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Life Extension and Orbit Maneuvering Strategies for Small Satellites in Low Earth Orbit Using Electrodynamic Tethers

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Life Extension and Orbit Maneuvering Strategies for Small Satellites in Low Earth Orbit Using Electrodynamic Tethers

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Abstract

Thermospheric drag is an important force acting on orbiting satellites with altitudes of 300-600km (e.g. space shuttle operating altitudes). This drag reduces orbit lifetimes to typically <100 days. Electrodynamic tethers (EDTs) could provide one means of maintaining, boosting, and/or orbit maneuvering small satellites in low Earth orbit without the use of propellant over extended periods. An analysis is presented which looks at the use of EDTs on small satellites and for multiple orbital configurations. We will discuss strategies and tradeoffs for using EDTs for satellite orbit-hold, orbit boost and coast, and inclination change.

Nomenclature

A_T effective tether cross-sectional drag area, m
A_s satellite's cross-sectional area, m^2
ß   ballistic coefficient
B   magnetic flux density, T
C_D drag coefficient
d tether diameter, m
e elementary charge
F_D drag force, N
F   generated tether thrust force, N
I current, A
l tether length, m
m satellite's mass, kg
m_e electron mass, kg
n_∞ unperturbed plasma density, m^{-3}
t tether thickness, m
v velocity, m/s
w tether width, m
y position on tether length, m
ΔV potential bias, V
V_0 nuetral voltage position

Introduction

The ability to boost a satellite's orbit or increase mission lifetime is often desirable. For a satellite operating at altitudes between ~300km and ~600km (low Earth orbit), thermospheric drag is the most significant nongravitational force.[1] The drag determines the effective lifetime and is determined by the ballistic coefficient, atmospheric density, and the velocity relative to the thermosphere. Compensating for the drag requires the addition of energy to the satellite's orbit. On-board thrusters using a consumable propellant is the principal method to compensate for this drag. EDTs, however, offer the possibility of propellantless propulsion using solar energy, a potentially distinct advantage when considering a long-term mission. An EDT requires electrical energy (e.g. from a solar array), an ionosphere, and a planetary magnetic field.

The purpose of this paper is to investigate how EDT's can be used to maintain and boost a satellite's orbit. The satellite is chosen to be small (~125kg) and initially deployed from low Earth orbit by either the Space Shuttle or commercial rocket. Analysis was performed from a starting altitude of 350km under both solarmax and solarmin conditions. The survivability of the tether from micrometeoroids and debris depends largely on the width of the tether. An example of this is the STEP-AIRSEDS mission where a tape tether is being considered.[2]

Electrodynamic Tether Background

EDT's make use of the Earth's magnetic field to create a non-fuel propulsion system. Figure 1 shows the basic physics involved in a deboost configuration. As the satellite orbits the Earth the

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gravity gradient forces experienced by the tether cause it to align itself in a local vertical (points towards) orientation with the center of the Earth. As it orbits at an angle relative to the Earth's magnetic field, its motion across the B-field causes an induced EMF along the length of the tether:

$$EMF = (\mathbf{v} \times \mathbf{B}) \cdot d\mathbf{l} \qquad (1)$$

where $\mathbf{v}$ is the tether velocity relative to the magnetic field $\mathbf{B}$, and $d\mathbf{l}$ is a small length of the tether.

The induced voltage causes the tether to attract readily available electrons from the Earth's inosphere. As the electrons flow through the conducting tether they experience a force that removes kinetic (mechanical) energy from the tether's orbit:

