2nd International Energy Conversion Engineering Conference
16 - 19 August 2004, Providence, Rhode Island

AIAA 2004-5670

Current Collection to Electrodynamic-Tether Systems in Space

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Three important electrodynamic-tether system configurations have been investigated: an insulated tether with an end body collector, bare tether, and bare tether with end body collector. This paper discusses the current collection capabilities of these configurations and their respective advantages and disadvantages. University of Michigan's TEMPEST computer model was used to conduct the analyses of the three configurations. Analysis has determined that all three configurations allow orbit raising from 400 km to 700 km in around 18.5 days under similar ionospheric and system conditions. In addition, the best tether geometry to use for any of these configurations would be a slotted tether oriented perpendicular to the plasma flow with the individual wires as far apart as possible and as narrow as possible. This would minimize atmospheric drag, increase collision survivability, and keep the electron collection level close to the orbital-motion limit, while increasing the redundancy of the tether in case of micrometer collision..

Nomenclature:

A_p	=	Physical Area of Cylinder [m^2]
B_{North}	=	North Magnetic Flux Density [T]
dF	=	Unit Force [N]
dl	=	Unit Distance [m]
e	=	Electron Charge Magnitude [eV]
I	=	Total Collected Current [A]
I_{PM}	=	Parker–Murphy Current Collection [A]
I_{ram}	=	Ram Current Collection [A]
I_t	=	Current along Tether [A]
I_{the}	=	Electron Thermal Current [A]
n_e	=	Electron Number Density [particles/m^3]
n_i	=	Ion Number Density [particles/m^3]
m_e	=	Electron Mass [kg]
ϕ	=	Probe Potential [V]
ϕ_0	=	Characteristic Potential [V]
r_0	=	Critical Radius [m]
r_p	=	Collecting Body Radius [m]
T_e	=	Electron Temperature [eV]
V	=	Applied Voltage [V]
V_{emf}	=	Electromotive Force [V]
v_{orb}	=	Orbital Velocity [m/s]
V_p	=	Plasma Potential [V]
ω_c	=	Cyclotron Frequency [radians/s]

I. Introduction

Electrodynamic tethers (EDTs) are being considered as a propellantless propulsion technology for spacecraft in low Earth orbit. An orbiting EDT system naturally tends to orient itself along the local vertical due to the gravity gradient. Current flowing along the tether interacts with the Earth's magnetic field to produce thrust without any propellant. To produce currents high enough for significant thrust, electrons must be collected at the end or along part of the tether and emitted at the other end. Passive collection of electrons from the ionosphere is relatively efficient. However, various collection methods are being debated as to which is the most effective for a given system configuration. This paper discusses and compares electron-collection techniques for an assortment of ionospheric and system-wide design conditions.

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For most missions, three primary electron-collection configurations are usually considered: insulated tether with end-body collector/emitter, a bare tether, and a bare tether with an end-body collector/emitter. In this paper we discuss the relative benefits of each technique in terms of performance and complexity. Factors such as tether geometry, plasma density, neutral constituents, magnetic field, and orbital velocity are included in our analyses.

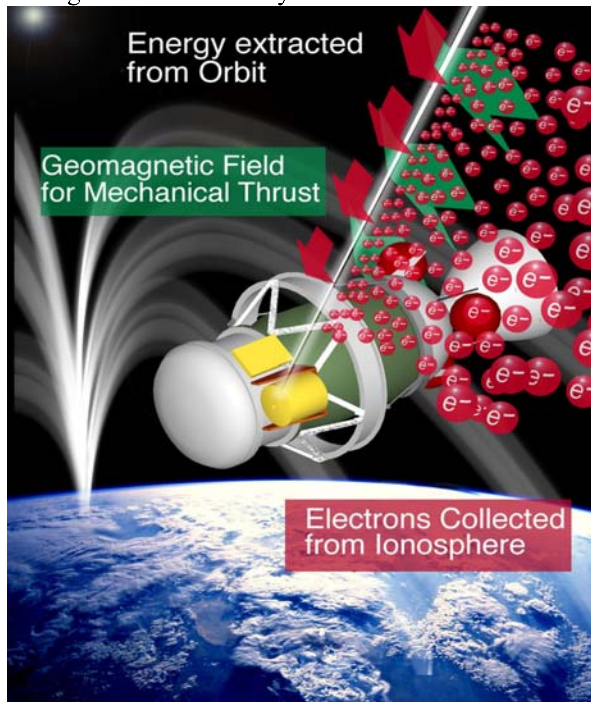

Figure 1: Illustration of the EDT concept

Tether Fundamentals

As an EDT system orbits the Earth, an electromotive force (EMF) is generated along the tether as given by

$$V_{\mathrm{emf}} = \left(v_{\mathrm{orb}} \times B_{\mathrm{North}}\right) \cdot dl \tag{1}$$

