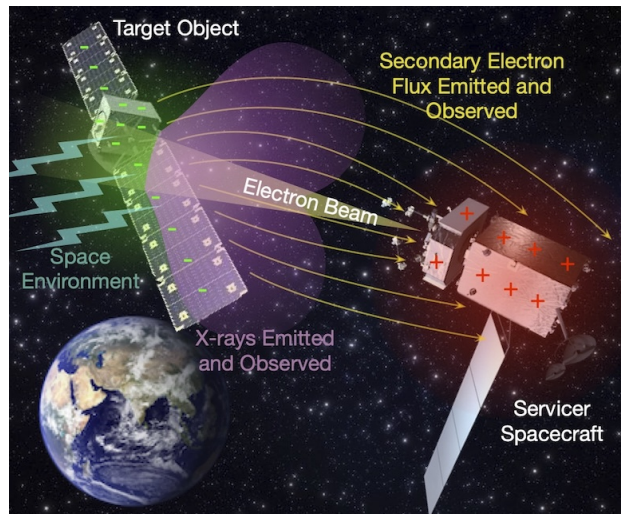


ANNUAL REPORT - 3RD PROJECT YEAR

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Touchless Charge Control of Neighboring Spacecraft in Geostationary and Cislunar Space



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1 Project Overview

The 3-year research study completed its third project year. However, \$27,466 of year 3 funding were not provided during the 3rd project year and has been provided as a 1 year extension. Thus, the project now extends into a 4th year where partial fall 2026 support is available for a graduate student to finish up related journal paper writing.

The project 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 3 achieved exciting progress in doing online (automated) charge sensing. Prior work from another AFOSR grant had solutions that were offline and required humans to process the sensor data. This has now enabled us to demonstrate forms of touchless charge control in our vacuum chamber. Further, prior work only looked at relatively low potentials. The online algorithm and sensor solution has been modified to function at potentials above the 2-3kV threshold that we identified during the last year with the prior method.

The project studied using UV- and Electron-controlled differential charging and evaluated how this can improve electrostatic detumbling. Further, novel means to estimate the potential from relative motion in high-charging regimes where Langmuir probes fail have been investigated.

Other notable progress this year includes a completed study of a power-constrained pulsed electron-beam architecture, showing that pulsing the beam at an optimal duty cycle can substantially increase electrostatic tractor force and reduce re-orbit time relative to continuous-beam operation at the same average power. A related study extended the project's charging models to bi-Maxwellian plasma environments, showing that hot, low-density substorm populations can introduce additional stable charging equilibria and equilibrium-branch transitions beyond what continuous single-Maxwellian modeling predicts. A third study incorporated coupled servicer-target proximity effects, including sheath overlap and electron recollection, into the project's charging models.

On the experimental side, a miniature floating electron gun was designed, built, and integrated onto a spacecraft analog, enabling the first fully coupled, two-object floating charge control experiments planned for this project. High-potential measurement biases in both the X-ray Method and the Secondary Electron Method were also identified and corrected, allowing both remote sensing techniques to be integrated into autonomous closed-loop charge control for the first time. Finally, the spacecraft charging models developed over the course of this project were implemented as new modules in the open-source Basilisk astrodynamics framework, enabling full mission-level simulation of touchless charge control scenarios.

The work of this project is being written up in numerous conference papers and journal papers. This report outlines the latest scientific contributions that this project has yielded.

2 Related Year 3 Travel

Project related research was presented at the AIAA SciTech in Orlando, Florida during January 12–16, 2026. Two students traveled to this conference to present their work on charge sensing and UV controlled differential detumbling.

Additionally, a student traveled to the Astrodynamics Specialist Conference, Whistler, Canada, July 26–30 2026. This paper covers electrostatic momentum management while tugging a tumbling debris object.

The conference paper list in section 9.4.1 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 2025 to Aug. 15 2026 is:

- Amy Haft, a Ph.D. who started in the fall of 2023. She was fully supported on this AFOSR grant through Feb. 2026. Then she won a NASA FINESST award. 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 leading studies on absolute potential sensing in high-charging conditions where existing method fail, exploring the effects of differential charging on charge sensing and active charge control, and led the purchase of the new x-ray sensor improving charge sensing performance.
- Sebastian Hampl, a Ph.D. student doing research on advancing the electrostatic tractor concept experimentally. He has designed and built a floating electron gun which will serve as the basis for coupled two-object charging experiments and ultimately two-object charge control experiments in the future.
- 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. She completed her Ph.D. in summer 2026 and is now no longer supports this project.
- 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 including leading active charging experimental research.
- Leah Kiner, a Ph.D. student doing her dissertation work on the Basilisk dynamics engine, supported year 3 for 2 semesters. She developed a Basilisk spacecraft charging module suitable to time-varying charging behavior.
- Daniel Huterer Prats, a Ph.D. student doing research on using Basilisk for autonomous spacecraft scheduling, supported this AFOSR project for one semester. He developed a Basilisk module that evaluates equilibrium charging conditions between two space objects.
- Landon Holligan, an undergraduate researcher who supported Kaylee's research on cislunar spacecraft charging environment. He was a member of the University of Colorado Discovery Learning Apprenticeship (DLA) program in 2025–2026 academic year.
- Ian Youngblood, also an undergraduate DLA student in 2025–2026 academic year. He supported Amy Haft's research on the modeling charged neighboring space objects in SPIS.

In project year three we have supported on average about 4 GRAs, along with two undergraduate researchers. As the PI Dr. Schaub is not charging summer salary to this project while being the department chair, the associated funds were used to support two 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. In year 3 our received budget was short \$27,466. These remaining funds were sent to CU in July 2026 with a one-year project extension to spend this out. 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 3 budget expectations and expenses are illustrated in Figure 1. The budgets shown in this table are the originally projected budgets. We are showing about \$17,194 remaining after the \$27,466 are included. These remaining funds will partially support a graduate researcher finish up publications on project related work.

The third project year supported on average about 4 graduate research assistants, depending on the semester. The project supported graduate research assistants to include the numerical evaluation of charged forces and torques between two space objects into the open-source Basilisk software.

	Budget	Actual	Balance
Salaries			
Faculty Salary	\$ 59,554.00	\$ 0.00	\$ 59,554.00
GRA Salary	\$ 286,526.00	\$ 307,795.00	\$ (21,269.00)
Benefits	\$ 50,813.00	\$ 59,397.00	\$ (8,584.00)
Salary Totals	\$ 396,893.00	\$ 367,192.00	\$ 29,701.00
Travel			
Travel Totals	\$ 27,023.00	\$ 58,926.00	\$ (31,903.00)
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	\$ 4,500.00	\$ 255.00	\$ 4,245.00
Misc. Equipment	\$ 13,500.00	\$ 1,813.00	\$ 11,687.00
Operating Totals	\$ 18,000.00	\$ 2,068.00	\$ 15,932.00
Tuition/Stipends			
Tuition Totals	\$ 113,625.00	\$ 93,811.00	\$ 19,814.00
Expense Totals	\$ 564,541.00	\$ 543,152.00	\$ 21,389.00
Indirect Totals	\$ 249,683.00	\$ 253,877.67	\$ (4,194.67)
Year 3 Project Budget	\$ 814,224.00	\$ 797,029.67	\$ 17,194.34

Figure 1: Comparison between budgeted and actual expenses up to year 3 end in August 15, 2026.



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

5 Accomplishments

The current project schedule is illustrated in Figure 2. Year 3 completed all three original research thrusts and produced several results beyond the original proposal scope.

On the potential sensing side, touchless charge sensing moved from an offline, human-processed technique to a fully autonomous, online capability, and was extended from the low-potential regime tested in

prior years to targets above 2–3 kV. This required identifying and correcting two previously unknown high-potential failure modes: spurious Bremsstrahlung spectra generated by secondary/backscattered electrons striking the X-ray detector itself (resolved with a biased deflecting grid), and a systematic bias in the Secondary Electron Method caused by non-ideal RPA grid fields at high potentials (resolved with a new “first significant drop” processing method). Both corrections are documented in Sec. 9.1.6 and are now integrated into closed-loop control.

A new research direction was also opened in Year 3: estimating absolute spacecraft potential from electrostatically perturbed relative motion, fusing trajectory/attitude perturbation measurements with touchless relative-potential sensing to recover both spacecraft’s absolute potentials without a Langmuir probe. Preliminary filter results and an initial validity-regime mapping support the feasibility of this approach; a conference and journal paper are in preparation.

On the hardware side, a miniature floating electron gun was designed, built, and integrated onto a spacecraft analog, and characterized up to 10 keV beam energies, currents from nA to $\sim 100 \mu\text{A}$, and divergence half-angles down to 2° . This closes a capability gap that prevented fully coupled, two-object charging experiments in prior years, and first positive-potential X-ray sensing results were demonstrated on this platform.

Three analytical/numerical studies advanced the environment-modeling thrust: a power-constrained pulsed electron-beam architecture showing up to an order-of-magnitude force increase and roughly twenty-fold reduction in re-orbit time relative to continuous-beam operation (published, J-8); a bi-Maxwellian charging study identifying multi-root, material- and environment-dependent equilibrium jumps (submitted, J-10); and a coupled servicer-target study quantifying sheath-overlap and electron-recollection effects on force and equilibrium selection (submitted, J-11).

Closed-loop active charge control experiments incorporated external (photoelectron) currents and non-normal beam incidence into the stability analysis, refined the SEM Dual sweep method, and validated numerical models against ECLIPS chamber data across incidence angle, remote sensing, and photoelectron effects. Numerical modeling of the AFRL JUMBO chamber charging experiments was completed and is being written up (J-6). Finally, the spacecraft charging code developed over the project was implemented as two new Basilisk modules (Equilibrium and Dynamics), enabling full mission-level simulation of touchless charge control scenarios. Finally, the X-ray sensor purchased in Year 2 was used for experiments on UV illumination to control absolute and differential spacecraft charge.

Results from all research directions were presented at AIAA SciTech (Orlando, Jan. 12–16, 2026). Further, four journal papers were published in Year 3 as well as two journal papers submitted and four in preparation. The full publication list can be found in Sec. 9.4.

6 Impacts

Development of the principal discipline(s) of the project: Year 3 demonstrated for the first time, closed-loop automated touchless charge sensing and control at kilovolt-level potentials operating fully autonomously rather than requiring human-in-the-loop data processing bringing the technology closer to in-situ implementation.

Separately, a study of field emission at representative ~ 10 m servicer-target separations showed that arcing risk remains negligible even at the high potentials produced by pulsed charging, and that feedback control compensates for the added field-emission current without loss of stability. This directly informs the safety envelope for close-proximity electrostatic operations.

Finally, the completed floating electron-gun spacecraft analog provides the AVS Lab with a ground-test capability for fully coupled, two-object floating charge control that did not previously exist, and that is required to experimentally validate the coupled charging models developed in this grant.

7 Changes

Project year 3 saw progress across all three of the proposed research thrusts as well as major developments beyond what was originally proposed. 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.

As discussed in the project year 2 report, the frequency modulation approach was found to be infeasible

with current sensor technology as the sensor takes too long to acquire a signal. Instead the project has expanded the work studying pulsed charging solutions, started the development of two-body floating charge control, and explored methods of enabling absolute potential measurement in environments where the Langmuir probe fails. Further, major progress has been made on closed-loop active charge control.

