AIAA 00-0329

THE TERMINATOR TETHER™: AUTONOMOUS DEORBIT OF LEO SPACECRAFT FOR SPACE DEBRIS MITIGATION

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38th Aerospace Sciences Meeting & Exhibit
10-13 January 2000
Reno, Nevada

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Abstract

The Terminator Tether™ is a lightweight, low-cost device that will use electrodynamic drag generated by a conducting tether to remove satellites and upper stages from low Earth orbit when they have completed their missions. In order to investigate and optimize the performance of the device, we developed a detailed numerical simulation that includes models for tether dynamics, electrodynamic interactions with the Earth's ionosphere, field emission aray cathode operation, and other relevant physics. Using this simulation, we examined the electrical behavior of the tether-plasma circuit, and found that a device with a tether length of 5-10 km can utilize some of the power generated by the tether to drive its own circuitry without severely affecting the deorbit rate. Thus the device can be independent of the host spacecraft's power systems during deorbit. Because an uncontrolled electrodynamic tether is dynamically unstable, we developed a feedback-control scheme and verified its operation using simulations. Using the same models and control scheme, we investigated the performance of the device for disposing of spacecraft from various orbital inclinations and altitudes. We found that a tether device massing 2% of the host spacecraft mass can deorbit an upper stage from a 50°, 400 km orbit in under two weeks, a mid-LEO satellite from a 50°, 850 km orbit in under three months, or a high-LEO satellite from a 50°, 1400 km orbit in less than a year.

Introduction

Electrodynamic tether drag can provide a cost-effective method for autonomously deorbiting low Earth orbit (LEO) spacecraft to mitigate the growth of orbital debris.[1] The Terminator Tether™ is a small, lightweight, low-cost device that will be attached to satellites and upper stages before launch. The device contains a conducting tether, a tether deployer, an electron emitter, and electronics to control the deployment and operation of the tether. During the operational period of the host spacecraft, the tether will be stored in the deployer and the Terminator Tether™ electronics will be dormant, waking up periodically to check the status of the host spacecraft. When the device receives an activation command, or when it determines that the host spacecraft is defunct, the Terminator Tether™ will activate springs in the deployer to kick the device down and away from the spacecraft, deploying the tether. A schematic of the device is shown in Figure 1.

The principle of electrodynamic tether drag is illustrated in Figure 2. The motion of the conducting tether through the Earth's magnetic field will generate a voltage along the length of the tether; in a direct orbit, the top of the tether will be charged positively relative to the ambient ionospheric plasma. Most of the tether length will be left uninsulated, so that the bare wires can efficiently collect electrons from the ionosphere.[2] These electrons will flow down the tether to the Terminator Tether™ endmass, where the electron emitter will expel them back in to the ionosphere. Thus a current will flow up the tether, and the current "loop" will be closed by plasma waves in the ionosphere.[3,4] This current will then interact with the Earth's magnetic field to generate a Lorentz **J**x**B** force on the tether. This force will oppose the orbital motion of the tether. Through its mechanical connection to the host spacecraft, the tether will thus drain the orbital energy of the spacecraft, lowering its orbit until it disintegrates in the upper atmosphere.

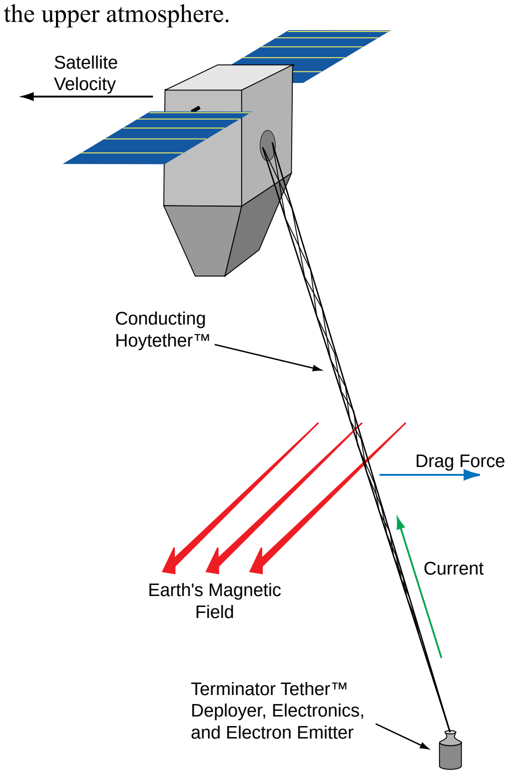

Figure 1. The Terminator Tether™.

