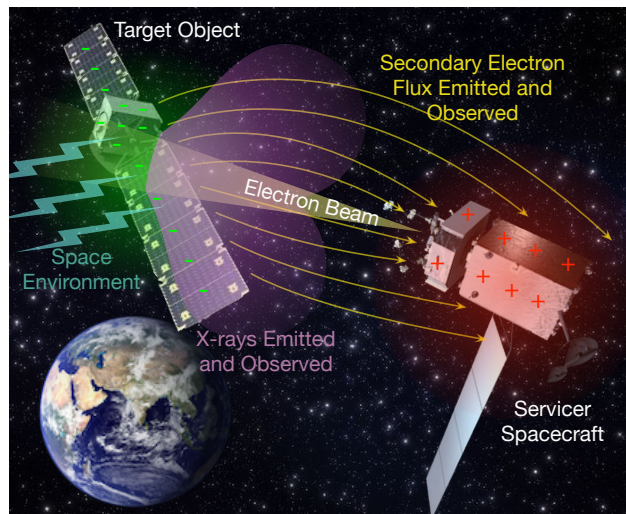


ANNUAL REPORT - 3RD PROJECT YEAR

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Touchless Sensing of Electrostatic Potential and Material Characterization Using Neighboring Spacecraft



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1 Project Overview

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

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

The third project year continued with many vacuum chamber experiments. Early in the year we did repeated experiments of the prior x-ray and electron sensing methods on a flat plate to have statistical information to be able to discuss the performance in journal manuscripts. Further, new spacecraft shape primitives were created to validate the method with additional shapes.

The SIMION based electron simulation tool has been expanded to include the effects of UV ejected electrons. The use of UV light diodes is explored as an alternate method to excite low-energy electrons that are emitted from the target vehicle surface. In contrast to the electron beam method which imparts electrons onto the target, the UV light causes a net-positive charging effect through the emitted electrons.

New floating potential experiments were created which are an exciting new research direction. The goal was to perform a proof-of-concept experiment to illustrate the ECLIPS chamber is capable of doing active charging with an electron beam. Early results were gathered in the fall and published. This work is in support of considering using a pulsed electron beam to excite the secondary electron emission. The pulsed beam has the benefit of lessening the impact of the target potential change. Research has shown that during the shaded orbit regions the electron beam required to create enough secondary electrons to measure the target potential will also significantly change the target potential. A pulsed e-beam is numerically shown to greatly reduce this charging effect and keep the target potential almost unchanged. Basic proof of concepts of being able to do pulsed charging experiments in ECLIPS were done.

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

2 Related Year 3 Travel

Project research was presented at the AIAA SciTech Forum, San Diego, CA, January 3-7, 2022 where 2 students traveled there to present their work. The 16th Spacecraft Charging Technology Conference was held as a virtual event in the end, but the students presented 3 papers there in a remote format. Research was also presented at the AAS Astrodynamics Specialist Conference, Charlotte, North Carolina, August 7–10 2022. Finally, a presentation on the spacecraft charging research was given at the 2nd International Stardust Conference, ESA European Space Research and Technology Centre (ESTEC), Noordwijk, Netherland, Nov. 7–11, 2022.

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

3 Staffing Update

The research grant contains support for two graduate research assistants (GRAs). In spring and summer 2022 the primary GRAs were Julian Hammerl, Álvaro Romero Calvo (partially supported with fellowship), Andrea López and James Walker. Further, Ph.D. student Kaylee Champion supported this project in 2022 but was fully covered with an NSF fellowship in spring and summer, and supported by a new NASA NST-GRO fellowship in the fall. The unused 2021 travel funds were used to provide increased GRA support, and Dr. Schaub used some of his PI funds to fully cover the students.

A highlight in 2022 was Álvaro Romero Calvo earning his Ph.D. degree in the summer. He became an assistant professor starting August 2022 but continues to work with my students on publishing joint work he did with them earlier in the year.

Kaylee has been working very closely with Álvaro and has taken over the SIMION related simulations. Julian remains my project lead and he was able to attend the program review meeting in November to provide the update presentation. Having Álvaro depart the project was a smooth event as he used the summer to create an efficient transition of the projects he worked on to Julian and James. Andrea continues work with Julian on the x-ray sensing research.

The list of the students involved in this research in 2022 is:

- Julian Hammerl, a Ph.D. student who started in the fall of 2020. He has started working on this AFOSR project in August 2020. His dissertation research is on the charged relative motion control for close proximity operations and debris mitigation. After Kieran graduated Julian took over the general project leadership, and is the lead researchers for the x-ray charge sensing method research as well as the charged relative motion GNC work.
- Álvaro Romero Calvo, a Ph.D. student who started in the fall of 2019. His dissertation research is on the use of electrostatic and magnetic fields in space applications. He is partially supported on the La Caixa fellowship, the IAF Luigi G. Napolitano Award and partially on the AFOSR grant. After fully supporting AFOSR project in summer and fall semester of 2021, he is now supported on the Napolitano award for his last semester. He defended in May 2022 and completed his dissertation tasks over the summer.
- Kaylee Champion, a Ph.D. student who started in the fall of 2021. She came to my lab with an honors thesis on spacecraft charging from the University of Texas. She won an NSF graduate fellowship and a NASA NSTGRO fellowship. Her research interests overlap with this project and she has been an active contributor.
- 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 has worked with Julian on the first proof of concept floating potential experiments.

4 Budget Update

The 3-year project has total funds of \$777,667. The proposal funding rate was \$267,524 (1st year), \$251,560 (2nd year) and \$258,583 for the third year. The cumulative year 3 budget expenses are illustrated in Figure [1](#). The project funds are projected to be spent out by the project end date of January 31, 2023.

In the 3rd year the small surplus of the prior project year was spent out on supporting an additional graduate student on this project for the academic year, as well as finally being able to have students travel to conferences again. As 3 students visited the SciTech conferences in the 2nd to last week of January using AFOSR project funds to present their related work, the final project figures will be worked out in the coming weeks as the travel reimbursements are processed. Figure [1](#) shows the estimated budget breakdown that will reach zero after the January expenses are processed.

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

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

5 Accomplishments

The current project schedule is illustrated in Figure 2. The GANTT chart lists the main research objectives. The project tasks are grouped by project thrusts and colored by their status. The 3rd project year wrapped up a lot of vacuum chamber experiments on the electron and x-ray sensing solutions to have statistical results suitable for journal publications. Further, experiments were performed with a new set of shapes to show the performance on non-box and box-panel shapes. A lot of research occurred studying the UV influence stimulating electron emission instead of using the electron gun. This UV method has the potential to be used for material identification as well. The details of the technical approach pursued are found in section 8.4.

The primary objective to wrap up year 3 project tasks was completed. Extensive experimental studies were performed to be able to publish the x-ray and e-sensing approaches in scientific journals. A key accomplishment was demonstrating experimentally that it is possible to measure more than 1 potential on a target object.

The research results were disseminated through conference and journal publications. The project related publications are listed in section 8.4.

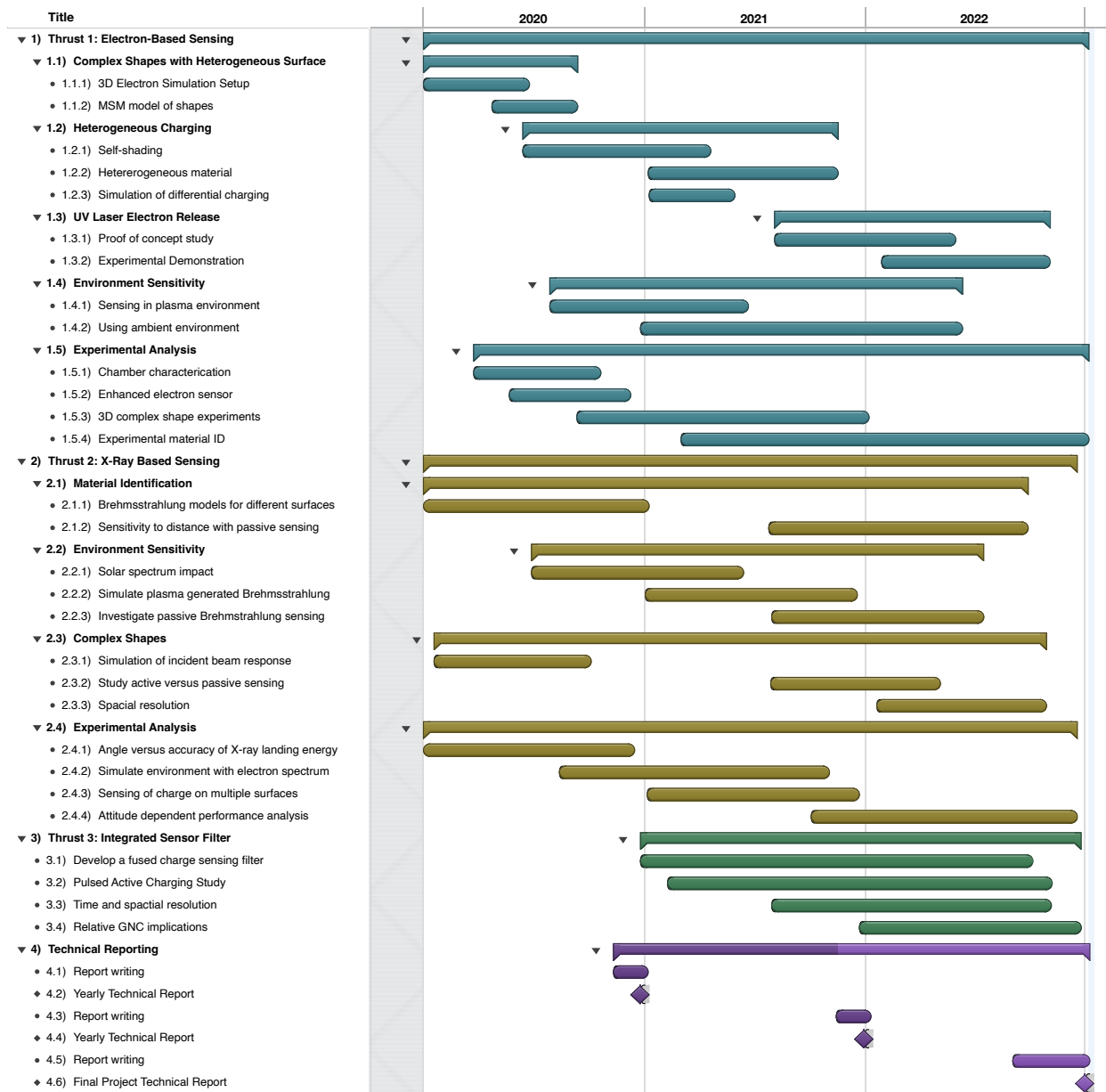


Figure 2: Current Project Schedule (darkened bar indicates degree of completion)

6 Impacts

Development of the principal discipline(s) of the project:. The project has successfully demonstrated that it is possible to measure the electrostatic potential of an object in a vacuum environment using either the electron or x-ray sensing technique. The concept was demonstrated using laboratory vacuum chamber experiments and through numerical simulations which were validated by the experiments. The project has demonstrated that relatively low-cost electron and x-ray sensors can yield voltage measurements within a few 10s of volts of accuracy depending on the sampling period. This has an impact on the GEO servicing and on-orbit assembly missions being developed as they will have to content with space weather related charging.

