ACTIVE SPACE DEBRIS CHARGING FOR CONTACTLESS ELECTROSTATIC DISPOSAL MANEUVERS

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ABSTRACT

We assess the feasibility of removing large space debris from geosynchronous orbit (GEO) by means of a tug spacecraft that uses electrostatic forces to pull the debris without touching. The advantage of this method is that it can operate with a separation distance of multiple craft radii, thus reducing the risk of collision. Further, the debris does not have to be detumbled first to engage the re-orbit maneuver. The charging of the tug-debris system to high potentials is achieved by active charge transfer using a directed electron beam and an auxiliary ion bleeder. Our simple charging model takes into account the primary electron beam current, UV induced photoelectron emission, collection of plasma particles, secondary electron emission and the recapture of emitted particles. The results show that by active charging high potentials can be both achieved and maintained. The resulting mN level electrostatic force is sufficient for the safe re-orbiting of debris objects over an acceptable period of a few months. The capability of debris removal is becoming a pressing need as the increasing population of dysfunctional satellites poses a threat to the future of satellite operations at GEO.

Key words: space debris, electrostatic tractor, electron beam.

1. INTRODUCTION

The threat of space debris on satellite operations has increased to the point where avoiding creating debris is no longer sufficient.[1] The tipping point has been reached where the low-Earth orbit space debris population will continue to increase even if no additional satellites are launched, due to debris-debris collisions.[2] While having less debris than the Low Earth Orbit (LEO) regions, the Geostationary Earth Orbit (GEO) region is a very narrow zone with a growing number of large, defunct Earth sensing and communication satellites. Of the over 1200 large GEO object tracked, less than 400 are controlled, functioning satellites.[3] The GEO satellites are high-value spacecraft, and the GEO space debris concern is a growing concern with operators and associate insurance agencies.[4] International guidelines specify that GEO spacecraft must move to a disposal orbit at their end of life. However, this is not done by all operators, or technical failures prevent this final step. Thus, active debris removal at GEO is a critical ability to avoid frequent debris avoidance maneuvers.[5]

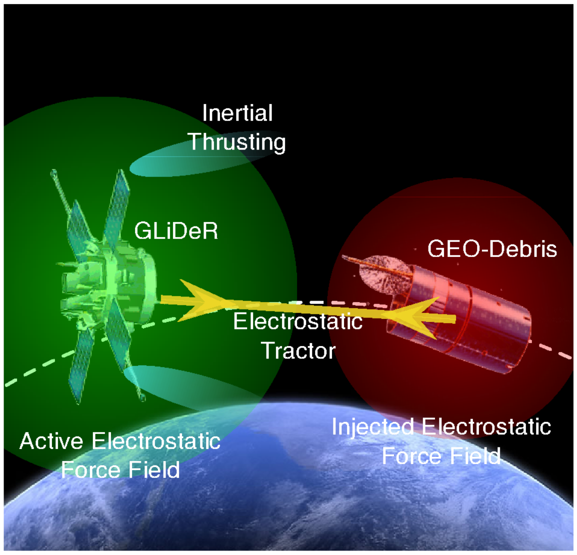

Figure 1. Illustration of the Geosynchronous Large Debris Reorbiter (GLiDeR^{TM}) concept

Active Debris Removal (ADR) remains a challenging discipline with no solutions operating in space.[6] Envisioned concepts range from robotic docking [7, 8], electrodynamics tethers for LEO applications [9], as well as space debris pushers using contactless directed ion exhaust plumes [10, 11, 12]. Schaub and Moorer [13] discuss a novel, patented approach to moving large, tumbling GEO debris to disposal orbits 250-300km above the geosynchronous zone as illustrated in Figure 1. Here

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the tug employs continuous electron emission to raise its own potential to a positive value of 10's of kilo-Volts, while the electron emission is directed at the space debris object to yield a negative potential. Simultaneously low-thrust inertial thrusters are employed on the tug to raise the two-vehicle system altitude.[1,2] The resulting attractive inter-vehicle force is referred to as the Electrostatic Tractor (ET) and will reach magnitudes of several milli-Newtons assuming a separation distance of 15-25 meters. Even large multi-ton debris objects can be moved or reorbited to a disposal orbit in 2-4 months [14]. The pulling configuration with attractive electrostatic forces is preferred due to a) increased forces for a given potential, b) passively stable relative orientation, as well as c) superior failure modes having the tug pull away safely if the ET fails.[15]

