IMPACTS OF TUG AND DEBRIS SIZES ON ELECTROSTATIC TRACTOR CHARGING PERFORMANCE

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Abstract. Active debris removal techniques enable relocating noncooperative geosynchronous (GEO) debris objects into graveyard orbits. One proposed method is the electrostatic tractor concept. Here a tug vehicle approaches a target debris object and emits an electron beam onto the debris. The charging that results yields an attractive electrostatic force that is used to tow the debris object into a new orbit. In this study, the impacts of relative sizing between tug and debris on the efficacy of this charge transfer process are considered. By applying a charging model and incorporating nominal, quiet GEO space weather conditions, limitations on the size ratio that preclude charge transfer are identified for different levels of beam energy. As an alternative to charge transfer, supercharging of the tug vehicle is considered as a method to generate an electrostatic force. Here, the tug is charged to a level equal to the beam energy. It is found that under certain conditions, supercharging the tug can provide better tugging performance than charge transfer via the electron beam. The results indicate that a larger tug vehicle will enable the tugging of a broader range of debris sizes, and that the tug size should be roughly as large as the expected debris size.

Keywords: Electrostatic tractor, spacecraft charging, active charge transfer, active debris removal
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INTRODUCTION

For GEO satellites, international guidelines for end-of-life operations call for removal of the spacecraft from the GEO region. With a goal of preventing reentry into GEO within 25 years, a minimum increase in altitude of 200–300 km is typically expected, though certain spacecraft may be raised higher.[1, 2] For the case of defunct satellites and other debris objects, a method is needed for achieving this transition into a graveyard orbit. To that end, the use of an electrostatic tractor, illustrated in Figure 1, has been proposed.[3] A tug vehicle approaches a target object and emits an electron beam onto the debris, charging it negatively. With the beam emission resulting in a positive charge on the tug, an attractive electrostatic force between the tug and debris results, which is then used in conjunction with low thrust to tow the debris object into a disposal orbit.[4] The charging that results is dependent on several current sources, and is impacted by the variations in the space weather environment at GEO.[5, 6, 7]

Due to the potential impacts of spacecraft charging on operations and spacecraft lifetime, much work has been performed in this area.[8, 9, 10, 11, 12, 13] Typically, these studies focus on a single satellite in orbit and investigate natural charging events that occur as a result of the space weather environment. A serious concern for spacecraft that experience differential charging across their outer surface is electrostatic discharge (ESD) events, where arcing occurs between different substructures possessing a significant surface potential difference.[11] These ESD events can be destructive to electronic the electron beam current must reach it in order to overcome the various currents it is subjected to. If the tug vehicle emitting the electron beam is small enough relative to the debris object, it will charge completely (referred to here as supercharging) and prevent sufficient beam current from reaching the debris. The amount of current that can be emitted by the tug is limited by the beam energy. Once the tug potential reaches the level of the beam energy, any additional beam current will be recollected by the tug.[16] The impacts of size differences on the resulting charging are studied, with hopes of identifying a threshold for the onset of charging. Even in the absence of charge transfer, an electrostatic force may still result between tug and debris if the tug vehicle is charged high enough. It is of interest to investigate the question of whether or not these forces are large enough to achieve acceptable tugging performance, and whether or not maximally charging the tug may actually be better than achieving charge transfer in certain cases.

The paper is structured as follows. First, an overview of the charging process and the model used to compute the potentials on tug and debris objects is presented. This is followed by a brief explanation of the method used to compute the electrostatic forces between tug and debris. Next, a threshold for the onset of charge transfer is defined, and the impacts of relative sizing on meeting this threshold are investigated. Then, the electrostatic forces acting between tug and debris are studied for a range of sizes and charging conditions. The forces achievable with charge transfer are compared with those resulting from maximally charging only the tug vehicle in order to determine if it is ever better to avoid charge transfer in favor of supercharging. Lastly, the impacts of relative sizing on the debris reorbiting performance are considered for a range of tugging configurations.

BACKGROUND

In this paper, it is assumed that the tug vehicle is equipped with an electron gun that is used to remotely charge a neighboring deputy (or debris) object up to 10's of meters away. The charge transfer, in combination with the near proximity of tug and deputy, results in an attractive electrostatic force used for tugging, as illustrated in Figure 1. Here, the problem of reorbiting a GEO debris object into a graveyard orbit is considered. A semi-major axis change is required and the tug and deputy maintain a constant leader-follower position throughout the duration of the maneuver.[4, 14] The study utilizes a charging model that accounts for the numerous current sources experienced by a satellite in the space environment. It is assumed that both the tug and deputy are conductive, with spherical geometries. While typical spacecraft do not necessarily satisfy these assumptions, the following analysis is used to provide first-order insight into the limitations of relative sizing between tug and deputy, and identify trends that would extend to more general spacecraft models.

Spacecraft Charging Model

The electrostatic tugging force used for towing is a function of the charging that results from the charge transfer between tug and deputy. Several factors influence this charging process. In the space environment the tug and deputy collect plasma electron and ion currents, and photoelectrons may be emitted depending on the spacecraft potential and presence of sunlight. Charge control is achieved through focused electron beam emission by the tug. When the electron beam is absorbed by the deputy, secondary electron emission occurs as the incoming beam electrons excite and release electrons from the deputy surface material. The potential levels achieved by the tug and deputy result from a balance of these various current sources. To compute these potentials, the charging model developed in Reference [6] is applied.

