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ELECTRODYNAMIC TAPE TETHER PERFORMANCE WITH VARYING TETHER WIDTHS AT LOW EARTH ALTITUDES

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Abstract

Increased tether survivability depends on wider and shorter tethers to enable longer life missions. Tethers that are several kilometers long and on the order of 1 centimeter wide have a significant amount of drag at low altitudes. This drag could deorbit a tethered satellite in a few days at altitudes of 400 km. Widening the tether, however, shortens the collecting portion needed to draw the necessary current. In order to minimize the effects of drag it is crucial to only use the length of collecting tether that is necessary. This paper shows the effect of drag on the tethered satellite in terms of satellite lifetime and drag force. Tether widths varying from 0.1-5.0 cm are also evaluated for 5 km long collecting tethers attached to 5 km of insulated tether and tethers with 5 km of insulated tether attached to a collecting tether using only the length needed to collect current. The orbit transfer time for these tethers operating at 1 kW is also presented.

Nomenclature

a	semi-major axis of the orbit
A	effective tether cross-sectional drag area
A_s	satellite's cross-sectional area
C_D	drag coefficient
d	tether diameter
e	elementary charge
E	effective tether width
F_D	drag force
H	atmospheric density scale height
I	current
l	tether length
L	lifetime of satellite
m	satellite's mass
m_e	electron mass
n	number of half twists
n_∞	unperturbed plasma density
P	period of a circular orbit
r	orbital radius
t	tether thickness
V	velocity
w	tether width
y	position on tether length
θ	angle of tether twist
ρ	atmospheric density
ΔV	potential bias

Electrodynamic Tether Background

Electrodynamic tethers can produce thrust for satellites by using a force that is produced when running a current through a wire in a magnetic field. A decelerating force on the tether is produced when a current flows up and in a direction away from earth. This can be a current produced purely by the earth's magnetic field and thus electricity can be generated at the expense of the satellite's orbit. However, if a current produced by the means of solar panels, batteries or some other source is forced to flow down or towards the earth by, an accelerating force is produced.

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For deboost, a simple conducting tether without insulation is used to collect electrons from the ionosphere. The tether naturally biases positive and an emf is induced across the wire as it passes through the magnetic field. For a boost, this induced emf has to be overcome by the use of an external voltage such as a battery or solar panels. The optimal boost tether configuration consists of an insulated tether attached to a collecting tether below it.[1] This insulated portion allows the maximum amount of current to flow through a significant length of tether.

The most efficient current collection uses a collecting tether with width, thickness or radius less than a debye length. These thin collectors have the maximum current collection per surface area possible.[1] However, of the multiple issues that drive a tether design, tether survivability is another important one. The STEP-AIRSEDS mission has a year operational requirement,[2] and the International Space Station could benefit greatly by a tether with a 10-year lifetime.[3] The survivability of the tether against micrometeoroids and debris over these lifetimes requires a tether width over a centimeter.[4] One of the best wide tethers for collecting current and increasing survivability is one with a rectangular cross section that is thin and wide, also known as a tape tether.

Tether Drag

Since wider tethers are essential for any mission of considerable lifetime, drag must also be considered. A tape tether that is 2.5-cm wide and 10 km long has a cross-sectional drag area of 250 m^2. This is a significant area, especially at low altitudes.

However, to be more accurate in estimating the drag area, twisting should be accounted for. It is likely that a tether of several kilometers will have several twists present. Figure 1 shows a tether with a half twist.