Overall, all three thrusts of the project have been explored or completed by the end of year 3, and considerable additional work exceeding the original proposal scope has also been completed. The supplemental year 4 funding will be used to document and publish the aforementioned two-body floating charge control.

8 Changes

Project Year 3 completed all three proposed research thrusts and produced several results beyond the original proposal scope, building on the shift identified in the Year 2 report away from frequency-modulation sensing toward pulsed-beam sensing, absolute potential sensing, and two-body floating charge control.

An unplanned hardware development was the floating electron-gun spacecraft analog (Sec. 9.2.5), built to enable fully coupled two-object charging experiments that the originally proposed chamber-mounted electron-gun configuration could not support.

A further extended result is the absolute potential sensing effort described in Sec. 9.1.7, motivated by a finding not anticipated in the original proposal: that Langmuir probes are unlikely to remain valid at the kilovolt-level potentials this project's actuation concepts require. The resulting relative-motion-based estimation approach and other high-potential charging techniques were not part of the original research plan but are a focus heading into Year 4.

Separately, an administrative change affects project timing rather than scope: \$27,466 of Year 3 funding was not disbursed during the Year 3 period. It was provided in summer 2026 along with a one-year no-cost extension, so a portion of these funds, along with roughly \$17,194 in remaining Year 3 balance, will carry into a partial Year 4 to support graduate student salary while finishing the journal papers listed in Sec. 9.4. This does not represent new research scope as all three thrusts are considered scientifically complete as of the end of Year 3, and Year 4 activity will focus on publication rather than new experimentation.

9 Schedule and Project Scope Update

The project schedule is illustrated in Figure 2. The proposal tasks are grouped by project thrusts and colored by their status. The technical research progressed very well through Year 3, with all three original thrusts completed and several results produced beyond the original proposal scope.

Building on the discovery in Year 2 that multiple charging equilibria are possible under a single-Maxwellian plasma environment, Year 3 extended this analysis to bi-Maxwellian plasma environments, showing that hot, low-density substorm populations can introduce additional stable equilibria and equilibrium-branch transitions beyond what was previously characterized. Power-constrained pulsed charging, identified in Year 2 as a promising but unplanned research direction, matured substantially in Year 3, with a full duty-cycle optimization study now published (J-8).

The project continued to use the ECLIPS chamber for a range of charge-control experiments, including active charge control of an electrically isolated object subjected to a charging bias through the photo-electron stimulator, and characterization/integration of the new high-speed X-ray detector.

Regarding analytical and numerical modeling, strong progress was made matching numerical charging models against the AFRL JUMBO chamber experiments from the prior year, and analysis has begun on the more recent ECLIPS chamber experiments, where touchless charge sensing is evaluated alongside photo-electron disturbances. High-potential failure modes affecting both the X-ray Method and the Secondary Electron Method were identified and corrected during this work (Sec. 9.1.6), enabling both methods to be integrated into autonomous closed-loop control for the first time.

The following sections provide summary discussions on each research thrust area. Where appropriate, we point to the full papers that have been written on this research and are available to view online in the Project Publication section 9.4.

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

9.1.1 Floating-Potential Modeling and Experiments

A central requirement for experimentally evaluating pulsed electron-beam sensing is the ability to generate and measure a genuinely floating spacecraft potential. In this configuration, the test object is neither grounded nor held at a prescribed voltage; instead, its potential evolves in response to the net current produced by electron-beam emission or impact and other chamber currents. Because the capacitance of a laboratory-scale spacecraft analog is small, its potential can change too rapidly for the charging transient and the disturbance caused by the sensing beam to be resolved directly.

Work in previous years of this grant investigated the use of an external RC network to increase the effective capacitance and slow the charging response.¹ A coupled circuit model was developed and validated experimentally, showing that the added capacitance and charging-path resistance can extend the potential transient to measurable time scales. The study also showed that the target and external capacitor cannot always be treated as a single lumped capacitance because their potentials may evolve independently. A simpler configuration using only an external capacitor was ultimately demonstrated to slow the charging response substantially, thereby meeting the primary objective of enabling transient charging measurements, although it does not reproduce the full current balance of a space environment.

For this project year, the newly developed spacecraft analog with an integrated floating electron gun, described in Sec. 9.2.5, provides a complementary approach in which electron emission drives the object to a positive floating potential. The system also includes a high-voltage capacitor intended to increase the effective capacitance and extend the charging time scale, although this configuration has not yet been experimentally validated. Together, these developments provide the experimental platform required to test whether pulsed sensing can measure a floating potential while introducing less disturbance than continuous-beam sensing, as discussed in Sec. 9.1.2.

9.1.2 Reducing Electron-Beam Disturbance

A central challenge in remote electric-potential sensing in space is that the sensing electron beam does not merely observe the target spacecraft potential, but also perturbs it. In the floating case of interest, the beam imposes an artificial current on the target and can therefore shift the object away from its natural equilibrium potential. This effect is undesirable because the measured potential should represent the undisturbed floating potential as closely as possible (see J-2). Earlier analytical work therefore examined whether pulsed electron-beam operation could reduce this disturbance while still producing a usable sensing signal (see C-9).

The motivation for pulsing is straightforward: a lower time-averaged beam current reduces the charging disturbance, while the instantaneous beam current during the pulse can remain high enough to generate measurable X-rays or secondary electrons. For on-off pulsing, the effective beam current is approximately reduced according to $I_{EB,eff} \approx d I_{EB}$, where d is the duty cycle. Analytical results further showed that pulsing can improve measurement conditions by separating the sensing signal from background noise in time or frequency space, and by allowing different beam settings to be used for different sensing objectives. A schematic illustration of the pulsed-beam concept is shown in Fig. 3.

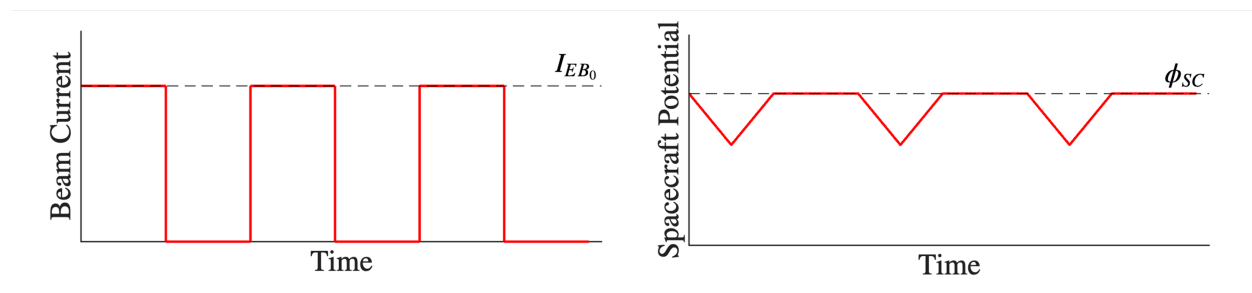


Figure 3: Conceptual illustration of electron-beam pulsing to reduce the time-averaged disturbance current while retaining sufficient instantaneous signal for remote potential sensing.

To date, however, this concept has not yet been tested experimentally under truly floating conditions. In previous experiments, negative floating potentials were generated by electron-beam irradiation, but a second electron gun was not available to independently perform the sensing measurement. In other sensing experiments, the target potential was prescribed using a high-voltage supply, which eliminated the effect of beam-induced disturbance but also removed the floating-potential behavior that is central to the present problem (see C-9). As a result, the analytical predictions for pulsed sensing have not yet received a direct experimental test on a freely floating target.

The floating electron-gun system developed in Sec. 9.2.5 now provides the missing experimental capability. By emitting electrons from an electrically floating object relative to the vacuum chamber, this system allows the object to charge to a naturally floating positive potential. This creates an ideal test case for pulsed sensing because the object potential is no longer prescribed externally and the disturbance introduced by the sensing beam can be assessed directly. In addition, sensing of positively charged has not yet been explored in previous work. The secondary-electron sensing approach is not expected to work in this regime as low-energy secondary electrons are recollected by the positively charged object rather than escaping to the sensor. The X-ray method, in contrast, is expected to be equally applicable to negatively and positively charged objects. For a positively charged target, the sensing beam can operate at a lower initial energy because the electrons are accelerated toward the target, whereas for a negatively charged target, the beam energy must exceed the retarding potential barrier. Therefore, as a first step, positive X-ray sensing for an object with a positive potential was shown experimentally as illustrated in Fig. 4.

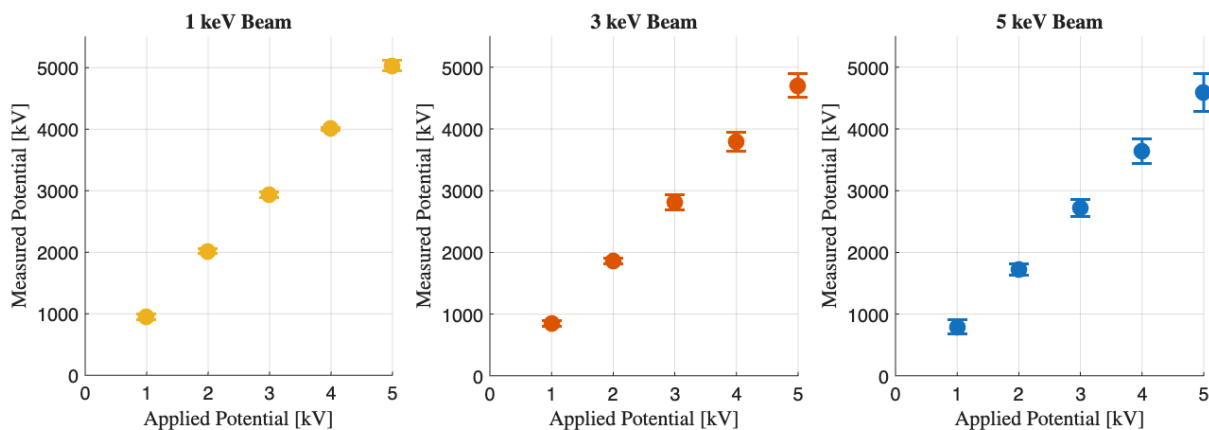


Figure 4: Sensing of positive target potentials between +1 and +5kV using electron-beam energies of 1, 3, and 5 keV. Error bars represent the uncertainty associated with different assumed noise floors when inferring the target potential from the X-ray spectrum.

These developments connect the earlier analytical pulsing study directly to the new experimental campaign. The planned experiments will use the spacecraft analog with the floating electron gun to generate a naturally floating positive potential and evaluate how strongly the sensing beam perturbs that potential. Continuous-beam and pulsed-beam X-ray measurements will then be compared with an independent voltage-divider measurement. The voltage divider is an invasive reference method because it draws a small bleed current from the floating object while converting the high potential to a measurable low-voltage signal. This comparison will provide the first direct experimental test of whether the analytical predictions for pulsed sensing hold and whether pulsing can enable minimally invasive potential sensing in space.

9.1.3 Frequency Modulation

As discussed in the year 2 report, initial testing and calibration showed that even with a new high-speed silicon drift X-ray detector, signal acquisition rates remained too slow for the intended frequency modulation techniques, and research has shifted away from frequency modulation. Still, the new X-ray detector has been put to use on multiple charge sensing and active control experiments. The improved noise floor and acquisition speed of the detector has enabled improved active charge control using Bremsstrahlung X-rays

and high-potential charge sensing, as discussed in Sec. 9.3.2 and 9.1.6.