When either spacecraft is in the sunlight, a photoelectron current occurs. This current is modeled by[16]

$$I_{ph}(\phi) = j_{ph,0} A_{\perp} e^{-\phi/T_{ph}} \qquad \phi > 0 \tag{1a}$$

$$= j_{ph,0} A_{\perp} \qquad \phi \leq 0 \tag{1b}$$

where ϕ is the spacecraft potential, $T_{ph} = 2$ eV is the temperature of the emitted photoelectrons, $j_{ph,0} = 20\ \mu\text{A/m}^2$ is the photoelectron flux, and $A_{\perp}$ is the cross-sectional area exposed to sunlight. For the spherical geometries assumed here, $A_{\perp} = \pi r^2$. For high positive potentials, the photoelectron current is effectively zero because all of the emitted electrons are recaptured.

The plasma electron current is modeled by[17]

$$I_e(\phi) = -\frac{A q n_e w_e}{4} e^{\phi/T_e} \qquad \phi < 0 \tag{2a}$$

$$= -\frac{A q n_e w_e}{4} \left(1 + \frac{\phi}{T_e}\right) \qquad \phi \geq 0 \tag{2b}$$

where $A = 4\pi r^2$ is the surface area exposed to the plasma environment, q is the elementary charge, n_e is the plasma electron density, T_e is the plasma electron temperature, and $w_e = \sqrt{8T_e/\pi m_e}$ is the thermal velocity of the electrons. The electron mass is represented by m_e. Note that for large negative potentials, I_e is very small. This is due to the fact that electrons are repelled by the negatively charged spacecraft.

The plasma ion current is modeled as[17]

$$I_i(\phi) = \frac{A q n_i w_i}{4} e^{-\phi/T_i} \qquad \phi > 0 \tag{3a}$$

$$= \frac{A q n_i w_i}{4} \left(1 - \frac{\phi}{T_i}\right) \qquad \phi \leq 0 \tag{3b}$$

which is very similar in form to the plasma electron current. Here, $w_i = \sqrt{8T_i/\pi m_i}$ is the thermal velocity of the ions. Additional variable quantities are defined as before, except the subscript i is used to denote they represent ions. In the space weather model for the GEO environment utilized here, the ion species consists solely of protons. For high positive potentials, the ion current is very small because the ions are repelled by the positively charged spacecraft.

Control of the tug and deputy potentials is achieved through electron beam emission from the tug onto the deputy. Depending on the charge levels of tug and deputy, as well as beam pointing accuracy, some fraction of the beam current will be absorbed by the deputy. This current is modeled as

$$I_D(\phi_D) = -\alpha I_t \qquad \phi_T - \phi_D < E_{EB} \tag{4a}$$
$$= 0 \qquad \phi_T - \phi_D \geq E_{EB}, \tag{4b}$$

where I_t is the beam current emitted by the tug, E_{EB} is the electron beam energy, and the subscripts T and D represent the tug and deputy, respectively. The parameter α is the fraction of the beam current emitted by the tug that is absorbed by the deputy and is analogous to the efficiency of the charge transfer process. In the current paper a value of $\alpha = 1$ is used, which maintains the standard established in Reference [6]. This assumes a well focused and accurately pointed beam, and better quantification of α is beyond the scope of this paper. Once $\phi_T - \phi_D = E_{EB}$, it is impossible for additional beam current to make it to the deputy. The emitted beam electrons do not have enough energy to cross the potential difference between tug and deputy.

The incoming beam electrons absorbed by the deputy give rise to emitted secondary electrons. These electrons will be lost, owing to the large negative potential on the deputy. This current source is significant and must be included in the computation of the deputy potential. Secondary electron emission is modeled by[18]

$$I_{\text{SEE}}(\phi_D) = -4Y_M I_D(\phi_D)\kappa \qquad \phi_D < 0 \tag{5a}$$
$$= 0 \qquad \phi_D \geq 0, \tag{5b}$$

where

$$\kappa = \frac{E_{\text{eff}}/E_{\text{max}}}{(1 + E_{\text{eff}}/E_{\text{max}})^2}$$

and $E_{\text{eff}} = E_{EB} - \phi_T + \phi_D$. Y_M is the maximum yield of secondary electron production, and E_{max} is the impact energy at which this maximum occurs. In this paper, the values of $Y_M = 2$ and $E_{\text{max}} = 300$ eV are used.

Because the tug will be charged to high positive potentials, the tug charging is dominated by the electron beam emission and plasma electron currents. The tug settles to a potential that satisfies the simplified current balance $I_e(\phi_T) + I_t = 0$, which is analytically solved as follows:

$$\phi_T = \left(\frac{4I_t}{Aqn_e w_e} - 1\right) T_e. \tag{6}$$

The current balance on the deputy object contains a few more contributions, and typically a numerical root finder must be used to obtain a solution. The deputy potential must satisfy

$$I_e(\phi_D) + I_i(\phi_D) + I_{\text{SEE}}(\phi_D) + I_{ph}(\phi_D) + I_D(\phi_D) = 0. \tag{7}$$

The presence of the photoelectron current implies the deputy is in the sunlight. If this is not the case, the current balance is modified so that it no longer contains I_{ph}.