Further, the experiments have demonstrated that it is possible to determine the material type using the x-ray sensing techniques if a uniform target potential is present. A revised algorithm is studied where

Table 1: Sensing for homogeneous servicer and target potentials analysis parameters

Parameter	Value
Beam energy, E_B	5000 eV
Initial divergence angle, δ	1 deg
Initial beam radius, r_B	1 mm
Number of particles, n	100
Servicer potential, V_{serv}	0 V
Target potential, V_{tar}	-500, -1500, -2500, -3500 V
Target angle about the x-axis, α	$0^\circ - 180^\circ$
Separation distance	30 m

multiple potentials could be measured if they are sufficiently different.

Further, this work has demonstrated the level of charging required to have a strong impact on rendezvous and docking operations. Using the charge sensing solution novel approach trajectories are discussed that would minimize the resulting target object tumbling that could result from electrostatic torques.

7 Changes

In the 3rd year not project changes were made and the original studies were completed. New studies were included looking at UV based methods to stimulate a secondary electron emission. These preliminary studies illustrate that these could be an interesting alternate method in contrast to the electron-gun approach as no charge is sent to the target object. Finally, preliminary experiments were performed to study how challenging it would be to experimentally do floating potential experiments in a vacuum chamber. This is critical work to study active charging to a target object.

There is no delay to the project timeline or expenditure. The project is ending on time and on budget.

8 Technical Updates

The following sections provide executive summary style discussions on each research thrust area. Where appropriate, we point to the full papers that have been written on this research and are available as downloadable PDF links in Project Publication section 8.4.

8.1 Thrust 1: Electron Based Sensing

8.1.1 Complex Shapes with Heterogeneous Surface

The study of complex shapes with heterogeneous surfaces is discussed in J-3 and J-9. The behavior of the electron beam is also investigated in a full-scale SIMION model of a servicer and target at a separation distance of 30 meters for varying orientations and target potentials in C-23. This model expands on the work done in J-9 in order to investigate particle dynamics that may not be possible to observe on the small scale of the ECLIPS vacuum chamber, such as beam deflection over distances of tens of meters. This simulation is applicable to GEO and cislunar environments in which the Debye length is larger than the separation distance between the servicer and target. Preliminary results investigated the target (SSL-1300) rotating 180° about the x-axis in order to simulate a servicer (GOES-R) orbiting around the target, and additional simulation parameters are shown in Table 1.

There are three possible scenarios that occur while detecting the electron emissions from a target as shown in Fig. 3 for a -2500 V target: the beam is deflected and does not impact the target ($\alpha=120^\circ$), the beam impacts the target but the secondaries are not detected ($\alpha=30^\circ$), and the beam impacts the target and secondaries are detected ($\alpha=5^\circ, 170^\circ$). These regimes have been presented in J-3 and J-9 but the studies were not full scale and have not included the presence of a servicer. The deflection of the electron beam as a result of changing target potential is also demonstrated in Fig. 4. In essence, as the target potential becomes more negative, the electron beam experiences more deflection, and at potentials more negative than -2500V, the beam no longer impacts the target.

Figure 5 plots the resulting number of particles detected versus angle for each target potential. The target is detectable from approximately 0° to 50° and 150° to 180° . Outside this range, the beam either

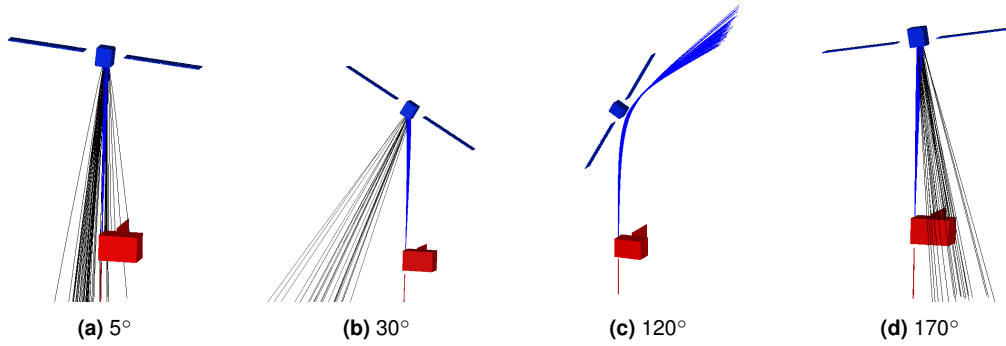


Figure 3: Electron beam (blue) and secondary electron (black) trajectories for different -2500 V target angles α

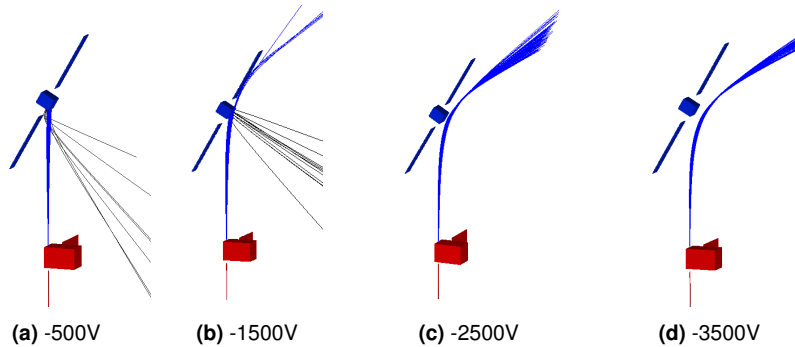


Figure 4: Electron beam (blue) and secondary electron (black) trajectories for target angle at $\alpha=120^\circ$

does not hit the target or does not generate secondaries with trajectories that impact the servicer. Thus, the optimal angles at which the target is detectable is as close to a normal incidence angle as possible. However, this may not be feasible during in-situ potential sensing, as the target may be rotating or may have a complex shape without an obvious flat surface to detect the potential. As a result, this SIMION model may be utilized to approximate the *source regions* of the target, or the regions in which electron emissions from the target may be detected. Furthermore, control algorithms may be developed using this SIMION model in order to make potential sensing using electrons more robust, as the servicer may adjust its position or electron beam properties in-situ in order to optimize detection of emissions.

The number of particles detected also increases as the potential of the target increases. This is likely the result of implementing a high energy electron beam, as the arrival energy E_{eff} of the beam is

$$E_{\text{eff}} = E_B + q_e V_{\text{tar}} - q_e V_{\text{serv}} \quad \text{for } q_e V_{\text{serv}} - q_e V_{\text{tar}} < E_B, \quad (1a)$$

$$E_{\text{eff}} = 0 \quad \text{for } q_e V_{\text{serv}} - q_e V_{\text{tar}} \geq E_B, \quad (1b)$$

where q_e is the elementary charge. In other words, as the target becomes more negative, the arrival energy of the beam decreases. The energy at which the secondary electron yield is highest for pure aluminum is 300 eV.¹ Therefore, as the arrival energy of the beam decreases, the energy approaches 300 eV and the yield increases. This demonstrates the importance of selecting an appropriate beam energy, as higher energy beams experience less deflection due to the electrostatic environment. However, if the target energy is low, a high energy beam may not be optimal for secondary emissions. Therefore, the beam energy must be selected such that the yield is sufficiently high, but the beam is not significantly deflected. This problem may also be countered through the use of UV lasers, as discussed in Section 8.1.3.

8.1.2 Heterogeneous Charging

The study of heterogeneous charging is discussed in in J-3 and J-9. Therefore, this task is considered complete.

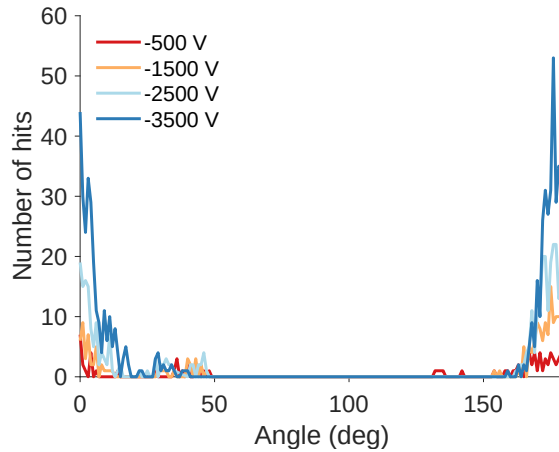


Figure 5: Number of SE particle impacts on the servicer versus target angle about the x-axis

8.1.3 UV Laser Electron Release

8.1.3.1 Proof of Concept Study

The employment of ultraviolet (UV) lasers is proposed to excite emission of photoelectrons from targets as conceptualized in Fig. 6. This eliminates a major source of uncertainty when exciting electron and x-ray emissions as photons are not susceptible to the electrostatic environment. Furthermore, UV lasers could be employed alongside a high energy electron gun to optimally excite photoemissions and x-ray emissions for sensing. The use of a UV laser also imposes a positive charge on the target, while the electron beam may be assumed to impose a negative charge. Therefore, the simultaneous use of a UV laser and electron beam may be used to control the charge of a target. A conceptual study of this method is investigated in C-15 and J-13.

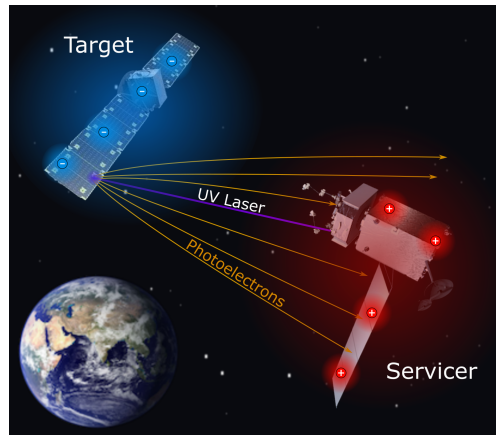


Figure 6: Conceptual representation of the photoelectron generation process

Photoelectrons can be regarded as a particular case of secondary electrons for which the impinging particle is a photon. The probability of emission of a photoelectron per collision is determined by the photoelectric yield²

$$Y[\omega, \phi, R] = Y^*[\omega, \phi][1 - R], \quad (2)$$

where $Y^*[\omega, \phi]$ is the yield per absorbed photon, ω is the photon energy (related to the wavelength λ through $\omega = hc/\lambda$, with h being Planck's constant), ϕ is in this case the photon incidence angle, and $R(\omega, \phi, \sigma)$ is the surface reflectance, which depends on the photon energy, incidence angle, and root mean square surface

roughness σ . The incidence angle effect on the yield is, in first order approximation and for $\cos \phi > 0.1$,³

$$Y^*[\omega, \phi] \approx \frac{Y^*[\omega, 0]}{\cos \phi}, \quad (3)$$

but since $1 - R(\omega, \phi, \sigma)$ also has the approximate dependence^{4,5}

$$1 - R(\omega, \phi, \sigma) \approx [1 - R(\omega, 0, \sigma)] \cos \phi, \quad (4)$$

both $\cos \phi$ terms cancel in Eq. 2. Therefore, $Y[\omega, R]$ is not, in first-order approximation, a function of the photon incidence angle.² This assumption is not appropriate for high incidence angles, as the reflection is heavily overestimated at angles close to 90° .³

The total reflectance is expressed as the sum of specular (R_s) and diffuse (R_d) reflectances

$$R(\omega, 0, \sigma) = R_s(\omega, 0, \sigma) + R_d(\omega, 0, \sigma), \quad (5)$$

which are defined as⁶

$$R_s(\omega, 0, \sigma) = R_0(\omega) \exp \left[\frac{-(4\pi\sigma)^2}{\lambda^2} \right], \quad (6)$$

$$R_d(\omega, 0, \sigma) = R_0(\omega) \frac{(4\pi\sigma)^2}{\lambda^2}, \quad (7)$$

with $R_0(\omega)$ being the normal reflectance of a perfectly smooth surface of the impacted material, $\lambda = hc/\omega$ the photon wavelength, h Planck's constant, and c the speed of light. The ratio of diffuse to specular reflectances is

$$\frac{R_d}{R_s} = \frac{(4\pi\sigma)^2}{\lambda^2} \exp \left[\frac{(4\pi\sigma)^2}{\lambda^2} \right], \quad (8)$$

implying that for small wavelength and large surface roughness the diffuse term is the major contributor to the total reflectance. Reflected photons experience negligible energy variations⁵ and generate photoelectrons at different surfaces.