The focus of this paper is the charge transfer process itself for this ET concept. Active charge control for space-based actuation is first discussed by Cover et. al. [16]. The GEO region is identified as ideal for active charging applications where kilo-Volts of potential can be achieved using as little as Watt-levels of electrical power. Cover discusses using these forces for electrostatic membrane inflation. Reference [17] discusses active charge control to directly control relative motion of spacecraft having identified that the naturally occurring space weather related charging observed on the SCATHA [18] and ATS missions could lead to significant disturbance force on nearby space objects. This has led to extensive research studying charged relative motion dynamics for cluster and formation flying [19, 20]. Recently the use of hybrid electrostatic actuation and inertial thrusters to control the relative motion while performing inertial orbit corrections is discussed by Hogan et. al. [21]. This work identifies the importance of ET effectiveness bounds in the relative motion stability analysis. The ET concept is also discussed by Murdoch et. al. [22] for asteroid deflection applications. This work illustrates that with large space object potentials relative to the plasma energies the Debye length related shielding of electrical charges is reduced. For the GEO debris application the average minimal Debye lengths are on the order of 180-200 meters [23], making Debye shielding concerns minimal for the ET operation.

The ET concept is also of interest for on-orbit servicing of satellites to enable novel relative motion control with the to-be-serviced satellite, including touchless repositioning as discussed by [24]. The servicing missions considered may include refueling, part replacement or repair and forced orbit change. There are a number of envisioned concepts, including using (a) robotic arms for docking and deployment of de-orbiting devices,[8, 25, 26] or (b) non-robotic capture with nets, tethers or inflatable devices.[9, 27]

The prior Coulomb actuation studies do not consider the electron charge transfer process between two space objects. The active charge emission is performed on each space object individually, and is assumed to not impact the charging of a neighboring object. This paper performs an analytical study of how well the ET concept will operate taking into account the diverse spacecraft charging effects due the plasma space environment, photoelectron current, secondary electron emission, as well as the charge imparted by the space tug. The charge transport onto space particles is studied by the dusty plasma community [28, 29]. Dusty plasma analysis tools are employed to study the ET effectiveness for GEO debris actuation. Of interest are what ideal tug and debris potentials yield the best ET magnitude given the limited charge emission energies, the effectiveness of the charge transfer process for a range of tug potentials, as well as the sensitivity of the ET performance on tug potential uncertainties.

The article is organized as follows. In section 2 the main forces acting on the tug-debris system are discussed. Of interest is if ET forces in the milli-Newton range are feasible at a distance of 10-20 meters. This force magnitude has been shown to yield multi-ton debris reorbiting times of 2-3 months [14]. Further, benefits of using electron rather than ion emission are investigated. In Section 3 the charging currents are presented, which include primary processes (photoelectron emission, collection of electrons and ions from the plasma environment and the active charge transfer) as well as secondary processes (secondary electron emission due to impinging primary electrons, collection of particles emitted by one craft by the other). Section 4 discusses the plasma conditions of the GEO environment. Numerical solutions to the charging problem are presented in Section 5.

2. ELECTROSTATIC FORCES BETWEEN TUG AND DEBRIS

In order to study the problem of active charging in a simple analytical form and to keep charge balance calculations simple, a number of simplifying assumptions are made throughout this paper. The first basic simplifying assumption is that both the tug and the debris are conductive spheres. This size is representative of typical spacecrafts at GEO. The two main forces acting between the objects are the attractive Coulomb force and the momentum transferred from the tug to the debris by the charging beam, which represents a repulsive force. The Coulomb force acting between charged objects in the plasma environment at a separation distance can be written in a simple form [30]:

$$F_C = \frac{1}{4\pi\epsilon_0}\frac{Q_T Q_D}{r^2} e^{-r/\lambda_D}\left(1+\frac{r}{\lambda_D}\right) \tag{1}$$

where Q_T and Q_D are the charges on the tug and the debris, respectively. The constant ϵ_0 is the permittivity of vacuum, r is the distance between the object center of masses, and λ_D is the effective Debye length of the

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[1] D. F. Moorer and H. Schaub, "Hybrid Electrostatic Space Tug," Patent No. US 2011/0036951-A1, February 17, 2011.