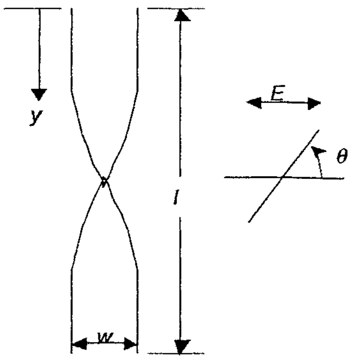

Figure 1 - Twisting Tether Effective Cross Section

The effective cross-sectional drag area, A, of a twisting tether for use in drag calculations can be found by solving Equation 1.

$$A = \int_0^L E\,dy. \tag{1}$$

E is the effective width and is given by:

$$E = \left| w \cos\theta \right| \tag{2}$$

where w is the tether width and θ is the twist angle as shown in Figure 1. θ is related to the position y along the tether by the relation:

$$\theta = \frac{\pi n}{l} y \tag{3}$$

where n refers to the number of tether half-turns and l is the overall tether length.

Substituting Equations 2 and 3 into Equation 1 and solving give the effective area to be:

$$A = \frac{2}{\pi} w l. \tag{4}$$

Thus, the factor $2/\pi$ is multiplied by the actual area regardless of the number of turns involved to give the effective area. Even though there will not be a complete number of turns in the actual tether, there should be a sufficient amount of twist that this is an accurate area multiplication factor.

The effect of drag on the tethered satellite is determined based on standard drag equations.[5] The lifetime of a satellite (L) in number of orbits is estimated as:

$$L \cong \frac{H}{2\pi \left(C_D A_S / m \right) \rho a^2} \tag{5}$$

where H is the atmospheric density scale height, C_D is the drag coefficient, A_S is the satellite cross-sectional area, m is the satellite mass, ρ is the atmospheric density, and a is the semi-major axis of the orbit[5]. Hence, design parameters that influence drag are the width, length, porosity and mass.

To determine the lifetime in minutes, the period of a circular orbit (P) of radius r in kilometers is calculated to be:[5]

$$P = 1.658669x10^{-4} \left(631.3481 r^{-1/2} \right). \tag{6}$$

Equation 5 is then multiplied by the period to give the estimated lifetime in minutes.

In order to derive the drag force, the velocity of the satellite must be determined. This velocity (V) is given in km/s for an orbital radius (r) in km as:[5]

$$V \cong 631.3481 r^{-1/2}. \tag{7}$$

The drag force (F_D) can then be calculated in Newtons by the relationship:

$$F_D = -\frac{1}{2}\rho C_D A_S V^2 . \qquad (8)$$

The previous equations can then be applied to estimate the effect of drag on the tethered satellite. For STEP-AIRSEDS, the satellite is assumed to have a mass of 1000 kg, a cross-section without the tether of 28 m^2, and a drag coefficient of 2.1. Atmospheric densities for the altitudes examined were found in Space Mission Analysis and Design.[5] The tether cross-section was calculated assuming a minimum of a half twist. As shown previously, the cross-section along the length is multiplied by the term $2/\pi$ to give the effective twist cross-section.

Figure 2 shows a comparison of the calculated satellite lifetime to the predicted lifetime results of the Satellite Tool Kit (STK) software. This was for a 10 km long, 2.5 cm wide tether. The densities used in STK calculations were from October 2000, which are close to those at the solar max timeframe. The STK results support those calculated from the drag equations.

The following results support the fact that drag is a significant factor for a wide tether. Figure 3 shows that, at solar max for varying tether widths, a non-operating tether at 400 km altitude has 3 to 10 days before falling back to earth. The corresponding drag forces for different altitudes and tether widths are shown in Figure 4. The thrust provided by the tether must be greater than the values in Figure 4. The drag force can be minimized by reducing the area cross section by shortening the tether or reducing the width.

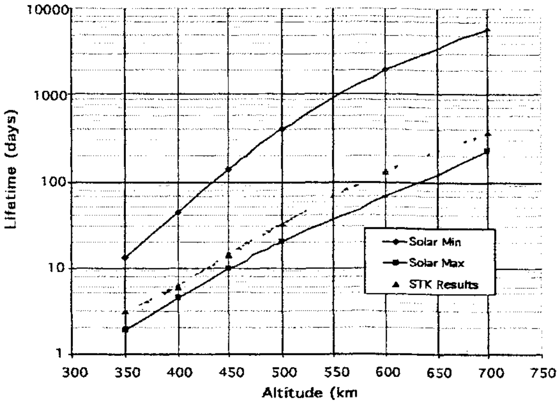

Figure 2 – Comparison of STK results to those predicted using Equations 1-8 for a 10 km long and 2.5 cm wide tether.