Because photoelectrons are a particular case of secondary electrons, their angular emission distribution follows approximately Lambert's cosine law. Their maximum emission energy, however, follows the relation

$$E_{p,\max} = \omega - \varphi. \quad (9)$$

The Ly- α line (121.6 nm, 10.2 eV) is dominant in the solar spectrum, and hence the photoelectron energy will reach a theoretical maximum of 5-6 eV after accounting for a work function of 4-5 eV. Because photoelectrons have to propagate through the material, their emission energy distribution is usually centered around 1-3 eV.⁵ Therefore, a small positive spacecraft potential will act as a potential dwell and attract photoelectrons back to the surface.⁷

The photoelectric yield $Y[\omega, R]$ depends on several properties, including surface roughness, reflectance, and work function,⁸ which motivate its characterization in laboratory environments. Similarly to the photoelectric yield, the normal reflectance of a perfectly smooth surface should be characterized experimentally. Photoelectric yield and reflectance results for aluminum, gold, Kapton, and Teflon are presented in Fig. 7 as a function of the photon impact energy and Fig. 7. For all materials, the reflectance decreases and yield increases as the photon energy increases. Therefore, high energy photons are optimal for potential sensing.

The photoemission current induced by a UV laser is then

$$I_{\text{ph}} = q_e Y(\omega, R) n_{\text{ph}}. \quad (10)$$

where n_{ph} is the number of photons emitted by the UV laser per second. This is found as

$$n_{\text{ph}} = \frac{P_{\text{ph}}}{\omega}, \quad (11)$$

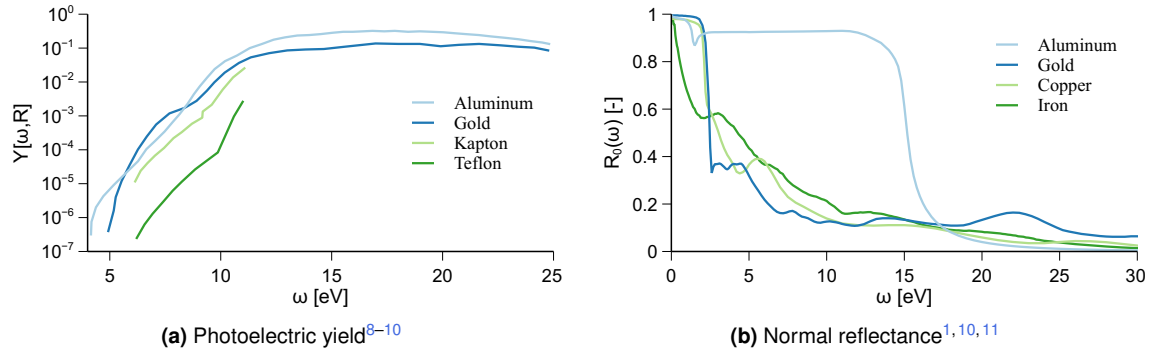


Figure 7: Photoemission properties for selected materials as a function of the impacting photon energy

where P_{ph} is the output power of the source and $\bar{\omega}$ is the average photon energy, computed as

$$\bar{\omega} = \int_0^{\infty} \omega S(\omega) d\omega. \quad (12)$$

It should be noted that for a positively charged spacecraft, the photoelectrons may not have sufficient energy to overcome the electrostatic barrier. The emissions will be attracted back to the spacecraft, cancelling the emitted current. Therefore, photoelectron current for a positively charged spacecraft is

$$I_{ph} = q_e Y(\omega, R) n_{ph} \exp\left(\frac{-q_e V}{k_B T_{ph}}\right) \quad \text{for } V > 0. \quad (13)$$

The photoelectron current induced by UV lasers as a function of output power and energy wavelength is shown in Fig. 8. The COTS lasers described in Table 2 are scattered on the figure as well, and their induced currents in aluminum targets range from 17nA to 261nA.

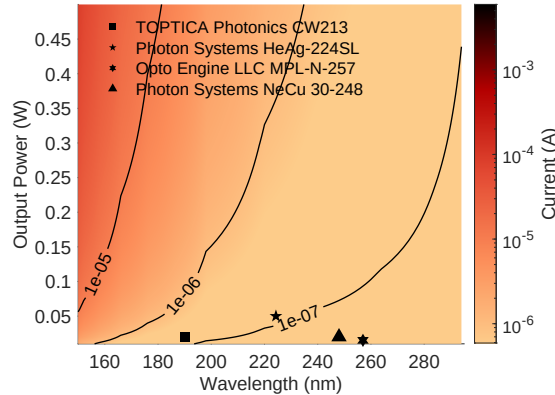


Figure 8: Photoelectron current as a function of UV laser energy wavelength and output power. COTS lasers listed in Table 2 are scattered for comparison.

8.1.3.2 Experimental Demonstration

Touchless potential sensing using photoemissions is investigated experimentally in J-13. The experimental setup pictured in Fig. 9 is installed in the ECLIPS vacuum chamber. Its geometrical configuration is almost identical to the one adopted in J-9 and includes a spacecraft-like electrode assembly composed of a $70 \times 70 \times 70 \text{ mm}^3$ cube and a $145 \times 60 \text{ mm}^2$ panel. The rotation of this structure is controlled by a stepper

engine and monitored by an incremental rotary high-vacuum Renishaw Tonic encoder. The assembly is irradiated by a Hamamatsu L10706-S2D2 UV light source that excites the emission of photoelectrons while a Retarding Potential Analyzer (RPA) located at least 95 mm away from the tip of the panel measures the outgoing flux of photoelectrons. Their energy spectrum is recorded for different angles, unveiling the spatial flux distribution.

The electrode assembly is connected to a Matsusada AU-30R1 high voltage power supply that imposes potentials between -100 and -900 V. The heading of the assembly spans from -40° to 100° , with 0° corresponding to a perfect alignment between the electron beam of the ECLIPS facility and the panel electrode. Although the electron beam is not used in this experiment, this reference point is kept in consistency with the results presented in J-9. The RPA forms an angle of $\sim 16^\circ$ with the electron beam axis. The SIMION framework discussed in J-9 is expanded to include photons and photoelectrons, and more details can be found in J-13.

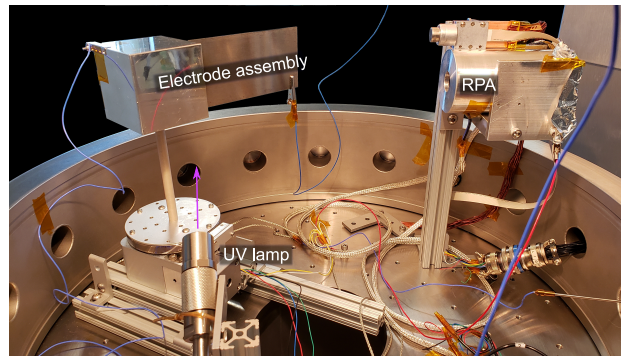


Figure 9: Photoemissions experimental setup

The trajectories of 500 randomly sampled photons are first propagated in Fig. 10 to characterize the flux of photoelectrons coming out of the electrode assembly. A single consecutive photon reflection is considered for -25° to illustrate this effect, but it is then removed from the other cases for clarity. The results obtained in this work are computed with an unlimited number of reflections. A brief study of the plots indicates that photoelectrons will be detected between -25° and 0° and between 75° and 100° . Reflected photons may also induce photoemission, but this may be considered a second-order effect due to the large volume of the vacuum chamber.

The described experimental assembly is set to -100 to -900 V with steps of -200 V while being irradiated by the UV source. The electrodes are rotated in steps of 2.5° while the electron signal is recorded. Figure 11 compares experimental results with numerical simulations performed in SIMION with and without diffuse photon reflections. In both cases, the model is able to identify the angles for which the photoelectron flux is detected, the overall trend with the applied electrode potential, and the order of magnitude of the signal. The most prominent difference with experimental results is observed in the peak between 75° and 100° , which is overestimated by one order of magnitude in the simulations. Figure 10 shows that this rotation corresponds to photon incidence angles close to 90° . Those fall beyond the validity range of Eq. 3, which heavily overestimates the photoelectron yield in this regime.³ However, this is not a critical concern for the technical applications presented in this paper, where the UV source and the detector are located on the same spacecraft and incidence angles close to the normal are expected.

Table 2: Representative parameters of COTS UV lasers.

Model	Divergence (mrad)	λ (nm)	$\bar{\omega}$ (eV)	P_{ph} (mW)
TOPTICA Photonics CW213	1	190	6.5	20
Photon Systems HeAg-224SL	4	224.3	5.5	50
Opto Engine LLC MPL-N-257	1	257	4.8	15
Photon Systems NeCu 30-248	4	248	5	50

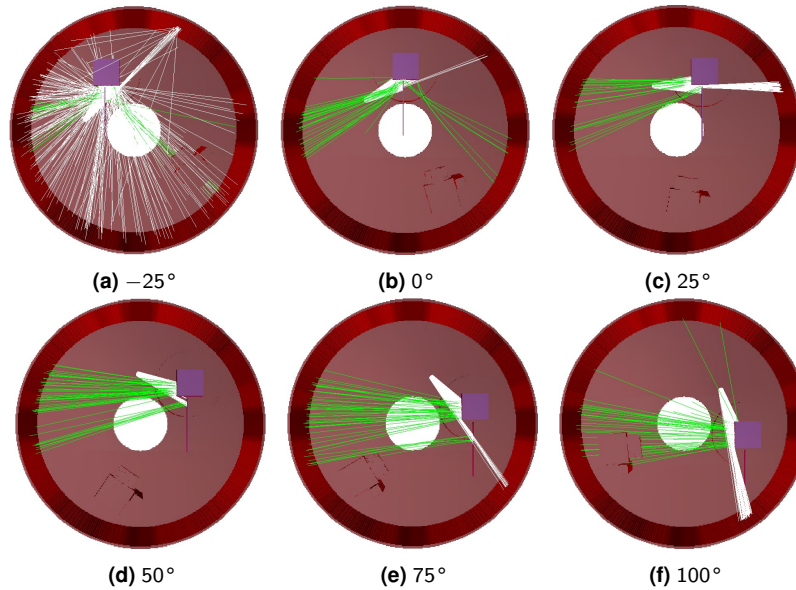


Figure 10: Overview of photoelectron trajectories (green) generated by the UV source (white) as a function of the electrode assembly heading angle. The first iteration of reflected photons is shown for -25° and removed for clarity in the other cases.