[2] D. F. Moorer and H. Schaub, "Electrostatic Spacecraft Reorbiter," Patent No. US 8,205,838 B2, February 17, 2011.

ambient plasma [22]. The charge and the potential on the objects are related through

$$Q_T = C_T \phi_T \tag{2a}$$

$$Q_D = C_D \phi_D \tag{2b}$$

where ϕ_T and ϕ_D are the potentials with respect to the undisturbed space potential of the tug and debris, respectively. The parameters C_T and C_D are the capacitances of the tug and debris and are given by the size and shape of the objects. With the $R \ll \lambda_D$ condition satisfied, the capacitance of a sphere is simply $C = 4\pi\epsilon_0 R$. For shorter Debye lengths, the plasma can increase the objects capacitance [30, 31]. The attractive force can be enlarged by increasing the potentials on the crafts, increasing the capacitance (size) of the tug, or reducing the separation distance. The latter would be the obvious choice, except that collisions with potentially devastating outcomes have to be avoided. It is shown below that a separation distance on the order of 10 to 20 m provides both sufficient attractive force at reasonable craft potentials, and is likely sufficient to avoid collisions.

A few additional assumptions are made. First, we will assume that the Debye shielding is negligible and therefore we drop the exponential terms from Eq. (1) for all future calculations. The justification for doing so is that λ_D is large for common conditions for GEO plasma (see Sec. 4) and that the Debye shielding effect is reduced for objects charged to much higher potentials than the temperature of the plasma particles [30]. Second, in the force calculation we will neglect the finite size of the crafts, and both objects are treated as point charges. At close proximity (r comparable to or smaller than R), the capacitance of the crafts increases and the mutual induction enhances the attractive force [32, 33, 30]. For real spacecrafts with complex geometries these effects will need to be included and carefully analyzed.

Charged particles can be actively transferred from the tug to the debris by electron or ion guns. A potential difference U is then driven between the tug and debris,

$$U = \phi_T - \phi_D \tag{3}$$

by the active charge transfer. This potential difference has to be smaller than the gun energy due to the ambient plasma environment, i.e.

$$U \leq E_{EB}/q$$

where q is the elementary charge and E_{EB} is the energy of the accelerated beam particles measured in eV. For a given potential difference U, the maximum Coulomb force occurs when the potential is equally shared between the tug and the debris:

$$\phi_T = \frac{U}{2} \qquad \phi_D = -\frac{U}{2} \tag{4}$$

This can be shown simply by substituting $Q = C_T \phi_T$ and $Q_D = C_D(\phi_T - U)$ into Eq. (3). The extrema (maximum) of force F_c can be found by solving the equation $\mathrm{d}F_c/\mathrm{d}\phi_T = 0$. The conclusion from this observation is that for maximum force (i.e., the most effective ET), the potentials on both the tug and debris need to be approximately equal in magnitude and maintained at these levels. It will be shown in Section 5 that this can be achieved in most cases by controlling the current of the primary charge transfer mechanism.

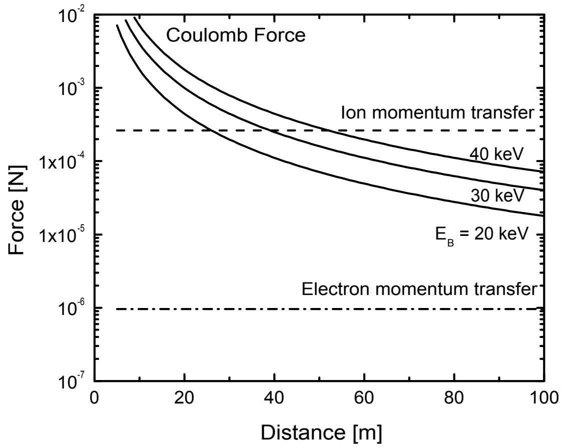

Figure 2. The comparison of the attractive Coulomb force (without Debye shielding) to the repulsive force of electrons or ions from the active charge transfer.