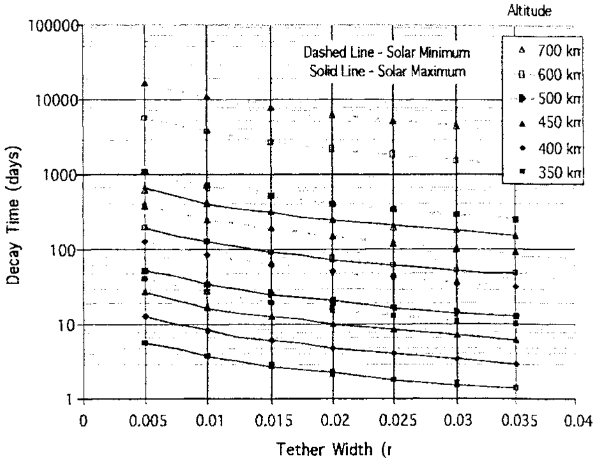

Figure 3 – Satellite lifetime for various tether widths (10 km long) at various altitudes

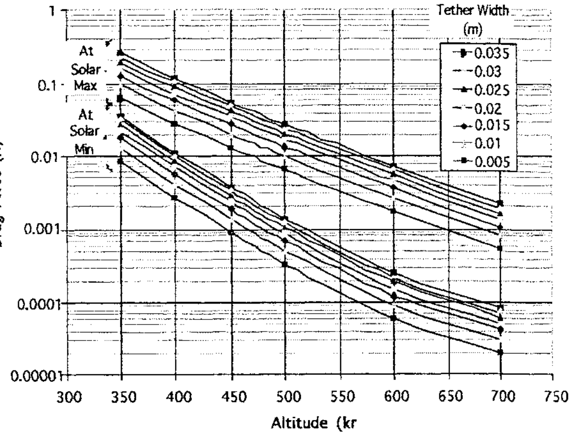

Figure 4 – Drag Force for a 10 km long tether at various widths and altitudes

Calculating Current Collection for Wide Tethers

Current collection was calculated using Orbit Motion Limited (OML) theory. Results are presented for the wide range of tether widths presented here. The current, I, per unit length, y, is given by the formula:[6]

$$\frac{dI}{dy} = e n_\infty d \left(2e\Delta V / m_e\right)^{1/2} \qquad (9)$$

where e is the elementary charge, n_∞ is the unperturbed plasma density, d is the tether diameter, ΔV is the potential bias, and m_e is the electron mass.

The tether diameter is related to the width and thickness of a tape tether on the basis of an equal collecting area. This equates the two perimeters and is given by:

$$d = \frac{2}{\pi}(w + t) \qquad (10)$$

where t is the tether thickness.[7]

The debye length, λ_D, is expected to be from 2.5-9 mm for the altitudes considered.[3] This would make the tethers evaluated here (with widths of 0.1-5.0 cm) to be 0.1-20 λ_D. Even though the original bounds of the theory were only a few λ_D, OML theory has been shown to be reasonable to 15 λ_D for tape tethers.[7] Further testing is planned for larger λ_D. Drag was incorporated in these calculations by using the $2/\pi$ area adjustment for a twisting tether.

Boosting by Tethers of Various Widths

5 km Insulated plus 5 km Collecting Tether

A 10 km long tether that is 50% insulated has been shown to be a good design for thin tethers (~1.8 mm).[8] However, drag becomes a considerable factor as the tether width increases. Figure 5 shows the orbit transfer time using the OML theory for a 1 kW, 10 km long, and 50% insulated tether to travel from 400 to 600 km.