In generator mode (i.e., de-orbit mode), this EMF can be utilized by the tether system to perform various functions, such as charge batteries, emit electrons at the emitting end, and drive current through the tether. In boost mode, onboard power supplies must overcome this motional EMF to provide the tether potential for current collection, electron emission, and tether resistive losses. These processes are shown in Fig. 1.

As an example, consider the ProSEDS mission.[1] The Earth's magnetic field is approximately 0.18–0.32 Gauss in low Earth orbit (LEO), and the orbital velocity with respect to the local plasma is about 7500 m/s at 300-km altitude. Assuming the tether is 5000 m long, the resulting V_{emf} is in the range of 35–250 V/km along the length of the tether. This established EMF dictates the potential difference between the bare tether and the local plasma, which controls where electrons are collected and or repelled. Here, a de-boost tether is setup to allow for electrons to be collected on the positively biased upper section of the bare tether and returned to the ionosphere at the lower end. This flow of electrons through the tether moving across the Earth's magnetic field creates a force that produces a drag thrust that helps de-orbit the system as given by[2]

$$dF = dl \cdot I_t \times B_{North} \,. \tag{2}$$

II. Current Collection Methods for Various Configurations

Insulated Tether with End Body

An insulated tether prevents any current collector or emitter to take place along the tether. All of the electrons are collected by the end body on the positive potential (with respect to the plasma) end. They subsequently move along the tether to be utilized by the orbiting satellite and then emitted. The length of the tether dictates the amount of V_{emf} available to drive the current through the tether, which in turn determines the maximum quantity of electrons that can be collected by the end body.

The electron collection at the end body is governed by the electron thermal collection process, which represents the quantity of electrons that randomly cross a given area per unit time. This value, which does not take into consideration the effects of the magnetic field or the electric fields from the object surface, is given by

$$I_{the} = A_p e n_e \sqrt{\frac{eT_e}{2\pi m_e}} \,. \tag{3}$$

There are specific conditions where a more refined method can be used to determine the electron current collection. Parker and Murphy did this calculation under the assumptions that the collecting body is spherical, the plasma is collisionless, and there are no ionization sources. In addition, they included magnetic field effects, assumed conservation of angular momentum, and ignored the effect of particle thermal motion at infinity. Their derivation resulted in collected current given by

$$I_{\mathrm{PM}} = I_{the}\left(\frac{r_0}{r_p}\right)^2, \tag{4}$$

where $\frac{I_{\mathrm{PM}}}{I_{the}} \le 1 + 2\sqrt{\frac{\phi}{\phi_0}}$, $\phi_0 = \frac{m_e \omega_{ce}^2 r_p^2}{2e}$, and $\omega_{ce} = \frac{eB}{m_e}$. In the case of most end body collectors on EDT systems, the Parker–Murphy approximation is sufficient.[3]

Bare Tether without End Body

Due to the nature of the bare EDTs, it is often not a good idea to have the entire tether bare. A significant portion of the bare tether should be insulated depending on the plasma density, the tether length and width, the orbiting velocity, and the Earth's magnetic flux density. Figure 2 shows what the current and potential profiles would be for an upward deployed EDT, where V_t and V_p are the tether and plasma potentials, respectively. Point A is the anode, or upper end, of the tether. Point C is the cathode, or lower end of the tether. Point B (L_B is the distance along the tether where point B occurs) is the location where the potential with respect to the plasma goes from positive to negative. As a result of this change in polarity, the electron current collection begins to decrease. The electron emission (or effective ion collection) from the negatively charged lower section of the tether (below B) emits at a much slower rate than the electron collection from the upper half (above B).