The current transferred by charged particles represents a repulsive force between the tug and debris. This force is from (a) the thrust from the particles leaving the tug, and (b) the thrust from the particles impacting the debris. The thrust force is calculated as the change of momentum over a unit time. Under the assumptions that the beam consists of singly charged particles, all particles leaving the tug impact on the debris and are absorbed, and equilibrium charge conditions ($|\phi_T| < E_{EB}/2$) are present, the magnitude of this force is approximated as

$$F_R = 2\frac{I_{tr}}{q} m_b v_\infty \tag{5}$$

Here I_{tr} is the current of transmitted beam, q is the elementary charge, and

$$v_\infty = \sqrt{\frac{2q(E_B - \phi_T)}{m_b}} \tag{6}$$

is the velocity of the beam particles at infinity. The parameter m_b is the mass of the beam particles, which are either electrons or ions. For electrostatic pulling to work, the Coulomb interaction has to be stronger than the repulsive thrust, i.e. $F_C > F_R$. Figure 2 shows the comparison of the two forces as a function of separation distance for typical charging current conditions. The calculations are for I_{TR}=0.8 mA, E_{EB} = 60 keV, $\phi_T = 28$ kV, Ar$^+$ ions and electrons. The tug and debris are sphere of R=2m radius. The values of these parameters are justified in Section 5. The Coulomb force for potentials 20 kV and 40 kV are also shown for comparison. The repulsive force is a factor $\sqrt{m_i/m_e}$ larger for ions with mass m_i than for electrons of mass m_e. The following observations can be made: For crafts with 2 m average radius charged to tens of kV potential, the Coulomb force is in the mN range for separation distance at around 20 meters. The repulsive force from an ion charging beam is close to the mN level and is independent of the separation distance. Active charging by an electron beam, on the other hand, transfers little momentum and its repulsive effect is negligible. Charging by an electron beam is thus the preferred option, which is incidentally also easier to implement and reduces the requirement for fuel mass. As a result, the tug will be positively charged and the debris negatively charged. The thrust forces from all other collected or emitted particles are assumed to be isotropic with a zero net effect.

3. CRAFT CHARGING MODEL

Besides the active charge transfer from the tug to the debris, there are a number of primary charging processes from the space environment and also secondary processes that will affect the attainable potentials. This section presents the analytical formulas for the charging currents. The equilibrium potential of the tug-debris system is achieved by the current balance; i.e. when the net current to each object is zero. The tug is charging positively because of the active emission of electrons, while the debris will acquire negative charge. For generality it is also assumed that the tug is equipped with an auxiliary ion gun that can purge unwanted charge, if necessary.

The photoelectron current from solar UV radiation is written in a form:

$$I_{ph}(\phi) = j_{ph,0} A_\perp e^{-\phi/T_{ph}} \qquad \phi > 0 \qquad (7a)$$

$$= j_{ph,0} A_\perp \qquad \phi \leq 0 \qquad (7b)$$

where $j_{ph,0}$ and T_{ph} are the flux and temperature of the emitted photoelectrons, $A_\perp$ is the cross section of the spacecraft exposed to UV. The value of is on the order of 10μA/m^2 depending slightly on surface material of the spacecraft and can vary by up to a factor of 8 with solar activity [34]. The values used in this article are $j_{ph,0} = 20\mu$A/m^2 and $T_{ph} \approx 2$ eV.