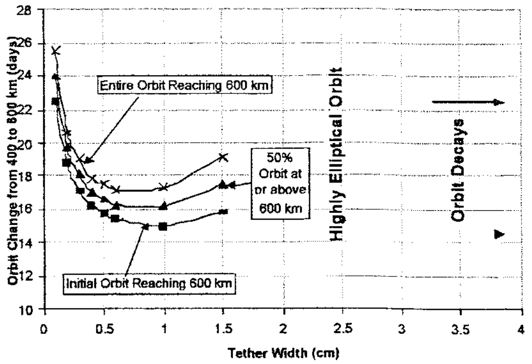

Figure 5– 400 to 600 km Orbit Transfer Time for Tethers of Varying Widths using OML theory

It is important to note that the resistance of the tether varied for the calculations here. The 2.5-cm wide tether had a resistance of 15 Ω/km. The resistance at other widths was adjusted based on the change in area cross section. This is a significant reason why the orbit transfer time decreases as the tether width initially increases. However, for a tether width greater then 1.0 cm, drag becomes a predominant factor such that the transfer time increases and the orbit becomes more elliptical as demonstrated in Figure 6. The more elliptical orbit is shown in Figure 5 by the time increasing between entering orbit at 600 km and fully arriving at 600 km. Wider tethers then approach a point when the drag cannot be overcome and their orbit decays back to earth.

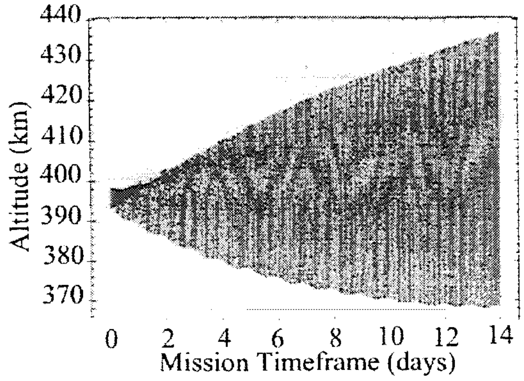

Figure 6 – 2.5 cm Wide 10 km Long Tether Starting at 400 km

Neutral Voltage Position

In order to minimize the effect of drag, it is important not to deploy any extra tether. In a boosting scenario for a fixed-power tether, only a portion of the bare tether is needed to collect electrons. Figure 7 depicts the location on the tether, the neutral voltage point, where the tether above it collects electrons and the tether below it collects ions.[1] The portion below the neutral point reduces the amount of current sent through the insulated tether, reducing thrust.

Figure 8 shows the neutral point for a 2.5 cm wide tether operating at 1000 W with 5 km of insulated tether plus 1 km of collecting tether. The top of the y-axis is at the point of transition between the insulated tether and collecting tether. The y-axis spans the length of the collecting tether so the bottom of that axis is 6 km from the upper unit and where the collecting tether ends. The x-axis is the day of the year, where the start of the mission is on day 230. Figure 8 also shows that for the 2.5 cm case, less than 1 km of bare tether is needed to collect the necessary current since the neutral point is rarely located beyond 1 km.

The variation of the location shown is due to the changing magnetic field and ionosphere densities throughout each orbit. This ability to compensate for varying conditions and provide the necessary current is one of the reasons why an electrodynamic tether is attractive. Yet it is important to not have excessive collecting tether because of increased drag and ion collection.