Electrostatic Force Modeling

The electrostatic tractor takes advantage of the attractive electrostatic force generated between the tug and deputy. Due to the various current sources detailed previously, the tug and deputy will achieve voltages of ϕ_T and ϕ_D, respectively. These are absolute potentials, as opposed to a potential relative to the plasma environment.[19] In order to compute the resulting electrostatic force, a relationship is needed between the potentials and charges for the spacecraft. Here, a position dependent capacitance model is used.[14, 20, 21] The voltage and charges on the tug and deputy are related through

$$\begin{bmatrix} \phi_T \\ \phi_D \end{bmatrix} = k_c \begin{bmatrix} \frac{1}{r_T} & \frac{1}{L} \\ \frac{1}{L} & \frac{1}{r_D} \end{bmatrix} \begin{bmatrix} q_T \\ q_D \end{bmatrix}, \tag{8}$$

where L is the separation distance between tug and deputy, $k_c = 8.99 \times 10^9$ Nm^2/C^2 is Coulomb's constant, and q_T and q_D are the charges on tug and deputy, respectively.

Once ϕ_D and ϕ_T are computed using the current balances detailed above, Eq. (8) is inverted to solve for the charges. The electrostatic force is then computed using

$$F_e = k_c \frac{q_T q_D}{L^2}. \tag{9}$$

This force acts equally and opposite on the tug and deputy, and its direction is dependent on the relative position between the two objects. A positive value signifies a repulsive force, while a negative value represents an attractive force.

The space plasma environment will partially shield the electrostatic force. The distance over which this shielding occurs is characterized by the plasma Debye length.[22] The nominal GEO space weather conditions considered here have Debye lengths of a few tens of meters, which is on the order of the electrostatic tractor separation distances. This is characteristic of quiet solar activity conditions, where there is an upflow of colder ions from the ionosphere.[5] This actually provides the worst-case charging performance, because these colder ions mitigate the charging on the deputy to a certain degree. Because of the high potential levels obtained by tug and deputy, the Debye shielding effect will be several times smaller than predicted by the standard Debye length calculation. As discussed in References [23] and [24], objects charged to high enough potentials in the space environment experience effective Debye lengths several times larger. In the quiet GEO space weather conditions used in this study, only several tens of Volts are required to yield larger effective Debye lengths than predicted with classical Debye-Hückel theory.[24] Thus, the space weather conditions are not expected to provide any significant shielding for the separation distances considered (15 meters or less). For this reason, the Debye shielding terms are not included in the electrostatic force model.

RELATIVE SIZING CONSIDERATIONS

The maximum allowable electron beam current is driven by the energy of the beam. If enough current is emitted, the tug will achieve a potential equal to the beam energy.

Beyond this limit, any emitted beam electrons will be captured by the tug because they do not have enough energy to escape the tug potential well. This has important implications regarding the relative sizing between tug and deputy that will still permit charge transfer. If the tug vehicle is much smaller than the deputy, the tug will reach its potential limit before it has emitted enough current to charge the deputy. This will significantly hinder performance if the sizing difference is large enough. Thus, it is of interest to identify how large a tug vehicle must be to tow a deputy object of a given size.

From a Deputy Potential Perspective

To identify the conditions under which charge transfer is no longer possible, a threshold condition must be defined. Here, ϕ_c is used to represent a cutoff deputy potential. Any scenario that yields a deputy potential below ϕ_c is no longer considered as a case of successful charge transfer. Note that a failure to achieve charge transfer does not necessarily mean that the electrostatic force is insufficient for tugging. The position dependent capacitance model in Eq. (8) illustrates that when a low voltage deputy is in the vicinity of a high-potential tug, there will be charge on the deputy. This charge will be smaller than if charge transfer had occurred, but it is still enough to generate a non-insignificant electrostatic force that can be used for tugging. For the following analysis the plasma parameter values of $n_e = 0.47$ cm^{-3}, $T_e = 1180$ eV, $n_i = 11$ cm^{-3}, $T_i = 50$ eV are used, which correspond to conditions typical during low solar activity periods.[5] It is assumed that the separation distance between tug and deputy is $L = 12.5$ meters.

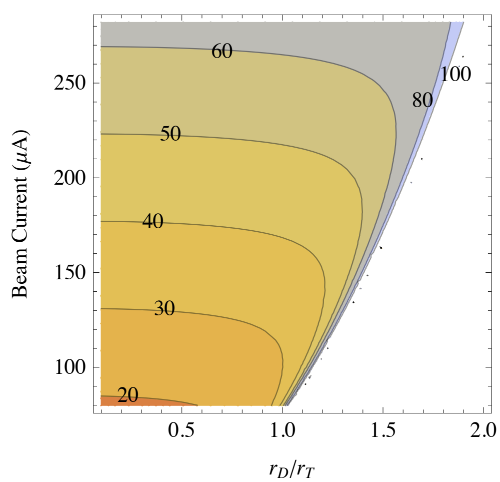

FIGURE 2. Beam energy (E_c, in kV) required to reach charging threshold of $\phi_c = -1$ kV for a variety of emitted beam currents and size ratios for a $r_T = 1$ meter tug radius.