The elimination of photon reflections results in a qualitatively better agreement with the experiments, particularly around -30° and 60° . The small divergence induced by the inclusion of diffuse reflections, besides unexpected, is also indicative of small geometrical modeling errors. From a technical perspective, however, the similarity between both results supports the use of computationally-efficient models without particle reflections in spacecraft charging applications.

8.1.3.3 Material Identification

The use of multiple UV lasers to determine the work function of a surface material has been proposed in J-13. The photoelectric effect has been traditionally employed to determine the work function of surfaces in laboratory settings. The material is exposed to a coherent laser beam with predefined wavelength, and the energy of the emitted photoelectrons is characterized with an RPA. The stopping potential, defined as the value that matches the energy of photoelectrons and prevents their collection at the RPA, is obtained. This process is repeated for lasers of various energies, leading to a stopping potential versus laser photon energy plot. Following

$$E_{p,\max} = \omega - \varphi, \quad (14)$$

where ω is the energy of the UV laser and φ is the work function, the y-intercept is the work function of the material.¹² From a remote sensing perspective, the value of the work function can be employed to constrain the range of possible surface materials.

The same process could be utilized to approximately characterize the materials employed at the surface of a target spacecraft. The servicer would utilize UV lasers of varying wavelengths to excite photoelectrons, which are then collected by an RPA. The stopping potential is thus determined, and with it, the work function of the material. However, the flux of photoelectrons arrives at the servicer with an energy equal to the potential difference between the crafts plus the stopping potential. Given that the work function is of the order of 5 eV (see Table 3) and that the maximum touchless potential sensing accuracy achieved to date is of the order of 20 V, as shown in J-9, uncertainties in the stopping potential determination may render this approach unfeasible. Instead, multiple lasers with energies between 2 and 10 eV could be employed from lowest to highest energy, as represented in Fig. 12. In order to excite photoemissions, the energy of laser must be greater than the work function of the surface material. Therefore, the lowest energy laser that produces photoemissions serves as an estimate of the work function of the material.

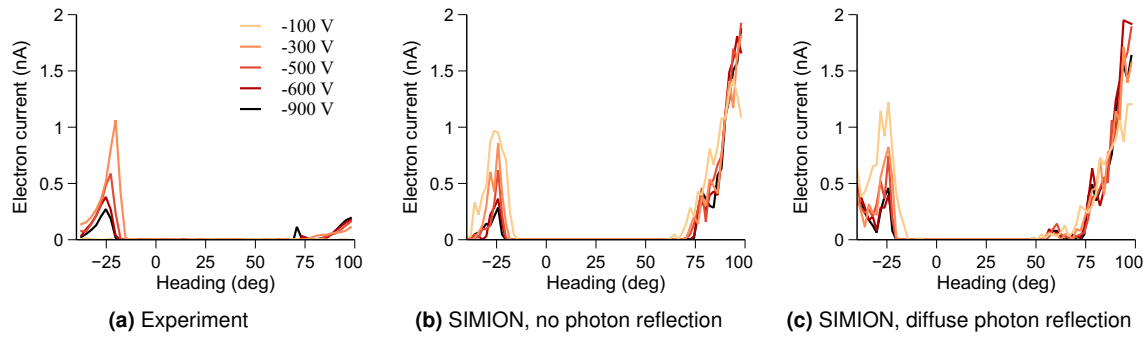


Figure 11: Comparison of experimental and simulated currents from the electrode assembly as a function of its potential and heading angle. The currents correspond to the electron flux entering the RPA in the ± 50 eV band around the electrode potential.

Table 3: Emission parameters for selected materials.^{1,13}

Material	Z	ϕ/χ [eV]	$\delta_{\max}$	$E_{\max}$ [eV]	E_1 [eV]	E_2 [eV]
Aluminum	13	4.20	1.0	300	300	300
Gold	79	5.47	1.4	800	150	>2000
Copper	29	5.10	1.3	600	200	1500
Iron	26	4.67	1.3	400	120	1400
Kapton	4.7	5.8	1.67	280	50	750
Teflon	3.8	4.1	2.4	350	50	180

8.1.4 Environmental Sensitivity

The environmental sensitivity when detecting secondary electron emissions in GEO has been addressed in J-1 and also as part of J-9.

The environmental sensitivity when detecting actively emitted photoelectrons is investigated in J-13. The photoelectron current must be stronger than the background plasma environment to ensure that its signal is detected by the RPA. The spacecraft charging scenario studied in J-5 is subsequently adopted to assess the feasibility of this process. Two generic spacecraft representing a servicer (GOESR, 0 V) and target (SSL1300, -2.5 kV) are simulated in MATLAB with 30 m of separation. Photoelectrons are then generated from a point on the target solar panel with energies of 1 eV and a Lambertian emission distribution, and their trajectories are propagated as they approach the target under the influence of the electrostatic environment approximated with the Multi-Spheres Method,^{14,15} discussed in J-8. Photoelectrons are displayed in Fig. 13 as it gets closer to the target. The area covered by the photoelectron flux at the servicer, A_{final} , is estimated from the average radius of the cross-section in the x-y plane, resulting in 2.42 m². Such a large area indicates that the system will be robust to small pointing errors of the UV laser or an imperfect characterization of the electrostatic environment. For an initial emission current $I_{\text{UV},0}$, the sensed current is found as

$$I_{\text{UV,sensed}} = I_{\text{UV},0} \frac{A_{\text{det}}}{A_{\text{final}}}, \quad (15)$$

where A_{det} is the area of the detector. For an initial current of 250 nA, or approximately equal to the current induced by the TOPTICA Photonics CW213 laser listed in Table 2, and a 2 cm radius RPA, the measured current is 0.13 nA. The incident electron current flux to an uncharged spherical spacecraft as a function of the electron velocity distribution in a Maxwellian plasma can be found as²

$$I(E_2) - I(E_1) = \frac{q_e n_e A}{(2\pi m_e)^{1/2} (k_B T_e)^{3/2}} \int_{E_1}^{E_2} e^{-E/k_B T_e} E dE \quad (16)$$

where A is the area of the sensor, m_e is the mass of an electron, and E is the electron energy, or $E = \frac{1}{2} m_e v_e^2$, assuming non-relativistic particles. The current is modeled for the worst case GEO environment

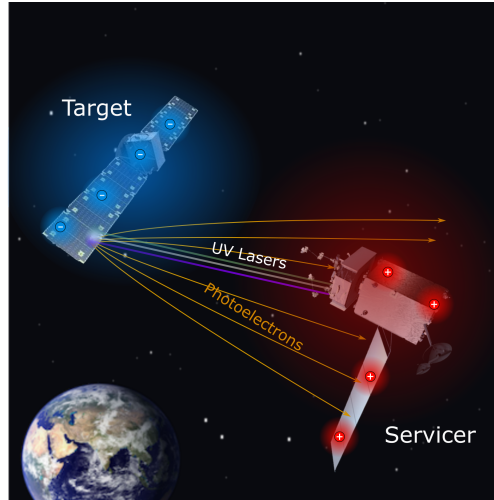


Figure 12: Conceptual representation of material identification with UV lasers

with electron and ion density of 30E5 m^{-3} , electron temperature of 12 keV and ion temperature of 30 keV.¹⁶ RPAs can filter between particles of different energies, allowing the electron spectrum to be captured. The energy resolution $\Delta E/E$ characterizes the detector and is chosen to be 8% for this study based on Ref. J-1 and 17. The current measured as a function of energy is shown in Fig. 13. The bin that contains the photoelectron current emitted from the target (2.5 keV) is approximately an order of magnitude larger than the neighboring bins, indicating that photoelectron-based touchless potential sensing is feasible even in worst-case GEO space weather conditions. If needed, an instrument with higher resolution or a collimator may be used to enhance the signal to noise ratio of the detector.¹⁸

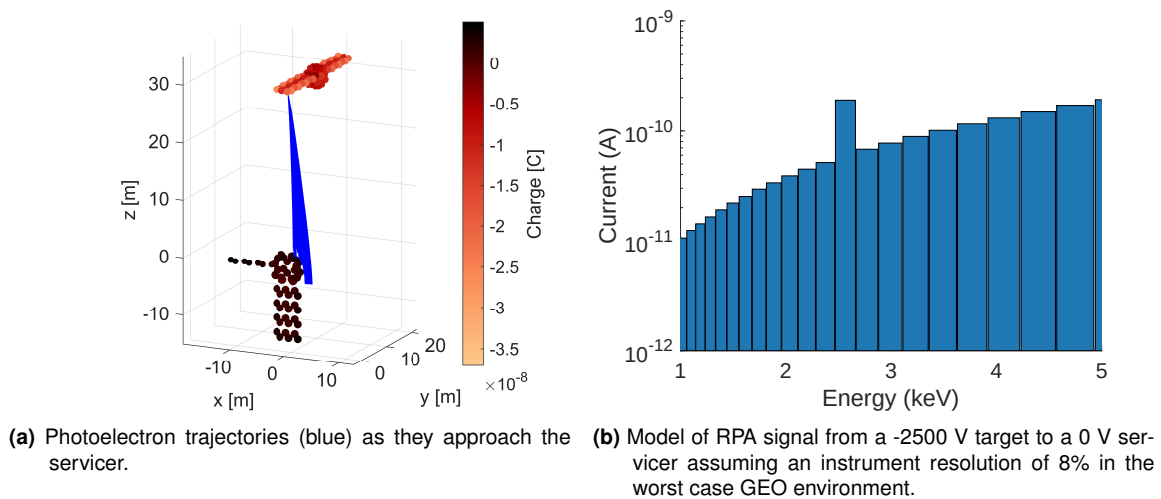


Figure 13: Photoemission environment sensitivity investigation.

The environmental sensitivity when detecting electron emissions in the cislunar environment is investigated in C-14 and C-23. The cislunar plasma environment can be divided into four regions: solar wind, magnetosheath, magnetotail lobes, and plasma sheet,¹⁶ and characteristic parameters of each region is shown in Table 4. The electron Debye length in the solar wind dayside and magnetosheath dayside regions have the smallest Debye lengths at approximately 10 meters, which is shorter than the 10-30 meter separation distance proposed for touchless potential sensing. Therefore, potential shielding in these regions cannot be neglected. This may limit the capability of a servicer to detect the potential of a target, as at

distances farther than the Debye length the emitted particles will not be attracted to the servicer and may not be detected. Thus, the servicer may not detect enough current to decipher the emissions from the ambient environment. Conversely, the electron Debye length is over 100 meters in the magnetotail lobes and plasmasheet, which is several times larger than the desired separation distance of 10-30 meters for touchless potential sensing. Therefore, the environmental sensitivity investigations in J-1, J-9, and J-13 is applicable to the magnetotail and plasmasheet regions.