If the tether were to be insulated starting at B, then the current that is emitted after that point could be saved. Since boost depends on collected current levels, this would allow for greater boosting forces. Since the plasma density and Earth's magnetic flux density are continuously changing, it is impossible to always have the point of zero potential where the tether begins[1], but enough knowledge of the EDT mission can allow a very accurate estimate. This effect is displayed in the simulations done in the next section and in Figure 4.[4]

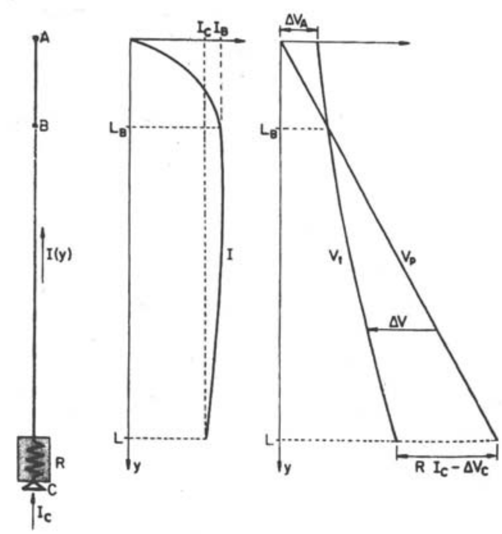

Figure 2: Current and Potential Profile Along Tether[4]

The orbital-motion limited (OML) regime applies when the Debye length is much greater than the object's size or, in other words, the object is small with respect to its sheath size. Here, the main factor limiting the collection of a particle is its angular momentum, however the probe has an influence over a large volume of plasma. The electron current collection of a probe in the OML regime can be derived and is given by

$$I = I_{the}\left\{\frac{2}{\sqrt{\pi}} \cdot \sqrt{1 + \frac{V - V_p}{T_e}}\right\}. \tag{5}$$

For repelling potentials, the relationship is different because particles with less energy than the encountered potential energy will not be collected. As a result, the electron current collection in the electron retardation region (when $V - V_p \le 0$) can be derived and is given by[3,5]

$$I = I_{the} \cdot \exp\left(\frac{V - V_p}{T_e}\right). \tag{6}$$

For large voltages, Eq. (5) becomes independent of the temperature, T_e, since the thermal current is proportional to $\sqrt{T_e}$. This normalization allows us to directly compare the OML theory, which only applies to thin cylinders in non-flowing plasmas, with our experimental results involving flowing plasma and various tether geometries.[6]

When integrating the two system configurations into a bare - insulated with end body hybrid, the OML theory for the tether and the Parker Murphy collection theory for the end body are employed.

Effects for All EDT Systems

All three of the configurations described above also are exposed to other electron emission processes; however, these processes have different effects that depend on the polarity of the tether and the end body with respect to the plasma. These processes are ion ram current collection, photoemission, and secondary electron emission. These processes occur along the negatively biased section of the tether because on the positive potential portion the electrons are just attracted back onto the tether, whereas on the negative end they are repelled out and emitted.

In most cases, the EDT systems travel at mesosonic speeds. As a result of the system traveling faster than the ion thermal velocity due to the larger mass of the ions, the tether "rams" into the slower ions and effectively collects ion current. These ions are even able to ram through the positively charged repelling force of the electron collecting end. This effect reduces the total electron collection by the amount indicated by

$$I_{\text{ram}} = A_p n_i v_{\text{orb}} e \,. \tag{7}$$

Other processes that would influence the current collection in an EDT system are photoemission and secondary electron emission. A typical value for current emission density due to photoemission in a low Earth orbit (LEO) is 2.4×10^{-5} A/m^2 assuming steel collecting bodies.[7] This value is only accurate for the surface area of the collecting body that faces the Sun. It varies according to orbital configuration and time of day. Depending on the surface area of the object, it is common that these other processes contribute less than 1% of the total electron collection.[3]

II. Tether Configuration Evaluations:

Various parameters of EDT systems were varied in order to observe the overall effect on system performance. The University of Michigan's computer model for simulating EDT systems, called TEMPEST, was used to conduct the analysis of each condition. For the following simulations, a number of assumptions were made: 1) the tether remained in a gravity-gradient orientation along the local vertical; 2) all simulations were performed under solar-max conditions (F10.7 Solar Flux is 188×10^{-22} W/m^2·Hz) at an inclination of 30 degrees, and with 1000 W of power delivered to the EDT system; 3) all the electron current collected at the positive end is emitted at the negative end across a hollow cathode at –40 V. The reference tether is 2.5 cm wide, 0.2 mm thick, with a resistance of 15 Ω/km. The peak power supply voltage is 2500 V.