The collection of plasma electrons from the surrounding plasma is given by:

$$I_e(\phi) = -\frac{Aqn_e w_e}{4} e^{\phi/Te} \qquad \phi < 0 \qquad (8a)$$

$$= -\frac{Aqn_e w_e}{4}\left(1 + \frac{\phi}{T_e}\right) \qquad \phi \geq 0 \qquad (8b)$$

where $A = 4\pi R^2$ is the surface area of the craft and $w_e = \sqrt{8T_e/\pi m_e}$ is the thermal velocity of the plasma electrons. The minus sign defines the polarity of this current. The collection of plasma particles is similar in form and in the definition of the variables:

$$I_i(\phi) = \frac{Aqn_i w_i}{4} e^{\phi/T_i} \qquad \phi > 0 \qquad (9a)$$

$$= -\frac{Aqn_i w_i}{4}\left(1 + \frac{\phi}{T_i}\right) \qquad \phi \leq 0 \qquad (9b)$$

The active charge transfer is performed by the means of an electron gun on the tug that is pointed at the debris. Some fraction of the emitted electrons from the gun reache the debris, depending on the charge state of the two crafts and the energy of the electron beam:

$$I_D(\phi_D) = -\alpha I_{T,0} \qquad \phi_T - \phi_D < E_{EB} \qquad (10a)$$

$$= 0 \qquad \phi_T - \phi_D \geq E_{EB} \qquad (10b)$$

where $I_{T,0}$ is the electron current emitted from the tug and α is the factor of charge transfer efficiency that incorporates the effects from pointing accuracy of the electron beam at the debris and the width of the beam at the location of the debris. Furthermore, α is in general a function of the potentials on the tug and debris and the beam energy. Upon impact on the debris, the primary electrons from the gun will induce the emission of secondary electrons. The secondaries will leave the debris because of its large negative potential and thus represent an additional charging current. We use the Draine & Salpeter approximation to describe the current of secondary electron emission from the debris:

$$I_{\text{SEE}}(\phi_D) = 4Y_M I_D(\phi_D)\kappa \qquad \phi_D < 0 \qquad (11a)$$

$$= 0 \qquad \phi_D \geq 0 \qquad (11b)$$

Here

$$\kappa = \frac{E_{\text{eff}}/E_{\text{max}}}{(1 + E_{\text{eff}}/E_{\text{max}})^2} \qquad (12)$$

and

$$E_{\text{eff}} = E_{EB} - \phi_T + \phi_D \qquad (13)$$

is the effective energy of the primary electron impacting the surface of the debris. Y_m is the maximum yield of secondary production, defined as the average number of electrons emitted for each impacting electron. E_{max} is the impact energy at which this maximum occurs. Typical values of Y_m are on the order of one for most metal surfaces but can be much larger for insulators. The values for aluminum, for example, are $E_{\text{max}} = 300$eV and $Y_m = 1$ for normal incidence. The electron yield, however, increases with impact angle and the average yield from a spherical object is approximately twice as large as from a planar surface at normal incidence.

4. PLASMA ENVIRONMENT

At geosynchronous orbits the crafts are exposed to a plasma environment that varies with local time and geomagnetic activity. The magnetospheric plasma consists of electrons, protons and singly-charged oxygen ions. The statistical studies by Denton et. al. [23] provide a convenient summary of electron density and temperature properties under various geomagnetic activity levels. Extreme plasma conditions related to solar flare do exist, however, these are short lived compared to the time scale of re-orbiting (approximately a few months). The prime interest is thus investigating the craft charging processes for the most common conditions. The best statistical representation of geomagnetic activity conditions is described by $K_p \leq 3$, which applies about 80% of the time [35]. The K_p value is an index of solar activity, with 1 being low, and 5 being a solar storm condition.

In general, the electron densities are highest on the morning side of the magnetosphere (under quiet conditions), and lower in the afternoon sector. The variation is roughly between 0.1–1 cm^{-3} and the typical value of $n_e = 0.5\ \text{cm}^{-3}$ is used in the calculations below. The electron temperature can vary in the range of 100–2,500 eV, but the temperature rises to or above 1,000 eV level only in the early morning section. The typical value of $T_e = 750$ eV is used. The ion density equals to that of the electrons for the charge neutrality requirement, however, their energy is higher and a representative value of 7.5 keV is used. It ought to be noted that with respect to the magnetic field, the temperatures of both the electrons and ions can be divided to parallel and perpendicular components, which can be somewhat different. This effect however is neglected and it is also assumed that all ions are protons.

The characteristic Debye length of the plasma,

$$\lambda_D = \sqrt{\frac{\epsilon_0 T_{e,j}}{q n_e}} \tag{14}$$

where the temperature is measured in the units of eV, is on the order of hundreds of meters [23]. It is thus justified to neglect the exponential shielding term in Eq. (1) for the calculation of the electrostatic force.