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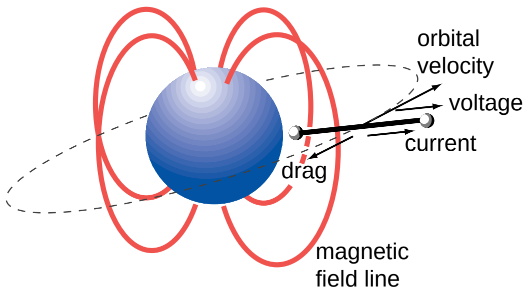

Figure 2. **Electrodynamic tether drag.**

In this paper, we present a system-level design for a Terminator Tether™ device suitable for use on LEO satellites and upper stages. We then use numerical modeling of tether dynamics and electrodynamics to determine the feasibility of using the power generated by the tether to power the tether device electronics during deorbit, so that the device can be independent of the host spacecraft's power system. Using the same numerical models, we test a feedback control method for stabilizing the tether dynamics. We then present results on investigations of the potential performance of the device for removing spacecraft from various orbital inclinations and altitudes.

The Terminator Tether™ Device

The Terminator Tether™ Satellite Deorbit System will be composed of several subsystems: a conducting, survivable tether, a tether deployment system, a device for emitting electron current, and an electronic control system called the Tether Control Unit (TCU).

Tether

In order to electrically insulate the host spacecraft from the tether, a short section of the tether nearest the spacecraft will be constructed of high-strength, nonconducting yarns. The rest of the tether will be a survivable Hoytether™ structure constructed of thin aluminum wires, shown in Figure 3. Aluminum is chosen as the conductor because it provides the best conductivity-per-mass of readily available conductors. The tether design will vary depending upon the mass and orbit of the host spacecraft, but for a typical LEO constellation satellite massing 1500 kg, the tether would be 5 km long and mass approximately 15 kg (1% of the host spacecraft mass). In the Hoytether™ design, the wires are knitted together in an open-net structure that provides redundant paths to carry the mechanical load and current. This design will enable the tether to provide a very high probability of surviving the orbital debris environment for the period of several weeks or months required to deorbit the spacecraft.[5] Most of the length of the conducting tether will be left uninsulated, so that the bare wires can collect electrons from the ionospheric plasma and conduct them down to the TCU.

Tether Control Unit

The TCU is part of the endmass that is deployed below the host spacecraft at the end of the tether. The TCU carries the responsibilities of monitoring the host spacecraft during the spacecraft's operational phase (the dormant phase for the Terminator Tether™), activating the deployment system when it is time to deorbit the host, monitoring and controlling the tether dynamics to optimize the descent rate, and responding to ground control signals to perform avoidance maneuvers.

The TCU will be composed of several components:

- An electronics package with a microprocessor, memory, and data acquisition electronics.
- A RF receiver to enable ground control of Terminator Tether™ descent rate.
- A sensor package consisting of a sensor for determining system attitude and a sensor for determining tether endmass dynamics.
- A Power System, which in turn consists of:
  - A battery with sufficient shelf life to survive the dormant phase.
  - A DC/DC power conversion system for recharging the TCU battery.

The electrons collected by the tether will pass through the DC/DC converter, and a portion of the tether power will be tapped off to provide power to maintain the TCU batteries. The electrons will then be fed to the electron emitter, which will discharge them into the ionospheric plasma.

Electron Emitter

The electron emitter will be a Field Emission Array Cathode (FEAC) device, also known as a Spindt Cathode.[6] This device will be designed to emit up to

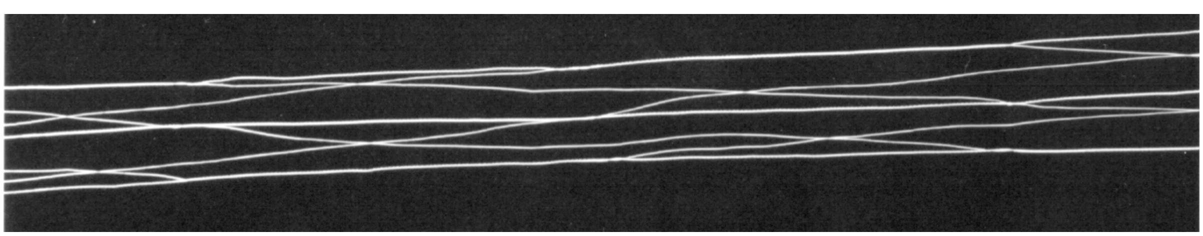

Figure 3. Photo of a 20-cm length of the conducting Tri-Line Hoytape made of 30 gauge aluminum wires knitted together with 22-Tex P.T.F.E. thread.