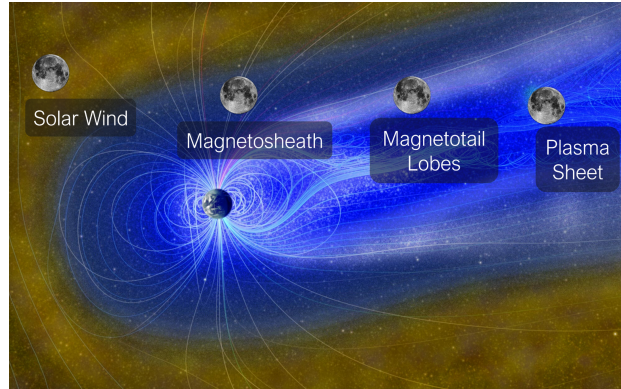


Figure 14: Cislunar Plasma Regions

Factors other than potential field shielding that may limit the ability of the servicer to detect the potential of the target are also considered, including the gyromotion and charged particle collisions. In the ambient solar wind at 1 AU, the interplanetary magnetic field (IMF) is approximately 4nT.¹⁹ The magnetic field in the magnetosheath is complex, and extensive studies have been conducted to parameterize it.²⁰ In general, the IMF may be amplified in the magnetosheath, and the magnetic field is estimated as 10nT based off data from Cluster 1.^{21,22} Using the parameters from Table 4 and assuming the electron velocity is entirely perpendicular to the magnetic field, the gyroradius of electrons is approximately 2.8 km in the dayside solar wind and 1.4 km in the dayside magnetosheath plasma. Separation distances of tens of meters are proposed for touchless potential sensing, which is significantly less than the gyroradius. Therefore, deflection from the servicer due to the magnetic field does not limit sensing capabilities. Furthermore, the mean free path of the particles is approximately 6.5E8 km in dayside solar wind and 10.8E8 km in dayside magnetosheath plasma, which is orders of magnitude larger than the proposed touchless potential sensing scale. Therefore, collisions also are not a limitation for sensing in these region.

Once it is determined that the gyromotion and collisions may be neglected, NASCAP-2k, a 3D spacecraft-plasma interaction code developed as a collaboration between NASA and the Air Force Research Lab, is utilized to investigate the feasibility of sensing in the cislunar solar wind region. The conclusions drawn from the simulations also apply to the dayside magnetosheath environment, as the effective Debye length is on a similar scale and the other factors investigated were also not found to be a concern in this region. Two active scenarios are investigated, eclipse and sunlit. The current measurements are simulated for a 3 cm RPA with energy resolution $\Delta E/E$ of 4%, also based on J-1. The target's electron emissions current is su-

Table 4: Cislunar regions average characteristic parameters¹⁶

Region	n_e (1/m ³)	T_e (eV)	v_i (km/s)	n_i (1/m ³)	T_i (eV)	λ_D (m)
Magnetotail Lobes	2.0E5	48	170	2.0E5	290	115.2
Plasmasheet	2.2E5	150	110	2.0E5	780	194.1
Magnetosheath Dayside	9.5E6	18	350	8.0E6	94	10.2
Solar Wind Dayside	6.0E6	11	420	6.0E6	7	10.1

perimposed on the ambient current, simulating the distribution of current densities measured by a servicer's RPA. The signal is assumed to be differentiable from the noise if it is approximately 1 nA larger than the ambient environment, based on J-1. The resulting current measurements are shown in Fig. 15. In eclipse, the emitted secondary electron current is orders of magnitude larger than the ambient environment, and in sunlight the measured current is approximately 13 nA larger than the ambient environment. Therefore, touchless potential sensing is feasible in cislunar space.

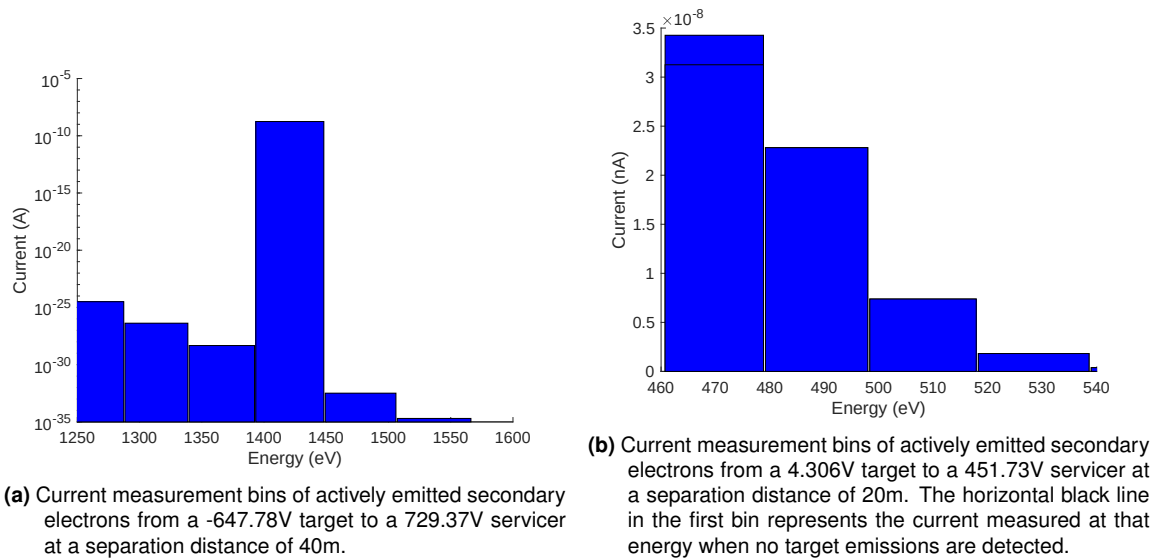


Figure 15: Current measurement bins of actively emitted secondary electrons in cislunar solar wind regions. Measurements are binned for an RPA with energy resolution $\Delta E/E$ of 4%.

8.1.5 Experimental Analysis

8.1.5.1 Chamber Characterization

The chamber characterization was completed and published in J-7.

8.1.5.2 Enhanced Electron Sensor

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

8.1.5.3 3D Complex Shape Experiments

The electron sensing method for 3D complex shapes has been addressed with vacuum chamber experiments using an aluminum sphere and cylinder as targets. Previous experiments have been conducted using flat plates and cubes; however spacecraft can have diverse shapes. The effectiveness of the secondary electron method depends on the trajectory of excited electrons, which is influenced by the shape of the target object, as discussed in Section 8.1.1. To validate the secondary electron method with different shapes, aluminum sphere and cylinder spacecraft primitives were made and used for vacuum chamber experiments. The electrostatic potential of targets with -0.8 kV, -1 kV, -1.5 kV, and -2 kV were measured with a resolution of 20 V using the secondary electron emissions. These potentials were held constant using the high voltage power supplies described in J-7 to ensure accurate results. Figure 16 shows the results for a charged sphere and cylinder with potentials of -1 kV and -2 kV. While only the results for potentials -1 kV and -2 kV are shown here, similar results were found for -0.8 kV and -1.5 kV. It can be seen that as long as the beam energy and current is sufficient to generate measurable secondaries, the secondary electron

method reliably measures the electrostatic potential of targets with more complex electron trajectories than that of a cube and a flat plate.

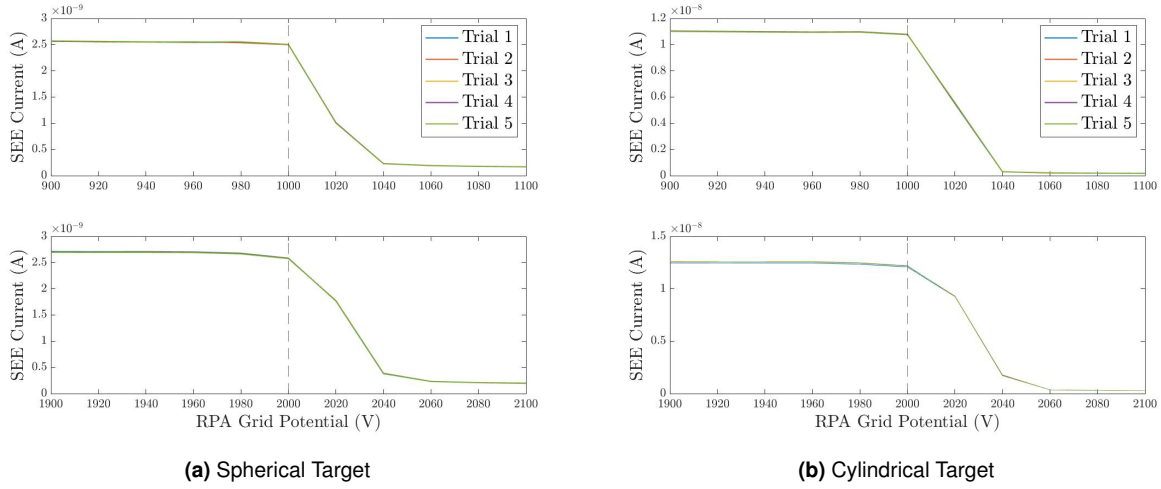


Figure 16: Using the secondary electron method with a 4 keV and 10 μ A electron beam, the electrostatic potential of a cylinder with a -1 kV (Top) and a -2 kV (Bottom) is measured with a resolution of 20 V.

8.1.5.4 Experimental Material Identification

The ideas discussed in Sec. 8.1.3.3 require a set of dedicated experiments and hardware, and therefore fall beyond the scope of this project. However, experiments analogous to those conducted in Sec. 8.1.1 are being carried out in 2022 using an UV source. The goal of this ongoing experimental campaign is to build a database that will be used to validate new multi-particle simulation frameworks where both the UV photons and the secondary electrons will be considered. The simulation of photons involves numerous coupled physical mechanisms that require special attention. As usual, the goal is to find the balance between computational efficiency and physical accuracy that will enable new applications.

8.2 Thrust 2: X-Ray Based Sensing

8.2.1 Material Identification

8.2.1.1 Bremsstrahlung models for various materials

The Bremsstrahlung models have been discussed in the 1st annual report and also in C-1 and J-10. For pure metals such as aluminum, copper or titanium, the Bremsstrahlung model used for the theoretical x-ray spectra is²³

$$\Delta I = G\sqrt{Z} \frac{E_0 - E}{E} \left(-73.90 - 1.2446E + 36.502 \ln Z + \frac{148.5E_0^{0.1293}}{Z} \right) \times \left[1 + (-0.006624 + 0.0002906E_0) \frac{Z}{E} \right] \Delta E \quad (17)$$

where ΔI is the intensity (number of photons per unit time) detected per incident electron with energies between E and $E + \Delta E$ when a sample of atomic number Z is irradiated with electrons of energy E_0 . The factor G involves losses due to absorption, backscattering, detector efficiency and solid angle. The parameters that depend on the material used are thus Z and G . The atomic number Z for pure metals is well known and available in the literature. The G factor for aluminum and copper are found in the literature,²⁴ while for titanium it was obtained from the set of experimental data from Ref. 25. The Z and G parameters for aluminum, copper and titanium are shown in Table 5.

