Electrostatic Actuation within Expanded Low Earth Orbit Plasma Wakes: Experiments and Analysis

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Vacuum chamber experiments are conducted to characterize the plasma wake behind an object in a streaming plasma, providing insight into electrostatic force-based actuation technologies for Low Earth Orbit (LEO). This technique, called electrostatic actuation, uses charge accumulated on spacecraft surfaces to accomplish relative position and attitude changes between two Resident Space Objects (RSOs). The experiments described investigate the applicability of the technique — originally intended for Geosynchronous Earth Orbit (GEO) — within LEO plasma wakes. A 1 cm spherical representative spacecraft with 2 cm thin booms extending radially outward is placed in a flowing plasma and charged positively to expand the wake region. Two spherical probes of different diameter and charged to various negative voltages are scanned through the wake while current is measured, providing data on the resulting wake geometry. This two-point measurement provides scaling insight for extrapolating experimental data to much larger objects in space. It is shown that the power required to charge an object within the wake is significantly lower than in the ambient plasma for low voltages, but comparable for large voltages.

I. Introduction

Electrostatic actuation [1, 2] is a technique which utilizes charge accumulated on spacecraft surfaces to generate electrostatic forces and torques between two Resident Space Objects (RSOs). While conventional spacecraft charging studies are focused on hazard mitigation, electrostatic actuation and similar technologies consider the naturally occurring phenomenon for technological benefit. The benefits of electrostatic actuation include extremely low resource costs, the ability to touchlessly influence another RSO, and having the capacity to despin an object — a capacity that conventional capture methods lack.[3–5]

Previous work on electrostatic actuation has been focused on Geostationary Earth Orbit (GEO) because the hot, spares plasma in this regime allows spacecraft to charge to large potentials with relatively low power consumption. Additionally, screening effects are minimal in the GEO environment, allowing electrostatic forces and torques to propagate much farther than in the ambient Low Earth Orbit (LEO) plasma, which is far more dense. However, the relatively sparse plasma in the wakes behind objects orbiting in LEO exhibit plasma parameters conducive to the technique.[6] Plasma wakes form behind LEO spacecraft because the orbital velocity is supersonic with respect to the plasma ions and neutrals. This creates a region antiparallel to the object's ionosphere-relative velocity that is nearly devoid of these species [7]. Electrons, which have extremely low mass, move much more rapidly and are therefore able to penetrate into the wake. However, the lack of ions in this region creates a negative space charge which screens out lower-energy electrons, so the electron density is decreased and the temperature increased as shown by [8] and [9], respectively.

LEO plasma wakes have been studied extensively. Numerical studies model wakes in LEO-like plasmas for objects of different sizes, geometries, and voltages.[10, 11] Experimental work has also been conducted analyzing wake formation given sizes, geometries, voltages, and atmosphere-relative velocities.[12, 13] A set of dimensionless scaling parameters were developed by Reference [14] to translate results obtained in terrestrial experiments to conditions in space. Several missions have studied LEO spacecraft charging and the interaction of plasma beams with the wake, including CHAWS [15] and SEPAC [16]. This latter mission showed that objects in the wake can be charged to ~ 5kV with a ~ 800W electron gun, motivating the investigation of electrostatic actuation techniques in LEO. Finally, recent experimental work has demonstrated that LEO wakes can be enhanced by charging the wake-forming craft positively.[17] This investigation also showed that small objects charged positively can generate relatively large wakes. This is explored in greater detail in this paper.

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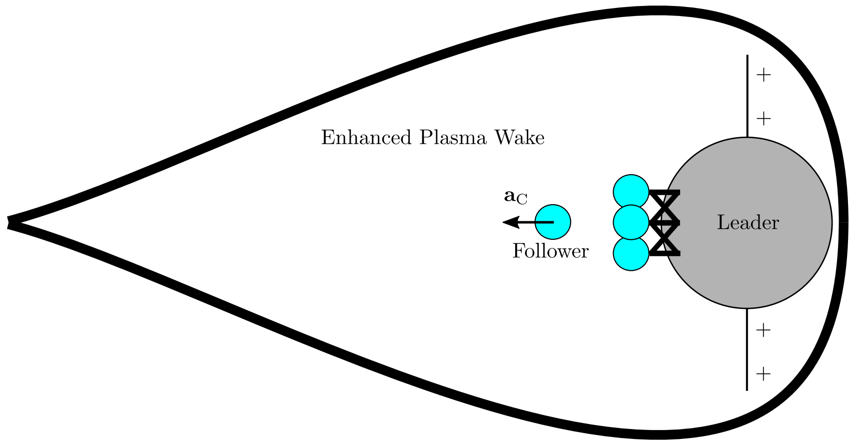