First, a relationship between emitted beam current and beam energy required to achieve charge transfer is considered for a range of tug and deputy sizes. That is, given a particular ratio of tug and deputy sizes and an emitted beam current, what beam energy E_c would be required to yield a threshold potential of ϕ_c? If the actual beam energy is below E_c, then charge transfer is not possible. If the beam energy is above E_c, then charge

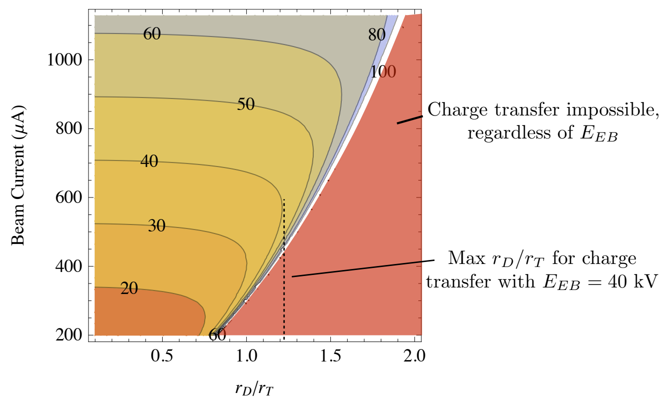

FIGURE 3. Beam energy (E_c, in kV) required to reach charging threshold of $\phi_c = -1$ kV for a variety of emitted beam currents and size ratios for a r_T =2 meter tug radius.

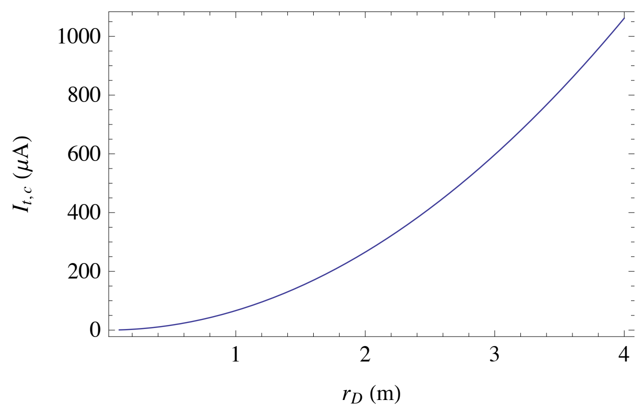

FIGURE 4. Minimum current required for charge transfer in the limit of $E_{EB} \to \infty$, assuming a threshold of $\phi_c = -1000$ V.

transfer is possible and deputy potentials above ϕ_c are achievable. Using a numerical root finder, the critical values of E_c are computed for tug sizes of 1 and 2 meters as a function of emitted current and the ratio of deputy and tug radii, r_D/r_T. The charging threshold is defined as ϕ_c = -1 kV. The results are shown in Figures 2 and 3, and several interesting conclusions can be drawn. First, for any given beam energy E_c, there is an upper limit on the deputy size for which charge transfer is possible. For example, considering the $E_c = 40$ kV contour has its outermost edge at roughly r_D/r_T=1.2 (see Figure 3), any deputy size beyond 1.2 times that of the tug would preclude charge transfer. From a vehicle design perspective, this implies that for better performance a larger tug vehicle should be used. If the tug vehicle is as large or larger than the biggest expected deputy object, then charge transfer will be possible. However, a smaller tug vehicle is limited in the variety of potential deputy candidates that may be towed.

Another interesting result shown in Figures 2 and 3 is the existence of a hard cutoff in the charging threshold, where higher beam energies no longer allow for sufficient charging of larger deputy objects to the ϕ_c potential level. It would seem that this might be a function of the size ratio r_D/r_T. However, this cutoff is merely a reflection of the fact that there is some minimum current required to balance the photoelectron and plasma ion currents and reach ϕ_c. An analytic expression for the cutoff is found by considering the limit of very large beam energies ($E_{EB} \to \infty$). While perhaps not practically realistic, computing this limit allows one to identify the minimum theoretical current that is required to accomplish charge transfer for a deputy object of a given size. In the limit of a very large beam energy, the secondary electron emission current is effectively zero, due to the fact that

$$\lim_{E_{EB}\to\infty} \kappa = 0.$$

Thus, the current balance on the deputy may be rewritten as

$$I_e(\phi_c) + I_i(\phi_c) + I_{ph}(\phi_c) + I_D(\phi_c) = 0, \tag{10}$$

which can be solved for I_t. Denoting $\mathscr{F}_e = qn_e w_e/4$ and $\mathscr{F}_i = qn_i w_i/4$ as the plasma electron and ion fluxes, the minimum beam current required to achieve ϕ_c is computed as

$$I_{t,c} = \left(4\mathscr{F}_i\left(1 - \frac{\phi_c}{T_i}\right) - 4\mathscr{F}_e e^{\phi_c/T_e} + j_{ph,0}\right)\pi r_D^2. \tag{11}$$

A tug vehicle that cannot emit at least this amount of current, no matter how high the beam energy, will not be able to achieve charge transfer. A plot of $I_{t,c}$ for $\phi_c = -1000$ V is shown in Figure 4. For finite beam energies, secondary electron emission contributes additional losses to the charge transfer process. More current than predicted in Eq. (11) is required to achieve charge transfer, and the beam energy must be high enough so that the total secondary electron yield ($4Y_M\kappa$) is less than one. Depending on the parameters of particular case, the actual current required to achieve charging could be much higher than predicted by $I_{t,c}$.

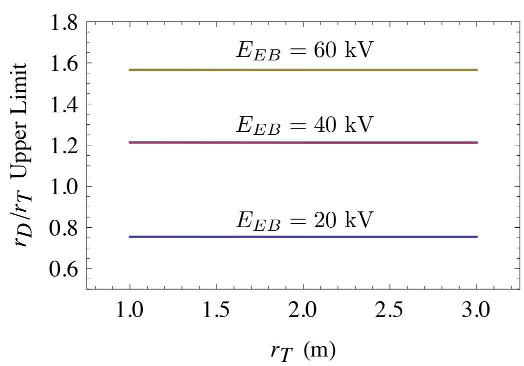

FIGURE 5. Size ratio limits for a variety of tug sizes for which charge transfer ($\phi_c = -1$ kV) is possible, given beam energies of $E_{EB} = 20,\ 40,$ and 60 kV.