$$\mathbf{F} = I\mathbf{l} \times \mathbf{B} \qquad (2)$$

However, in this paper we discuss the orbit boosting tether configuration. For this case the current flow is reversed such that force $\mathbf{F}$ is acting in the opposite direction. This results in energy being added to the satellite orbit, thereby raising its altitude. A power supply is attached at the cathode end of the tether to overcome the motional EMF and drive the electrons in the opposite direction.
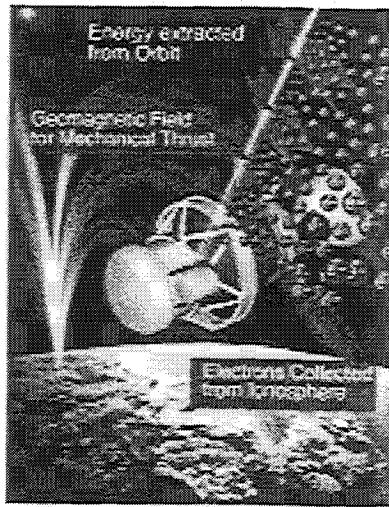

Figure 1 - Basic Operation of an electrodynamic tether system (Courtesy of NASA).

Tether Drag

As mentioned previously the thermospheric drag is the significant factor in determining useful orbit lifetime. We can decrease the drag by minimizing total cross-sectional area. The ballistic coefficient is commonly used to characterize this:

$$\beta = \frac{m}{C_D(A_s + A_T)} \qquad (3)$$

where m is the satellite mass, C_D is the coefficient of drag, A_S is the satellite cross-section area, and A is the tether cross-section area. We will consider the coefficient to be constant for each specific satellite configuration. We used a value of 2.2 for C_D throughout the analyses.

A tape tether has a significant cross section area. For example, a 2.5cm wide and 2km long tether has a drag area of 50m^2. To account for a twisting effect the tether will likely encounter in orbit, the equation used to calculate the effective cross-sectional drag area is:[3]

$$A = \frac{2}{\pi} wl \qquad (4)$$

where w and l are the tether width and length, respectively.

Current Collection for a Wide Tether

Orbit motion limited (OML) theory was used to calculate the collected current. The formula used to calculate the current, I, per unit length, y, is given by:[4]

$$\frac{dI}{dy} = e\, n_\infty\, d\, \sqrt{\frac{2e\Delta V}{m_e}} \qquad (5)$$

where e is the elementary charge, n_∞ is the unperturbed plasma density, d is the effective tether diameter (assumed cylindrical), ΔV is the potential bias, and m_e is the electron mass. The effective tether diameter is equated to the width and thickness of a tape tether on the basis of equal area and is given by:

$$d = \frac{2}{\pi}(w + t) \qquad (6)$$

where t is the tether thickness.

The tethers we evaluated have widths of 0.5cm and 2.5cm. This corresponds to debye lengths between 2.5 and 10 λ_D. Although the OML theory was originally applicable in applications of a few debye lengths, it has been shown to be reasonable out to 15 λ_D for tape tethers.[5]

Tether Systems Analysed

The *TEMPEST* computer software was used to perform all tether system analyses. The computer

program is written in the standard C language and was developed by Nestor Voronka and Brian Gilchrist at the University of Michigan.

We analysed 2km tether systems with a total system mass of 125kg and 146.6kg. Three satellite cross-sectional areas of 1, 3, and 10m^2 were investigated under three separate tether widths and system mass configurations.

The first configuration used a 0.5cm wide, 2km solid aluminum tether. The tether itself had a mass of 5.4kg, which set the default satellite mass at 119.6kg for an overall system mass of 125kg.

In order to compare the 0.5cm wide tether to a similar 2.5cm tether, the satellite mass was kept constant (119.6kg). This second configuration used a 2km, 2.5cm wide solid aluminum tether. The tether mass was 27.0kg, which set the system weight for this configuration at 146.6kg.

A third configuration we investigated was that of a 2.5cm wide porous tether with a mass and resistance equal to the 0.5cm wide system. Although the porous tether had a width of 2.5cm, the effective cross-section drag was assumed equal to that of the 0.5cm wide tether. This implies a porosity of 80%.