Fig. 1 Electrostatic Actuation in an Enhanced LEO Plasma Wake

A host of electrostatic actuation techniques have been developed for GEO, but can potentially be modified to function in LEO. The electrostatic tractor technique [18] employs an electron/ion beam to charge another orbiting body, generating electrostatic forces and torques for touchless interactions, much as in Figure 1. Application of this method in LEO is explored in Reference [19]. Proposed applications of the electrostatic tractor include space debris removal [20, 21], detumbling of rapidly rotating objects on orbit [18], orbital corrections [22], and electrostatically inflated gossamer structures [23]. Extension of such techniques to LEO requires that the wake region where electrostatic actuation is possible be large enough to envelop the follower — this minimizes power usage while also allowing electrostatic forces and torques to propogate farther due to the reduced plasma shielding in the wake. Wake expansion techniques described in [17] are applied to the work described below.

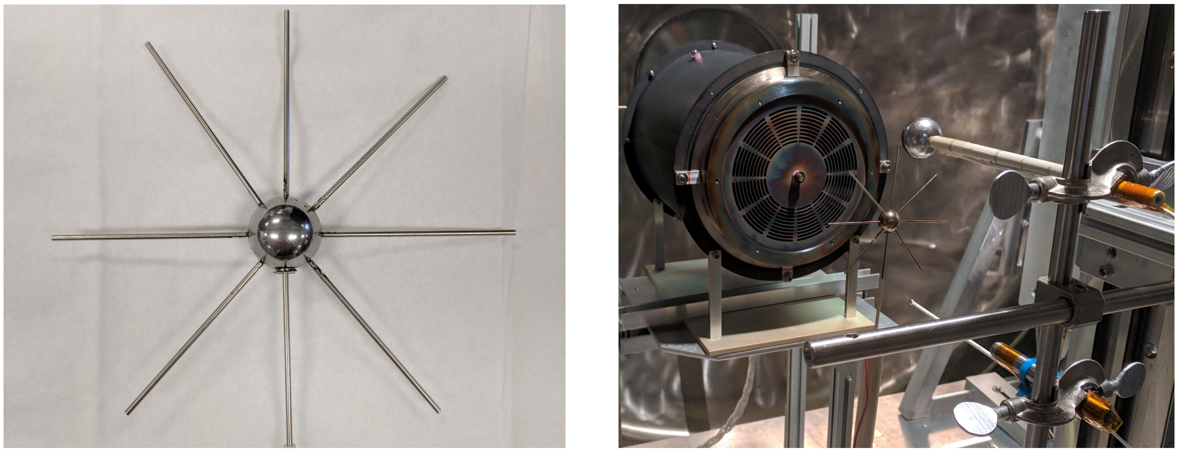
The experimental campaign described herein is aimed at developing a model for the power required to charge an object in the wake of another craft. The proposed technique is illustrated in Figure 1. The presence of positively charged thin booms attached to the hub of the leader craft serves to expand the wake generated by the leader, providing a larger working volume for electrostatic actuation techniques. In the experiments described, three measurements were taken — the current collected by the leader as it generates an enhanced wake and the current to two probes of different sizes which are swept both spatially and in potential through the wake. The combination of these three measurements provides a basis for estimating the power required for a functioning LEO electrostatic actuation system. Additionally, the identical measurements from probes of different sizes gives scaling insight, allowing for extrapolation of results to a mission scenario.

This paper provides a detailed explanation of the experiment outlined above followed by a brief discussion of the analysis methods employed to extract results from the raw data. Results are presented and the insight into the feasibility of electrostatic actuation techniques within LEO plasma wakes is discussed.

II. Experimental & Data Analysis Methods

Plasma wake experiments were conducted within the JUMBO chamber at the Spacecraft Charging Instrumentation and Calibration Laboratory (SCICL) at the Air Force Research Laboratory (AFRL) at Kirtland Air Force Base, NM. JUMBO is a 2 m diameter cylindrical chamber with length of roughly 3 m and is described in greater detail in [24]. The plasma source manufactured by Plasma Controls LLC used in this study and pictured in the background of Figure 2b uses magnetic filtering to produce a representative LEO plasma — one in which the thermal velocity of the streaming, directional ions is roughly equivalent to the velocity of a LEO spacecraft relative to ionospheric ions. Argon gas is ionized by a filament within the source to generate the ions which are then accelerated to the desired velocities by a system of charged grids. Argon is chosen because its mass is representative of the higher-concentration elements within the ionosphere and because Ar^+ is not as corrosive as elements such as O^+. This source is not differentially pumped, meaning that neutral Argon atoms are present within the flow, allowing for charge exchange between the fast-moving ions and the slow neutrals. The effect of this phenomenon is currently under investigation.