Returning to Figures 2 and 3, the upper limit on the scaling parameter (r_D/r_T) for a given beam energy is consistent between the two plots. For example, for the 40 kV contour the maximum size ratio for which charge transfer can still be accomplished is roughly 1.2. The primary difference between the two cases where r_T = 1 m and r_T = 2 m is the amount of current required to reach this peak. The increased current for the larger object sizes is required to offset the higher plasma and photoelectron

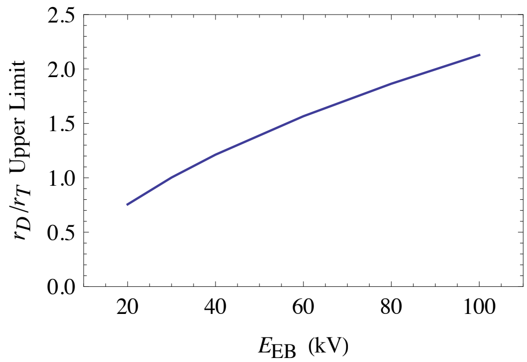

FIGURE 6. Size ratio limits permitting charge transfer ($\phi_c = -1$ kV) as a function of beam energy.

currents that result from increased surface areas. While it is difficult to determine an expression for the maximum size ratio that still permits charge transfer, the peaks can be computed numerically. To investigate the sensitivity of the upper limits to the tug size, the maximum allowable size ratios are computed for a range of tug radii. The results for beam energies of 20, 40 and 60 kV are shown in Figure 5. It is clear that the upper limits on the relative sizes are not sensitive to the tug size, but rather to the beam energy. A higher beam energy allows for charge transfer onto a larger object. The upper limits on the size ratio for a range of beam energies is shown in Figure 6. At the lower end of the spectrum, a tug vehicle equipped with a 20 kV electron beam would only be capable of achieving charge transfer onto an object roughly three-quarters of its size or smaller. To achieve charge transfer onto a similarly sized object ($r_T = r_D$), the tug vehicle would need an electron beam in excess of 30 kV. As the beam energy increases, larger and larger objects can be charged. This is reflective of the fact that higher beam energies allow the tug vehicle to emit more current before it achieves charge saturation ($\phi_T = E_{EB}$). Larger deputy objects require more current for charging, as reflected in Figure 4. Increasing the beam energy allows the tug to provide these higher currents for larger deputy objects.

From the perspective of achieving charge transfer, the results thus far suggest that a larger tug is better. A larger tug achieves charge transfer for a wider range of deputy object sizes while requiring less beam energy than a smaller tug. With a 40 kV electron beam, a tug vehicle with a 3 meter radius can perform charge transfer onto a deputy object with a radius in excess of 3.5 meters. A one-meter tug similarly equipped could only perform charge transfer on an object with a 1.2 meter radius.

From a Force Perspective

The charge transfer analysis for varying sizes has thus far only been concerned with achieving a potential on the deputy object. However, this is really only part of the bigger picture when it comes to assessing electrostatic tractor performance. An attractive electrostatic force still exists between tug and deputy even when deputy potentials are small, due to the position dependent capacitance relationship. For the deputy to be at a small potential in the near vicinity of a tug vehicle with a potential of 10s of kV, it must

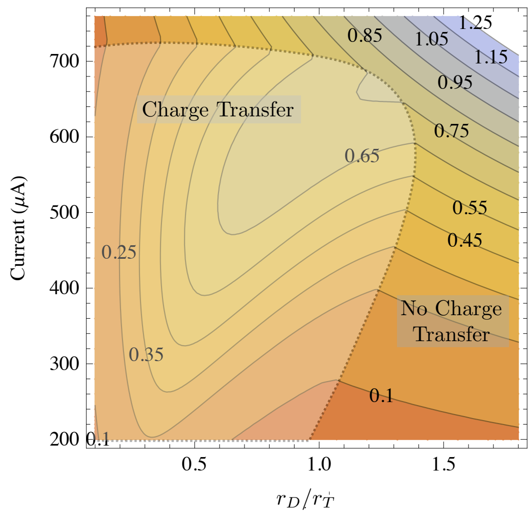

FIGURE 7. Electrostatic force magnitude (in mN) for a range of beam currents and deputy sizes, assuming a tug radius of 2 m.

accumulate a charge. This charge is absorbed from the plasma environment. Inverting Eq. (8) reveals the charge on the deputy is

$$q_D = \frac{L r_D (L\phi_D - r_T \phi_T)}{k_c (L^2 - r_D r_T)}.$$

In the case of no charge transfer, deputy potentials are very low compared with the tug potential. The charge may then be approximated as

$$q_D = -\frac{L r_D r_T}{k_c \left(L^2 - r_D r_T\right)} \phi_T. \tag{12}$$

Clearly, there will be some amount of charge on the deputy when a charged tug is nearby, even if it is at a low potential. This means that an attractive electrostatic force still exists between the objects even if charge transfer is not possible. Indeed, if the deputy is too large relative to the tug the best course of action would be to supercharge the tug ($\phi_T = E_{EB}$). This would maximize the charge on the deputy and lead to the largest possible electrostatic force.