Neutral Voltage Position

Limiting the tether length and using only that amount necessary to collect current will also minimize drag. As an EMF is generated across the tether, electrons are collected only where the bare tether is biased positive with respect to the plasma. Figure 2 shows the neutral voltage location on a basic tether. In the boost configuration the portion above the neutral voltage point collects electrons. The portion below the neutral point collects positively charged particles (ions), thereby cancelling some of the collected electrons. The result is that tether current and thrust is reduced.
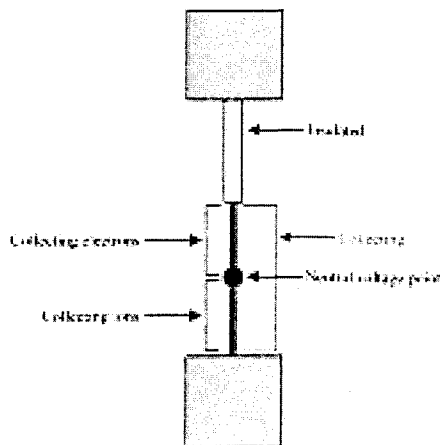

Figure 2 - Tether neutral voltage point.

Figure 3 shows the location of the neutral voltage point (V$_0$) for a 2km tape-like tether with a width of 0.5cm and total system mass of 125kg, an inclination of 28 degrees, initial altitude of 350km, under solarmax conditions. The tether starts at 0 meters and extends to –2000 meters. The negative numbers describe a downward deployed (boosting) tether configuration. Above the V$_0$ position the bias is positive and the bare portion of the tether collects electrons. Below the V$_0$ position the tether is biased negative and ions are collected.
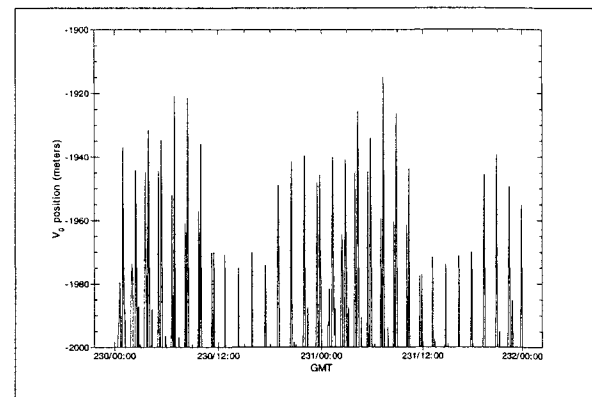

Figure 3 - Neutral voltage position (V$_0$) along a 0.5 cm wide tether over a 2 day boosting maneuver. The y-axis indicates the location along the tether and the x-axis displays the mission lifetime in Greenwich Mean Time format (GMT). The end of the tether is at the –2000 meter position.

The estimated tether collecting length required for current collection is 200 meters for the 0.5cm and 2.5cm porous wide tether. A collecting length of 100 meters was used for the analysis of the 2.5cm non-porous tether. As the tether gets wider the required collecting length will shorten.

Atmospheric Drag

An analysis of atmospheric drag was performed for the three tether configurations (0.5cm wide, 2.5cm wide, and 2.5cm wide porous) using a satellite with a cross-sectional area of 1m^2. Figures 5-7 show the drag for each configuration over a simulated 1-day boost maneuver under solarmax conditions starting at an altitude of 350km while applying a constant power of 150W. The significant point to make is that the drag of the 2.5cm wide non-porous tether is significantly higher than that of the other two. In fact this tether never increased altitude, but rather started to de-orbit at every power level (75W to 300W). For this reason the 2.5cm wide non-porous tether is not appropriate for low earth orbit tether

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applications using a 125kg system mass when the available power is <300W. The power must be increased or the starting altitude has to be raised above 350km. Lift is generated if the same 300W tether system begins its initial orbit at 375km. In addition, raising the applied power to 350 watts resulted in an altitude boost.

Figure 4 - Drag for a 125kg, 0.5cm wide tether system at an initial altitude of 350km.

Figure 5 - Drag for a 146.6kg, 2.5cm wide non-porous tether system at an initial altitude of 350km.