1 A of electron current. Electron emission is achieved by applying a gate voltage of approximately 75-100 V between an array of millions of microscopic needle points and a gate electrode. The emitted current can be controlled very precisely by varying this gate voltage.

Tether Deployer

The tether deployer for the Terminator Tether™ system will be an endmass/deployer system in which the tether is wound on a spool with a 8-10 cm diameter and the TCU electronics and other components are contained inside this spool. It is envisioned that the Terminator Tether™ system could be housed inside the host satellite, with the top surface (with the RF antenna) positioned flush with the satellite surface. The TCU, electron emitter, and batteries are contained in a cylindrical housing that slides inside of the deployer spool, so that during the dormant phase the electronics will be shielded from radiation by the several-cm of the wound aluminum wire tether. The Terminator Tether™ unit will be secured to the host spacecraft by a Frangibolt which also compresses several ejection springs between the Terminator Tether™ and the host spacecraft. When the TCU activates the deployment sequence, it triggers a Frangibolt, releasing the deployer, and the springs eject the entire Terminator Tether™ unit away from the host spacecraft at a velocity of several meters per second, deploying the tether behind it.

Device Mass and Sizing

TUI, with the assistance of Primex Aerospace, has completed a mass and sizing design of a prototype Terminator Tether™ suitable for removing 1000 to 2000 kg satellites from LEO.

Figure 4 shows a schematic of the Terminator Tether™ prototype. The tether is wound on a spool inside the shroud, and the entire assembly bolts to the host spacecraft via the mounting bracket at the bottom. When it is time to deorbit the spacecraft, an ejection mechanism propels the device down and away from the host spacecraft, leaving only the mounting bracket and the tether anchor.

A mass breakdown for this prototype is given below.

Tether mass:	10.0	kg
Shroud:	2.1	kg
Spool Assembly:	5.8	kg
Ejection Mechanism	3.5	kg
Electron Emitter:	1.2	kg
TCU Electronics:	3.7	kg
Tether Anchor	0.15	kg
Total Tether system mass:	26.45	kg

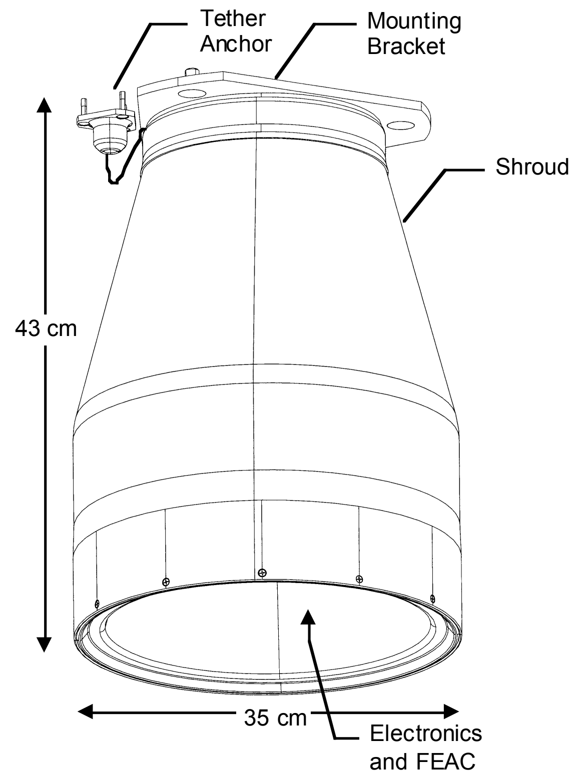

Figure 4. Schematic of the Terminator Tether™ Assembly.

Numerical Simulation of the Terminator Tether™: TetherSim

The physics of the Terminator Tether™ involve many different interrelated phenomena, including orbital dynamics, tether librations and oscillations, interactions with the ionospheric plasma, day/night variations of the ionospheric density, solar and ohmic heating of the tether, magnetic vector variations around an orbit, and the electron emission characteristics of the FEAC device. In order to enable accurate analyses of the performance and behavior of the Terminator Tether™ system, we have developed a numerical simulation of electrodynamic tethers called "TetherSim™" that includes models for all of the aforementioned physical phenomena.[7]

Tether Dynamics

The dynamics of the tether are modeled by approximating the continuous tether mass as a series of point masses linked by massless springs. This method is similar to that used by Kim and Vadali,[8] and also by Carroll's BeadSim.[9] Because the temperature of the tether can fluctuate significantly due to solar heating and ohmic dissipation, the simulation uses a temperature-dependent model for the stress-strain behavior of the aluminum tether. The model also assumes that the tether has no torsional or flexural rigidity. The explicit "bead-and-spring" method, however, requires the use of rather small time steps (typically tenths or hundredths of a second, depending upon the tether and number of elements).