Material	Z	G
Aluminum	13	3.35×10^{-7}
Copper	29	9.78×10^{-7}
Titanium	22	3.20×10^{-7}

Table 5: Material parameters for Bremsstrahlung spectrum

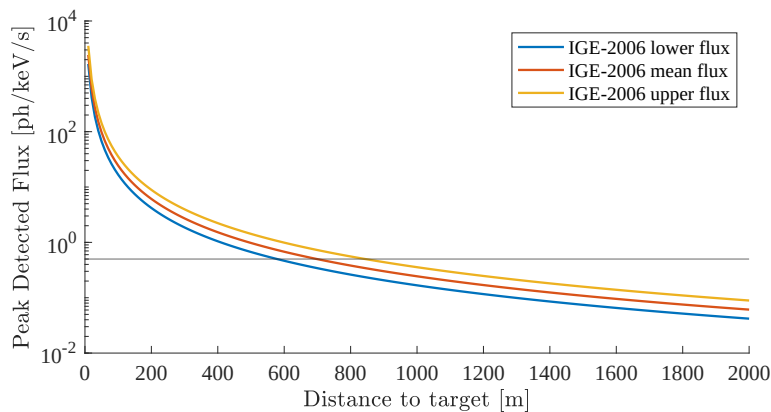
8.2.1.2 Sensitivity to Distance with passive sensing

The sensitivity to distance with passive sensing for debris sensing and space situational awareness applications has been addressed in the previous annual report and also in [C-1](#) and [J-10](#). The sensitivity of the passive x-ray method in terms of material identification was investigated in the 3rd project year.

The x-ray spectrum generated by a spacecraft in GEO is simulated as described in [C-1](#), using IGE-2006 models for lower, mean and upper electron fluxes. The maximum distance at which a neighboring spacecraft can be detected, and material identification can be performed, is given by the signal-to-noise ratio observed at the characteristic peak, defined as

$$\text{SNR} = \frac{\mu}{\sigma} \quad (18)$$

where μ is the signal at the characteristic peak and σ is the square root of the variance of the noise. To determine the minimum SNR value needed to identify the characteristic peak, a case of a 5 m² aluminum spacecraft in GEO with mean electron flux conditions was simulated. The target spacecraft is assumed to be not charged, at a distance of 100 m, and the detector is a SiPIN diode with a sensor area of 75 mm². The noise is modeled as additive white Gaussian noise with standard deviation given by the different SNR values. The simulated noisy signal is processed with a low-pass filter and an algorithm is applied to find the characteristic peak. The algorithm failed to obtain the characteristic peak for SNR between 2 and 3. An analysis of the noise levels obtained experimentally in the ECLIPS chamber shows that for the Amptek X-123 SiPIN detector used, the typical noise has bounds of $3\sigma = 10$ ph/keV for a 20 s collection time, or $3\sigma = 0.5$ ph/keV/s. Thus, to obtain an SNR = 3, the intensity of the characteristic peak is $\mu = 0.5$ ph/keV/s. The variation of the intensity of the characteristic peak with distance is shown in [Fig. 17](#) for a 5 m² aluminum spacecraft in GEO. The black horizontal line marks the SNR = 3 limit for the given detector noise levels. This results in a distance of 580 m, 700 m, and 850 m for the lower, mean, and upper electron flux models, respectively.

**Figure 17:** Photon flux at the characteristic peak with distance

8.2.2 Environmental Sensitivity

The environmental sensitivity has been investigated thoroughly in the 1st year. For Solar spectrum impact, see [C-1](#) and [J-10](#). The simulation of plasma generated Bremsstrahlung and the theory of the passive x-ray method are discussed in [C-1](#). For the experimental validation of the passive x-ray method, see the year 2 report.

8.2.3 Complex Shapes

8.2.3.1 Simulation of incident beam response

The electron beam expansion and deflection for spacecraft charging applications have been discussed in the 1st annual report as well as in [C-4](#) and [J-5](#). The SIMION particle tracing software framework (see Sec. [8.1.1](#)) is used to verify the electron beam trajectory in the vacuum chamber during our experiments. This is especially helpful for experiments with complex shapes, as the landing location of the electron beam on the target object is non-trivial due to the complex electric field, as discussed in Sec. [8.2.4.3](#). The response of the electric potential of the target object to the incident beam is discussed in Sec. [8.3.3](#). The electron beam expansion and deflection is also investigated in [C-23](#), which is discussed in Section [8.1.1](#).

8.2.3.2 Active vs passive sensing summary

The active x-ray sensing method requires an electron gun on the servicing spacecraft that is aimed at the target object and excites x-rays. This method utilizes the fact that x-rays are only excited with energies up to the landing energy of the incident electrons. By finding the maximum energy of the x-ray spectrum, one can estimate the landing energy of the electrons and infer the electric potential of the target object if the potential of the servicing craft is known. The passive x-ray method uses the x-rays excited by the ambient plasma environment to estimate the electric potential of the target object. By measuring the electron energies at the servicing spacecraft, one can compute a theoretical x-ray spectrum and compare the number of photons with the actually detected number of photons to infer the electric potential. While the active method requires an electron beam, the passive method requires means to measure the electron population. Due to the significantly higher current of the electron beam compared to the ambient plasma currents, the ambient plasma does not interfere with the active method (see previous annual report and [C-1](#), [J-10](#)).

8.2.3.3 Spatial resolution

This task is discussed in Sec. [8.2.4.4](#) and [8.3.3](#).

8.2.4 Experimental Analysis

8.2.4.1 Angle versus accuracy of X-ray Landing Energy

This task was completed in the 2nd project year and is discussed in the year 2 report.

8.2.4.2 Simulate environment experimentally

This task was completed in the 2nd project year and is discussed in the year 2 report.

8.2.4.3 Sensing of charge on multiple surfaces

The work in this section is presented in [C-21](#) and builds upon the work discussed in Sec. [8.2.4.4](#) and publication [J-11](#). The experiments in Sec. [8.2.4.4](#) and [J-11](#) included a target object consisting of two components that were both made of aluminum. In contrast, the target object used in the experiments in [C-21](#) consists of three components, each made of a different material and charged to a dissimilar potential, as shown in Fig. [18](#). This enables investigating the effects of target material inhomogeneity and differential charging on the robustness of the x-ray based electric potential sensing method. Aluminum, titanium and copper components are used, resulting in characteristic x-ray peaks with energies between 1.5 and 8.9 keV in the recorded x-ray spectrum. The presence of characteristic peaks in the upper energy part of the x-ray spectrum provides some challenges for the potential estimation as they have to be filtered out from

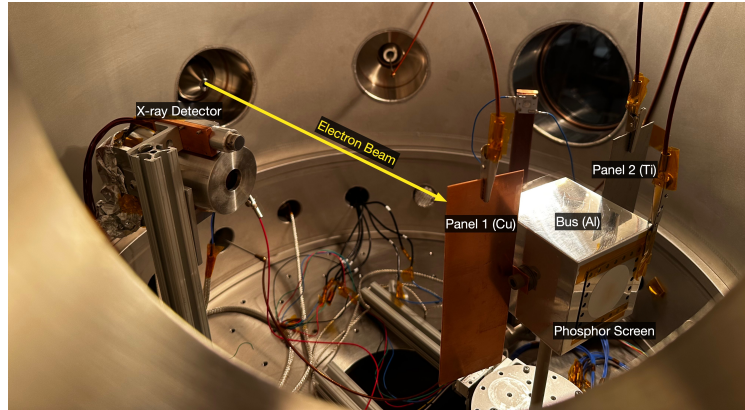


Figure 18: Experimental Setup with three components

the recorded spectrum. This interferes with the linear least squares that is used for both the estimation of the electric potential and for the computation of the theoretical x-ray spectrum that is needed to estimate multiple potentials simultaneously from one recorded x-ray spectrum.

While the estimation of the first potential (the potential that is the least negative or most positive) is solely based on data from the recorded spectrum, the estimation of any additional potentials requires the computation of theoretical spectra. The dependence of the following estimations on the theoretical spectra also affects the accuracy of the estimations. Additionally, the errors of each estimation affect the next estimation, so as the errors pile up, the estimations become less accurate with every step. While the measurement of multiple potentials may be somewhat inaccurate in terms of the estimated potentials, the implemented method allows for the identification of differential charging on a target object.

8.2.4.4 Attitude Dependent performance analysis

Experiments with the aim of estimating the electric potentials of complex-shaped differentially charged objects were started in project year 2 and presented in C-11. The test object was a spacecraft shape primitive with two components that are charged to different potentials, as shown in Fig. 19. The experiments show that the orientation of the target object and the deflection of the electron beam affect the landing location of the electron beam. This is also confirmed by numerical simulations with SIMION. Thus, the orientation of the object affects which component's potential is measured. Using a focused electron beam with a small landing spot size helps to excite x-rays from only one component at a time. For such an electron beam configuration and a non-rotating object, several x-ray spectra taken from different angles are required to measure the potential of multiple components.

To estimate multiple potentials simultaneously from a single x-ray spectrum, the beam must hit multiple components during the sensing time frame. However, with the conventional x-ray spectroscopic method that was used so far, only the higher potential of the two components can be measured. That is, only the potential that is either less negative or more positive is detected. A new approach was proposed in C-11 that uses theoretical x-ray models and the principle of superposition of individual x-ray spectra to measure multiple potentials using a single recorded x-ray spectrum.

Dynamic experiments were conducted in project year 3 and discussed in C-13 and J-11 with a rotating target object (Fig. 19) to excite x-rays from multiple components during the sensing time frame. The target object is rotated 30° with different starting angles, and the stepper motor speed is chosen such that this takes about 20 seconds. While the object is rotating, an x-ray spectrum is recorded using an accumulation time of 20 seconds, meaning that x-rays of all energies between a few eV and 20 keV are recorded simultaneously during a time frame of 20 seconds. Thus, if the electron impacts different components during the rotation of the target object, the resulting x-ray spectrum includes x-rays excited from both components. The experiments conducted include a bus potential of $\Phi_B = -3$ kV and panel potentials of $\Phi_P = 0$ kV and $\Phi_P = -1$ kV.