9.1.4 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, both in what components can be sensed and where the touchless sensing emissions can be measured from. This leads to a time varying optimal charge sensing problem under uncertainty that requires novel charge inspection techniques. Preliminary work has begun on formulating this charge sensing problem as a belief space Markov Decision Process (MDP), and preliminary results are expected by the end of year 4.

The measurement of potentials over time is also being explored through the use of relative motion to estimate absolute potentials over time in high-charging environments, as discussed in Sec. 9.1.7. Results from the time varying potential estimation work developed in C-8 are being used to inform filter design to improve estimation of time-varying absolute potentials.

9.1.5 Challenges in Absolute High-Potential Sensing

The touchless charge-sensing techniques developed in this project and under prior AFOSR grants provide information on the relative potential between two spacecraft and require knowledge of the absolute potential of one spacecraft to fully resolve the charging state of both objects. Previous electrostatic actuation concepts have generally assumed that the servicer potential relative to the ambient plasma can be measured using a boom-mounted Langmuir probe, after which the absolute target potential can be reconstructed from the measured inter-spacecraft potential difference. A Langmuir probe infers spacecraft potential from the inflection point of the measured ambient-plasma current-voltage curve.² However, this approach may not remain valid at the kilovolt-level potentials relevant to electrostatic tractors and active charge control.

Langmuir probes suffer a systematic failure mode in the high-energy, low-density plasma environments present in GEO and cislunar orbit, where the Debye length, λ_D , can substantially exceed realistic boom lengths. At large Debye lengths and high spacecraft potentials, the probe may remain deep within the spacecraft's electrostatic sheath rather than sampling the undisturbed ambient plasma, biasing both the inferred spacecraft potential and the measured plasma parameters.² Recently developed directional-probe techniques can detect and partially correct this bias using the divergence between two oppositely facing probe halves.³ However, these corrections are limited to sheaths with negligible photoemission currents and cannot accurately recover plasma parameters when the probe is deeply embedded within the spacecraft sheath.³ Spacecraft in GEO and cislunar orbit also spend much of their time in sunlight, where photoemission further limits the applicability of these corrections. In addition, kilovolt-level spacecraft potentials increase the sheath extent and therefore the boom length required to reach sufficiently undisturbed plasma.⁴

These limitations have motivated an ongoing review of relative and absolute spacecraft-potential sensing methods. The review examines the expected operating ranges and limitations of Langmuir and emissive probes, retarding potential analyzers, natural and actively generated X-ray measurements, space-weather-based estimates, and dynamics-based inference. Particular attention is given to whether these methods remain practical at high potentials, where extended sheaths, long booms, large voltage sweeps, low ambient particle fluxes, and measurement-induced disturbances may limit conventional diagnostics. This work remains in progress, but it has reinforced the need for alternative techniques that can recover absolute spacecraft potentials in regimes where Langmuir probes are unreliable. This need directly motivates the dynamics-based estimation and filtering approach described in Sec. 9.1.7, which combines electrostatically perturbed relative motion with touchless relative-potential measurements to estimate the absolute potentials of both spacecraft.

9.1.6 Remotely Sensing Large Potentials

Prior work supported by AFOSR grant FA9550-20-1-0025 developed techniques to remotely sense the electric potential of a conducting spacecraft. These methods have been extensively validated in a vacuum chamber environment; however, only low target potentials (smaller in magnitude than 3kV) have ever been

tested. A goal of this proposal is to integrate remote sensing into active charge control experiments, which require potentials larger than -3 kV. During this investigation, it was discovered that both the X-ray Method and Secondary Electron Method (SEM) can not properly measure high potential objects: the error in the SEM increases with target potential while the X-ray Method eventually fails entirely. These concerns had to be addressed before the remote sensing methods can be integrated for closed-loop control experiments.

The inaccuracies in each sensing method are caused by separate phenomena. For the X-ray Method, high potentials could not be measured properly. This was found to be attributed to additional X-ray spectra generated due to electron impacts on the X-ray detector itself. As electron beam electrons impact a charged target, Bremsstrahlung X-rays are emitted and measured by the detector. However, these electron impacts also generate secondary and backscattered electrons. These electrons are accelerated away from the target and impact the grounded X-ray detector where they generate additional Bremsstrahlung X-rays. At higher potentials, these additional spectrum dominate and prevent the target from being accurately measured. Figure 5 shows the measured X-ray spectrum for a -4 kV target along with three theoretical Bremsstrahlung spectra.

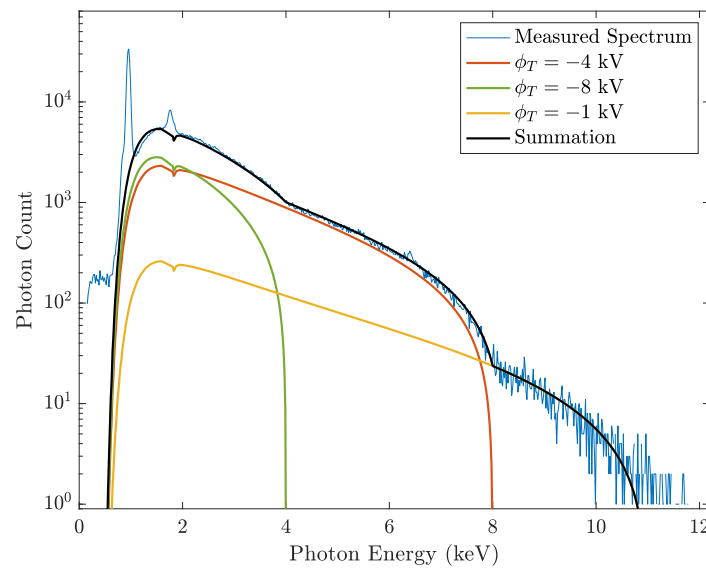


Figure 5: Measured and theoretical Bremsstrahlung spectra for a -4 kV copper target irradiated by a 12 keV electron beam

It can be seen in Fig. 5 that there are two “knees” corresponding to the three separate spectra. For this trial, $\phi_T = -4$ kV is the spectrum generated by the electron beam radiation. The next spectrum with $\phi_T = -8$ kV, is generated by 4 keV electrons impacting the ground grid of the X-ray detector. This 4 keV electron population is secondary electrons emitted from the target with low energy and subsequently accelerated towards the grounded detector. The third spectrum corresponds to ϕ_T and is caused by 11 keV electrons impacting the X-ray detector. This corresponds to the backscattered electron population. Backscattered electrons can have energy up to the electron beam energy, 12 keV, but the emission also has an angular dependence: 12 keV electrons are emitted directly back at the electron gun. Backscattered electrons with energies of 11 keV or less have a large enough emission angle to impact the X-ray detector and be measured. This behavior is seen using across every tested combination of target potential, electron beam energy, and surface material.

Because these corrupting spectra are caused by electron impacts on the X-ray detector, a charged deflecting grid is added to the experimental setup to eliminate these spectra. By placing the grid between the target and detector and maintaining an electric potential of $\phi_{\text{grid}} = qE_{\text{beam}}$, secondary and backscattered electrons are not energetic enough to pass the electric field and impact the detector. Figure 6 shows the successful removal of these two additional spectrum. With the deflecting grid included, the resulting measurements only consist of the expected characteristic and Bremsstrahlung spectra, allowing for proper

measurements.

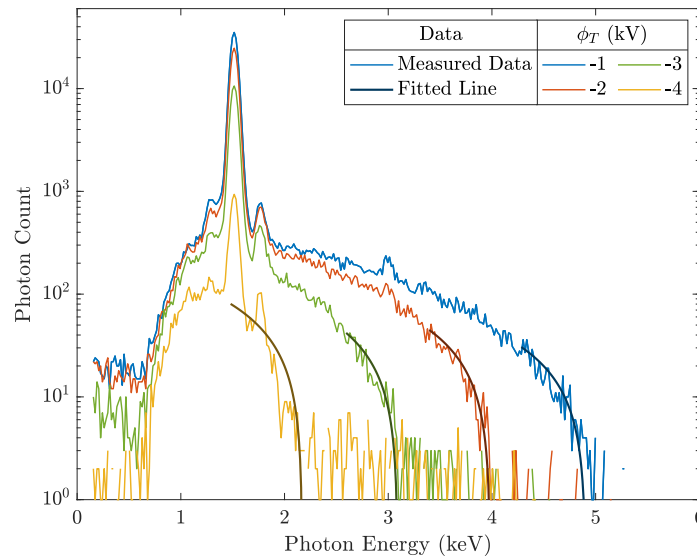


Figure 6: The measured X-ray spectra with a -5 kV conducting grid in front of the X-ray detector

The SEM also has increased error when measuring target potentials. Figure 7 shows the measured SEM data for a -500 V and -5 kV target irradiated by a 7 keV electron beam. A retarding potential analyzer is employed to measure the secondary electron currents and generate the required current vs energy figures. For these experiments, “grid” refers to the internal conducting grid of the RPA.

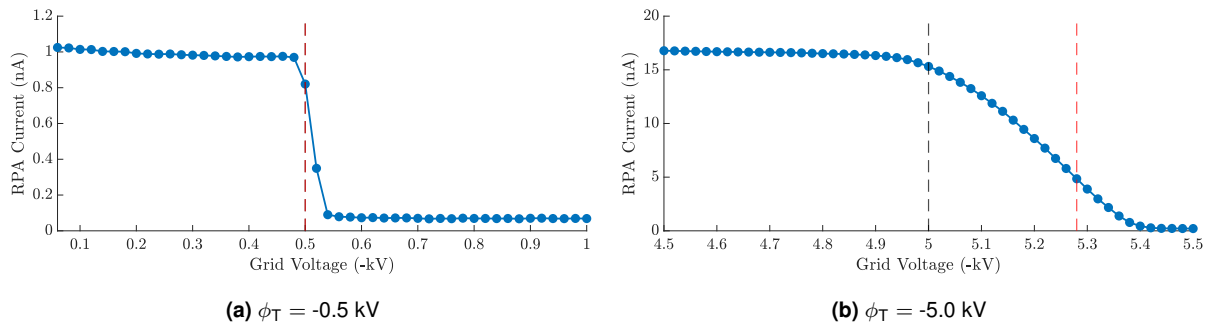


Figure 7: The measured secondary electron energy spectra for different target potentials.

To determine the energy of electrons using the SEM, the numerical derivatives are computed and the largest value is taken to correspond to the energy of impacting electrons. However, from Fig. 7, the black line indicates the target's potential and the red line indicates the largest derivative. For the -500 V target, these lines perfectly overlap with a 20 V step size. However, as the target potential increases, the red lines trends to larger grid voltages. At -5 kV, the largest tested potential, the largest derivative occurs at -5.28 kV, 280 V larger than the prescribed value. At these higher potentials, instead of getting the expected step function-like behavior, the measured secondary electron current gradually decreases, yielding a continuous spectrum of currents. The upshot of this is, the electron energy no longer corresponds to the largest derivative. Instead, this value is indicated by the start of the monotonically decreasing section of the spectrum.

This extended spectrum occurs because the grid of the RPA does not generate a uniform planar electric field. Each wire of the mesh is at a constant potential V_{grid} , but the open space is not. As the distance from the wire increases, the potential decreases. According to Fig. 7, the RPA used here as a potential field decrease of 6%, meaning a grid potential of -4.24 kV is required to fully deflect 4 keV electrons. Using finer grid would reduce this effect, but the lower open area would result in lower RPA measurements.

