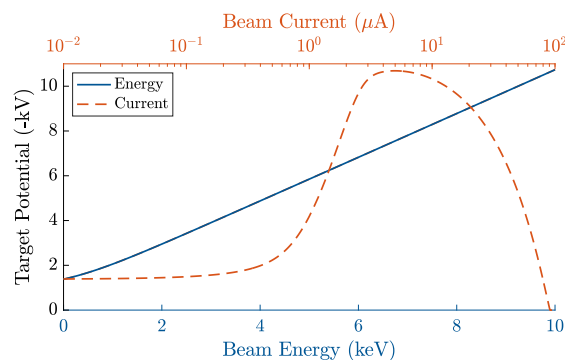


Figure 9: A comparison of the effects that electron current and energy have on the steady state potential of a target in a calm geostationary environment.

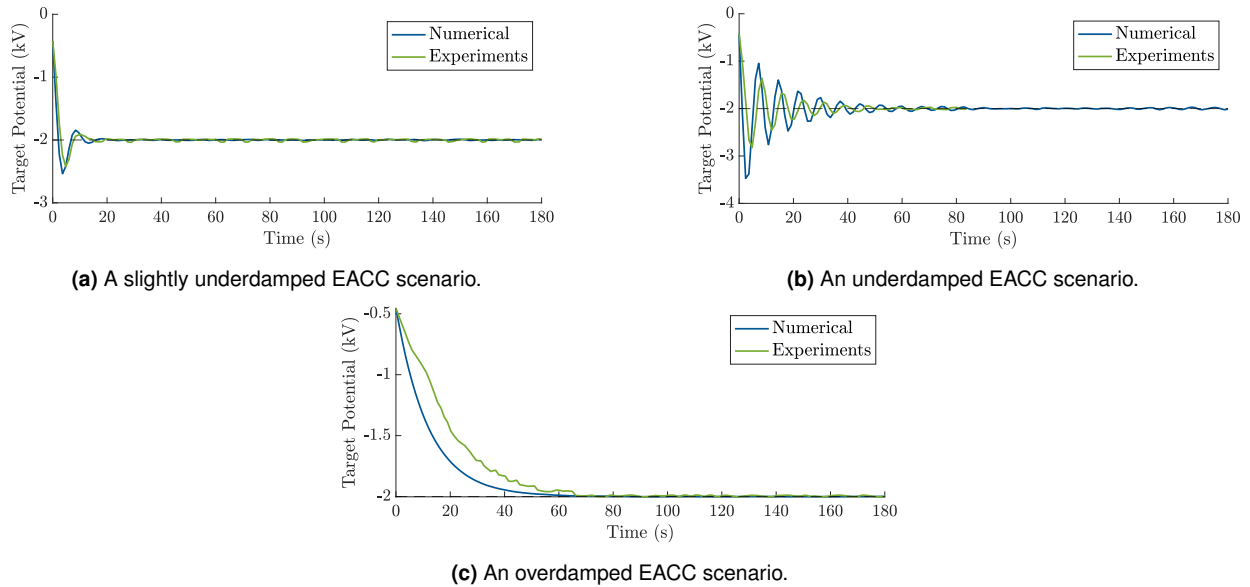


Figure 10: A comparison between experimental and numerical results using energy active charge control (EACC).

Using a VUV lamp, a photoelectron current is applied to the target, adding a positive current to the target. This allows the control to be explored when factors other than the electron impact the charging behavior of the target. Figure 11 shows EACC using both the constant and dynamic SEM when the target is exposed to a photoelectron current. Using both sensing methods, the desired goal potential of -2000 V