Figure 6 - Drag for a 125kg, 2.5cm wide porous tether system at an initial altitude of 350km.

Life Extension Strategies

Orbit Boost

0.5cm Wide Non-Porous Tether System

The 125kg, 0.5cm wide non-porous tether system provides a means to generate significant lift over a short amount of time. This system used 200 meters of bare tether collection length. Figures 7-10 show the altitude changes versus the tether thrust duration for both solarmax and solarmin conditions at 28 degrees and 51 degrees inclination. Three different powers were used: 75, 150, and 300 watts. Graphs for the three different powers are shown for the 28 degree inclination system, while a 300 watt simulation is only shown for the 51 degree inclination system. The solarmin cases in Figure 7 show an altitude increase of nearly 100km in only 15 days for satellites with up to $10m^2$ of cross-sectional area. However, under solarmax conditions a power of 75W cannot generate lift for any satellite.

A larger power supply will drive more current. Figure 8 shows how the 150W system begins to generate sufficient thrust under solarmax. As the altitude increases the drag is less and the altitude profile becomes linear.

300 watts of constant power results in a significant altitude boost as shown in Figure 9. Note how a denser atmosphere (solarmax) allows for a greater altitude increase. The tether can drive more current with a larger power supply.
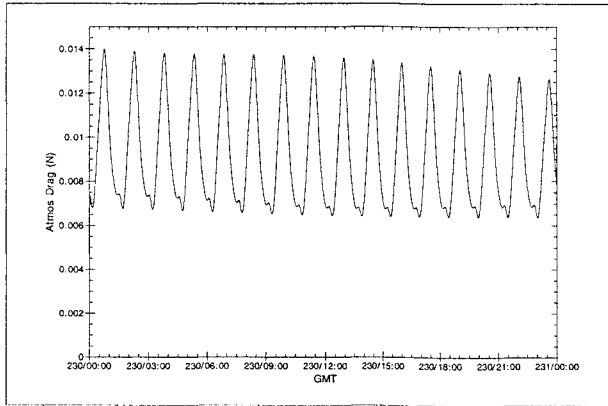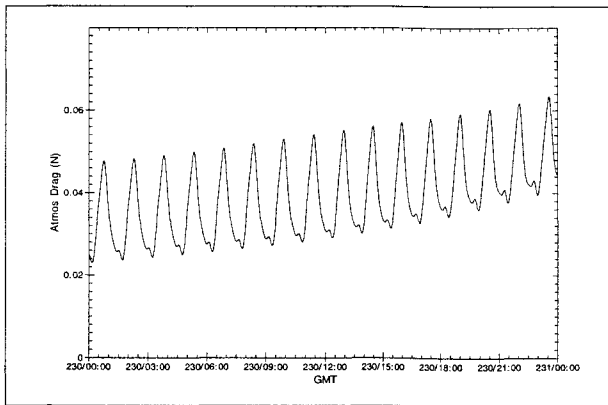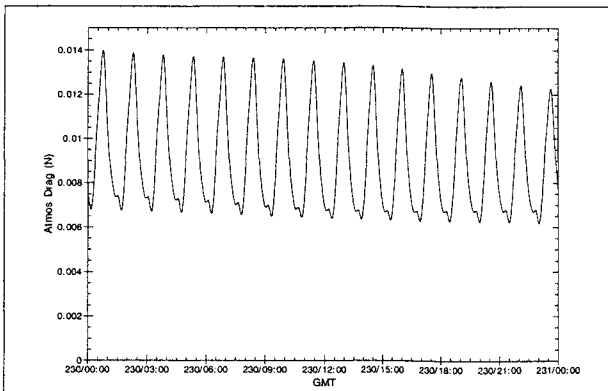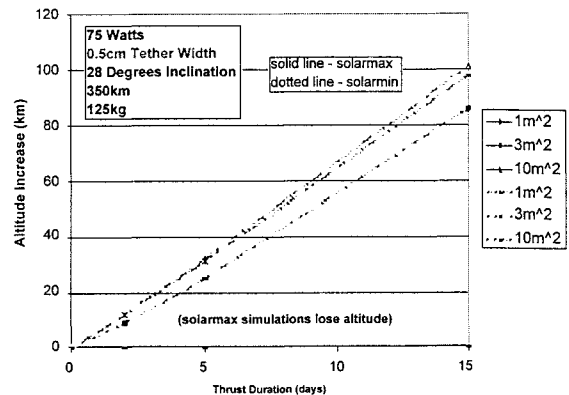