To illustrate the impact of relative sizing on the resulting electrostatic force, a 2 meter tug radius is considered with a beam energy of $E_{EB} = 40$ kV. The electrostatic force magnitudes (in mN) are computed for a range of deputy sizes and beam currents. The results are shown in Figure 7. The upper limit on the current range is chosen as the condition that provides a tug potential equal to the beam energy ($\phi_T = E_{EB}$). Additional current emission is not possible, because the beam electrons would be recaptured by the tug.

There are two distinct regions on the plot: conditions where charge transfer occurs, and conditions that prevent charge transfer. In the region where charge transfer is not possible, the electrostatic force results from the fact that the tug has a large enough

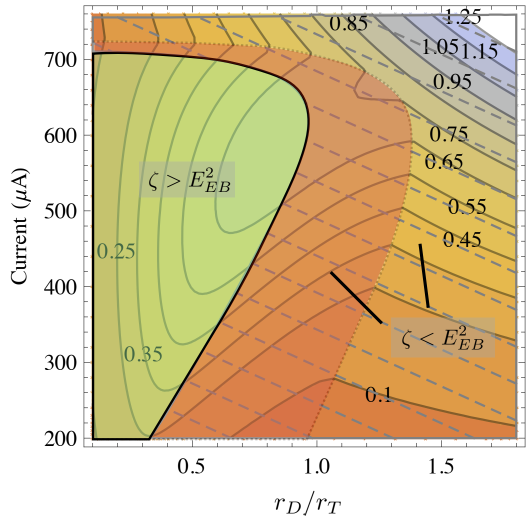

FIGURE 8. Region where $\zeta > E_{EB}^2$ for the 2 meter tug and an electron beam with $E_{EB} = 40kV$.

potential to provide a significant charge on the deputy object, as predicted by Eq. (12). For smaller deputy sizes, the largest forces are found in the region of charge transfer. It is better to get a potential split between tug and deputy than to completely charge the tug. However, there is a critical size ratio where it is better to maximally charge the tug than to perform charge transfer. To identify the conditions under which this is true, note that the electrostatic force can be written as a function of tug and deputy potentials using[6]

$$F_c = -\frac{r_T r_D}{k_c(L^2 - r_T r_D)^2}\left(r_D\phi_D - L\phi_T\right)\left(L\phi_D - r_T\phi_T\right). \tag{13}$$

For the case of maximally charging the tug ($\phi_T = E_{EB}$, $\phi_D \approx 0$), the force reduces to

$$F_c = -\frac{r_T r_D}{k_c(L^2 - r_T r_D)^2} L r_T E_{EB}^2. \tag{14}$$

For any set of conditions that produces a force smaller than this value, it would be better to simply maximize tug current emission and allow the tug potential to be equal to the beam energy. This boundary is defined by

$$\underbrace{\frac{r_D}{r_T}\phi_D^2 - \phi_D\phi_T\left(\frac{r_D}{L} + \frac{L}{r_T}\right) + \phi_T^2}_{\zeta} = E_{EB}^2. \tag{15}$$

A given electron beam current, in combination with particular tug and deputy sizes, will yield a ζ value. If $\zeta < E_{EB}^2$, maximizing the tug potential is a better option. If $\zeta > E_{EB}^2$, then the charge transfer process yields a larger force than would be obtained with maximum beam current. Returning to the 2 meter tug scenario, this boundary is computed and shown in Figure 8. The green shaded region represents the condition $\zeta > E_{EB}^2$, where charge transfer produces a larger force than the maximum current case.

The red shaded region shows the region where charge transfer is possible, but $\zeta < E_{EB}^2$. Indeed, there is a significant range of conditions for which charge transfer is possible, but a larger force is obtained by maximally charging the tug. The most important conclusion drawn from this analysis is that for any size ratio r_D/r_T greater than approximately 0.95, the best strategy for achieving the maximum force is simply to maximally charge the tug. Even though charge transfer is possible up to a larger size ratio, charge transfer actually yields worse performance. This is because with $r_D/r_T > 0.95$ the tug is becoming much smaller than the debris, and this limits how much charge can be stored on the tug at a given potential, and how much charge can be transferred to the debris.

From an Orbit Raising Perspective

Computing the electrostatic force magnitudes only tells half of the story. Larger objects produce larger forces for a given potential, because the total charge on the objects increases linearly with radius. But larger objects also tend to be heavier, meaning they are accelerated more slowly for a given force magnitude. Ultimately, the most important performance criteria that may be considered for the electrostatic tractor is the rate at which the deputy orbit is changed. Returning to the debris reorbiting scenario, where the objective is increasing the deputy orbit radius by approximately 300 km, the semi-major axis increase over one day is used to quantify the tugging performance. Again, there is a need to define a lower threshold on performance to characterize acceptable performance levels. A one kilometer per day increase in the deputy semi-major axis is used as this lower bound. Other studies are considering much higher orbit raising performances of 2-3 km/day.[14] Thus, 1 km/day is a convenient conservative lower bond. Assuming a nearly circular deputy orbit, the semi-major axis increase in the deputy orbit over one day is[3]

$$\Delta a \approx \frac{4\pi}{n^2}\frac{F_c}{m_D}, \tag{16}$$

where n is the mean motion of the deputy orbit and m_D the deputy mass. A GEO orbit radius of 42,164 km is assumed for this analysis. The deputy mass is required to compute the semi-major axis change. Considering publicly available data on GEO satellites, Reference [14] provides a relationship between spacecraft mass and an approximate sphere radius. The simple linear expression

$$r_D(m_D) = 1.152\text{ m} + 0.00066350\frac{\text{m}}{\text{kg}}m_D \tag{17}$$

provides a deputy radius for use in the charging model. While certainly not perfect, this linear relationship does capture the general trend of increased mass for larger objects and is based on actual data for GEO objects.