5. NUMERICAL SOLUTIONS

Figure 3 shows the magnitude of the different currents to the debris as a function of its potential. This example is calculated for a case of 1m radius spherical objects, the electron beam energy is $E_{EB} = 20$kV. The electron gun operates at $I_{T,0} = 120\mu$A emission and normal plasma conditions are assumed. The potential established on the tug is calculated from the current balance, $I_e + I_{T,0} = 0$, and results in a potential of $\phi_T = 7.647$kV. It is assumed that electron beam is well focused and accurately pointed at the debris and thus $\alpha = 1$ from above. The potential established on the debris is also calculated from the current balance and results in $\phi_D = -7.936$kV. The potential difference reached between the two objects is thus $U = 15.583$kV. While smaller than the energy of the electron beam by about 25%, this still leaves a considerable potential difference that is suitable for electrostatic tugging.[15]

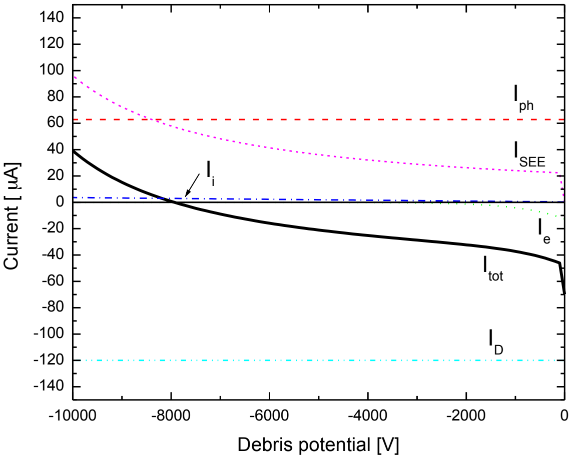

Figure 3. Current Illustration for Ranges of Debris Potentials

A parametric study of the S/C and debris charging is performed as a function of the magnitude of the active charging current. The results are shown in Figure 4 and the observations can be summarized as follows. The tug potential (top figure) increases linearly with the emitted current. This is because the only compensating current is plasma electron collection from the environment, which is also a linear function of the tug potential. The debris potential (second from top) is a non-linear and non-monotonic function of the transferred current. At the beginning, the debris potential increases because of the increasing electron beam charging current. The subsequent decrease is due to the fixed energy (20 kV) of the electron beam and since the S/C potential keeps increasing, the debris potential has to decrease. The potential difference between the tug and debris (third from top of Figure 4) keeps increasing with increasing beam electron current. The bottom figure shows the product of the tug and Debris potentials, which is a proxy for the electrostatic attractive force. The vertical line indicates the $\phi_T = -\phi_D$ conditions, i.e. where the absolute values of the tug and the debris potentials are equal. As seen, this is not the location of the maximum electrostatic force. This is because the potential difference between the crafts keeps increasing. The force is a flat function of the active beam emission current and thus the tug-debris interaction is insensitive to small potential variations that could be caused by varying plasma conditions, for example.

6. CONCLUSIONS AND SUMMARY

It is tempting to have as small separation as safely possible without the risk of collision. However, it is important to keep in mind that the electrostatic force magnitude can vary significantly as the towed vehicle's orientation