The experiments conducted apply a wake expansion methodology similar to that described in [17]. Rather than use a sparse sphere as in that work, a positively charged “spacecraft" with thin booms extending radially outward from a



(a) Wake-Forming Representative Spacecraft

(b) Experiment Setup

Fig. 2 Experiment Depictions

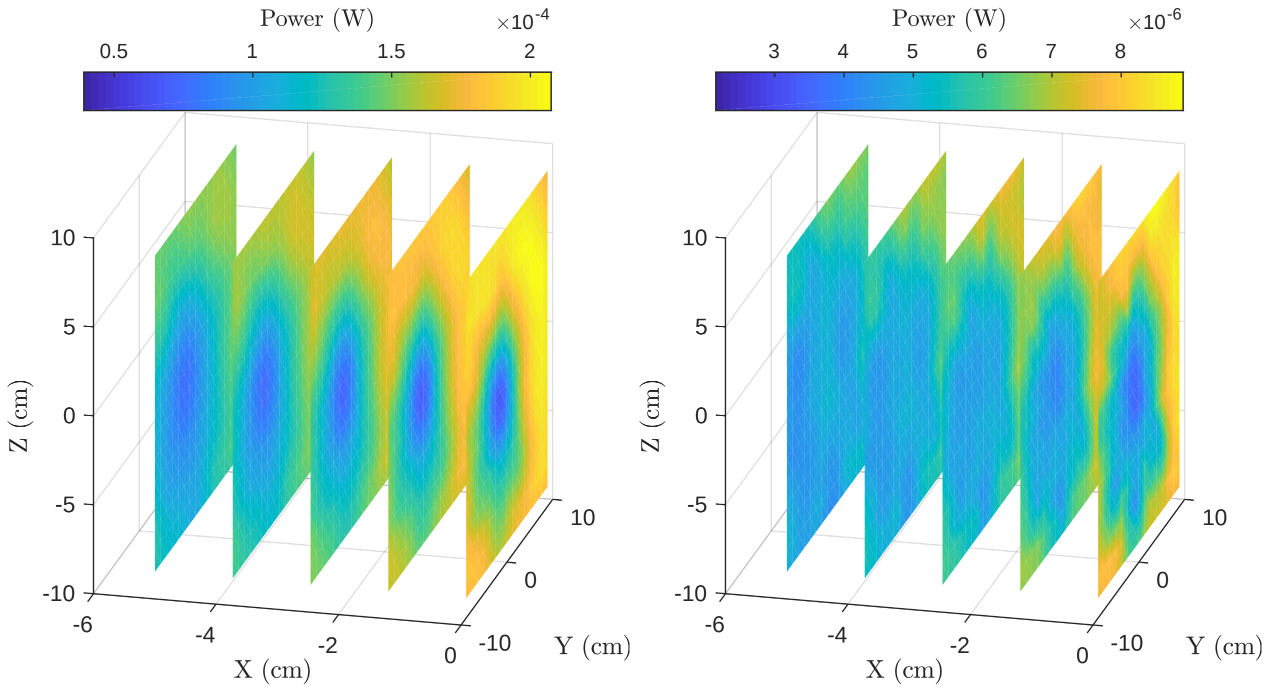
central hub as pictured in Figure 2a generates the enhanced wake. The presence of the thin booms is negligible when the object's positive charge is small relative to the 5 eV kinetic energy of the ions. However, as the electrostatic potential energy exceeds this value the thin booms expand the wake significantly, creating a larger region in which electrostatic actuation is feasible [17].

Two spherical probes of different sizes take current measurements at each point of a 3-dimensional grid of size 30 cm $\times$ 18 cm $\times$ 18 cm beginning ~1 cm behind the spherical conductor. The probes, picture in Figure 2b, are chosen to provide insight into the effects of placing differently-sized objects in the wake. Note that the large probe is significantly larger than the hub of the spacecraft. Two Keithley 2410 Source-Measure Units (SMUs) are used to collect current to the probes at each node of the 3-dimensional grid decribed above while sweeping through potentials ranging from -10 V to -200 V. The current on the wake-forming spacecraft held at Φ = 10 V is measured constantly to provide insight into mutual effects between the probes, drift in the plasma source, and the power required to expand the wake.

Determining the local voltage surrounding a charged object in a streaming plasma is extremely difficult. Suffice to say that a power supply set to 1 V relative to chamber ground is not at 1 V relative to the local plasma. It may indeed be negative relative to the plasma. For this reason, only large voltages relative to the plasma are considered. This greatly simplifies analysis and provides all relevant information, as electrostatic actuation techniques do not provide sufficient control authority at voltages on the order of 1 V.