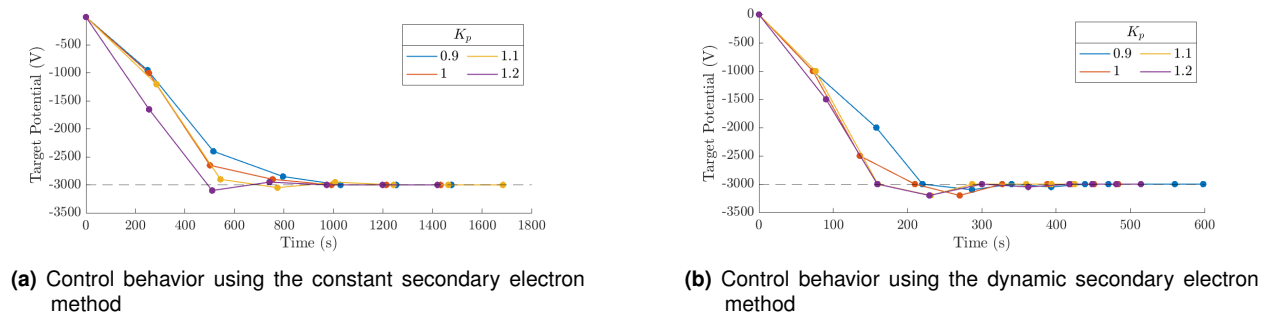


Figure 11: The charging behavior when using energy active charge control with the target exposed to a photoelectron current.

is achieved. The most significant difference between the two methods is the time it takes to reach the steady state behavior. Using the CSEM takes significantly longer than using the DSEM. This makes sense as the CSEM searches the entire sample space with high accuracy for each measurement, while the DSEM repeatably refines the search, allowing it to measure the target's potential much faster. However, regardless of the chosen method, both drive the target to the desired potential

Using the VUV lamp, a dynamic environment can be explored as well. The experiment begins with the target irradiated by only the electron beam. After the target converges to the desired potential, the VUV lamp is turned on, simulating a target coming out of the Earth's shadow. With this additional photo-electron current, the charging behavior changes and the control must re-converge to the goal potential. These experiments are preformed using only the remote sensing methods.

Figure 12 shows the charging behavior of the target when controlled by EACC in dynamic plasma environment. When using the CSEM, once the goal potential of -3 kV is achieved and the VUV lamps

are activated between 940 s and 1200 s. This additional current increases the potential to ≈ -1 kV. The control is able to accurately measure this new potential and drive the target back to -3 kV for all tested gains. When using the DSEM, the behavior is different. After the goal potential is reached and the photo-electron current added, the target potential is not properly measured: according to the DSEM, the target is at -2.9 kV when in reality the target potential is closer to -1 kV. This occurs because the DSEM, once the target reaches the goal potential, does not measure the entire experimental space. It only measures ± 100 V. Interestingly, even with an inaccurate measurement, the target potential is still driven back to the goal potential. The control measures that the target potential is too positive and continually increases the beam energy as much as possible (in this case 100 V) until an accurate measurement can be achieved.

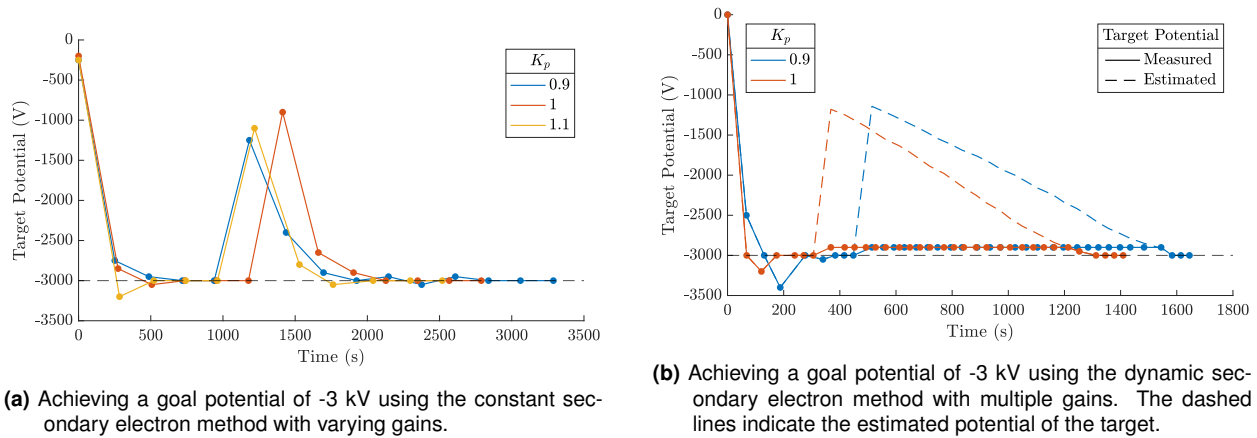


Figure 12: The charging behavior of EACC in a dynamic plasma environment.