Orbital Dynamics Model

The code calculates the orbital motion of the satellite, endmass, and tether elements using a 4th order Runge-Kutte algorithm to explicitly integrate the equations of motion according to Cowell's method.[10] The program has the capability to use an 8^{th}-order spherical harmonic model of the geopotential and can include perturbations caused by lunar gravity. However, the perturbations caused by these effects are typically very small compared to electrodynamic effects, so these effects were ignored in the calculations presented in this report for the sake of computational speed.

Geomagnetic Field Model

The TetherSim code has two options for calculation of the Earth's magnetic field: a simple tilted dipole model for fast calculations, and the International Geomagnetic Reference Field (IGRF 1995).

Simple Model: The Earth's magnetic field is modeled as a a magnetic dipole with the magnetic axis of the dipole tilted off from the spin axis by φ=11.5°. In this model, we have ignored the 436 km offset of the dipole center from the Earth's geometric center.

The magnetic field vector is given by

$$\mathbf{B} = \frac{\mathrm{B_E\ R_E^3}}{r^3}\begin{bmatrix} 3xz/r^2 \\ 3yz/r^2 \\ 3z^2/r^2 - 1 \end{bmatrix},$$

where B_E = 31 μT is the dipole moment of the Earth, R_E is the Earth's mean radius, and x, y, and z are cartesian coordinates expressed in a reference frame that has been rotated so that the z axis is aligned with the magnetic axis.

The geomagnetic field rotates with the Earth as it spins, so in calculations of **v**x**B** induced voltages experienced by the tether as it orbits the Earth, the local velocity of the geomagnetic field is subtracted from the tether's velocity before the cross product is calculated.

IGRF Model: For more detailed calculations, the code also can utilize the IGRF model.[11] For use in TetherSim, the FORTRAN code available from the GSFC server has been translated into C.

Atmospheric Drag Model

For calculating atmospheric drag and heating, TetherSim can use one of two methods: a fast heuristic model of the neutral density, and a more detailed, but slower model based upon the MSISE90 Neutral Atmospheric Empirical Model.

Heuristic Model: At low altitudes, neutral particle drag on the tether may become a significant effect. The code thus calculates the neutral particle drag on the satellite, endmass, and tether elements according to

$$F_{drag} = \frac{1}{2}\rho C_D V_{rel}^2 A$$

where C_D≈2.2 is the coefficient of drag for a cylindrical tether in free-molecular flow, V_{rel}^2 is the relative velocity between the tether and the atmosphere (assumed to rotate with the Earth), A is the cross-sectional area the tether presents to the wind, and ρ is the neutral density, calculated according to the heuristic formula developed by Carroll:[12]

$$\rho = \frac{1.47\times10^{-17}\ \ T_{ex}(300 - T_{ex})}{1 + \dfrac{2.9(h-200)}{T_{ex}}} \quad (h > 200km),$$

where h is the altitude and T_{ex} is the average exospheric temperature, 1100K.

MSISE 90 Model: For more detailed simulations, the code can utilize an aero drag and heating model developed by Stuart Bowman and Professor Mark Lewis of the University of Maryland, which uses the MSISE 90 model to calculate the atmospheric density.Bare Wire Tether Anode Model

The tether used in the Terminator Tether™ system will have a portion or all of its length uninsulated so that the bare metal of the tether wire can collect current from the ionospheric plasma. The tether is modeled as collecting electrons from the plasma according to the bare wire anode theory developed by SanMartín, Martínez-Sánchez, and Ahedo.[13] According to their theory, when the tether voltage is greater than the plasma voltage, the tether wire collects electrons from the ionosphere, and the electron current collected along the tether depends upon the square root of the voltage difference between the tether and the ambient plasma:

$$d_z I = -e\, n_e\, d\, [2e\, (V_t - V_p)/m_e]^{1/2}, \qquad (3)$$

where d is the tether diameter, m_e is the electron mass, n_e is the electron density, and V_t and V_p are the tether and plasma voltages, respectively. The sign in this equation is chosen for the case where the tether hangs below the satellite, the electron emitter is on the endmass at the bottom, and we are integrating the current as we go up the tether. When the plasma voltage is greater than the tether voltage, the tether repels electrons and collects ions in a similar manner, but much more weakly due to the ions significantly greater mass:

$$d_z I = e\, n_e\, d\, [2e\, (V_p\text{-}V_t)/m_i]^{1/2}. \quad (4)$$

FEAC Electron Emitter Model

The FEAC device emits electrons when a voltage is applied between the array of nanoscale emitter points and the gate electrode. The FEAC device for the Terminator Tether™ will be capable of emitting up to 1 A of current, and will be designed to operate at typical voltages between 50-100V. The dependence of the emission current on the gate voltage can be modeled according to the current-voltage relationship:

$$I = naV^2 e^{-(b/V)}, \quad (5)$$

where n is the number of tips in the array, and a (A/Volts^2/tip) and b (Volts) are parameters that can be obtained from a Fowler-Nordheim plot of the I-V data of a field array.[14]

Tether Reeling and Deployment

In order to study the dynamics of deployment of the Terminator Tether™, the code has recently been extended to include the capability to model the deployment physics. The tether can be deployed/reeled by either endmass. Currently, the code has models for:

- Free deployment (with deployment tension depending upon deployment rate)
- Deployment at a controlled tension
- Deployment at a controlled rate or rate program
- Tether retraction at controlled tension
- Tether retraction at controlled rate or rate program

These models have been used to model the deployment of a Terminator Tether™ and spin-up of the TORQUE experiment.[15]

Electrical Characteristics of the Terminator Tether™

One of the potential major advantages of the Terminator Tether™ relative to other satellite disposal options is the possibility it can derive its own power from the voltage and current generated by the tether's interaction with the Earth's magnetic field. In other words, a Terminator Tether™ system could power its Tether Control Unit (TCU) using the orbital energy of the satellite it is deorbiting. A self-powered Terminator Tether™ would not be dependent upon the health of the host vehicle's power system, and, unlike solar electric or other such thrusters, could deorbit a satellite even if the satellite's power bus has failed.

However, powering the TCU using the tether voltage comes at a price: the TCU electronics will consume a portion of the voltage induced by the tether. This will reduce the voltage available to collect current and drive it through the tether, reducing the tether current and thereby reducing the rate at which the Terminator Tether™ system can deorbit its host satellite. Consequently, we investigated the behavior of the electrodynamic tether circuit in order to develop guidelines for designing a Terminator Tether™ system that can derive its power from the tether while minimizing the impact on the device's deorbit performance.

Tether Voltage vs. Plasma Voltage

The Terminator Tether device will be deployed downwards from the host spacecraft at the end of a several-kilometer long conducting tether. The motion of the tether relative to the geomagnetic field and the ionospheric plasma will induce an electric field in the tether's frame of reference the +**z** direction.

If we compare the tether voltage and the voltage of the ambient plasma in the frame of reference moving with the tether, and chose the top of the tether (at the host vehicle) as our origin, the voltages plotted versus vertical distance from the host vehicle will appear as shown in Figure 5, where V_p is the plasma voltage and V_t is the tether voltage. The total voltage induced by the orbital motion of the tether across the geomagnetic field, $\Delta V_{induced}$, will be consumed by by three voltage drops: ΔV_a, the anode voltage drop which acts to collect electrons to the top section of the tether, ΔV_R, the resistive drop due to current flow along the tether, and ΔV_c, the voltage drop at the cathode (bottom) end of the tether. The cathode-end voltage will likely be caused by a load voltage, ΔV_{load}, which will drive the TCU control electronics, and by the gate voltage of the FEA electron emission device, $\Delta V_{emitter}$. The ratio of

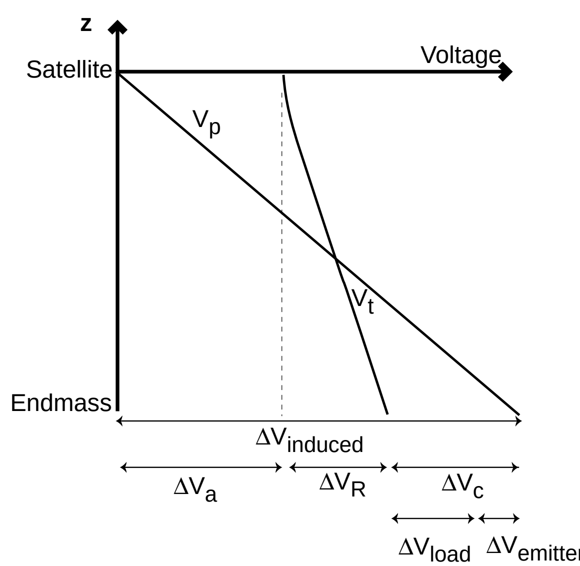

Figure 5. Tether voltage and plasma voltage along the tether length.