All data is considered in terms of power, but knowledge of the signs of voltage and current are also highly relevant to the analysis. Being that the plasma output by the source contains both positive and negative charges, changes in power sourced by a probe at a given voltage provides qualitative insight into dynamics within the plasma. For example, a negatively charged probe whose current is decreasing in time could indicate either that the number of ions coincident on the probe surface is increasing, or the number of electrons decreasing. Arriving at a solid conclusion is complicated by variations in the plasma source and other factors. However, correlation of the three measurements taken throughout the experiment provides a means to eliminate mistaken hypotheses.

It is important to recognize in interpreting results that the "ambient" wake is not being measured in this experiment. Rather, an effective wake resulting from the placement of a charged object in the wake of another is described. The presence of this charged object necessarily changes the wake's shape and properties. It should also be noted when considering the figures below that each measurement shown is separated in time — the wake structures are not snapshots. Finally, the power values for each experiment should only be considered in a relative sense. Each individual point provides no insight into the feasibility of electrostatic actuation techniques. Only through consideration of all experiment data together can such conclusions be reached.



(a) Large Probe (b) Small Probe

Fig. 3 Power Required to Hold Probes at Φ = -10 V

III. Results & Discussion

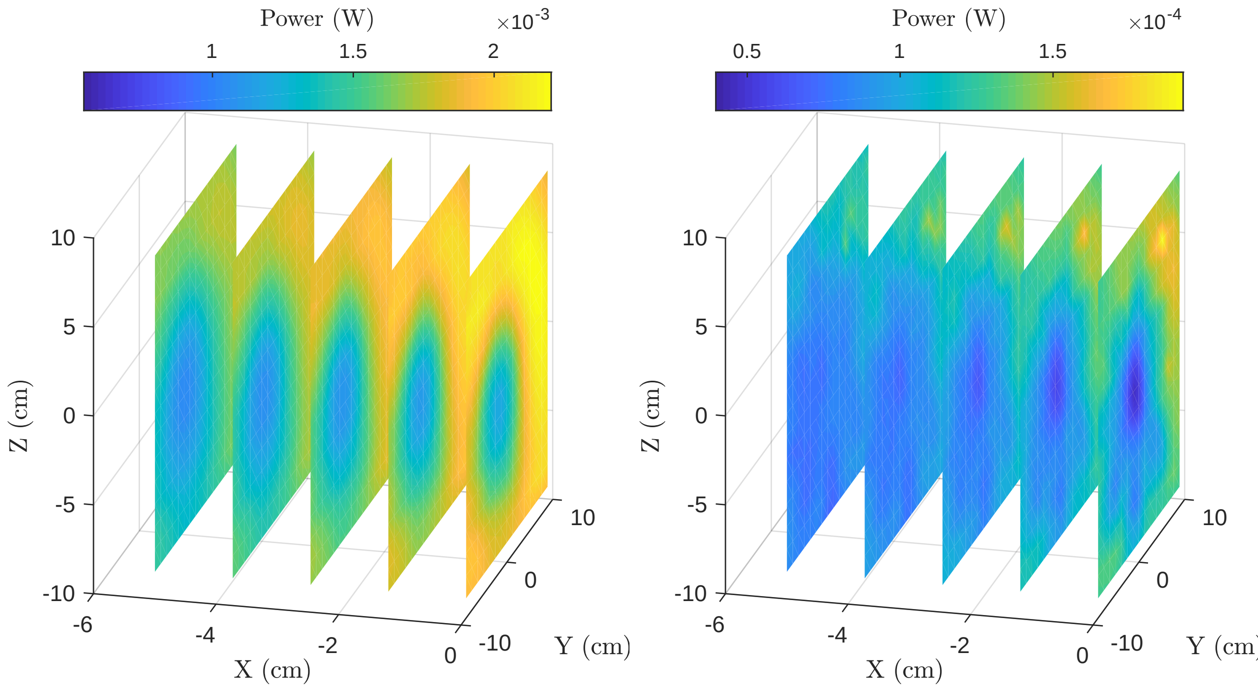
A. Probe Power

The current measurements described above provide an indication of the wake shape resulting from a charged object at a certain position. Given that the wake is ion-deficient, there is little shielding of negative potentials [25]. This means that, when the negatively charged spheres are deep in the wake, very little current is collected. However, when a sufficient negative potential approaches the edge of the wake, the streaming ions will be attracted down onto the sphere, causing a significant increase in current. This effect is seen in Figures 3-5, which show the power consumed by both probes at a given voltage and location.

An interesting difference in Figures 3a and 3b is the sharpness of the features at the X=0 cm plane. Recall that the spacecraft is held at 10 V. Ion trajectories are therefore deflected away and, in the wake, will not be collected by probes charged negatively to this same potential. This results in the structure in Figure 3b, which clearly matches the shape of the spacecraft shown in Figure 2a. Notably, the wake region directly behind the thin booms on the spacecraft are significantly larger than their diameters. This matches the conclusion from Reference [17] that thin, lightweight objects can be charged to significantly expand wakes. Indeed, the ambient wake behind such an object would certainly be even larger, but is compressed by the fact that the probes are charged negatively.