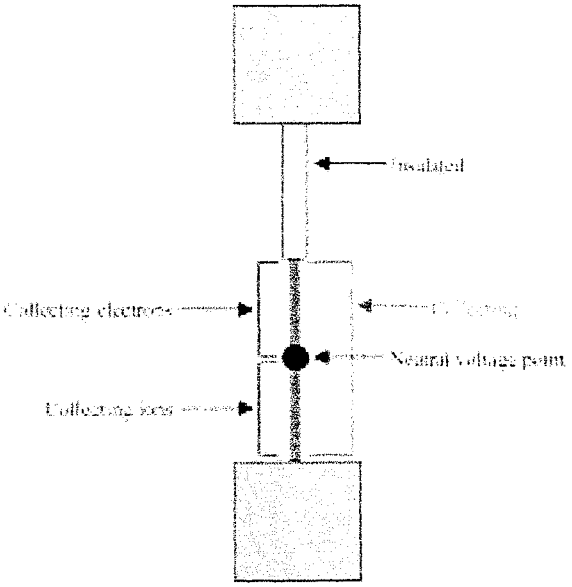

Figure 7 - Tether Neutral Voltage Point.

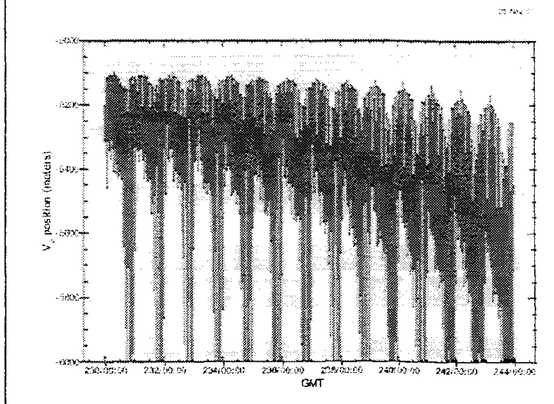

Figure 8 - Position of Neutral Voltage along a 2.5 cm wide ribbon tether over a period of 14 days during a simulated STEP-AIRSEDS maneuver. The y-axis indicates location along the conducting portion of the tether. The insulated tether is above the –5000 m point and the collecting tether extends below the –5000 m point.

The estimated length needed to collect the electrons a majority of the time for a 2.5-cm wide tether based on the data in Figure 8 is 700 meters. Figure 9 shows how this similarly estimated length changes with tether width, with 5km of insulating tether and a system running at 1 kW. The lengths required for wide tethers is only a fraction of what is needed for the tethers previously considered that have widths of a few millimeters.

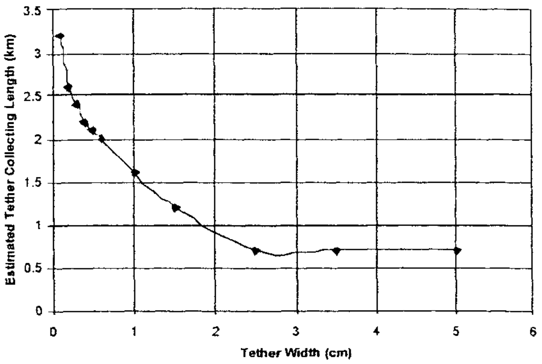

Figure 9 - Estimated length of tether needed to collect electrons with 5 km of insulated tether in a 1 kW system for altitudes up to 700 km.

5 km Insulated plus Varying Collecting Tether Lengths

It would be more realistic to compare the performance of tethers of varying widths by factoring the collecting tether lengths that are necessary. Figure 10 shows the orbit transfer time for tethered satellites to travel from 400 to 600 km. They all have 5 km of insulated tether and the length of the collecting tether corresponds to the lengths shown in Figure 9.

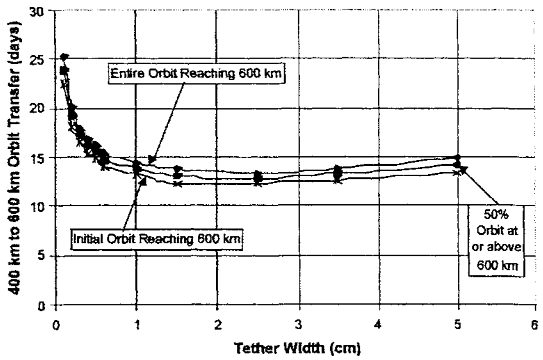

Figure 10 - 400 to 600 km Orbit Transfer Time for Tethers of Varying Widths and Collecting Lengths

By using shorter length collecting tethers, the drag is reduced and the performance is increased for tethers larger than 1 cm in width. The lower drag also creates less elliptical orbits. The time between the satellite first entering the orbit at 600 km and the time that all of the orbit is at 600 km is noticeably less in Figure 10 than in Figure 5.