Case 1

For the first case, the EDT system analyzed had a 10 km long, 50% insulated–50% bare tether with no collecting end body. Total altitude increase was from 400 to 700 km. Tether widths were varied from 0.1 cm to 5.0 cm, for which we determined the time it took to change altitude as well as monitored the maximum and minimum currents along the tether. The results of this analysis are shown in Figure 3. An important item to note in this figure is that the tether drag for the cases where the tether width is above 1 cm is significant and as a result the EDT system cannot climb from its initial 400-km altitude.

It can be seen in Figure 3 that as the width of the tether gets larger the orbit change time drops up to the point where drag forces dominate. This means it changes orbits faster and thus has a stronger boosting force as the width increases. Since the boosting force is stronger, Eq. (2) indicates that the current must be increasing. Figure 3 confirms this fact as it shows how the current increases as the width of the tether increases. This makes sense because at the width increases the collecting surface area increases. It can also be seen that the maximum current in the tether increases faster than the minimum current.

Case 2

The second case was analyzed to study the relationship between the tether's width and the length of bare section needed to start the insulated section where zero potential began on the tether, while keeping the insulated portion 5 km long. Table 1 displays the results of this analysis. As described above, the point of zero potential changes because of the changing current (i.e., the wider the tether the more current collected) The overall conclusion from this data is that the narrower the tether the longer the bare tether section needs to be up to a certain point.

Figure 4 shows the current that corresponds to the tether lengths defined in Table 1. It can be seen that as the width of the tether gets smaller, the required length of bare tether decreases, and the current along these tethers increases, correspondingly. The 'Max Iend' and 'Min Iend' value are the maximum and minimum values, respectively, of the current along the tether and they are different values because the collected current changes depending on the plasma density and the Earth's magnetic flux density. 'Rough Avg Iend' is the average of these maximum and minimum values. The V_{emf} on these tethers varies linearly depending on the total length according to Eq. (1), varying from 800 V at the 2.5 cm width to 1050 V at 0.1 cm width. The boosting thrust generated by these tethers, given by Eq. (2), is plotted in Figure 5. Since the only variable that differs between the cases is the current, the curves look similar to those in Figure 4.

Table 1 Bare tethers necessary to begin insulation at zero potential

Total Tether Length (m)	**Bare Tether Length** (m)	**Insulated Length** (km)	**Tether Width** (cm)	**Boost Time** (days)
5700	700	5	5.0	18.8
5700	700	5	3.5	18.1
5700	700	5	2.5	18
6200	1200	5	1.5	18.6
6600	1600	5	1.0	19.6
7000	2000	5	0.6	21.3
7100	2100	5	0.5	21.9
7200	2200	5	0.4	22.9
7400	2400	5	0.3	24.5
7600	2600	5	0.2	27.1
8200	3200	5	0.1	33.4

Figure 6 shows the results of Table 1 and how the bare tether length influences the boosting time for each respective tether. The tether width above 2.5 cm does not appear to decrease the boosting time despite the increase in thrust. The atmospheric drag increase as tether width increases is more than enough to counter the additional thrust generated. An important item to note about Figure 6 is that the total length of the tether changes with each respective tether width according to Table 1.