Even though both methods function properly in a dynamic plasma environment, each has their drawbacks. Using the CSEM is very slow, taking 1000 s to converge in a simplified scenario and the DSEM not being able to properly measure the entire sample space. Because of this, a dual method of sensing has been explored: combining the x-ray method and secondary electron methods. The x-ray method is able to quickly measure the entire sample space, so using an unrefined measurement to seed the more accurate secondary electron methods results in a fast and accurate method for sensing. This method is outlined in C-19. This "dual method" has been used experimentally in experimental testing; however, future work must be conducted to refine this method to make it viable for realistic charging scenarios. This will be completed in year 3.

8.3.4 Closed-Loop Charge Control Simulation

Developing this simulation framework has been a focus of year 2. Using the charging equations outlined in Sec 8.3.2, closed loop charge control simulations are preformed in MATLAB. Some of these simulations are shown in Fig. 10, however these are tailored to accurately represent the experimental environment of the JUMBO vacuum chamber. This task still uses an environment where the electron beam is the dominate current, but uses more realistic target and beam properties, like capacitance and emitted current. A simulation frame work has been developed for both CACC and EACC in J-6.

Using only a proportional controller, stable CACC is achieved, however it still takes over a minute for the servicer to converge to the desired value. A proportional and derivative (PD) control was then implemented and two trials are shown in Fig 13. With the inclusion of derivative control, the system is able to converge to the desired potential much faster.

With PD controller, there are two gains that can be tuned. More in depth tuning would allow for even faster convergence times. With the discovery of EACC being a more viable method for contactless target charge control, development of CACC is no longer a priority.

Implementing EACC using numeric simulations demonstrates that proportional control only is sufficient to achieve fast charge control of a target's potential. Figure 14 shows that, with a gain of 1, the control converges after one time step for multiple charging scenarios, given an ideal set up.

An uncertainty analysis for the parameters of EACC was also preformed and presented in J-6. It was

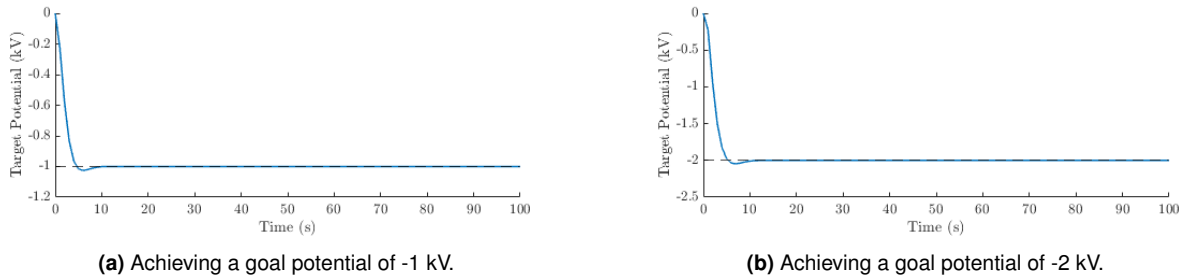


Figure 13: The charging behavior when using PD current active charge control.