Figure 7 – Altitude increase for a 75 Watt, 2km, 0.5cm wide tether at 28° inclination.
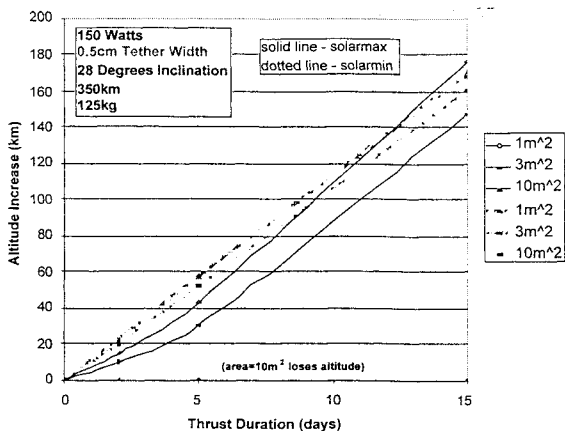
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Figure 8 – Altitude increase for a 150 Watt, 2km, 0.5cm wide tether at 28° inclination.
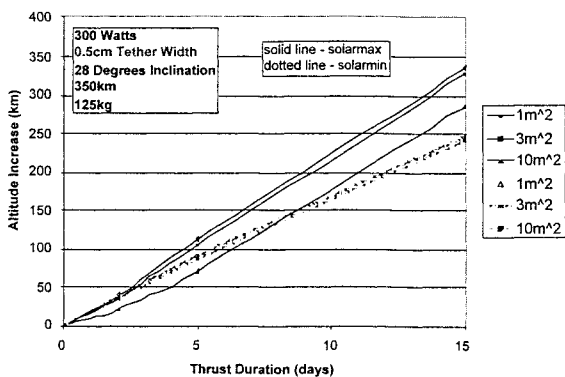

Figure 9 – Altitude increase for a 300 Watt, 2km, 0.5cm wide tether at 28° inclination.
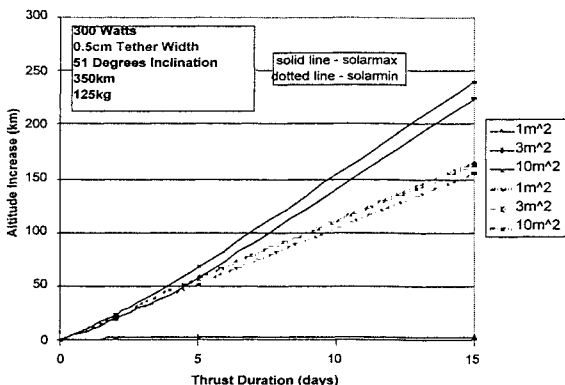

Figure 10 - Altitude increase for a 300 watt, 2km, 0.5cm wide tether at 51° inclination. The change to a higher inclination results in a smaller altitude increase for the same power.

The initial tether inclination also affects orbit boosting maneuvers. Figure 10 shows how the 10m^2 cross-sectional area satellite cannot raise its orbit. The magnetic field changed orientation with the tether such that the cross-products in the governing equations for generated EMF and thrust (equations 1 and 2) have changed. The simulations suggest that the 150W and 300W tether systems are a good choice for boosting a 125kg tether system with relatively low cross-sectional area for both solarmax and solarmin conditions. The most nearly linear altitude profile is achieved with the 300W supply. It is reasoned that even a more dense atmosphere can be taken advantage of by the larger power supplies.