The structure shown so clearly in Figure 3b appears significantly washed out in Figure 3a. This is due to the larger collection area of the large probe and persists in Figures 4a and 5a. Importantly, the diameter of the large probe is greater than the distance steps on the 3-dimensional grid described in previous sections. This circumstance provides insight into the feasibility of manipulating large craft within the wake electrostatically. It is clear from comparison of Figures 3b and 3a that a larger object has a smaller working area for electrostatic actuation techniques.

The spacecraft structure shown in Figure 3b persists in Figure 4b, though the difference in power sourced by the probe within the wake is far more comparable to that in ambient in this latter experiment. This results from an increase in the probe voltage while holding the spacecraft voltage fixed at 10 V. This effect is even more pronounced in Figure 4a. However, this and Figure 3a have an interesting quality not as clearly shown by the small probe measurements — an increase in the wake diameter for increasing values of X. This is also seen in the results discussed in Reference [17], but



(a) Large Probe

(b) Small Probe

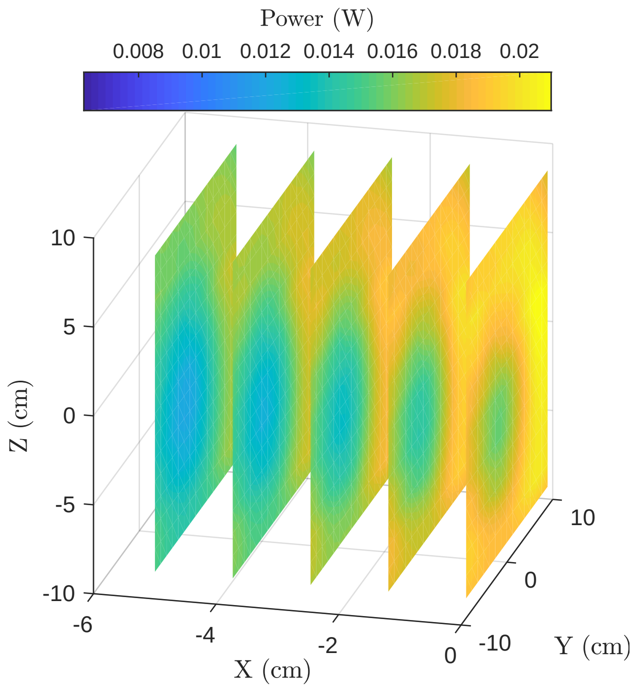
Fig. 4 Power Required to Hold Probes at Φ = -50 V

was assumed the result of excessive potentials on the wake-forming craft disrupting the entirety of the limited volume of plasma output by the source. The persistence of this feature in the presence of a much smaller spacecraft potential indicates that the enhanced wake does not close in the same way as the ambient.

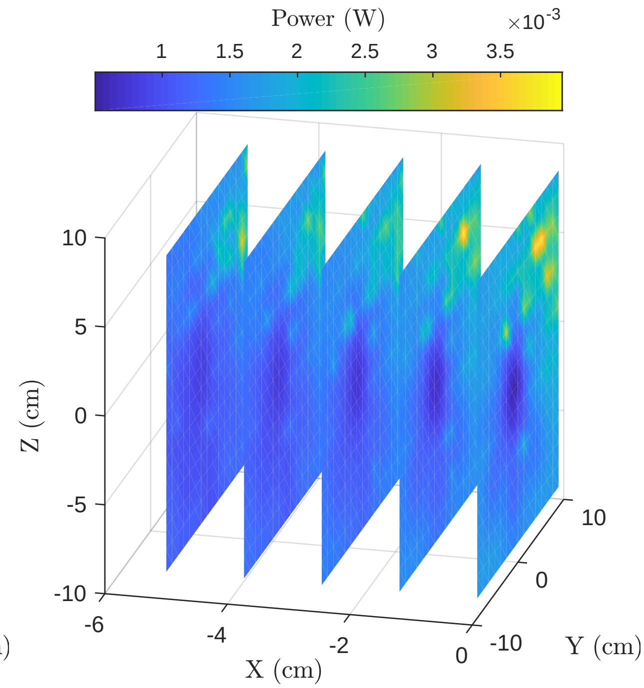
Consider a lone craft in LEO. If uncharged, ions are initially deflected via interactions with the sheath and surface in the very near vicinity of the craft. As discussed previously, this results in the wake behind the craft which exhibits a negative space-charge. The trajectories of ions deflected only slightly around the craft by the initial interaction are affected only by this space-charge, which pulls them toward the wake axis resulting in wake closure a short distance behind the craft. However, a craft at 10 V interacts differently. Firstly, the initial trajectory deviation is much greater, as ions enter a potential gradient significantly larger than their kinetic energy relative to the craft. After they pass the craft, the decreased shielding in the wake mentioned above allows the electric field of the craft to continue repelling them. This repulsion will continue until the combination of the reduced shielding and natural $1/r^2$ falloff of the field is less than the space-charge in the wake.