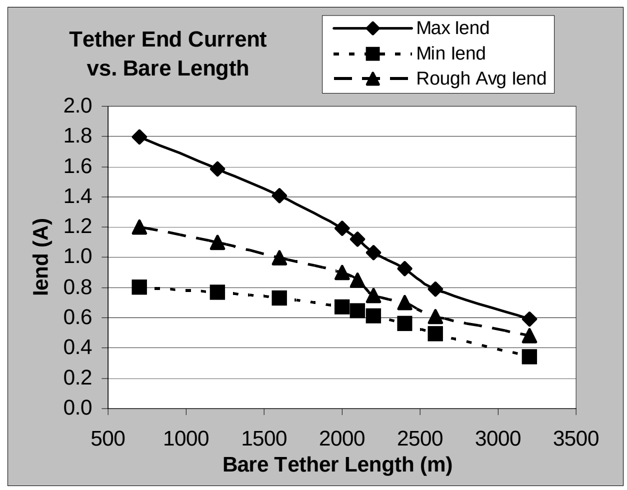

Figure 4: Case 2

Case 3

The third scenario that was evaluated considered the time required for the EDT system to boost or deboost between 400 and 700 km using a 2.5-cm-wide, 5-km-long completely insulated tether with spherical collecting bodies at each end varying in radius from 0.5 to 10 meters. The Parker–Murphy (PM) end collector model was implemented for the boost (downward deployed) and de-boost (upward deployed) configurations. To summarize the PM boost simulations, using a larger end-collector results in more current being collected at a lower bias potential. Data for the 10-m radius sphere showed the current was so large that the corresponding anode voltage dropped to near 0 V. Using a total tether length of 5000 m, simulations with end-body radii greater than 7 m were not possible because the atmospheric drag becomes so great that lift is not generated. Figure 7 shows how long it takes for a boost maneuver from 400 km to 700 km as the end-collector radius is varied. End tether current for the boost is shown in Figure 8.