Figure 20 shows the estimated potential for a bus potential of -3 kV and panel potential of -1 kV as

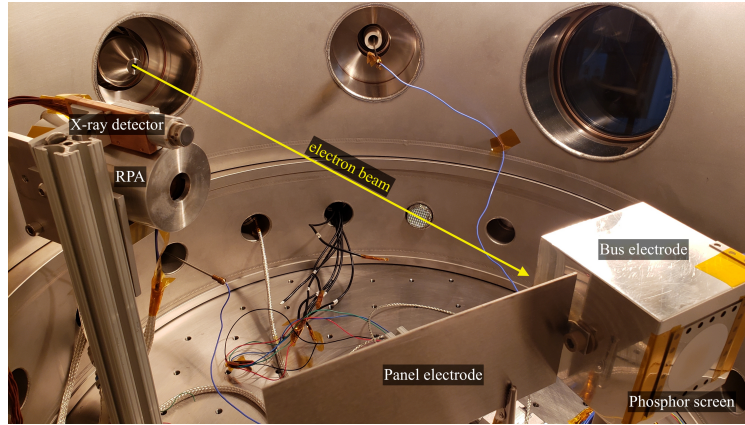


Figure 19: Experimental Setup with two components

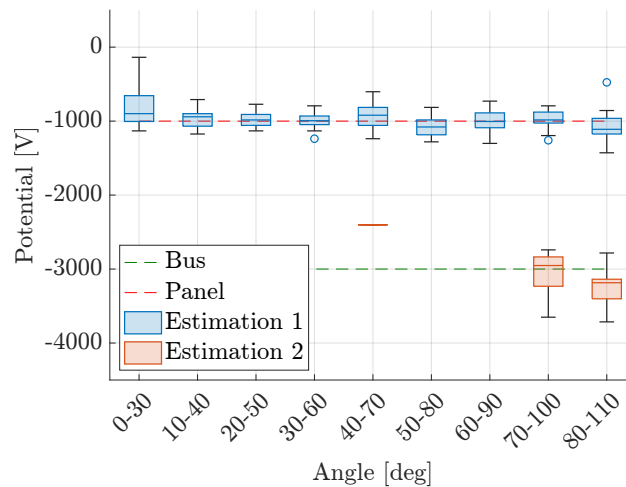


Figure 20: Dynamic Experiment Results. $\Phi_B = -3000$ V, $\Phi_P = -1000$ V

a function of the orientation of the target object. An angle of 0-30 deg, for example, means that the target object is rotating between 0 and 30 degrees during the 20 second x-ray accumulation time. Estimation 1 accurately measures the potential of the spacecraft panel over all angles. Estimation 2 measures the potential of the cube for higher angles, where the beam impacts the cube. The reason why the second estimation is not as accurate is the low intensity of the residual spectrum. In one case ($40^\circ - 70^\circ$), a second estimation is attempted for one of the 20 samples, even though no second potential should be detected for these angles. Figure 21 shows the experimental results for a bus potential of -3 kV and panel potential of 0 kV. The results are similar to Fig. 20. The first estimation measures the potential of the panel relatively accurately, while the second estimation is less accurate due to the low intensity of the residual spectrum. In both Fig. 20 and Fig. 21, the presence of a second potential is detected for orientations between 70° and 110° .

The results are promising for the electric potential estimation of tumbling objects where the landing location of the electron beam changes during the recording time frame.

8.3 Thrust 3: Integrated Sensor Filter

8.3.1 Develop Fused Charge Sensing Filter

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

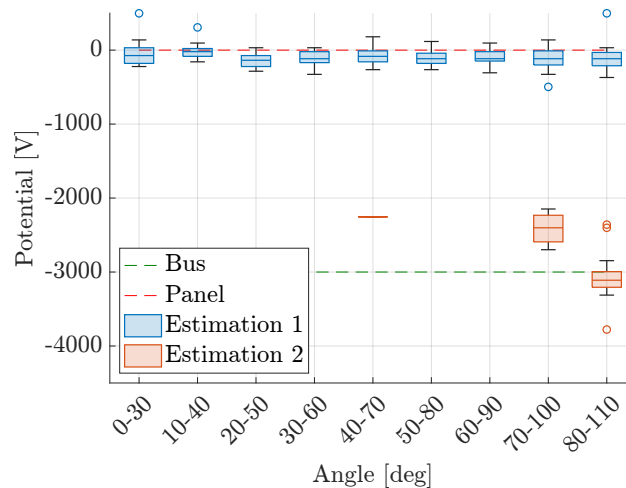


Figure 21: Dynamic Experiment Results. $\Phi_B = -3000$ V, $\Phi_P = 0$ V

8.3.2 Pulsed Active Charging Study

Methods for remotely measuring an object's electric potential have been explored and experimentally validated in vacuum chamber conditions in J-9 J-3 and 26, 27. To use these methods however, an additional current is applied to the target by a continuously emitting electron beam, altering the potential of the target. Depending on the geomagnetic activity, the electron beam current can increase the magnitude of the target potential by kilo-volts. The use of a pulsed electron beam was proposed to reduce the net current applied to the target. Simulations of a continuous electron beam and pulsed electron beam applied to a target were conducted in Ref. 28. It was discovered that the potential of the target will decrease while being sensed with an electron beam, especially when eclipsed. Also, by pulsing, the energy and current parameters of the beam can remain unchanged while the net current applied to the target is reduced, allowing for more accurate measurements of a target's natural potential. Figure 22 shows a simulation of a target and servicer in eclipse charging due to electron beam impacts and emission respectively. The plot on the left shows that a continuous electron beam can charge the target more than ten thousand volts while the plot on the right shows a pulsed beam with the same beam energy and current will charge the target less than 200 V.

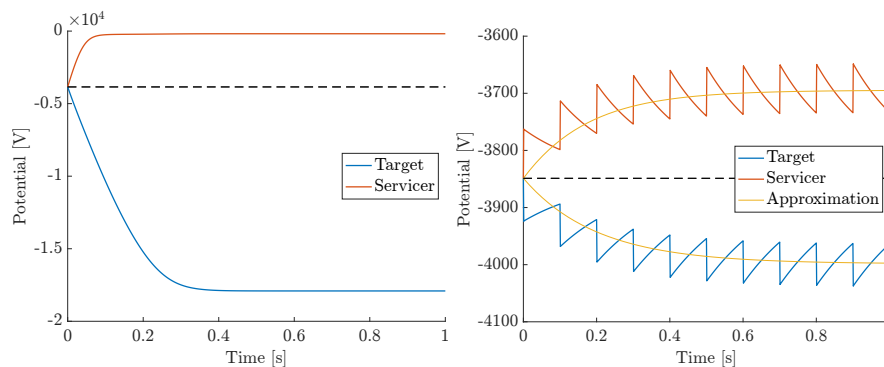


Figure 22: A simulated comparison between a continuous beam (Right) and a pulsed beam (Left). The electron beam energy and current are 20 keV and 10 μ A and the pulsed beam has a frequency of 10 Hz and a duty cycle of .01.

To explore the charging effect caused by the electron beam experimentally, modifications to the vacuum chamber had to be added; the spacecraft primitives used in the experiments have very low capacitance, such that they charge instantly. To account for this, an RC circuit was designed and connected outside the vacuum chamber. The additional circuit increases the total capacitance of the system, simulating a realistic

spacecraft capacitance and extending the time it takes to charge. This allows for the transient behavior to be measured. By including a resistor, the response of the space environment can be simulated as well. A relationship between the environmental currents experienced by a spacecraft and the RC circuit was derived and used to determine the values of the resistor and capacitor such that these environmental currents are approximated by the resistor. Reference C-17 presents this additional circuit and its derivation. A comparison between the spacecraft charging model and experimental results with the circuit demonstrated that, for smaller deviations from the natural potential, the behavior of the circuit and the natural currents from the spacecraft charging model yield similar charging behavior.

Reference C-22 experimentally explores the pulsing capabilities of the electron beam and the charging behavior between a pulsed and continuous beam. It was determined that a pulsed electron beam is capable of exciting secondary electrons from the target's surface such that the target's electric potential can be measured without modifying the secondary electron method: for a spacecraft shape primitive with a constant potential, a pulsed electron beam was able to correctly measure a -500 V potential with varying pulse frequencies. Additionally, experiments comparing the transient charging behavior of the spacecraft primitive exposed to $3\text{ }\mu\text{A}$ pulsed beam with a duty cycle of 0.5 and a $1.4\text{ }\mu\text{A}$ continuous beam demonstrates that scaling the continuous beam by the duty cycle yields the similar results as the pulsed beam as shown by Fig. 23. This suggests that a pulsed beam and a scaled continuous beam apply the same net current to the target object.

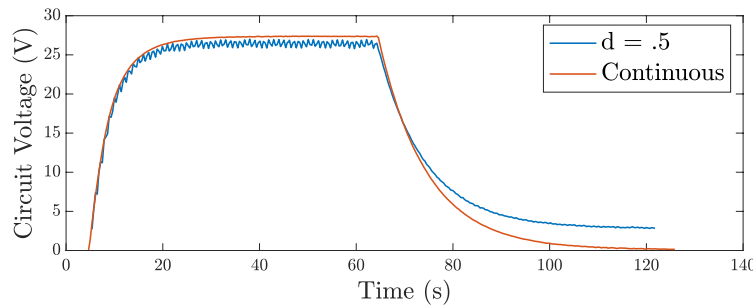


Figure 23: A comparison of the charging response to a pulsed beam with a current of $3\text{ }\mu\text{A}$ and duty cycle of .5 to a continuous beam with a current of $1.4\text{ }\mu\text{A}$. The charging behavior for both beams is nearly identical while the discharging behavior, while similar, varies slightly.

Finally, the continuous and pulsed beam with a duty cycle of 0.01 were applied to the target using the same beam parameters: a current of $3\text{ }\mu\text{A}$ and beam energies of 4 keV and 5 keV. As shown by Figure 24, the continuous beam charges the object up to 30 V while the pulsed beam marginally charges the object. In fact, it was determined that, for these parameters, the pulsed beam does not significantly charge the object for energies up to 6 keV. With these experiments, it is shown that a pulsed beam does reduce the applied current while still being capable of measuring the electrostatic potential of a target. Also, that for a given set of electron beam parameters, the current is low enough that there is not enough current to significantly charge the object. This suggests that using a pulsed beam would be an effective method for reducing target charging while still yielding accurate results for the secondary electron method.

8.3.3 Time and Spatial Resolution

To detect the presence of multiple potentials in a realistic scenario of application, the electron beam needs to irradiate the corresponding component for a sufficient amount of time. This determines how fast the target spacecraft can rotate such that a measurement is still possible. Some of the residual spectra of the experiments from Sec. 8.2.4.4 have a total number of photons as low as $N_{\min} = 20,000$. Taking this as the minimum required value for the residual spectrum to detect the second potential, the maximum rotational rate is determined by the flux of photons arriving at the detector. Using theoretical x-ray models with a distance between the detector and the target of $L = 15\text{ m}$ and a detector area of $A_{\text{det}} = 70\text{ mm}^2$, a count rate of about $f = 3,400$ photons per second is found for an electron beam current of $I_{EB} = 100\text{ }\mu\text{A}$ and a beam energy of 10 keV. Therefore, the target spot needs to be irradiated for at least $t_{\min} = N_{\min}/f = 5.9\text{ s}$. Assuming for simplicity a spherical aluminum spacecraft of $R_{\text{SC}} = 1\text{ m}$ radius and a characteristic co-

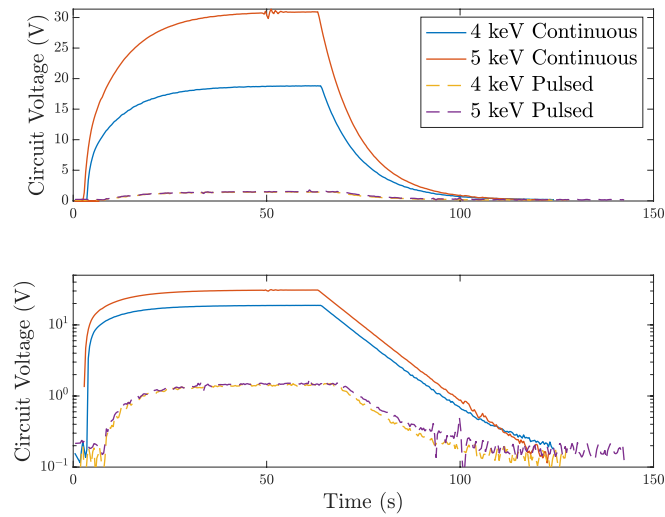


Figure 24: A comparison between a continuous and pulsed beam with $3 \mu\text{A}$ and energies of 4 keV and 5 keV. The beam is pulsed with a frequency of 1 kHz and $10 \mu\text{s}$ pulse width. The values between the plots are the same; however, the bottom has log scale on the y axis. The y-axis shows the magnitude of the circuit voltage.

centered beam spot radius of $R_b = 1.5 \text{ cm}$ at 15 m, the maximum rotational rate that allows the collection of x-ray photons from a small component with a width of $L_t = 20 \text{ cm}$ located on the equator of the sphere becomes

$$\omega_{\max} = \frac{(L_t + 2R_b)/t_{\min}}{R_{\text{SC}}} \quad (19)$$

which returns 2.2 deg/s for the problem under consideration. Larger components will be irradiated for longer times, increasing the maximum allowed rotational rate. A Silicon Drift Detector (SSD) with an area of 70 mm^2 is the largest x-ray detector available from Amptek and is capable of count rates over 1,000,000 counts per second. The maximum rotational rate can be increased by using several detectors to increase the effective detector area. In the case of the experimental setup used in Sec. 8.2.4.4, the beam impacts the cube (the component with the second potential) over more than 20 degrees, allowing for rotational rates of more than 5 deg/s with a 6 mm^2 detector and a beam current of $1 \mu\text{A}$.