To account for this generally, a new approach is developed. There are three regions in each plot in Fig. 7: two flat regions and the monotonically decreasing region in the middle. The beginning of this decreasing region corresponds the first instance when population of secondary electrons starts being rejected: the beginning of this region must be determined to compute the target's potential.

Interestingly, this is the opposite goal of the new X-ray processing method. A similar method could be employed, although it requires significantly more data points than achieved in this paper. Instead, the numerical derivatives at each grid voltage are still examined, but now, rather than finding the maximum drop off in current, the first 'significant drop' is computed based on the percent decrease in current. For the vacuum chamber environment, a 2% drop in yields consistently accurate measurements for the target's potential. This value is estimated by examining the variations in measured current in the initial flat segment of previous trials.

With these adjustments, both the X-ray Method and SEM are now able to measure high potential objects, an important capability for electrostatic actuation techniques and proximity operations in highly charged space environments. The next step is to integrate the sensing techniques into closed loop active charge control. This is addressed in Section. 9.3.2

9.1.7 Absolute Potential Sensing using Relative Motion Dynamics

Motivated by the limitations of conventional absolute-potential sensing discussed in Sec. 9.1.5, a new avenue of research began during Year 3 to address the need for absolute potential estimation at high spacecraft potentials. In this method, high-potential electrostatic force and torque perturbations are used to tie touchless relative potential measurements to absolute values without the need for a Langmuir probe.

When two conducting spacecraft fly in close proximity ($\sim 10\text{--}50$ m separation), inter-craft Coulomb forces and torques perturb the relative motion of both spacecraft. These forces depend directly on the charge, Q , present on each spacecraft and their relative orientations, as shown in Equation 1.

$$\mathbf{F}_{Coulomb} = \frac{1}{4\pi\epsilon_0} \frac{Q_i Q_j}{r_{ij}^2} \hat{\mathbf{r}}_{ij} \quad (1)$$

The charge distribution on each spacecraft is directly tied to their absolute potentials through the mutual capacitance of the formation, given by Equation 2,

$$\mathbf{Q} = [\mathbf{C}]\Phi \quad (2)$$

where $\mathbf{Q}$ is a vector of the charge on each spacecraft, $[\mathbf{C}]$ is the capacitance matrix, and Φ is a vector of both spacecraft's potentials. Through this relation, the electrostatically perturbed relative motion of the formation encodes information about the absolute potentials of both spacecraft. By fusing this information with the developed touchless potential measurement techniques that constrain the relative potential $d\Phi = \Phi_S - \Phi_T$, the absolute spacecraft potentials are recoverable.

The relative motion perturbations can be broken down into three specific measurement streams. The first is the perturbation of the relative trajectory/position between each spacecraft caused by the inter-craft electrostatic forces, the second is the target spacecraft's attitude perturbation caused by electrostatic torques, and the third is the servicer's attitude control effort required to counteract the electrostatic torques. The first two measurement streams can be achieved using LIDAR relative pose estimation techniques while the third measurement stream is predicted from the servicer's attitude control system control effort. Electrostatic forces and torques are estimated using the SMSM model, and dynamics are simulated using Clohessy-Wiltshire-Hill relative motion equations and Euler's rotational equations of motion. Because the perturbations due to electrostatic forces and torques are small, the perturbations are integrated over long measurement windows, allowing the perturbations to build up and overcome navigation noise.

Preliminary results from a basic implementation of the proposed estimation framework are shown in Figure 8 for a servicer and target spacecraft operating in GEO space, charged to 10 kV and -20 kV, respectively. In the plot, each line represents a different combination of the measurement streams described above. These results support the underlying observability theory and feasibility of the proposed method: electrostatic perturbations combined with touchless potential measurements enable absolute potential estimation without a Langmuir probe.

Beyond simply showing that the filter converges, it is necessary to show what environments we expect the filter to converge. Electrostatic forces and torques scale directly with the electric potential of both

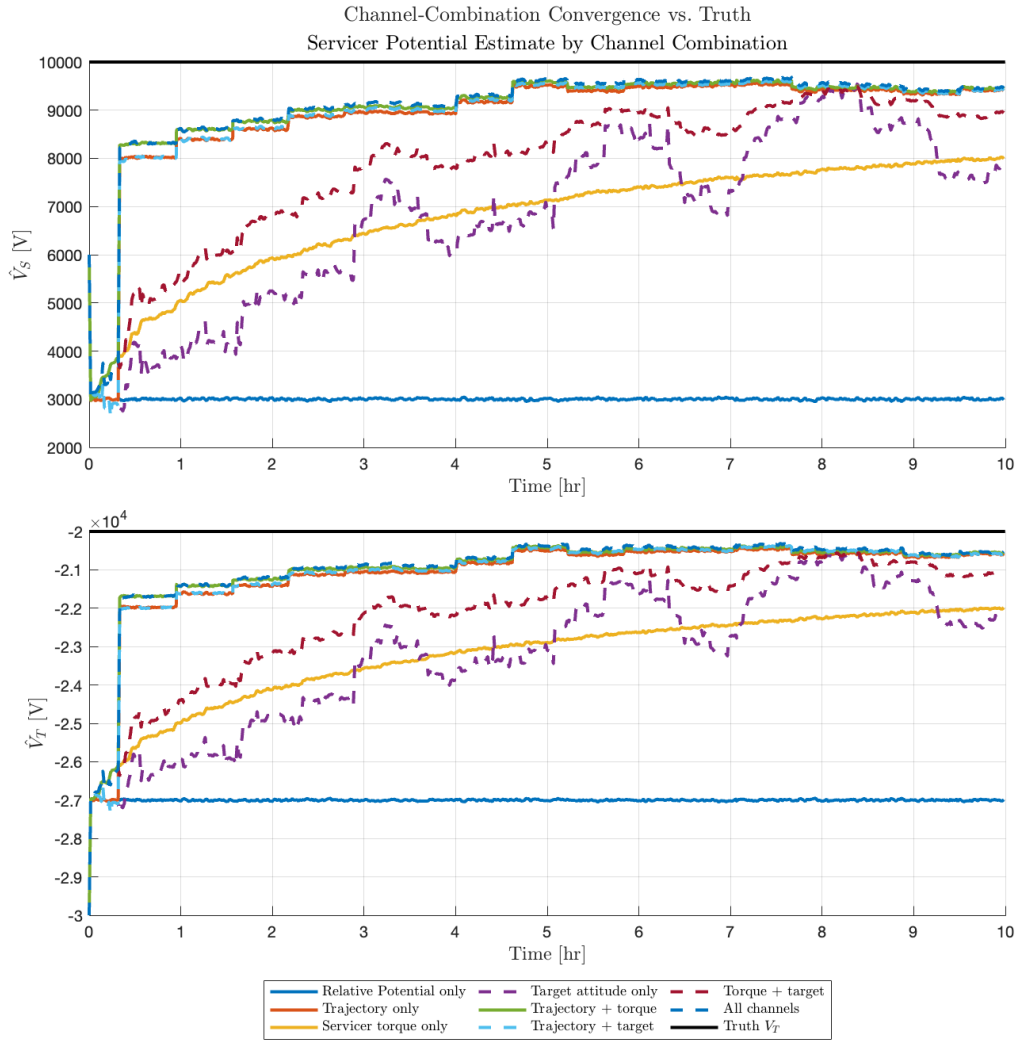


Figure 8: Preliminary Absolute Potential Estimation Results Comparing Relative Motion Measurement Channel Combinations

spacecraft and their separation distance. As such, the filter is naturally well suited for the high-potential relative motion scenarios where the Langmuir probe fails, but its use becomes limited for lower potentials and large separation distances. A major objective of this work is to map the validity regimes of this filter for varying relative navigation uncertainties, charging levels, and relative motion scenarios. Preliminary mapping showing the required trajectory perturbation measurement cadence to overcome navigation noise levels across varying spacecraft potential combinations are shown in Figure 9 for two spacecraft modeled after the SSL-1300 at a 20 meter separation distance in GEO.

These results show how the integration time needed for trajectory perturbations to overcome navigation noise follow a bilinear curve directly related to the inter-craft electrostatic force and thus the electrostatic potentials. Work continues on validating this method across varying spacecraft charging environments, assessing performance for varying measurement and navigation noise levels, and introducing other uncharacterized perturbations such as solar radiation pressure. Both a conference and journal paper are currently in preparation on this novel method.

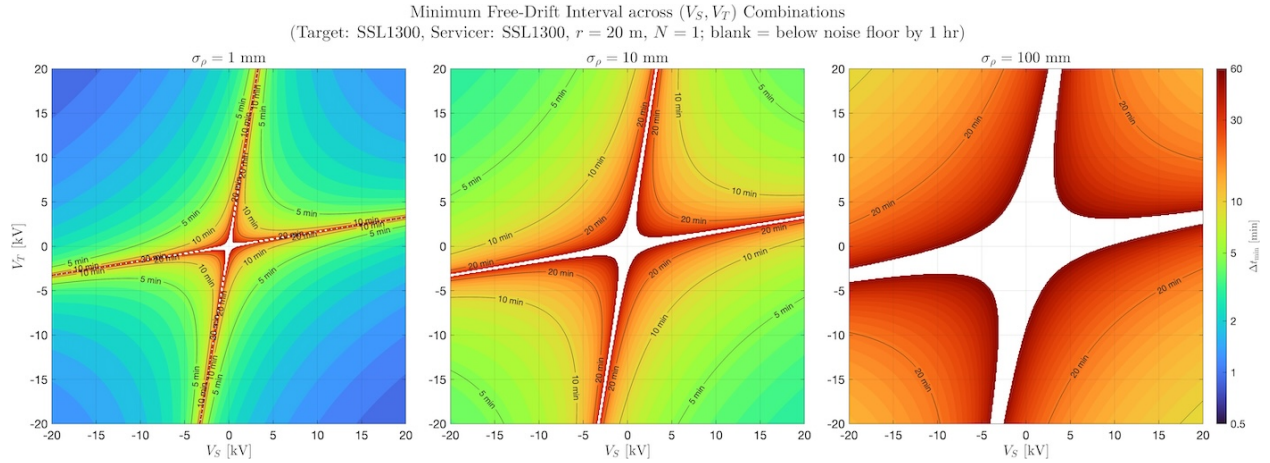


Figure 9: Minimum trajectory perturbation integration cadence for two SSL-1300 spacecraft at 20 meter separation

9.2 Thrust 2: Environment and Open-Loop Charge Control

9.2.1 High Fidelity Environment Modeling

Power-Constrained Pulsed-Beam Electrostatic Tractor

During this reporting period, a power-constrained pulsed electron-beam architecture was investigated to increase the force available to the electrostatic tractor in geosynchronous Earth orbit (GEO). A servicer emits electrons toward a debris target, charging itself positively and the target negatively. The resulting attractive force can support contactless detumbling or gradual re-orbiting. Because continuous-beam implementations generally produce forces on the order of millinewtons or less, the study examined whether the same average electrical power could be used more effectively through short, high-energy, high-current pulses.