In the experiments described in Figures 3-5, the presence of a negatively charged objects affects the closing distance, but this value is highly dependent on the location of the object. Placing it on the wake axis clearly maximizes the size of the wake, but the optimal position of this object on this line will be a function of both the spacecraft and probe potentials. Applying this knowledge of position-potential coupling would allow for minimal power usage for a given electrostatic actuation technique.

Figure 5 bears similar hallmarks to the previous experiments, including the tendency for in- and out-of-wake power differences to decrease with probe voltage. While the effective wake — such as it is — continues to expand as the probes move away from the spacecraft, the power savings are negligible. This result combined with the preceding discussion indicates that the magnitude of the spacecraft potential must be comparable or greater than that of the probes in order to reap any benefit from charging within the wake.



(a) Large Probe



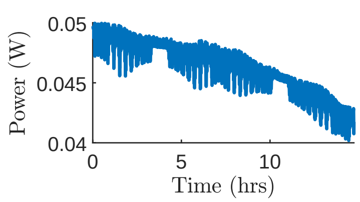
(b) Small Probe

Fig. 5 Power Required to Hold Probes at Φ = -200 V

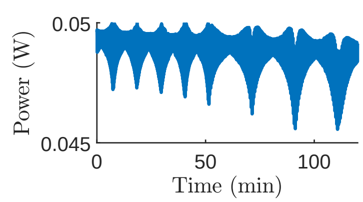
B. Spacecraft Power

A sample of the power sourced by the spacecraft is shown in Figure 6. Three separate timescales are shown, each with the same starting time. Each of Figures 6a-6c shows different behaviors. The decrease in power on the timescale of hours indicates drift in the plasma source — a common occurrence of such systems. For a positively charged probe, this indicates either a decrease in electrons collected or an increase in ions collected. It can be inferred from this information that the energy and/or density of one or both of these species is varying in time. Inspection of Figure 3b provides an additional clue. The scanning method employed to navigate the 3-dimensional grid at which measurements are made is such that measurements on the Z=10 cm plane are taken days before those on the Z=-10 cm plane. The lower power values on the -Z half of Figure 3b must be considered alongside the plasma parameters of the source.

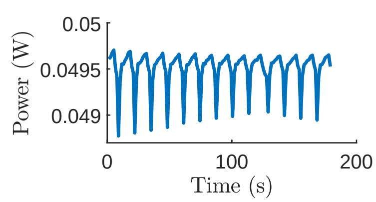
In simulating LEO conditions, the ion and electron energies are necessarily different. Calibration values for the plasma source indicate that, for the parameters used in this experiment, the electron temperature distribution is centered at about 1 eV, while the ions are streaming directionally with a temperature distribution centered at roughly 5 eV. Assuming these distributions are relatively narrow, a probe at -10 V in this plasma should repel almost all electrons while collecting most of the ions. On the other hand, the spacecraft charged to +10V would collect some number of ions (from the high-energy tail of the distribution), while collecting almost all electrons. This information combined with



(a) Hours



(b) Minutes



(c) Seconds

Fig. 6 Spacecraft Power Signal Structure at Different Timescales

time-correlated decreases in power to both the positively charged spacecraft and negatively charged probe indicate a general decreases in energy/density of the plasma output by the source.

Different behavior is seen in the spacecraft power curve on the order of minutes as shown in Figure 6b. This can be understood by considering the current as the time derivative of charge. For this discussion, the current from the plasma is neglected, as it is not expected to vary significantly over the timescale of minutes and is therefore considered a baseline value upon which other effects are superimposed. Consider the current as the time derivative of the well-known voltage to charge relationship.

$$\boldsymbol{I} = \frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{Q}) = \frac{\mathrm{d}}{\mathrm{d}t}(C\boldsymbol{V}) \tag{1}$$

Here, C is the capacitance matrix which modifies charge on an object given nearby charged objects. Expanding Eq. (1) according to the experiment configuration described above yields

$$\begin{pmatrix} I_L \\ I_S \\ I_{SC} \end{pmatrix} = \frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} Q_L \\ Q_S \\ Q_{SC} \end{pmatrix} = \frac{\mathrm{d}}{\mathrm{d}t}\left\{\begin{bmatrix} C_L & C_{L,S} & C_{L,SC} \\ C_{S,L} & C_S & C_{S,SC} \\ C_{SC,L} & C_{SC,S} & C_{SC} \end{bmatrix}\begin{pmatrix} V_L \\ V_S \\ V_{SC} \end{pmatrix}\right\} \tag{2}$$