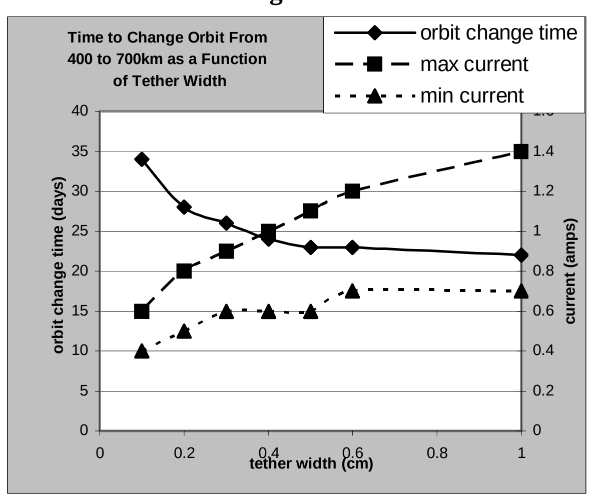

Figure 3: Case 1

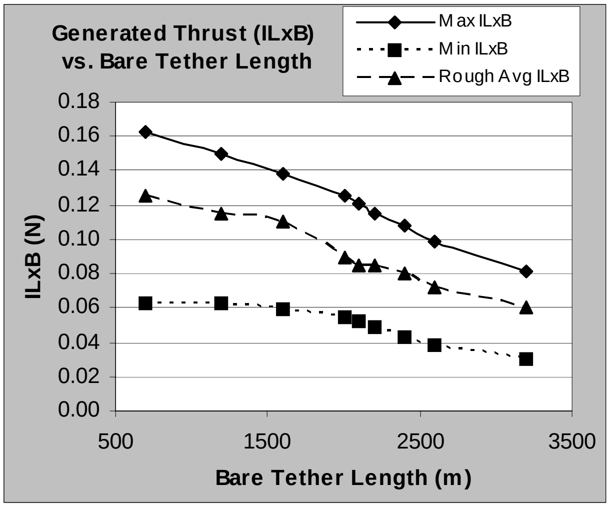

Figure 5: Case 3

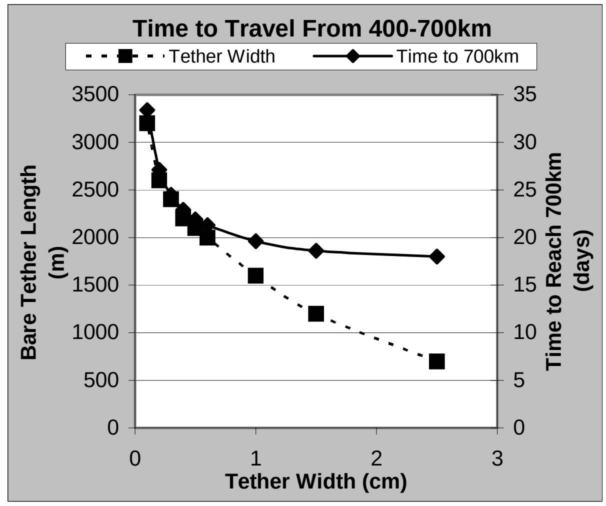

Figure 6: Case 3

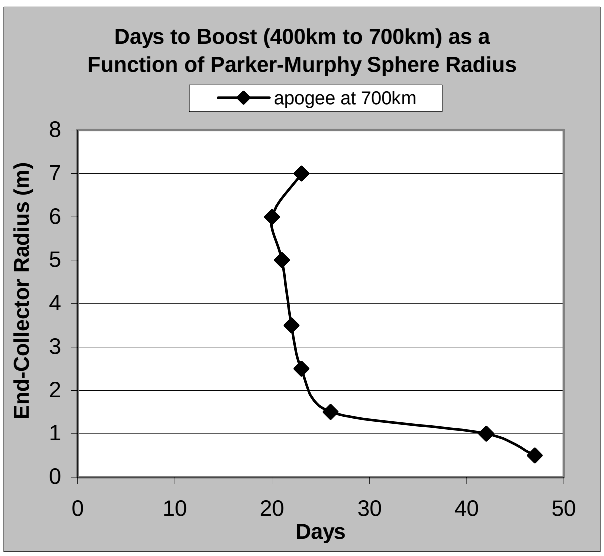

Figure 7: Case 3

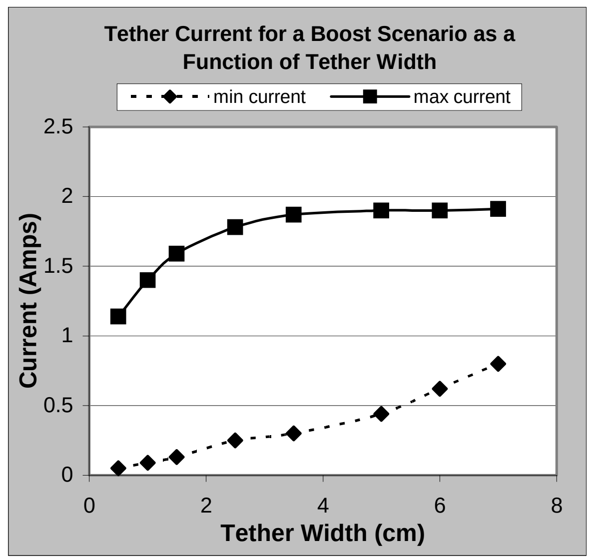

Figure 8: Case 3

The de-boost case was also analyzed. These simulations were run with a 2.5-cm-wide, 5700-m, completely insulated tether where the end-collector is at the top. Figure 9 shows a plot of how long it would take a 1000-kg satellite to lower its orbit from 700 km to 400 km with different end-collector sizes. The power consumption is completely due to self-generated EMF (no power supply contributions). The plot shows when the satellite first reaches 400 km at periapsis and also when the entire orbit altitude has dropped below 400 km. While remembering the significance of atmospheric drag, the data shows that there is little gain in using an end collector with a radius greater than 5 m. The major factor with a sphere of this size is the weight and difficulty of deploying something so large.

The current at the lower end of the tether for the de-boost case is shown in Figure 10. It is easy to see the dramatic difference in the current within the tether for the de-boost case. This is the result of the changing plasma density encountered during the normal orbit. Electron densities can range from 5×10^{9} electrons/m^3 to 2×10^{12} electrons/m^3, and from Eq. (3) and Eq. (4) it can be seen why there is such a large current range.

Case 4

The final configuration examined was a combined end-collector and an insulated–bare tether configuration. Notice in Table 2 how adding a larger (i.e., 5.0-m) solid spherical end collector significantly increased the drag area. Scenario 6, however, was modeled such that the end collector was 90% porous, and so the drag area contributed by the end body is reduced by 90% while still using the assumption that current collection will be equal to that of a solid-surface sphere[11] The end result is that the porous-sphere tether system experienced an initial atmospheric drag 40% smaller, and so it reached 700 km in 18.5 days as compared to 20.5 days for the non-porous sphere.