For a continuous beam with current I_c and voltage V_c , and a pulsed beam with duty cycle D , pulse current I_p , and pulse voltage V_p , the power constraint is

$$\bar{P} = DI_p V_p = I_c V_c.$$

This permits substantially larger instantaneous beam parameters while preserving the same mean power. Spacecraft potentials were propagated using

$$\frac{dV}{dt} = \frac{I_{\text{net}}}{C},$$

and the electrostatic force was averaged over each pulse cycle.

The results confirmed that an optimal duty cycle exists. Decreasing D initially increases the peak potentials and average force, but sufficiently short pulses do not allow the spacecraft to charge before the beam turns off. In one representative active-GEO case, the optimum occurred near $D \approx 4.5\%$, producing approximately an order-of-magnitude force increase and a twenty-fold reduction in estimated re-orbit time relative to a continuous beam at the same average power. Across the broader parameter survey, reductions of one to two orders of magnitude were possible.

The optimum depended strongly on the environment. Photoelectron emission reduced target charging in sunlight, while cold, dense plasmaspheric populations could dominate the beam current during quiet geomagnetic conditions. Pulsed operation performed best during active periods, and stronger beams were required in quiet conditions. Field emission from surface asperities was also evaluated with a Fowler–Nordheim model. Although sharp features reduced the attainable potential, the pulsed architecture generally retained an advantage, and additional beam current could compensate for the field-emission current. The primary implementation constraints are therefore electron-gun capability, surface condition, sunlight, and space weather.

Spacecraft Charging in Bi-Maxwellian Plasmas

A second study developed a more realistic description of natural and active GEO charging using a bi-Maxwellian plasma. Geomagnetic substorms introduce a hot, low-density population into the colder background plasma, giving

$$f(E) = f_1(E) + f_2(E), \quad f_j(E) = n_j \left(\frac{q_e}{2\pi m T_j} \right)^{1/2} \frac{E}{T_j} \exp \left(-\frac{E}{T_j} \right).$$

Because the two populations interact differently with material-dependent secondary and backscattered electron emission, the net-current curve can contain multiple equilibrium potentials.

The Draine, Nascap-2k, and Sanders yield models were compared using the flux-weighted total yield

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

An initially uncharged surface tends to charge positively when $\langle \delta + \eta \rangle > 1$ and negatively when $\langle \delta + \eta \rangle < 1$. The models predicted substantially different critical temperatures and charging regions, demonstrating that an unsuitable yield model can produce large potential errors and incorrect safety assessments for proximity operations.

The simulations reproduced the triple-root jump, in which two stable equilibria are separated by an unstable root. Environmental evolution or a perturbation can push the potential across the unstable equilibrium, causing a rapid transition between strongly negative and slightly positive states. Electron-beam impact increased the number of possible roots to as many as five, with three stable equilibria in some cases. Beam-energy changes or short pulses could deliberately trigger transitions between branches, suggesting a means to maintain negative charging for electrostatic actuation or drive a spacecraft toward a safer state before docking.

Coupled servicer–target calculations further showed that the final target potential depends on charging history. In some environments, the target can transition to a positive equilibrium even while the beam continues to impact it, effectively eliminating the desired attractive force. Active-charging control must therefore account for equilibrium-branch stability rather than relying only on an instantaneous current balance.

Coupled Spacecraft-Plasma Interactions

The third study addressed proximity effects neglected when the servicer and target are modeled as isolated bodies. Fast analytical approximations were developed for sheath overlap, repulsion of ambient particles, and recollection of electrons emitted from the target. These approximations were validated against particle-in-cell simulations in SPIS and charged-particle trajectory calculations.

Sheath overlap was represented by evaluating ambient currents with an effective potential,

$$V_{\text{eff}} = V + \phi_{\text{nbr}}(r),$$

where $\phi_{\text{nbr}}(r)$ is the neighboring spacecraft potential at the body of interest. A positive servicer can repel ions from the target region, driving the target more negative, while a negative target can repel electrons and alter servicer charging. Including these effects shifted predicted potentials by several kilovolts in representative cases.

Electron-beam impact also generates secondary and backscattered electrons at the target. Trajectory calculations quantified their recollection by the positive servicer as functions of separation, beam divergence, landing energy, and spacecraft potential. At close separation with a nearly collimated beam, most low-energy secondary electrons returned to the servicer. This additional negative current lowered the servicer potential by several kilovolts and could create triple-root solutions in the servicer current balance. Secondary-electron recollection was generally more important than backscattered-electron recollection because the higher-energy backscattered population escaped more readily.

The electrostatic force was evaluated as

$$F_E = k_e \frac{Q_S Q_T}{d^2}.$$

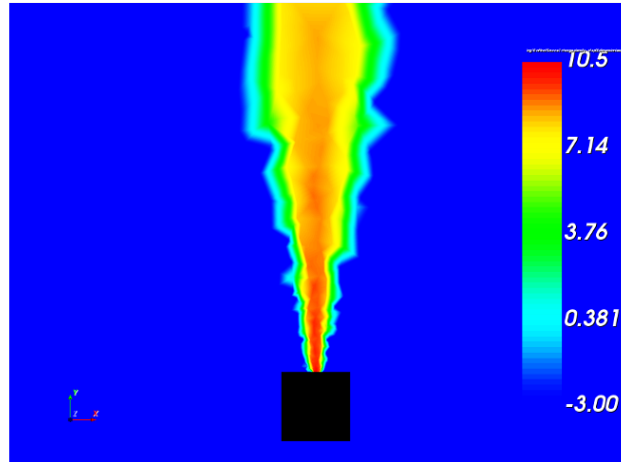


Figure 10: Electron Beam Emission Modeled in SPIS

The force depends on the product of spacecraft charges, not only their potential difference. For cases with multiple equilibria, the largest force generally occurred when the spacecraft charges were most nearly equal and opposite. Recollection shifted the beam current required to reach this favorable branch and required larger currents to reproduce forces predicted by isolated-body models. Increasing separation reduced recollection but did not increase force because the d^{-2} dependence dominated. Charging the servicer without directly striking the target produced a slightly smaller but comparable force in some cases, potentially easing beam-pointing requirements.

Overall Progress and Impact

Together, these studies establish a more complete framework for active spacecraft charging. The pulsed-beam work quantifies mission-level performance gains; the bi-Maxwellian work identifies material- and environment-dependent potential jumps; and the coupled-interaction work incorporates sheath overlap and electron recollection. The combined results show that electrostatic actuation depends not only on beam power, but also on charging timescales, plasma history, material yields, equilibrium-branch selection, proximity effects, and separation distance. This framework supports reduced-order modeling and environment-aware control for debris re-orbiting, detumbling, docking, and other electrostatic proximity operations. This research resulted in 3 journal papers: [J-8](#), [J-10](#), and [J-11](#).

9.2.2 Particle-In-Cell E-Tractor Modeling

During this reporting period, the electron beam (and thus, the electrostatic tractor concept), was modeled in Spacecraft Plasma Interaction Software (SPIS), which includes a 3D explicit particle-in-cell (PIC) electrostatic plasma solver. PIC simulations provide a more robust tool for investigating the charging of both spacecraft and the resulting plasma effects. It also makes it possible to visualize varying beam angles and their impact on particle emissions on the target. Ultimately, SPIS modeling of the electron beam opens up many additional research avenues and provides more accurate results for the electrostatic tractor simulations. Figure 10 illustrates electron beam emission from a cubic spacecraft in SPIS.

9.2.3 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. It was shown in year 2 that experimentally, the a VUV lamp is capable of flooding the target with a strong positive current to prevent negative charging. This experimentally demonstrated open loop charge control, but in year 3, this work is extended to a more general case using numerical analysis. Further details are presented in [9.3.1](#) and will be published in [J-15](#). The major result is that, for a strong enough VUV lamp, the target object will always charge to near 0, regardless of the additional currents acting on the target. As shown by Fig. [15a](#), for a target exposed to both a photo-electron current and electron beam current, regardless of the electron

energy, the net current acting on the target is positive. The only instance where it crosses 0 (the equilibrium point) is when the target's potential is ≈ 0 . This equilibrium point is stable, so regardless of the target's potential, it will always trend back to 0. There is no need to measure the target's potential: as long as a strong enough VUV lamp is directed at the target (which could be confidently estimated using available environmental data), this near zero equilibrium will be maintained on the target.

With these results and the experimental analysis presented for year 2, we have demonstrated the ability for a spacecraft to preform Open-loop Charge Neutralization using a servicer space equipped with a VUV lamp.

9.2.4 Electrostatic Tractor in LEO Conditions

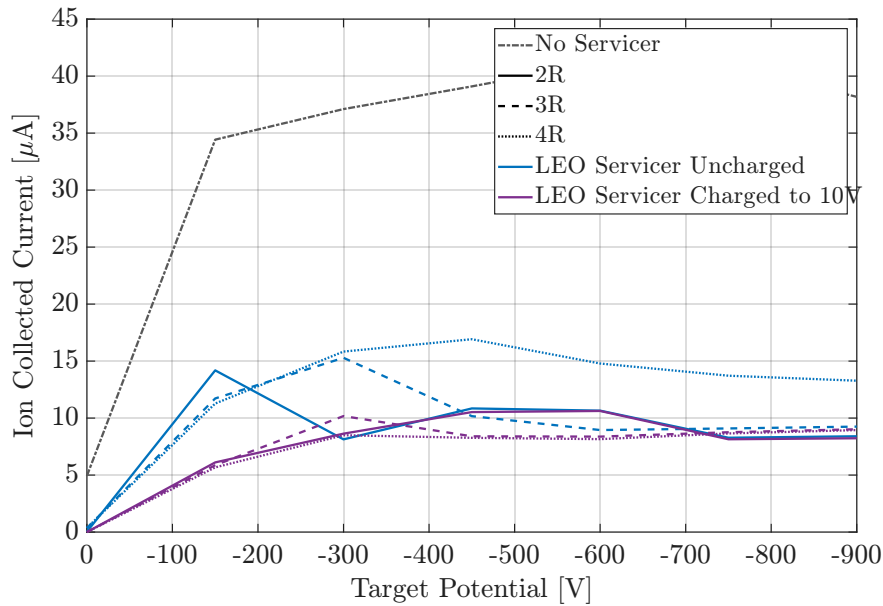


Figure 11: Ion Current Collection on Target in Servicer Wake

Because LEO plasma is dense and fluid-like with particles that refill the wake only short distances behind the spacecraft, it is crucial for the ET concept to understand the effect of a charged object in the wake. Fig. 11 shows the collected ion and electron current on a target spacecraft in the wake of a servicer spacecraft, where the ratio of the servicer to target radii is 2:1 and the servicer is uncharged. The spacecraft center-to-center separation distance varies with R , the radius of the servicer spacecraft, such that the target is placed $2R$, $3R$, and $4R$ into the wake of the spacecraft. The potential on the target spacecraft ranges from 0 V to -900 V in increments of -150 V. Interestingly, the ion current on the target does not increase with its potential as it does for spacecraft that adhere to OML charging currents, which are heavily dependent on the spacecraft potential. Instead, the ion current on the target increases from 0 V to around -300 V before leveling out and maintaining the same current for the remaining potentials. This is because in sheath-limited LEO, the collected current is heavily dependent on the sheath thickness, according to the Bohm criterion for particles entering the sheath. The sheath thickness increases from $\sim \lambda_D$ for the uncharged spacecraft to a few λ_D when the spacecraft begins charging, but levels out for increasing potentials. This is because the electrons follow the Boltzmann relation, $n_e = n_0 \exp(-q\phi/T_e)$.⁵ As ϕ becomes negative, the electron density near the spacecraft n_e drops and sheath region extends further. However, the Boltzmann relation dictates that the effect becomes saturated as ϕ continues to increase. As a result, the number of ions that enter the sheath of the target and feel the effect of its electric field also saturates and the ion current on the target does not increase. Instead, ions attracted by the target's high negative potential converge behind it in a focused wake. This result is significant because it means that a target can charge to high potentials in the wake of a servicer spacecraft without the risk of wake collapse.