To understand the structure in Figure 6b, only the bottom row is necessary.

$$I_{SC} = \frac{\mathrm{d}}{\mathrm{d}t}(C_{SC,L}V_L + C_{SC,S}V_S + C_{SC}V_SC) \tag{3}$$

Given that the spacecraft is held at a constant 10 V potential and its shape — which determines its self capacitance C_{SC} — does not change, the final expression for the power on the spacecraft resulting from the probes is

$$P_{SC} = I_{SC}V_{SC} = (\dot{C}_{SC,L}V_L + C_{SC,L}\dot{V}_L + \dot{C}_{SC,S}V_S + C_{SC,S}\dot{V}_S)V_{SC} \tag{4}$$

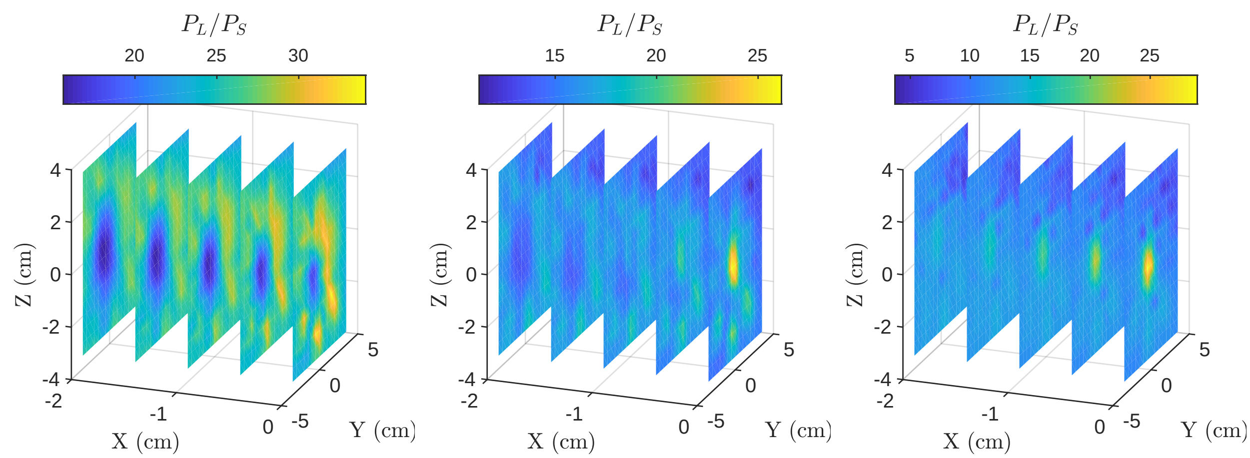
From the experiment setup, it is known that the mutual capacitance terms — which are a function of separation distance between the probes and the spacecraft — change on timescales of minutes, while the voltages change must faster. Therefore, the structure seen in Figure 6b results from the motion of the probes relative to the spacecraft. The voltage derivative terms in Eq. (4) generate the structure seen in Figure 6c.

Finally, consider the magnitude of power used by the spacecraft relative to the probes. The total area of the spacecraft is comparable to that of the large probe, yet the former uses far more power even when the latter's voltage is orders of magnitude larger. This indicates that wake expansion techniques are more expensive than implementing the electrostatic tractor itself. However, the sheer difference in power consumption motivates the use of such techniques. Even when the probe is charged to extremely large negative voltages, the local plasma environment is significantly less dense than the ambient experienced by the wake-forming spacecraft. The power required by electrostatic actuation increases strongly with plasma density, as increases in both the current to the object and the shielding of electrostatic forces and torques motivate larger sourced currents and voltages, respectively. Therefore, application of wake expansion techniques could result in a decrease in power required to electrostatically actuate a follower craft that is large relative to the size of the wake in which it flies.

C. Probe Scaling

Comparison between the power on the large and small probes provides an indication of how the power scales with increasing craft size. Figure 7 shows the ratio of power on the large probe to that of the small probe for each voltage measurement. As expected, the large probe always requires more power than the small probe. However, the ratio between these two is a function of both voltage and position. Figure 7a has a great deal of structure. At the center, the ratio is relatively small because the the spacecraft diverts most ions away from the probes. However, near the thin booms, the ratio increases significantly. This is because the small probe is completely in the wake of the booms, while the large probe integrates over an area that is only partially within the wake.