It is also evident that tether widths larger than 2 cm, for this tether scenario, do not improve performance much. To increase the performance of these wider tethers, it is essential to minimize the drag on the tether even further.

DEBOOST

A short collecting tether is desirable for boost operations since the current flows through the insulated tether to produce a significant amount of the thrust. However, in the deboost case, the insulated tether is only contributing drag and no current is flowing through it. Therefore, the thrust and the amount of current drawn by the collecting tether during deboost is highly dependent upon the collecting tether length. Three deboost cases will be examined here. These cases are derived at solar max and have a tether width of 2.5 cm and a 5 km length of insulated tether. The three cases have different collecting lengths: 1 km, 3 km, and 5 km. Figure 11 gives the end tether current for the 3 km case. In this figure the current dropping to zero at the final part of the time scale is a result of the satellite falling back to earth (below 300 km). This is neglected when determining the minimum current.

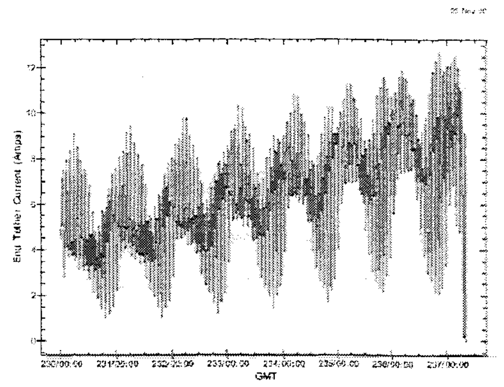

Figure 11 - Deboost Tether Current for 3 km of Collecting Tether

Table 1 gives the deboost time and current collected for the various lengths. From this table it is evident that the length of the collecting portion greatly affects the amount of current collection and the effectiveness of the deboost. It is important to note that this is not for powered deboost, so the insulated portion remains under utilized. One way to increase the deboost performance would be to collect electrons on the upper unit using a collecting body and run a current through the insulated portion. Another would be to use extra solar panels to increase the emf for deboost. These are currently under investigation.

Table 1 - Deboost Time and Current

Bare Tether Length (km)	1	3	5
Deboost Time from 700 to 300 km (days)	~50	~7	~3
Peak Tether Current (A)	8.5	12	13
Minimum Tether Current (A)	0	1	2
Estimated Average Tether Current (A)	1-4.5	5-9	8-10

Conclusions

It is important to understand the performance of wider electrodynamic tethers since widths of a few centimeters are required for survival during longer lifetime missions. However, drag is a significant factor at these widths. The drag is sufficient to deorbit a 10 km long tethered satellite with widths greater than 1 cm in a few days if no restoring force is enacted. It is predicted that a electrodynamic tether with widths greater than 2 cm and 10 km long (50% insulated) will not be able to overcome the drag at 400 km.

However, wide tethers need significantly less length to draw the current necessary. The collecting tether on the end of a 5 km long insulated tether should not need to be more than a kilometer for a 1 kW system below 700 km in altitude.

Reducing the collecting tether by 4 km produces significantly less drag and allows for orbits to be raised 200 km in approximately 2 weeks. However, this shorter collecting tether greatly hampers the ability of the system to deorbit. This should be easily improved through the use of a collecting body to provide a small amount of current to pass through the insulated portion or solar panels to increase the emf.

It will be important to determine what the minimum tether length is for stable flight. A short electrodynamic tether should still provide sufficient performance and allow for a lifetime in the order of years.

Acknowledgements

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