9.2.5 Open-Loop Charging of Two Spacecraft

The original AFOSR proposal and our current work focus on closed-loop charge control. The proposal did not explicitly include the development of an electron gun integrated onto a floating servicer spacecraft. However, our previous and current work motivates developing this capability the natural next step. There is a need for a more realistic electrostatic tractor demonstration in which both spacecraft float electrically and respond naturally to the exchanged beam current. Although the coupled charging behavior of a servicer and target has been studied extensively through analytical models and simulations, experimental validation requires the electron source, power electronics, and eventually the potential-sensing hardware to float with the servicer itself. Previous chamber-mounted electron-gun configurations could charge a floating target but could not reproduce this fully coupled two-object system. The floating electron-gun spacecraft analog was therefore developed as the key enabling capability for the planned open-loop experiment shown in Fig. 12, which will provide an experimental test of the predicted coupled charging dynamics and establish the foundation for integrating sensing and progressing toward closed-loop charge control.

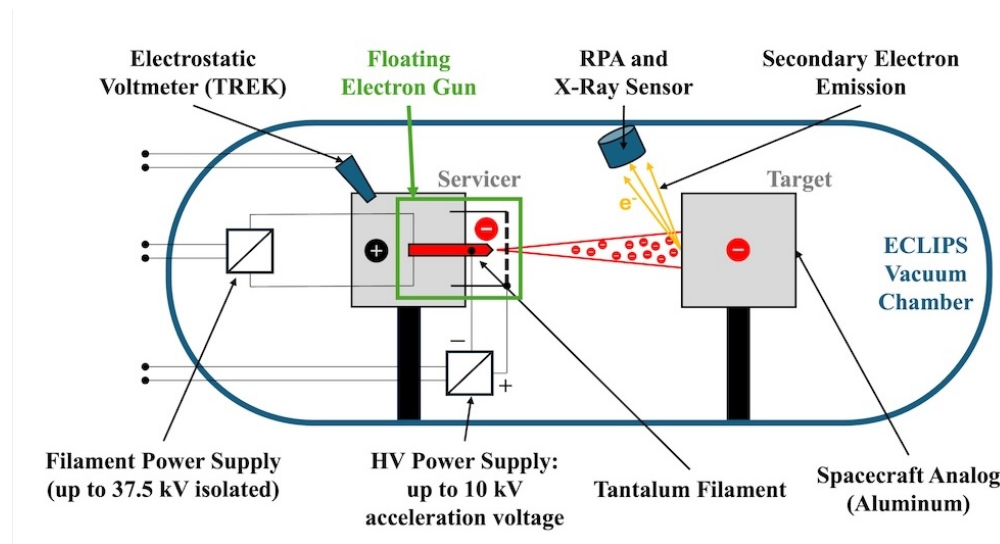


Figure 12: Proposed experiment with a floating electron-gun servicer directing an electron beam toward a separate floating target.

To enable this experiment, a miniature electron gun was designed, manufactured, and integrated directly onto a 3" × 3" aluminum spacecraft analog, as shown in Fig. 13a. The thermionic tantalum cathode, Wehnelt focusing electrode, extraction aperture, high-voltage acceleration supply, and supporting electronics are all referenced to the cube and therefore float electrically as a single emitting body. The completed system provides independent control of beam energy, transmitted current, and focusing while remaining isolated from the grounded vacuum chamber. Operation has been demonstrated at beam energies up to 10 keV, transmitted currents from the nanoampere range to approximately 100 μA , and beam-divergence half-angles as small as 2°.

Characterization with a retarding potential analyzer confirmed stable thermionic emission, controllable beam current, and the expected electron-energy cutoff. Phosphor-screen measurements, shown in Fig. 13b, further demonstrated a nearly circular beam footprint whose divergence can be reduced through adjustment of the Wehnelt bias. Electron emission also drives the electrically isolated spacecraft analog to a positive floating potential, demonstrating the fundamental servicer-side charging behavior required for the future two-object experiment. Together, these results establish the floating electron gun as an operational platform for experimentally validating coupled charging and subsequently integrating the potential-sensing hardware required for closed-loop control.



(a) Floating electron-gun spacecraft analog installed in the ECLIPS vacuum chamber. (b) Electron beam intercepted by the phosphor screen during source characterization.

Figure 13: Completed floating electron-gun spacecraft analog and demonstrated electron-beam operation.

9.3 Thrust 3: Active Charge Control

9.3.1 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 focused on analyzing these methods analytically, computing stability requirements for electron beam energy and current based active charge control. Year 3 has continued this work by incorporating external currents, non-normal beam incident angles, and longer sensing times into the stability analysis.

Active charge control for a target spacecraft exposed to electron beam irradiation is governed by the following equation:

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\phi}_T \\ \dot{E}_{EB} \end{bmatrix} = \begin{bmatrix} \frac{1}{C_{sc}} (I_T (\delta(E, \theta) + \eta(E, \theta) - 1) + I_{ph}) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ u \end{bmatrix}. \quad (3)$$

where I_T is the electron beam current impacting the target, δ and η are electron yield parameters, and I_{ph} is an external photo-electron current (I_{ph} was not included in years 1 and 2). The electron yield parameters are dependent on electron impact energy E , the sum of the electron beam energy, E_{EB} and target potential ϕ . Finally, the control applied to the electron beam is represented by u . By including the external current I_{ph} , a non-ideal charging environment is explored.

A key factor of this analysis is recognizing the speed at which the electric potential of the target reaches equilibrium state, E_{eq} . With representative GEO satellite capacitance and feasible electron beam currents, the spacecraft with charge to a steady state value in $t_{ss} \ll 1$ s. Figure 14 shows a section of the simulated charging behavior of a GEO spacecraft.

The equilibrium point occurs when the net current acting on the target reaches 0 A, and this occurs in ≈ 0.008 s, about 2 orders of magnitude faster. Because of this, the system has reached the equilibrium far before the target potential is measured and control applied. This allows the stability analysis to be simplified. Rather than taking the full dynamics, by assuming the system has converged to the equilibrium,

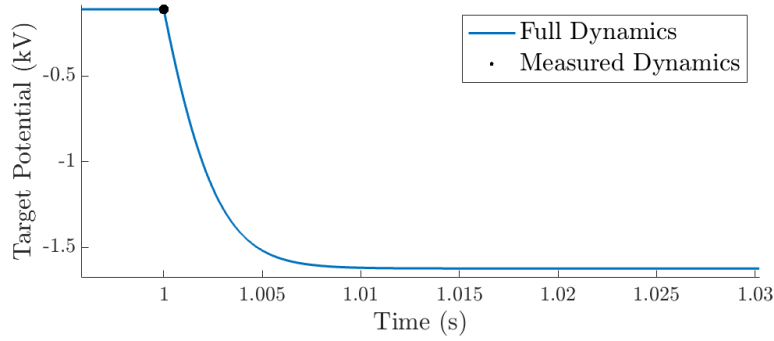


Figure 14: The transient charging behavior of a GEO spacecraft irradiated by an electron beam.

$\dot{\mathbf{x}}$ can simply be represented as a discrete system govern by the equilibrium behavior:

$$\mathbf{x}_{k+1} \approx \mathbf{x}_k + h(\mathbf{u}_k) = \mathbf{x}_k + h([B][K](\phi_k - \phi_g)), \quad (4)$$

where $h(\cdot)$ maps the system to the equilibrium value given the applied control $\mathbf{u}$. Here, $[B] = [-1, 1]^T$ and $K = [P, 0]$. As shown in Year 2, ϕ_{eq} and EB_{EB} have a 1-to-1 negative linear relationship. Practically, it is expected that increasing the beam energy by 100 V will decrease the target potential by 100 v. Control is applied directly to the beam energy, so increasing the beam energy by $\mathbf{u}$, will increase the target potential by the same amount such that $h(x) = x$ and $\mathbf{x}_{k+1} = \mathbf{x}_k + [B][K](\phi - \phi_g)$. Writing this out in full, with some algebraic manipulation, gives

$$\begin{bmatrix} \phi \\ E_{EB} \end{bmatrix}_{k+1} \approx \begin{bmatrix} \phi_k(1 - P) + P\phi_g \\ E_{EB_k} + P\phi_k - P\phi_g \end{bmatrix} = \begin{bmatrix} (1 - P) & 0 \\ 1 & P \end{bmatrix} \mathbf{x}_k + \begin{bmatrix} P\phi_g \\ -P\phi_g \end{bmatrix}. \quad (5)$$

Solving for the eigenvalue of this system gives the required stability condition of

$$0 \leq P \leq 2. \quad (6)$$

This is a very powerful result, as it has been shown that, even considering controlled external forces, stable control of a target's electrostatic potential can be achieved using the control we have developed. The key assumption to this work is that this steady state equilibrium exists. More specifically, there is at least one instance where a non-zero electron impact energy results in a net current of 0 A. When considering only electron beam induced currents, this impact energy vs net current is a mirror of the total electron yield curve. This yield curve is determined by the δ and η value of Eq. (3). However, these properties also depend on θ , the impact angle between electron beam and the target. An analysis of common spacecraft materials is conducted in Fig. 15b. It is showed that, regardless of incident angle, this equilibrium value exists. Preforming an additional analysis considering the photo-electron current revealed this is not always the case when considering external currents.

For negatively charged spacecraft, the photo-electron current is constant with respect to the spacecraft potential. Figure 15a shows that this shifts the I_{net} curve up or down, but does not affect the overall shape. Increasing the photo-electron current enough results in $I_{net} > 0$ for all electron impact energies. This means the equilibrium required for active charge control does not exist: the photoelectron current is large enough that the negative current from the electron beam does not significantly affect the target's potential. While this may initially appear to be a concern, this simply reveals an additional consideration: the electron beam current must be larger than the environmental currents for active charge control.