Table 2: Comparing all cases

Scenario	**Total Tether Length** (m)	**Bare Tether Length** (m)	**PM Radius** (m)	**Total Drag Area** (m^2)	**Boost Time 400 km–700 km** (days)
1	5700	700	none	100.7	18
2	5350	350	none	95.1	De-orbits
3	5350	350	1	98.2	18.5
4	5000	0	1	92.7	30
5	5000	0	5	168.1	20.5
6	5000	0	5 **(90% porous)**	97.4	18.5

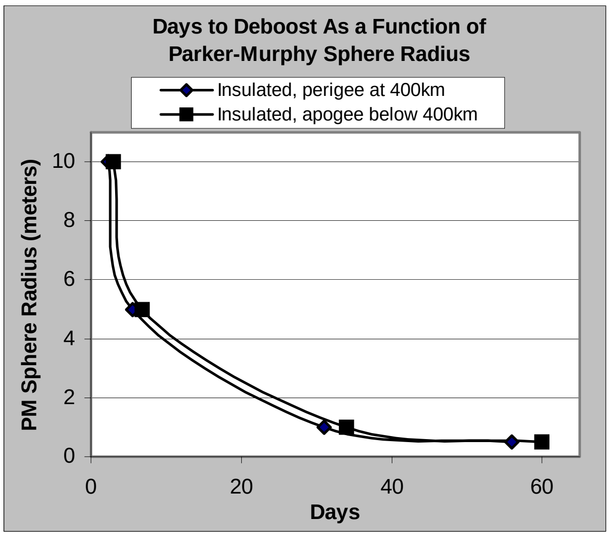

Figure 9: Case 3

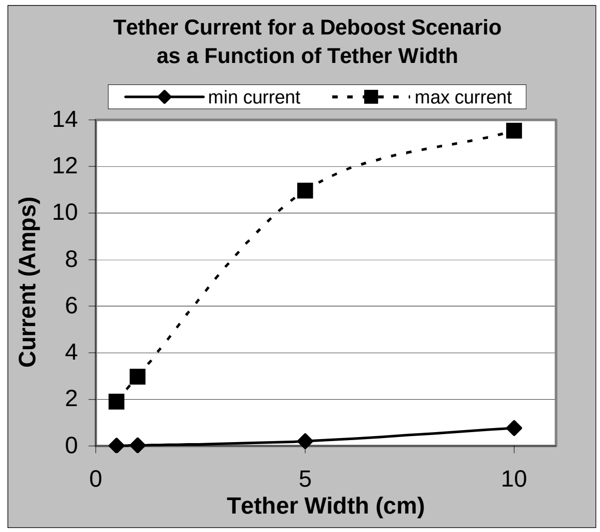

Figure 10: Case 3

We can see from this analysis that adding a 1-m-radius end collector allows us to cut in half (i.e., from 700 to 350 m) the length of bare tether (at 2.5-cm width) used and still have the same boost time. Adding an end collector with a radius larger than 1 m starts to significantly increase the total drag area if it is solid, which impacts the low-altitude performance. This atmospheric drag would be significantly more important if the initial altitude was below 400 km (during solar maximum)[8].

Additional Tether Investigations

The use of a bare section of a space EDT as an electron (or ion) collection device has been suggested to be a promising alternative to end-body electron collectors for certain applications, provided that electrons are collected in a quasi-OML regime. The bare tether concept was to be first tested during NASA's Propulsive Small Expendable Deployer System (ProSEDS) mission. Although this mission has been canceled, the bare-tether concept is being considered for future missions. Current bare-tether designs, such as the one employed for the ProSEDS mission, use a small, closely packed cross-section of wires or even a single wire as the anode. In future designs, addressing concerns such as survivability to collisions with micrometeoroids and space debris will require the use of distributed or sparse tether cross-section geometries, which could span tens of Debye lengths, depending on plasma density.

Since the merits of bare tethers are closely related to the current collection efficiency of the OML regime, one needs to consider how these new distributed or sparse geometries will perform in terms of electron current collection, as compared to thin cylinders. In addition, the effect of the high-speed flow on the electron collection to these alternative geometries, as well as to thin cylinders, has yet to be clearly understood. Ultimately, designers will need to know how to configure a tether for adequate survivability and minimum mass, for example. The OML electron current collected by a thin cylinder is given above by Eq. (6) and Eq. (7).