2.5cm Wide Porous Tether System

The 2.5cm wide porous tether has an atmospheric drag very similar to the 0.5cm wide tether. We've simulated the cross-sectional area for both to be the same. The tether resistance and weight are also assumed to be the same. The only difference between the two is the geometric shape. The wider tether, although porous, still adds additional satellite lifetime because of the nature of the 'meshed' structure. If one portion is damaged it will most likely not cause a catastrophic failure of the entire tether.

The simulations in figures 11-14 show again that 75 watts is sufficient for this configuration for solarmin but too small for solarmax. A close look at the 300 watt scenario shows that the altitude increase at the end of 15 days is roughly 100 km higher than the same power for the 0.5cm wide tether. The reason for this has to do with the collected current. The average maximum current in the 0.5cm wide tether is ~0.5A. The 2.5cm porous tether collects an average maximum of ~0.65A. More current results in more thrust and a higher altitude.
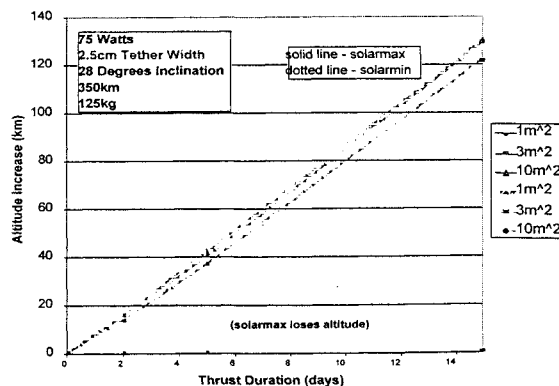

Figure 11 - Altitude increase for a 75 watt, 2km, 2.5cm wide porous tether at 28° inclination.
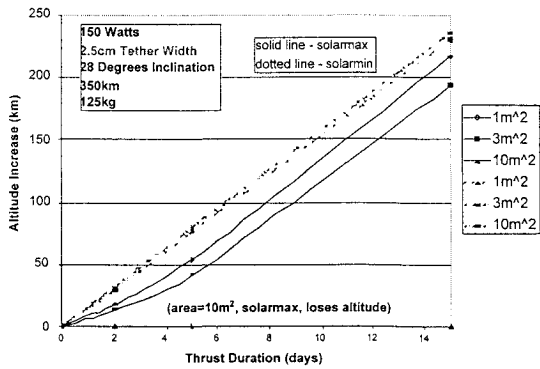
Figure 12 - Altitude increase for a 150 watt, 2km, 2.5cm wide porous tether at 28° inclination.
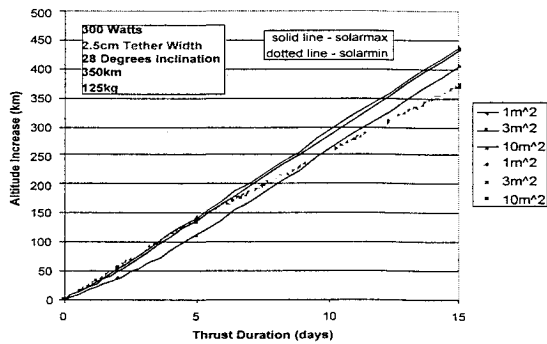

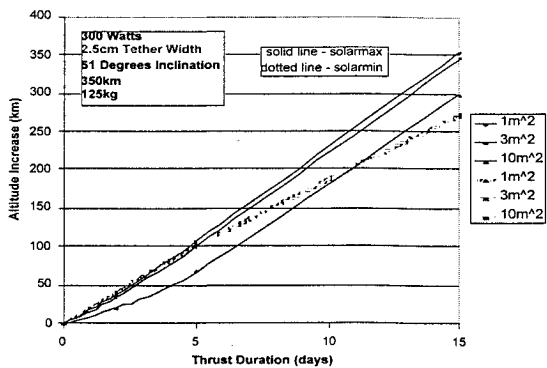**Figure 13 - Altitude increase for a 300 watt, 2km, 2.5cm wide porous tether at 28° inclination.**

Figure 14 - Altitude increase for a 300 watt, 2km, 2.5cm wide porous tether at 51° inclination.