An additional assumption required for these stability conditions is that the target must reach the equilibrium state before control is applied. This can also be affected by the environmental currents. If the photo-electron current is comparable to the electron beam current, the net current acting on the target is small enough such that control is applied before the target potential reaches steady state. Relaxing this assumption means it may no longer be accurate to model the charging behavior as a discrete system, but

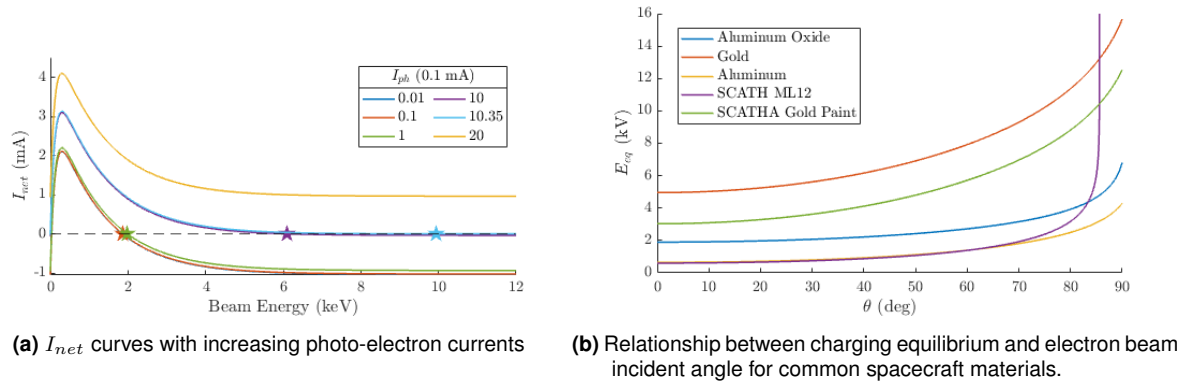


Figure 15: Investigations how external currents and non-normal incidence angles affect the existence of E_{eq} .

this not a concern. Representing the system as a linearized continuous system reveals that the stability condition allows for gains (P) greater than 2. Because larger values are still stable, fixing the gains to satisfy Eq. (6) will still result in stable control even when the target charges slowly. The work discussed in this section as well as additional investigations couple with simulation and experimental data will be published in J-15. Several conference papers presenting intermediate steps have been published as well: C-22, C-19, and C-6.

Additional work to be completed before the end of Year 3 involves including other environmental currents to the stability analysis. Both the ambient ion and electron current have a dependence on the spacecraft potential, therefore, unlike the photo-electron current, they may alter the shape of the I_{net} curve. The effect on the I_{net} and the existence of the charging equilibrium will be investigated. It is expected to yield similar results to that of the photo-electron current: as long as this equilibrium exists, active charge control can be performed in any space environment. All of the work investigating the stability of the control when considering long measurement times, external currents, and rotating targets will be published in Ref. J-15 once this final analysis is complete. This paper will also be supported by experimental and numerical results.

9.3.2 Closed-Loop Charge Control Experiments

Using the capabilities of the ECLIPS vacuum chamber in the AVS lab and CU Boulder, we have the unique capability to investigate spacecraft charging using hardware-in-the-loop. Active charge control experiments allow for novel investigations into the presented control as well as general spacecraft charging behavior. Year 1 presented initial investigations into active charge control demonstrating the ability to control a target's potential in a vacuum chamber environment through a collaboration with AFRL at Kirtland Airforce Base. Year 2 furthered these investigations, demonstrating that applying control to the energy of the electron beam, rather than the current, results in the most robust control. Additionally, methods for remotely sensing the target's electric potential were integrated into active charge control in C-6 and C-19. This allowed for more realistic experiments to be conducted. Year 3 continued this integration, revealing previously unknown concerns with remote sensing methods. These are addressed in Sec. 9.1.6. These sensing methods were then integrated into closed loop control and preliminary results are published in C-22. A comprehensive journal paper outlining the changes made to the remote sensing methods is given by J-14, however a brief overview of this paper is presented here.

During the development of these sensing methods, a human-in-the-loop was necessary to implement these sensing methods.^{6,7} Data is collected via vacuum chamber equipment, but is then processed by a human operator to obtain measurement data. For these methods to be viable for in situ applications, they must be able to function autonomously. For the X-ray Method, this required developing a new technique for processing the data.

To process the data of the X-ray Method, an estimate for the background noise is required.⁶ Typically, this was added during post processing when the operator analyses the measured X-ray spectrum. This is not viable for continuous control. Simply selecting a single value as the noise floor for all trials would be

valid in a vacuum chamber environment because the noise comes from minor chamber artifacts. However, the real environment fluctuates throughout an orbits and geomagnetic activity and simply selecting a single noise floor would result in inconsistent measurements. Instead, a method for periodically measuring the background noise is developed.

Before the measurement of the target's X-ray spectrum is collected, the electron beam is turned off and the environmental X-rays are measured. Next, the beam is turned back on and the target's X-ray spectrum collected. Previously collected noise is subtracted from the measured spectrum and the used to compute the target's potential. The resulting data will consist of only the characteristic and bremsstrahlung spectra, such that a small threshold can be selected for data processing. This is tested in a vacuum chamber environment using a VUV lamp to generate a photo-electron current on the target to act as the background noise of the system. Figure 16 shows continuous measurements of the target considering a variable potential. Two methods for processing the X-ray Method data are shown. "Background Removal" refers to the method previously described. "Slope Method" describes a second method that involves tracking the change in the slope of the measure spectra and is fully presented in J-14. One important note is that measurements are collected at different rates, therefore the data is presented in terms of measurement "counts" rather than absolute time for an accurate comparison.

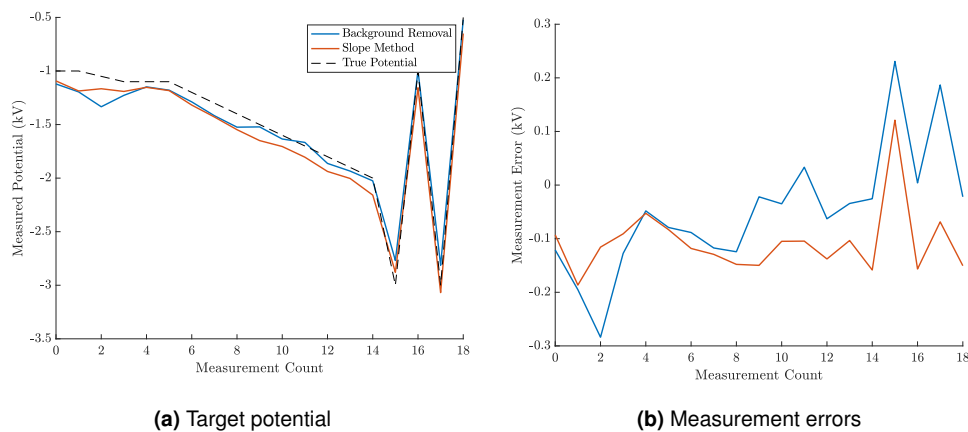


Figure 16: Continuous X-ray measurements using two methods for processing X-ray data.

Employing both methods allows continuous measurements of the target's electrostatic potential to be continuously measured. Using a high voltage power supply to alter the target's potential, it can be seen that as the voltage is changed, the measured potential follows. The error in the measured potential reaches up to 230 V, however this is still less than 10% error. Manually processing the measured data yields similar results, suggesting this error is likely due to inconsistencies with the equipment rather than the physical phenomena. Both methods struggle when the landing energy of the electrons falls below ≈ 2 keV; this is a known concern of the X-ray Method and addressing this is not a goal of this work.

For the SEM, other than implementing the new analysis described in Sec. 9.1.6, the data processing is relatively trivial to implement; the difficulty stems from integrating the instrumentation into closed loop control. The SEM uses a retarding potential analyzer (RPA), to collect the required electron current/energy measurements. In order to collect this, a voltage must be applied to the internal grid of the RPA, limiting the measured electrons to those with greater energy. In prior work, this voltage sweep was predetermined by an operator and must be adapted for continuous control. Year 2 developed the constant sweep, Dual, and moving window sweep methods to account for this, demonstrated by initial experiments. Year 3 refined these techniques for consistent and robust experiments. The Dual method saw significant refinement in year 3, supported closely by the improvements to the X-ray Method.

With remote sensing methods now adapted for continuous measurements, they can now be integrated into closed loop control. Reference J-14 presents the improvements to the sensing methods, including a more robust method for achieving continuous control using the X-ray Method. Reference ?? will present active charge control utilizing these remote sensing methods as well as additional analysis, evaluating

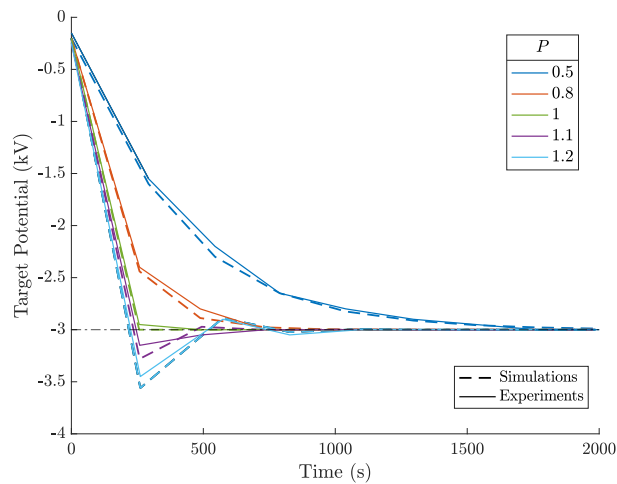


Figure 17: Experiments vs simulations when including extending measurement times and an incidence angle of 18° .

known limitations of these sensing methods and how they affect the ability to preform active charge control. These experiments are mainly preformed to support the numerical simulations described in the following section.

9.3.3 Closed-Loop Charge Control Simulations

While the active charge control experiments are incredibly useful and expose behavior that would be otherwise absent from numerical simulations, they are limited by the capabilities of the ground testing facilities. Simulations are conducted to support both the analytical and experimental analysis, expanded the behavior and phenomena that is evaluated. Developing this simulation framework was a focus of year 2, demonstrating both current and energy control. Year 3 has focused on using the simulation framework to explore stability and other charging behavior un non-ideal conditions.

The first goal was to validate the numerical model by comparing the active charge control chamber results to the simulations. Figure 17 presents this comparison using the ECLIPS vacuum chamber. Similar experiments were conducted in year 2 using the Jumbo vacuum chamber, however this new validation includes electron incidence angle, remote sensing, and photo-electron currents.

It can be seen that the two sets of data appear similar: The largest errors are ≈ 100 V, but overall the numerical simulations are an accurate reflection of the expected physical behavior. This difference occurs because of inconsistent electron yield properties. Analytical secondary and backscattered electron yields are based pure materials. However, this is infeasible (and unrealistic) for spacecraft charging experiments; in reality there are surface roughness effects and contamination that affect the yield values, causing the equilibrium point $I_{net} = 0$ to occur at a different energy. Even with these inaccuracies, both the experiments and simulations demonstrate the same behavior, giving confidence that the numeric simulations are representative of physical behavior.

With the model shown to reflect realistic charging behavior, it can now be used to investigate more complex behavior. The big area expanded by the simulations is the behavior when considering beam incidence angle and photo-electron current, as discussed in Sec. 9.3.1. Many numerical simulations were implemented to support and confirm the charging behavior outlined by the stability analysis. The most significant result from this numerical analysis is that stable control can be achieved when E_{eq} exists. As mentioned before, E_{eq} is the stable equilibrium electron impact energy at which $I_{net} = 0$. If E_{eq} exists, the only limit on achieving the goal potential on the target is the maximum energy of the electron gun. If E_{eq} does not exist, then control can not be achieved as the external currents are too large to overcome with the electron beam. However, this can be avoided by ensuring the servicer is equipped a large enough electron beam current.

The final area this work will explore is rotating targets. As the object rotates, the incidence angle between

the target and the electron beam changes. This means the yield parameters will depend on time, and therefore, the equilibrium state will also vary with time. All prior work has so far only considered a stationary equilibrium, meaning there is no limit to how much the servicer can take to measure the target's potential: it will not change until control is applied to the beam energy. With rotating targets, this is no longer true. The affect this has on control must be explored. Preliminary investigations suggest that the rate at which control must be applied depends on the rotation speed of the target. When targets rotate slowly, the change in equilibrium is minimal and the control be applied at a slow rate. In contrast, quickly rotating targets can result in large potentials if control is not applied fast enough. The goal of this analysis is to quantify the relationship between target spin rates and minimum control requirements. This work was presented and published in C-22, with the journal paper J-15 currently in preparation.