In a previous investigation,[12] it was concluded that tape tethers with widths up to 10 Debye lengths would perform at 80% of an equal-area reference cylinder in the OML regime. Tape tethers at 4 Debye lengths would perform at 94% of OML theory. Also, the perpendicular tape orientation, with respect to plasma flow, would consistently outperform the parallel orientation in terms of collected current. Since the electrons in the ionosphere have an energy of 0.1 eV and the largest plasma density encountered is $\sim 2\times10^{12}$ electrons/m^3, the smallest Debye length the EDT would see is 0.525 cm. This means that tether widths up to 5.25 cm can be assumed to collect current according to the OML equations. The largest width used in the above analysis was 5 cm, so the finding in Reference 9 holds for this case.

From recent research[9], a number of conclusions resulted from investigations comparing tape and slotted tether geometries. The following conclusions were obtained, as summarized here:

1) The plasma flow leads to current enhancements over that predicted by the OML theory. The greater the energy of the plasma flow the more efficient the current collection. It was found that at a bias of 100 T_e with a plasma flow of 25 eV there was a 40% increase in collection efficiency.
2) The electron collection efficiency of solid tapes (on a per area basis) decreases as the width of the tape is increased.
3) Beyond a threshold bias close to the beam energy, solid and slotted tapes both collect more current when oriented transverse (perpendicular) to the flow. The potential of the tether is far greater than this beam energy for the majority of the length of the tether.
4) Equivalent-width slotted tapes are more efficient electron collectors than solid tapes on a per area basis.
5) The electron collection efficiency of slotted tapes decreases with increasing line spacing until a possible minimum efficiency is attained, beyond which it is expected to start increasing again. This minimum occurs within the first few Debye lengths. The further apart the individual wires are in the slotted configuration the closer to OML collection would result. This phenomenon is not completely understood yet, however.

III. Overall Evaluation

All three EDT system configurations investigated in this paper have comparable results as far as the time required to boost the tether system. In order to determine which configuration is best for a given mission the attributes of each must be weighed.

For insulated tethers with end-body collectors, the positive attributes are that it is almost the fastest orbit-raising technique. It is also a proven technology. The TSS–1 mission produced evidence that the EDT system was producing anticipated results[10]. However, this method has the largest drag associated with it. As a result of the large drag it is also shown to de-orbit the orbiting system the fastest, but not due to EDT force enhancements. Other negative attributes of this system configuration are that it involves the largest amount of mass to send up and is the most difficult to manage and deploy.

The bare tether configuration appears to be the fastest orbit-raising technology. It is also the easiest to deploy because it is a simple wire that can be deployed by using gravity to pull the ends of the system apart, after an initial push. On the negative side, it changes collection efficiency quickly as it depends on the density of the plasma, which varies by a factor of almost 100 every orbit. Since the best place to have the insulation begin is at the point of zero potential difference with respect to the plasma, the system can never be at optimal efficiency, only an approximate best average efficiency can be achieved. Additionally, this technology is not proven yet, although a great deal of work has been done on this system setup and a NASA mission was proposed.[10]

Bare tethers with end-body collectors appear to have almost the fastest orbit-raising performance, similar to the insulated tether with an end body. It also has the lowest drag of the three systems. However, this technology has not been proven yet, nor has much work has been done. More analysis and testing will needed to further prove the effectiveness of this configuration.

The best tether geometry to use for any of these cases would be a slotted tether configuration (or equivalent) oriented perpendicular to the flow of the plasma with the individual wires as far apart as possible. This would minimize the drag, improve collision survivability, and keep the collection efficiency close to OML[8]

IV. Conclusions

Further analysis of the bare tether–end body combination is required to fully understand the trade-offs involved Further, it can be concluded that an end-body collector of adequate radius can be used to eliminate the need for a bare tether as long as it generates less drag than a solid sphere. More detailed performance trade-offs considering electrodynamic and dynamic performance, as well as other practical factors, will have to be considered before recommending a particular approach between the three possible configurations: (1) bare tether with no end body; (2) bare tether with end body; and (3) insulated tether with end body.

Future research will involve investigating the porous end body to determine whether it can collect an equivalent amount of electron current as a solid sphere while reducing the atmospheric drag drastically.

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