Considering a tug size of $r_T = 3$ meters and an electron beam energy of 40 kV, the semi-major axis increase over one day for a range of deputy sizes is shown in Figure 9. Again, there are two distinct regions of the plot, which correspond to successful charge transfer and no charge transfer. Using charge transferm the 3 meter tug can tow objects in excess of 4000 kg faster than the $\Delta a = 1$ km/day threshold. As an alternative to charge

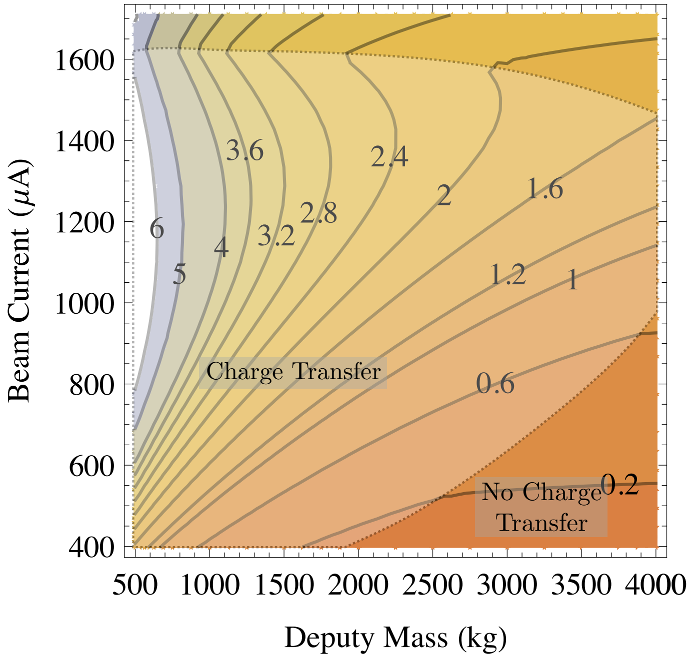

FIGURE 9. Deputy semi-major axis increase per day (in km) for a range of deputy sizes and electron beam currents. The tug size is $r_T = 3$ meters.

transfer, the tug can be supercharged. Doing so here actually provides better performance beyond a certain critical mass. Note that the upper limit on the beam current corresponds to the maximum current that can be emitted from the tug vehicle ($\phi_T = E_{EB}$). By supercharging the tug instead of using charge transfer, better performance is achieved for deputy masses above 1900 kg. Objects as large as 4000 kg can be towed at a Δa in excess of 2 km/day using supercharging, while the charge transfer performance for objects of that size is limited to a Δa of 1.6 km/day.

Revisiting Eq. (14), which yields the electrostatic force when $\phi_T = E_{EB}$, it is possible to derive an expression whose solution yields the largest mass that may be towed for a given tug configuration. With a supercharged tug, the increase in the semi-major axis after one day is given by

$$\Delta a = \frac{4\pi}{n^2} \frac{L r_T^2 r_D}{k_c m_D (L^2 - r_T r_D)^2} E_{EB}^2. \tag{18}$$

Using the mass-radius relationship in Eq. (17) to substitute in for r_D, this function may be rearranged as

$$r_T^2 b^2 m_D^3 + 2 r_T b (r_T r_0 - L^2) m_D^2 + \left(r_T^2 r_0^2 + L^4 - 2L^2 r_T r_0 - \frac{b}{\beta} \right) m_D - \frac{r_0}{\beta} = 0, \tag{19}$$

where $r_0 = 1.152$ meters and $b = 0.0006635$ m/kg are the coefficients from Eq. (17), and

$$\beta = k_c \frac{\Delta a n^2}{4\pi L r_T^2 E_{EB}^2}. \tag{20}$$

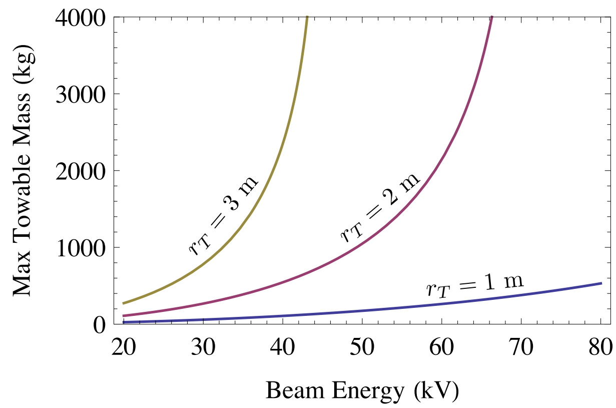

FIGURE 10. Maximum towable mass, considering only super-charging, that can still achieve a 1 km/day SMA increase for various tug configurations.

Finding a positive root of this third order polynomial provides the mass that can be towed at a rate of Δa km/day for a given tug size, separation distance, and beam energy if the tug is allowed to supercharge. This is a useful result because it provides insight into how large of a deputy object can be towed with a particular tug configuration. While the results in Figure 9 indicate that a larger object can be towed with supercharging instead of charge transfer, in general this might not always be the case. Depending on the particular scenario, it is possible that charge transfer would allow for towing of a larger mass than supercharging. Thus, the roots of Eq. (19) provide a conservative lower bound on the maximum towable mass. If charge transfer produced better results than supercharging, a larger mass than predicted by Eq. (19) could be towed for a given tug configuration.