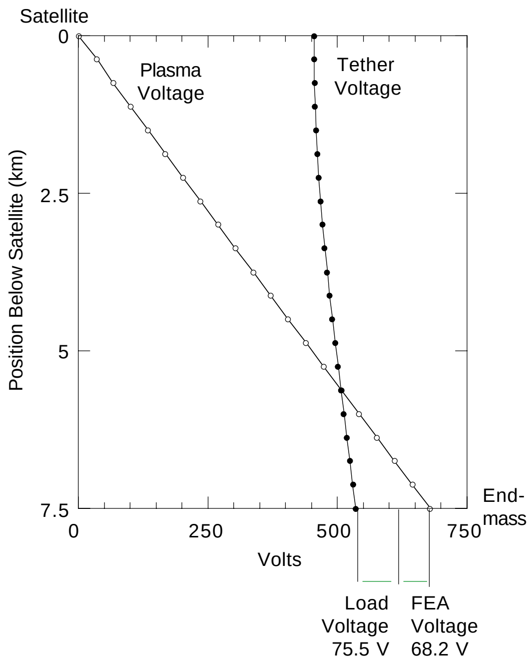

Figure 6. Tether and plasma voltage for a 7.5 km, 15 kg Terminator Tether hanging below a satellite in a 850 km, 50° inclination orbit, with a 250 ohm load resistance.

ΔV_a to ΔV_c will vary as the tether current is varied, so in Figure 5 the tether voltage curve can "slide" horizontally under different operating conditions.

Results

Our analytical and numerical studies revealed that the voltage induced by the motion of the tether through the Earth's magnetic field is consumed primarily by the anode fall voltage, which serves to collect electrons to the bare wire of the tether. A comparison of the voltage of the tether along its length to the local plasma voltage is shown in Figure 6, and the tether current along its length for the same system is shown in Figure 7. The current level thus is limited primarily by the ability of the tether to collect electrons, and thus tether designs with high effective collecting area are favored.

Using the numerical model of the Terminator

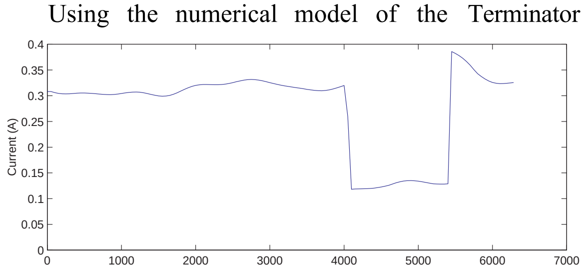

Figure 8. Tether current over one orbit for a 10 km, 15 kg tether deployed from a spacecraft in a 1000 km, 50° orbit with a load resistance of 250 Ω.

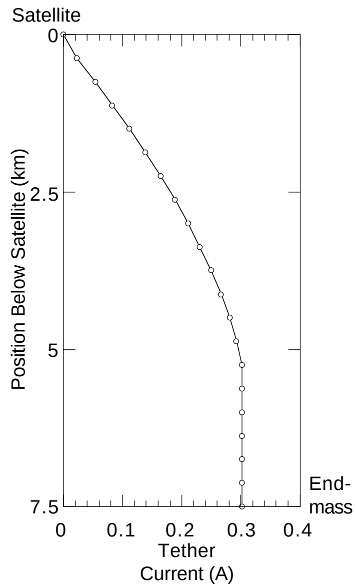

Figure 7. Tether current as a function of distance below the host satellite.

Tether™ system, we studied the behavior of the tether circuit with series loads to determine the feasibility of running the tether current through a DC/DC converter to power the TCU electronics.