Figures 7b supports the previous conclusion that the size, voltage, and location of a probe determines the wake closure distance. Near the point $[0,0,0]^T$ cm, the large probe collects a great deal more current than the small probe. However, as the probes are moved backward along the Y=0 cm, Z=0 cm line, the ratio decreases and, eventually, becomes lower than the ambient. A similar decrease is seen in Figure 7c, though it never drops near the ambient value. Additionally, very little structure is seen in this figure besides at the very center. This supports the conclusion that a probe voltage so much larger than that of the spacecraft minimizes the power savings gained from charging in the wake.



(a) Φ = -10 V (b) Φ = -50 V (c) Φ = -200 V

Fig. 7 Ratio of Large Probe Power to Small Probe Power at Various Potentials

The two-point probe measurements allow for linear extrapolation of the power required to charge a craft of given size in the wake according to Eq (6).

$$P_{\text{object}} = \frac{\text{dP}}{\text{dA}} A_{\text{object}} \tag{5}$$

$$\frac{\text{dP}}{\text{dA}} \approx \frac{\Delta\text{P}}{\Delta\text{A}} = \frac{\text{P}_L - \text{P}_S}{\text{A}_L - \text{A}_S} \tag{6}$$

The transformation $\Delta P/\Delta A$ is plotted throughout the volume of the given experiment in Figure 8. According to these results, charging a 10 cm diameter spherical probe in the wake to -50 V — a feasible parameter set for an application of electrostatic actuation — would require an estimated 15 mW of power. Maneuvering much larger objects would require much more power, because both the current collecting area and object inertia increase. Applying this same concept to a larger craft would require more force and therefore larger voltages. However, the experiment configuration is such that electrostatic actuation at voltages significantly larger than that of the wake-forming spacecraft are not power efficient, as discussed previously. The data collected here indicates that a 1 m diameter craft at -200 V would require 63 W of power. In optimizing for heavier objects, a larger spacecraft voltage would be applied to expand the wake further, potentially leading to a overall power savings relative to the 63 W requirement estimated from the data.

IV. Conclusions

Experimental results indicate that, for certain configurations, significant power savings can be achieved by charging in the wake. However, as potentials increase relative to that of the wake-forming craft, the savings decrease. This effect is less true for small objects in the wake than larger ones and depends on location. Results indicate that manipulating a small daughter craft in the wake of a mother craft using electrostatic actuation — as described in Reference [19] — could be quite power-efficient. Additionally, maneuvering lighter craft requires less control authority, so lesser voltages could be used.

The dataset presented provides a great deal of insight into the application of electrostatic actuation within LEO plasma wakes, but can also be used as a physical model using scaling insight and interpolation schemes. Future work will use this and similar datasets in control simulations for technological insight.

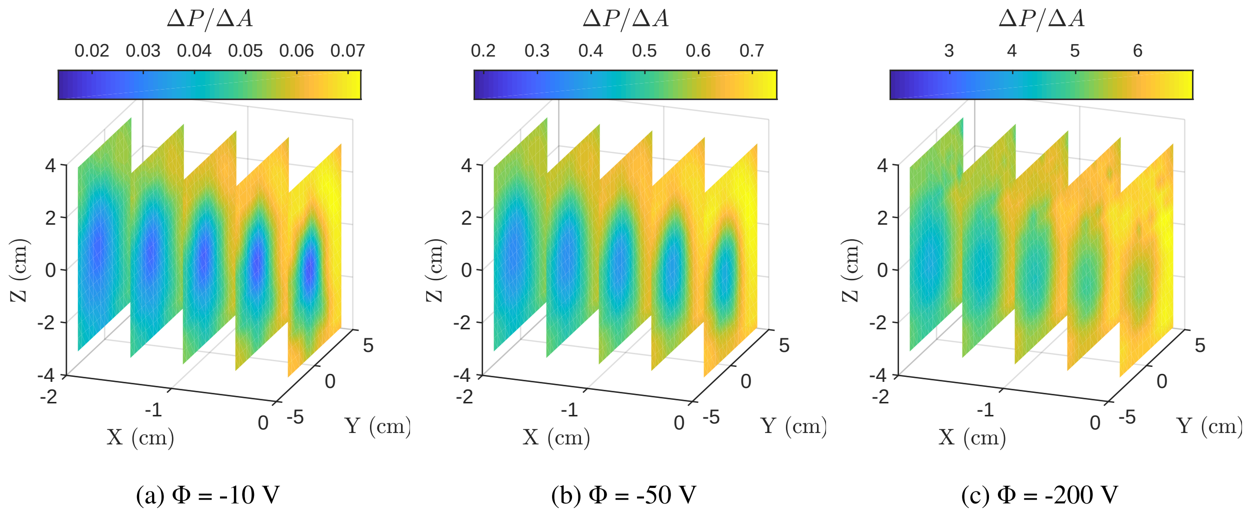


Fig. 8 Area to Power Transformation

V. Acknowledgments

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