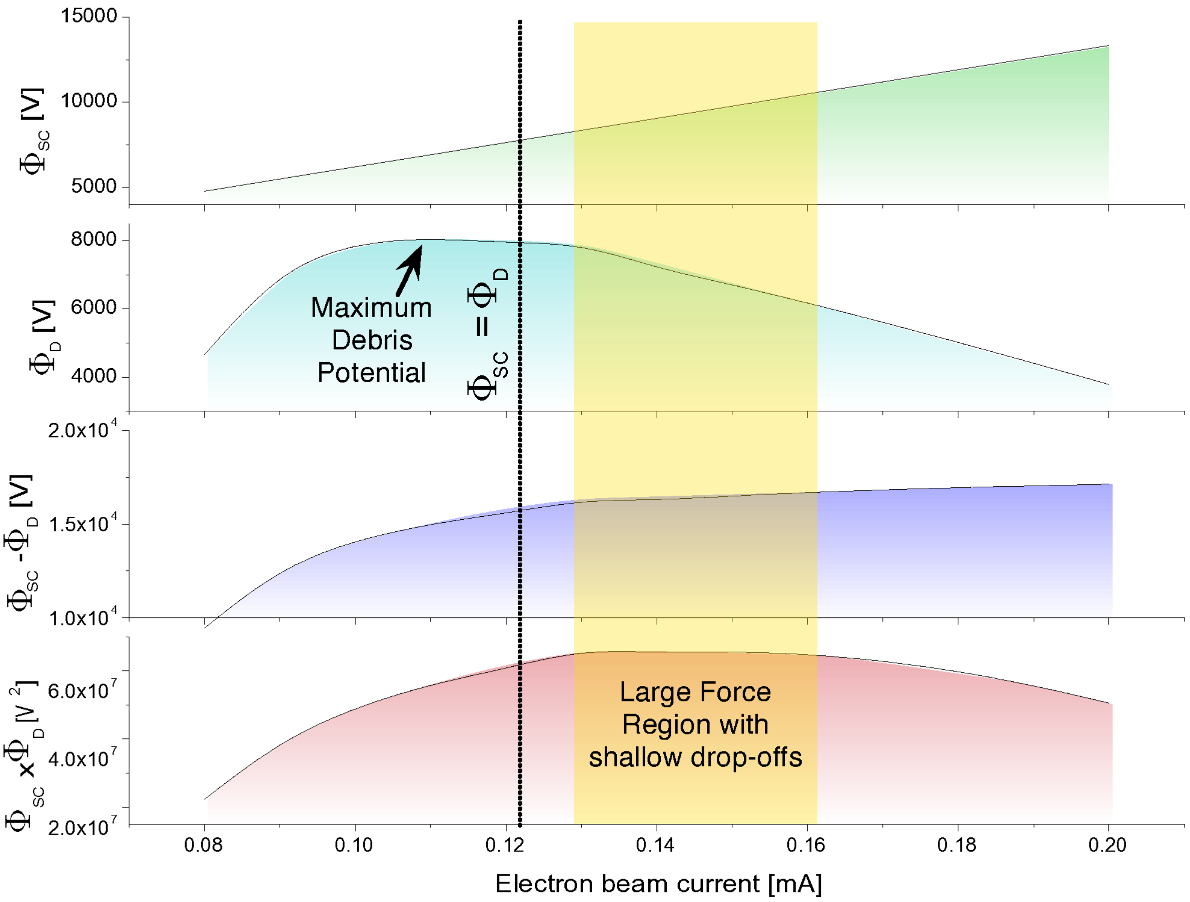

Figure 4. Potentials for a range of Electron Beam Currents

changes. In particular, the more non-spherical the second vehicle is, the larger these force variations can be. A cause of this is the induction charge redistribution. Thus, to fly less than 1 craft radii apart, it is important to have a detailed model and knowledge of the debris geometry. However, with a robust stationkeeping feedback control method, these force variations have been shown to have a minor variation on the ET efficiency for debris mitigation. Another reason for being cautious of flying too close is the recapturing of the secondary charge that the debris will emit, such as photo-electrons or secondary electrons. Future analysis will explore an optimal distance for operation which considers such recapture events.

To increase the Electrostatic Tractor (ET) effectiveness, the tug should be made roughly at least the size of the debris to be moved. The larger surface area provides the benefit of a larger capacitance, and thus larger electrostatic force at the same potential. Note that a large tug dimension does not mean necessarily a large tug mass. Rather, a lightweight charged outer tug surface is envisioned to provided the desired capacitance. The result in this paper that the idealized maximum ET force (ignoring plasma effects) is obtained when the potential magnitudes are matched provides critical insight that the electrostatic tug can have a range of shapes without impacting the ideal potential requirement.

Finally, the numerical simulations illustrate that non-idealized maximum ET potential are close to the equal potential solution. The insight that the maximum ET force is insensitive to the precise electron beam current is promising in that it will simplify the ET sensing and control concerns.

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