Figure 8 shows a plot of the tether current over one orbit for a 10 km, 15 kg tether on a spacecraft in a 50°, 1000 km orbit. The plot shows that the current drops

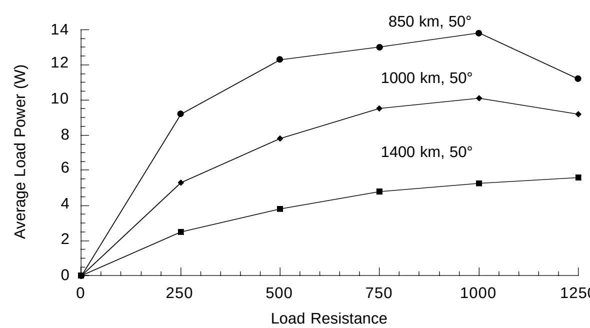

Figure 9. Average load power over one orbit as a function of series load resistance for the 5 km tether.

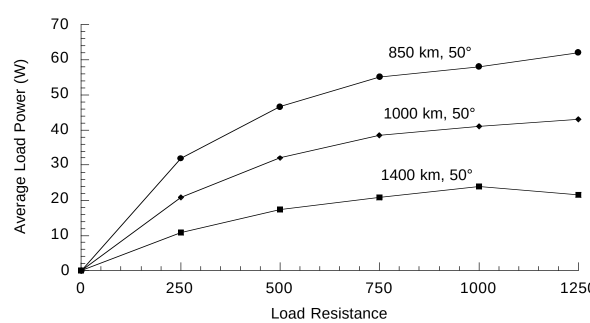

Figure 10 Average load power as a function of series load resistance for a 15 kg, 10 km aluminum tether.

by roughly 1/3 during the portion of the orbit when the satellite is on the night side of the Earth. The higher tether current experienced immediately after the satellite passes out of eclipse is due to the fact that the tether cools significantly during eclipse, and thus has a lower resistance for several hundred seconds.

Figure 10 shows the average power that can be supplied to a DC/DC converter in series with the tether at various altitudes and inclinations, as a function of the converter's series resistance.

We found that for systems designed for high-LEO constellation satellites, such as the SkyBridge™ and Teledesic™ constellations, tether lengths on the order of 7.5-10 km are desirable in order to provide an average power of 20-30 W to the DC/DC converter used to recharge the TCU battery without greatly degrading the deorbit performance. For mid-LEO constellations, shorter tether lengths of 5 to 7.5 km are adequate.

Tether Deployment Modeling

As a part of our designing of the Terminator Tether™ technology, we are in the process of developing a simulation of the system capable of modeling the entire operation of the device. As a part of that, we are investigating the dynamics of the deployment of the tether to determine the requirements on the deployment system and rendezvous vehicle to assure reliable tether extension.

Tension Model:
The dynamics of space tether deployment are highly dependent on the tension at which the tether deploys from its storage system. Although it is desirable to deploy the tether with as small a libration angle as possible to maximize the electrodynamic drag, because the electrodynamic forces on the tether will induce significant librations in an case, for the Terminator Tether™ it will not be necessary to control the deployment tension to a great degree of accuracy. Rather, the device will use a simple passive braking scheme to minimize system complexity and cost, and design the electrodynamic tether control feedback system to deal with any resultant librations and tether oscillations. In the simulations presented here, we modeled the tether as composed of three segments: a first segment of 500 m of high strength, lightweight nonconducting polymer to provide a very low initial deployment tension to assure initiation of the tether deployment, a 6500 m long segment of bare multiline wire tether, and finally a 500 m length of insulated tether wound with an adhesive to provide passive braking to bring the tether deployment to a gradual halt. In these simulations, we assumed that the ejects itself from the host vehicle at a ΔV of 2 m/s to start deployment.

For the first tether segment, the model of tether deployment tension used was based upon testing of a

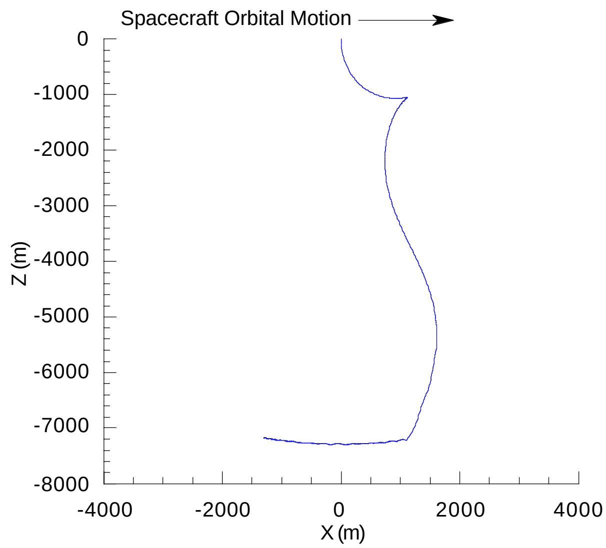

Figure 11. Deployment of the tether from the Terminator Tether™, with segmented tether model.