8.3.4 Relative GNC Implications

This task was completed in the 2nd project year and is discussed in the year 1 and year 2 report.

8.4 Associated Publications

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

8.4.1 Conference Papers

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

- C-4 Á. Romero Calvo, G. Cano Gómez and H. Schaub, "[Electron Beam Expansion And Deflection Uncertainty For Active Charging Applications](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1540](#)
- C-5 M. T. Bengtson, K. T. Wilson and H. Schaub, "[Broad-Spectrum Electron Gun for Laboratory Simulation of Orbital Environments](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1539](#)
- C-6 K. T. Wilson, M. T. Bengtson, J. Maxwell, Á. Romero Calvo and H. Schaub, "[Characterization of the ECLIPS Space Environments Simulation Facility](#)," AIAA SciTech, Nashville, TN, Jan. 11–15, 2021.
doi:[10.2514/6.2021-1538](#)
- C-7 K. T. Wilson and H. Schaub, "[Constrained Guidance For Spacecraft Proximity Operations Under Electrostatic Perturbations](#)" IEEE Aerospace Engineering Conference, Big Sky, Montana, March 6–13, 2021
- C-8 J. Hammerl and H. Schaub, "[Effects of Electric Potential Uncertainty on Electrostatic Tractor Relative Motion Control](#)," 8th European Conference on Space Debris, Darmstadt, Germany, April 20–23, 2021
- C-9 J. Hammerl and H. Schaub, "[Debris Attitude Effects on Electrostatic Tractor Relative Motion Control Performance](#)," AAS/AIAA Astrodynamics Specialist Conference, Big Sky, MT, August 8–12, 2021
- C-10 Á. Romero Calvo, J. Hammerl, and H. Schaub, "[Touchless Potential Sensing Of Complex Differentially-Charged Shapes Using Secondary Electrons](#)," AIAA SciTech Forum, San Diego, CA, January 3-7, 2022.
doi:[10.2514/6.2022-2311](#)
- C-11 J. Hammerl, Á. Romero Calvo, A. López, and H. Schaub, "[Touchless Potential Sensing Of Complex Differentially-Charged Shapes Using X-Rays](#)," AIAA SciTech Forum, San Diego, CA, January 3-7, 2022.
doi:[10.2514/6.2022-2312](#)
- C-12 J. Hammerl and H. Schaub, "[Uncertainty Analysis of the Electrostatic Tractor Control Performance](#)," AAS Guidance and Control Conference, Breckenridge, CO, Feb. 3–9, 2022
- C-13 J. Hammerl, A. López, Á. Romero Calvo and H. Schaub, "[Measuring Multiple Potentials of a Rotating and Differentially-Charged Object Simultaneously Using X-rays](#)," 16th Spacecraft Charging Technology Conference, Virtual, April 4–8, 2022
- C-14 K. Champion and H. Schaub, "[Effective Debye Lengths in Representative Cislunar Environment Regions](#)," 16th Spacecraft Charging Technology Conference, Virtual, April 4–8, 2022
- C-15 Á. Romero Calvo, K. Champion and H. Schaub, "[Touchless Spacecraft Potential Sensing Using Energetic Electron Beams And Active Photoemission](#)," 16th Spacecraft Charging Technology Conference, Virtual, April 4–8, 2022
- C-16 A. López, J. Hammerl and H. Schaub, "[Detecting Space Objects With Binary Wide Field Of View X-Ray Sensing](#)," AAS Astrodynamics Specialist Conference, Charlotte, North Carolina, August 7–10 2022. Paper No. AAS 22-602
- C-17 J. Walker, J. Hammerl and H. Schaub, "[Design and Analysis for Experimental Validation of Touchless Charge Control Testing](#)," AAS Astrodynamics Specialist Conference, Charlotte, North Carolina, August 7–10 2022, Paper No. AAS 22-661
- C-18 J. Hammerl and H. Schaub, "Spacecraft Charging Considerations for On-Orbit Servicing and Debris Mitigation in High Earth Orbit," 2nd International Stardust Conference, ESA European Space Research and Technology Centre (ESTEC), Noordwijk, Netherland, Nov. 7–11, 2022

- C-19 A. López, J. Hammerl and H. Schaub, "[Dynamic Detection of Nearby Space Objects with Binary Wide Field of View X-Ray Sensing](#)," AIAA Science and Technology Forum and Exposition (SciTech), National Harbor, Maryland, January 23–28, 2023.
- C-20 K. Champion and H. Schaub, "[Spacecraft Wake Formation in Cislunar Plasma Regions](#)," AIAA Science and Technology Forum and Exposition (SciTech), National Harbor, Maryland, January 23–28, 2023.
- C-21 J. Hammerl, A. López and H. Schaub, "[Electric Potential Estimation of Inhomogeneous and Differentially Charged Objects Using X-Rays](#)," AIAA Science and Technology Forum and Exposition (SciTech), National Harbor, Maryland, January 23–28, 2023
- C-22 J. D. Walker, J. Hammerl and H. Schaub, "[Experimental Concept Validation of Touchless Electric Potential Sensing using a Pulsed Electron Beam](#)," AIAA Science and Technology Forum and Exposition (SciTech), National Harbor, Maryland, January 23–28, 2023
- C-23 K. Champion, Á. Romero Calvo and H. Schaub, "[Large Scale Particle Tracing Simulation For Touchless Potential Sensing](#)," AIAA Science and Technology Forum and Exposition (SciTech), National Harbor, Maryland, January 23–28, 2023

8.4.2 Journal Papers

- J-1 M. Bengtson, J. Hughes and H. Schaub, "Prospects and Challenges for Touchless Sensing of Spacecraft Electrostatic Potential Using Electrons," *IEEE Transactions on Plasma Science*, Vol. 47, No. 8, 2019, pp. 3858–3866.
doi:[10.1109/TPS.2019.2912057](#)
- J-2 K. T. Wilson and H. Schaub, "Impact of Electrostatic Perturbations on Proximity Operations in High Earth Orbits," *Journal of Spacecraft and Rockets*, Vol. 58, No. 5, Sept-Oct 2021, pp. 1293-1302,
doi:[10.2514/1.A35039](#)
- J-3 M. Bengtson and H. Schaub, "Electron-Based Touchless Potential Sensing of Shape Primitives and Differentially-Charged Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 58, No. 6, Nov.-Dec. 2021, pp. 1847-1857,
doi:[10.2514/1.A35086](#)
- J-4 J. Hammerl and H. Schaub, "Effects of Electric Potential Uncertainty on Electrostatic Tractor Relative Motion Control Equilibria," *Journal of Spacecraft and Rockets*, Vol. 59, No. 2, March–April 2022, pp. 552–562,
doi:[10.2514/1.A35165](#)
- J-5 Á. Romero-Calvo and H. Schaub, "Simulation and Uncertainty Quantification of Electron Beams in Active Spacecraft Charging Scenarios," *Journal of Spacecraft and Rockets*, Vol. 59, No. 3, 2022, pp. 739–750,
doi:[10.2514/1.A35190](#)
- J-6 K. T. Wilson, M. Bengtson and H. Schaub, "Remote Electrostatic Potential Sensing for Proximity Operations: Comparison and Fusion of Methods," *AIAA Journal of Spacecraft and Rockets*, Vol. 59, No. 5, Sept.–Oct. 2022, pp. 1425–1536,
doi:[10.2514/1.A35071](#)
- J-7 K. T. Wilson, Á. Romero-Calvo, M. Bengtson, J. Hammerl, J. Maxwell, and H. Schaub, "Development and Characterization of the ECLIPS Space Environments Simulation Facility," *Acta Astronautica*, Vol. 194, May 2022, pp. 48–58,
doi:[10.1016/j.actaastro.2021.12.037](#)
- J-8 K. T. Wilson, Á. Romero-Calvo, and H. Schaub, "Constrained Guidance for Spacecraft Proximity Operations Under Electrostatic Perturbations," *Journal of Spacecraft and Rockets*, Vol. 59, No. 4, July–August 2022, pp. 1304–1316,
doi:[10.2514/1.A35162](#)

- J-9 Á. Romero-Calvo, J. Hammerl, and H. Schaub, "Touchless Potential Sensing of Differentially-Charged Spacecraft Using Secondary Electrons," *Journal of Spacecraft and Rockets*, Vol. 59, No. 5, September – October 2022, pp. 1623–1633, doi:[10.2514/1.A35355](https://doi.org/10.2514/1.A35355)
- J-10 K. T. Wilson, J. Hammerl, H. Schaub, "Using Plasma-Induced X-ray Emission to Estimate Electrostatic Potentials on Nearby Space Objects," *Journal of Spacecraft and Rockets*, Vol. 59, No. 4, July–August 2022, pp. 1402–1405, doi:[10.2514/1.A35161](https://doi.org/10.2514/1.A35161)
- J-11 J. Hammerl, A. López, Á. Romero Calvo and H. Schaub, "Touchless Potential Sensing of Differentially-Charged Spacecraft Using X-Rays," *Journal of Spacecraft and Rockets*, 2022, doi:[10.2514/1.A35492](https://doi.org/10.2514/1.A35492)
- J-12 K. Champion and H. Schaub, "Electrostatic Potential Shielding in Representative Cislunar Regions," Submitted to *IEEE Transactions on Plasma Science*, in press 2022, doi:[10.1109/TPS.2023.3236246](https://doi.org/10.1109/TPS.2023.3236246)
- J-13 Á. Romero Calvo, K. Champion and H. Schaub, "Enabling Ultraviolet Lasers for Touchless Spacecraft Potential Sensing," Submitted to *IEEE Transactions on Plasma Science*

9 Project Conclusions and Outlook

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

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