9.3.4 Exploiting Natural GEO Charging for Electrostatic Tractor Operations

The electrostatic tractor concept conventionally uses an electron beam directed toward a noncooperative target, charging the target negatively while electron emission charges the servicer positively. The resulting opposite charges generate the attractive electrostatic force used to tow the target. However, active charging of the target is not always the most effective or practical operating strategy. If the target is substantially larger than the servicer, the servicer may reach its beam-energy-limited positive potential before it can deliver sufficient current to drive the target to a large negative potential. Prior analysis therefore suggests that, particularly when the target is more than approximately 1.5 times larger than the servicer, it may be preferable to actively charge only the servicer while exploiting the target's natural GEO charging state.^{8,9}

In this servicer-only configuration, the electron beam is directed away from the target so that electron emission charges the servicer positively, while the electrically floating target remains at its natural GEO potential. The target is typically a few volts positive in sunlight and can reach kilovolt-level negative potentials in eclipse. The coupled capacitance relation

$$\begin{bmatrix} q_T \\ q_D \end{bmatrix} = \frac{\rho}{k_c(\rho^2 - r_T r_D)} \begin{bmatrix} r_T \rho & -r_T r_D \\ -r_T r_D & r_D \rho \end{bmatrix} \begin{bmatrix} \phi_T \\ \phi_D \end{bmatrix} \quad (7)$$

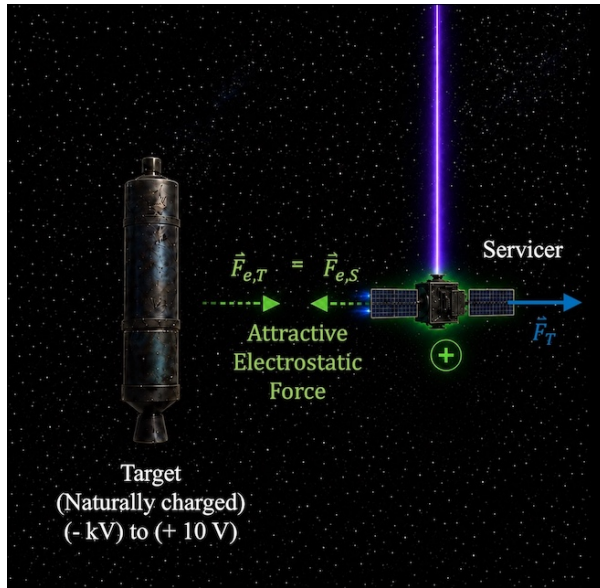
shows that the strongly positive servicer induces an oppositely signed charge on the nearby target even when the target potential is slightly positive, resulting in an attractive electrostatic force.

This architecture is attractive because active regulation of both spacecraft would likely require an ion source in addition to the electron gun and would require continuous knowledge of the target potential. Eliminating active target charging therefore reduces both the charge-control hardware and sensing requirements. It may also enable a smaller and simpler servicing spacecraft, avoiding the large conductive or deployable structures that could otherwise be required to charge a servicer sufficiently while towing a much larger target. The two configurations and the active charge-transfer limitation identified in prior work are illustrated in Fig. 18.

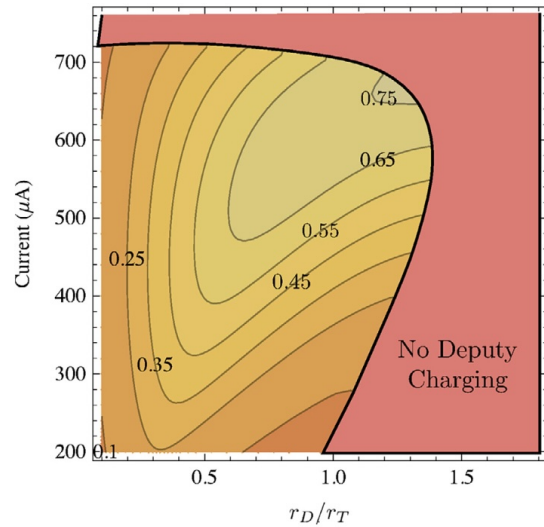
Work is under way to evaluate this naturally coupled configuration over a complete GEO re-orbit mission, building directly on the charging and relative-motion models developed in prior electrostatic tractor studies. The AVS spacecraft-charging code, together with the Denton GEO plasma model, will be used to predict the target's natural potential under varying space-weather and eclipse conditions. The resulting servicer-only architecture will then be compared with conventional two-object active charge control to determine how natural-potential uncertainty affects electrostatic force, relative-motion control, and re-orbit performance, and to identify the regimes in which reduced hardware and sensing complexity outweigh the associated loss in performance.

9.3.5 Spacecraft Charging Module Addition in Basilisk

Throughout this project, analytical charging calculations were performed using an in-house MATLAB charging code. While this code works great for fast, standalone charging analysis and charge control simulation, it is not designed to directly interface with existing astrodynamics and mission simulation tools to model a full active charge control mission. In addition its spacecraft charging research, the AVS lab is known for its high-fidelity, open source astrodynamics framework, Basilisk. Therefore, to round out this project, the spacecraft charging code developed over the three project years was implemented as spacecraft charging modules in Basilisk, enabling the full dynamical simulation of a touchless charge control mission.



(a) Electrostatic tractor configuration that exploits the natural charging state of the target.



(b) Representative operating regions for active target charging, adapted from Fig. 5 of Hogan and Schaub.⁸

Figure 18: Motivation for exploiting natural GEO charging in electrostatic tractor operations. Active target charging becomes increasingly difficult as the target size grows relative to the servicer, motivating a simpler configuration in which only the servicer is actively charged.

The charging code was implemented in two separate spacecraft charging modules in Basilisk, each corresponding to two solution methods.

- The [Equilibrium](#) module computes spacecraft equilibrium electric potentials in a plasma environment using two sequential 1-D root solves, enforcing a zero net current condition on each spacecraft surface. The model includes ambient plasma electron/ion collection, photoelectron emission, secondary electron emission (SEE), electron backscattering, and electron beam coupling.
- The [Dynamics](#) module integrates the electric potential of two spacecraft in a plasma environment using a first order ordinary differential equation for each spacecraft. The charging model includes plasma electron current, plasma ion current, photoelectric current, and an optional electron beam current.

These two modules represent the two main methods for calculating spacecraft charging and are relevant to separate use cases. The equilibrium module solves an algebraic current balance at each timestep. Ongoing work is developing the scenario *NaturalCharging* which uses this to calculate spacecraft charging over a full orbit under slowly varying plasma conditions. The dynamics module is best suited for short time-scale transient charging, such as active charge control with an electron beam. Because the charging ODE is stiff (the charging time constant is orders of magnitude shorter than any practical simulation timestep for orbit-length scenarios) the dynamics module is limited to short simulations on the order of minutes, and the in-development scenario *TwoBodyCharging* simulates the changing electric potentials as an electron beam is fired from a servicer to a target spacecraft.

9.4 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.

9.4.1 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 E. M. Weber and **H. Schaub**, "Touchless Electrostatic Detumbling of Differentially Charged Spacecraft in Geosynchronous Earth Orbit," AIAA SciTech Forum 2026, Orlando, FL, January 12–16, 2026
- C-21 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
- C-22 J. D. Walker, S. Hampl and **H. Schaub**, "Combined Remote Sensing Methods for Active Charge Control Using an Electron Beam in a Dynamic Space Environment," AIAA SciTech Forum 2026, Orlando, FL, January 12–16, 2026

9.4.2 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.
doi:[10.1109/TPS.2024.3503356](https://doi.org/10.1109/TPS.2024.3503356)
- J-4 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.–Oct. 2024, pp. 1258–1271.
doi:[10.2514/1.A36010](https://doi.org/10.2514/1.A36010)
- J-5 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-6 J. D. Walker and **H. Schaub**, "Electron Gun-Based Active Charge Control of Nearby Spacecraft," *IEEE Transactions on Plasma Science*, Vol. 53, No. 12, Dec. 2025, pp. 3756–3770.
doi:[10.1109/TPS.2025.3627474](https://doi.org/10.1109/TPS.2025.3627474)
- J-7 K. Champion and **H. Schaub**, "Cislunar passive potential sensing through nonmonotonic sheath and ion wake barriers," *Physics of Plasmas*, Vol. 23, No. 2, February 2026.
doi:[10.1063/5.0302512](https://doi.org/10.1063/5.0302512)
- J-8 A. Haft and **H. Schaub**, "Spacecraft Electrostatic Tractor Using A Power-Constrained Pulsed High-Energy High-Current Electron Beam," *Advances in Space Research*, Vol. 77, No. 6, March 2026, pp. 7168–7182.
doi:[10.1016/j.asr.2026.01.050](https://doi.org/10.1016/j.asr.2026.01.050)
- J-9 K. Champion and **H. Schaub**, "Improving Electron Emission Observability for Spacecraft Touchless Potential Sensing," *Journal of Spacecraft and Rockets*, March 2026.
doi:[10.2514/1.A36576](https://doi.org/10.2514/1.A36576)
- J-10 A. Haft and **H. Schaub**, "Numerical Modeling of Spacecraft Charging in Bi-Maxwellian Plasmas," *IEEE Transactions on Plasma Science*. *submitted*.
- J-11 K. Champion, A. Haft and **H. Schaub**, "Coupled Spacecraft-Plasma Interactions During Active Charging Operations," *IEEE Transactions on Plasma Science*. *submitted*.

- J-12 A. Haft, K. Champion and **H. Schaub**, "Single- and Multi-Body Wake Formations in Thin- and Thick-Sheath Plasma Regimes," *Journal of Geophysical Research*. *In preparation*.
- J-13 S. Hampl and **H. Schaub**, "Development and Validation of a Floating Electron-Gun Spacecraft Analog for Electrostatic Tractor Ground Demonstrations," *Advances in Space Research*. *In preparation*.
- J-14 J. Walker and **H. Schaub** "Closed-Loop High Potential Remote Sensing for Nearby Spacecraft" *In preparation*.
- J-15 J. Walker and **H. Schaub** "Electron Gun Based Active Charge Control of Rotating Spacecraft in Transient Environments" *In preparation*.

10 Project Conclusions and Outlook

In Year 3, the project completed its originally proposed 3-year research plan on schedule, on budget, and with all three thrusts either completed, modified, or exceeded relative to the original proposal. Year 3 in particular delivered multiple research accomplishments beyond the original project scope including developing a floating electron-gun platform for coupled two-object experiments, refined high-potential sensing methods, a new absolute-potential-sensing capability, and new Basilisk charging modules that extend this work's usability beyond the project team.

Because \$27,466 of Year 3 funding was disbursed as a one-year no-cost extension, and roughly \$17,194 remains from the Year 3 budget, the project will continue into a partial Year 4. This extension is administrative rather than scientific: no new research thrusts are planned, and the funds will support a graduate researcher in completing the remaining journal manuscripts documenting Year 3 results, along with continued development of the novel research directions listed above.

The ECLIPS chamber and the newly completed floating electron-gun platform are expected to remain in active use during this closeout period, primarily to finalize data supporting the in-preparation manuscripts. Year 4 is expected to conclude the project in full.

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