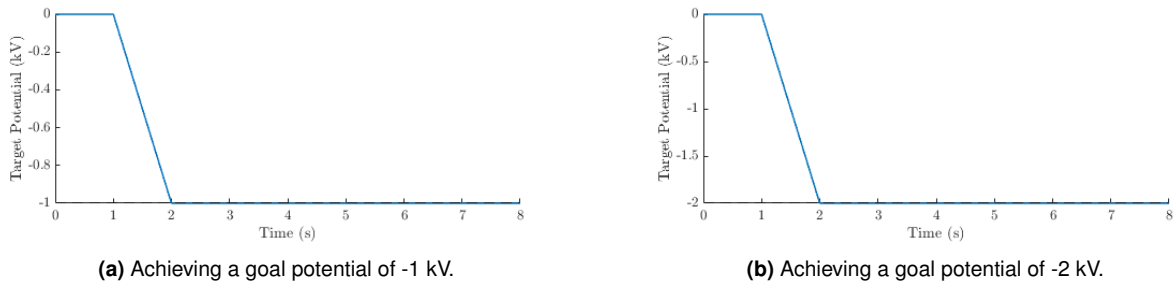


Figure 14: The charging behavior when using proportional energy active charge control with a gain of 1.

demonstrated that realistic uncertainty in target material properties and beam current errors do not significantly affect the charging behavior of the target. This means that, in a vacuum chamber environment, EACC is robust to uncertainties in the most important parameters. With the linear proportional controller proven to be stable and robust in a vacuum chamber environment for small deviations, the next step is to apply EACC to a more realistic environment. Implementing EACC numerically for a more realistic plasma environment and with both a servicer and target will be achieved in year 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.
- C-14 K. Champion and **H. Schaub**, "Passive Potential Sensing in Cislunar Space: Simulations Using Nascap-2k and SPIS," AAS Space Flight Mechanics Meeting, Kauai, HI, January 19–23, 2025.
- C-15 A. Haft and **H. Schaub**, "Increasing the Electrostatic Force Between Spacecraft Using a Pulsed Electron Beam," AAS Space Flight Mechanics Meeting, Kauai, HI, January 19–23, 2025.
- C-16 A. Haft, E. Weber and **H. Schaub**, "Characterizing Field Emission in Electrostatic Tractor Operations for Geosynchronous Orbit Debris Removal," 9th European Conference on Space Debris, Bonn, Germany, April 1–4, 2025
- C-17 K. Champion and **H. Schaub**, "Cislunar Touchless Potential Sensing Through Barriers," Applied Space Environments Conference, Houston, TX, May 5–8, 2025
- C-18 K. Champion, A. Haft and **H. Schaub**, "Multi-Spacecraft Wake Formations," Applied Space Environments Conference, Houston, TX, May 5–8, 2025
- C-19 J. D. Walker, S. Hampl and **H. Schaub**, "Development of Experimental Methods for Active Charge Control Using Combined Remote Sensing Methods," Applied Space Environments Conference, Houston, TX, May 5–8, 2025
- C-20 S. Hampl, J. D. Walker and **H. Schaub**, "Analytical Investigation of Two-Vehicle Active Charge Control for Experimental Validation," Applied Space Environments Conference, Houston, TX, May 5–8, 2025

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*, Vol. 61, No. 5, Sept.–October, 2024, pp. 1258–1271.
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*, Vol. 52, No. 11, 2024, pp. 5402–5413.
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- J-4 K. Champion and **H. Schaub**, "Electrostatic Lenses for Laboratory Spacecraft Wake Generation," *IEEE Transactions on Plasma Science*, Vol. 53, No. 4, April 2025, pp. 649–660.
doi:[10.1109/TPS.2025.3547749](https://doi.org/10.1109/TPS.2025.3547749)
- J-5 A. Haft and **H. Schaub** "Spacecraft Electrostatic Tractor Using A Pulsed Electron Beam," In preparation.
- J-6 J. Walker and **H. Schaub** "Electron Gun Based Active Charge Control of a Vacuum Chamber Target Surface" In preparation.

9 Project Conclusions and Outlook

The project is progressing on schedule and on budget. Strong graduate student researchers have been lined up for the final year to support the numerical modeling, the experimental research, but also look to integrate the charging control and charging physics behavior into our open-source Basilisk spacecraft simulation framework.

Year 2 provided exciting progress matching up the first vacuum chamber based active charge control experiments with numerical models. The e-gun beam energy charge control method has been found to work effectively and more robustly than we expected. We plan to use our modeling tools to fully analyze the charge control behavior during the final project year.

In the final project year we expect to wrap up our research goals and finish writing associated conference and journal papers. The ECLIPS chamber is expected to be under heavy use.

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