Inclination Change

An analysis was performed to investigate how the generated thrust alters tether orbit inclination. Figure 15 shows that satellite cross-sectional area is not a significant factor in inclination change. All satellites experience a nearly equal change in inclination.
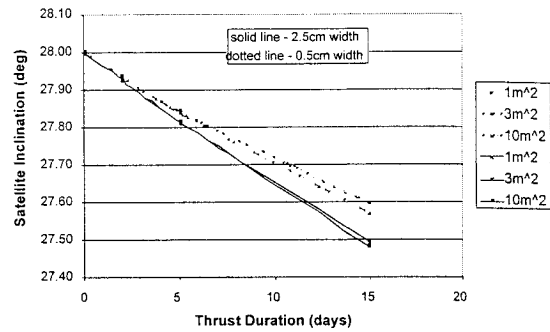

Figure 15 - Inclination change resulting from tether thrust for a 300W, 125kg, 2km tether system in solarmax conditions.

As a tether orbits the Earth there are forces that cause it to oscillate about its vertical orientation (e.g. atmospheric density, temperature, and gravity gradient oscillations). With a constant thrust the tether's orbital configuration will change. Further research is required to determine how to minimize the change in inclination.

Maintaining Orbit Altitude (Hold Strategy)

We've discussed how the thrust and drag will both vary over a tether's orbit. Variations in the ionospheric density and temperature affect the current collected and alter the dynamics of the orbit that cause it to become increasingly elliptical over time. Figure 16 shows orbit altitude variations at 350km for a 2km, 125kg, 0.5cm wide, $1m^2$ satellite cross sectional area tether system as 101 watts is applied to maintain a constant average altitude of 350km. Note how the orbit grows more elliptical over a 10-day constant thrust maneuver, nearly 25km between apogee and perigee.
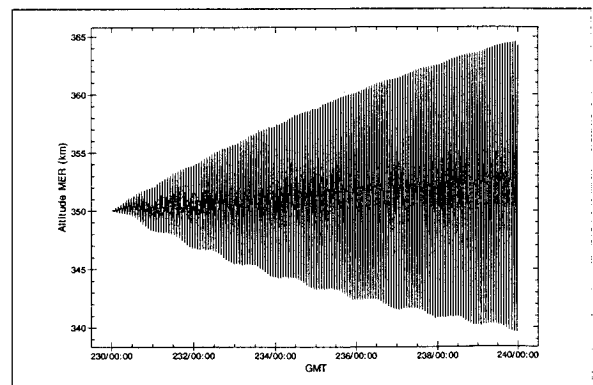

Figure 16 - Orbit grows more elliptical as thrust duration time continues.

The highly elliptical orbit resulting from this hold maneuver demonstrates the need to research new methods of controlling the elliptical growth.

Conclusions

Thermospheric drag is a significant contributor to limiting the mission lifetime of low Earth orbit satellites. Electrodynamic tethers provide a propellantless means of compensating for the drag and raising orbit altitudes of small satellites with limited power supplies.

Ribbon-like tape tethers add increased mission lifetime because of their survivability. Although useful for larger satellite systems with more available power ($\geq$350W), the 2.5cm wide non-porous tether encounters significant drag. Comparison of the 0.5cm solid ribbon tether and the 2.5cm wide porous tether (all other parameters equal) indicates that the porous tether collects more current for the same cross-sectional area and mass. Although both tethers are well-suited for orbit maneuvering strategies of small satellites (125kg) with limited power (150-300W), the 2.5cm wide porous tether boosted the payload to a higher altitude.

Inclination changes and elliptical orbit growth are two effects of tethered propulsion. Further research is required to answer how to best correct these issues.

Acknowledgements

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