Considering the more typically assumed semi-major axis increase of 2.5 km/day, the maximum towable mass predicted by Eq. (19) for three different tug sizes is shown in Figure 10. The effects of tug size are striking. Even with an 80 kV beam energy, a one meter radius tug is limited to deputy sizes below 600 kg. By increasing the tug size to a 2 meter radius, a deputy object 4000 kg can be towed at a rate of $\Delta a = 2.5$ km/day, but a high beam energy (66 kV) is required. With an even larger tug radius of 3 meters, objects in excess of 4000 kg can be towed with a beam energy of 43 kV. These results support the conclusion that a larger tug size is better. For the range of deputy sizes considered here, a 3 meter (or larger) tug radius would allow for good performance while requiring beam energies of no more than 40 kV.

POWER CONSIDERATIONS

All of the results regarding limitations on tug and deputy sizing highlight the challenges of tugging a deputy object larger than the tug. There are no issues achieving charge transfer when the deputy is much smaller than the tug ($r_D/r_T \ll 1$). On the contrary, charge transfer and tugging performance in general suffer when the deputy is significantly larger than the tug. Failure to achieve charge transfer does not necessarily mean

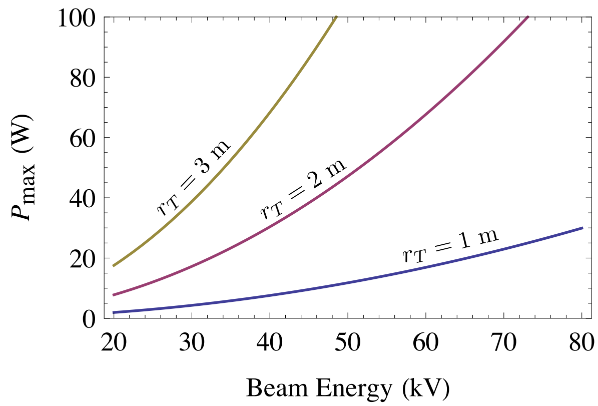

FIGURE 11. Power required to supercharge tug vehicle as a function of beam energy.

that an object cannot be towed, however. Because the deputy is effectively grounded to the plasma environment, the near proximity of a highly charged tug allows it to accumulate charge from this environment, as noted in Eq. (12). This can provide a significant electrostatic force, especially when supercharging the tug, and there are a wide range of conditions for which it is better to allow the tug to supercharge than to try and achieve charge transfer. Of course, there are tradeoffs to using a larger tug that must be considered. A larger tug vehicle, owing to its larger surface area, will require significantly more current to achieve a desired potential, and this current increases with the square of the tug radius. This means that doubling the tug radius will require four times as much power to achieve supercharging for a given potential. The expression

$$P_{\max} = I_{t,\max} E_{EB} \tag{21}$$

provides the power required for supercharging a tug vehicle. The variable $I_{t,\max}$ is the maximum current that may be emitted for the given beam energy and is computed as $I_{t,\max} = -I_e(E_{EB})$. The power required to supercharge tug sizes of 1, 2, and 3 meters is presented in Figure 11. In general, these may be considered as worst-case power requirements. If a scenario occurs where charge transfer achieves a better force than supercharging, then less current will be emitted and the required power will be lower. Recalling the results from Figure 10, towing a 4000 kg deputy object requires a 2-meter radius tug with a 66 kV electron beam or a 3-meter radius tug with a beam energy of roughly 43 kV. For the 2 meter tug, this is a required power of 81 Watts. For the 3-meter tug the required power is actually lower, at roughly 78 W. While the 3 meter tug is larger, it does not require supercharging to as high a potential as the smaller 2 meter tug. This illustrates that going to a larger tug size does not necessarily require more power to achieve similar performance, because the same levels of electrostatic forces can be achieved with smaller potentials. However, if a larger tug is supercharged to the same potential as a smaller tug, which will require more power, a significant boost in performance is possible owing to the larger electrostatic force that results.

CONCLUSION

In this study, the impacts of relative sizing between a tug and deputy object on electrostatic tractor performance are investigated. Assuming nominal, quiet GEO space weather conditions, an upper limit on the size ratio is determined that still enables charge transfer between tug and deputy. In general, a tug vehicle will be unable to achieve charge transfer onto an object much greater than itself. A comparison is performed between using charge transfer to generate an electrostatic tractor force and simply supercharging the tug object. It is found that charge transfer is not always the best option with regards to tugging performance. Even for conditions when charge transfer is possible supercharging can provide a larger electrostatic force, depending on the size of the deputy object relative to the tug. An analysis of the force resulting from supercharging provides a lower bound on the maximum mass that may be towed for a given tug size and beam energy. Significant gains in performance are achieved by increasing the tug size. For example, a tug with a 3 meter radius and a 32 kV electron gun can increase the semi-major axis of a 1000 kg deputy object by 2.5 km/day. To achieve the same level of performance with a two meter radius tug would require a beam energy of nearly 50 kV. The power required for tugging is on the order of several tens of Watts, even for the largest considered tug size of three meters. Further, increasing the tug size does not necessarily require more power to achieve similar levels of performance. The results support the notion that a larger tug size allows for the towing of a wider range of deputy sizes, and that charge transfer performance is significantly hindered if the deputy object is too big relative to the tug. Still, even if charge transfer is impossible, the electrostatic tractor concept can still be viable if the tug vehicle is supercharged.

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