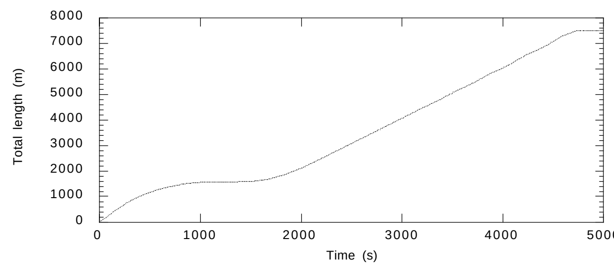

Figure 12. Deployed length as a function of time with segmented tether model.

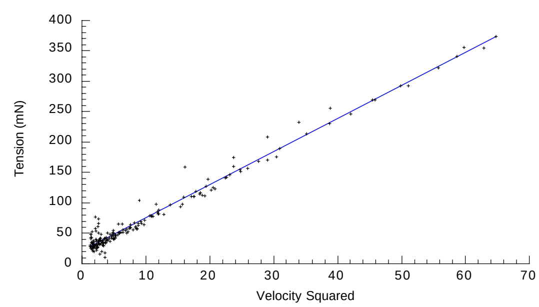

Figure 13. Plot of deployment tension versus the square of the deployment speed for the Spectra Hoytether paying out from the SEDS deployer with no braking applied.

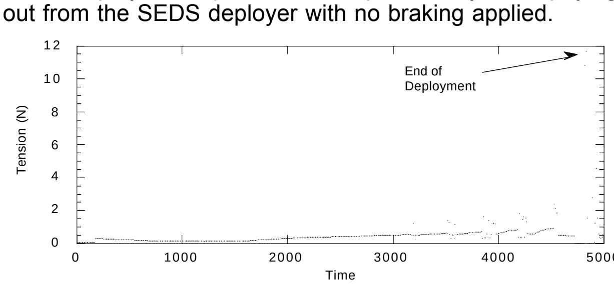

Figure 14. Tension experienced at the endmass, with segmented tether model.

3330 denier Spectra/PTFE Bi-Line Hoytether in the SEDS deployment system.[16] In those tests, the tether deployment tension varied with the square of the deployment velocity, as illustrated in Figure 13. A linear fit to the data shown in this figure predicts a deployment tension dependence of

$$T = 22.7 + 5.41\ v^2\ (\text{mN}).$$

The second segment will be a conducting aluminum Hoytether™. It was modeled with a higher deployment tension. The final 500 m of tether will a segment of conducting aluminum tether that has an insulating polymer overbraid, and is wound with a light application of adhesive. The adhesive is intended to increase the deployment tension as the endmass nears the end of its deployment in order to reduce the tension spike experienced at the end of deployment. It also helps to reduce the final libration angle.

Figure 11 shows the position of the endmass during deployment. The sudden transition from the low-tension nonconducting tether to the higher tension wire tether causes the endmass to rebound slightly. Since this rebound could potentially cause difficulties in the deployment, it may be desirable to make the tension transition more gradual, rather than a sudden spike. Figure 12 shows the deployed length over time. Figure 14 shows the deployment tension; with the passive braking at the end of the deployment, the tension spike at the end of deployment is less than 1 N. In Figure 11, the final libration angle is shown to be less than 10° in amplitude.

Feedback Control of Terminator Tether™ Dynamics

The Terminator Tether™ deorbits a spacecraft by inducing an electrodynamic drag force on the tether that opposes the velocity of the host spacecraft. If the mass at the end of the tether is significantly smaller than the mass of the spacecraft at the other end of the tether, as is the case in the Terminator Tether™, the drag force causes the tether to swing behind the spacecraft. Variations in this drag force over an orbit can cause the tether to librate back and forth in the plane of the spacecraft's orbit with a period of approximately √3 times the orbital period. In addition, variations in the direction of the Earth's magnetic field over an orbit will cause forces on the tether in the out-of-plane direction, resulting in "side-to-side" tether libration with a period of approximately 1/2 times the orbital period. If variations in the electrodynamic forces have time characteristics that are close to these libration periods, the forces on the tether can cause growth of the libration, and can lead to instabilities in the tether dynamics.

One potential source of instability is the apparent resonance between the orbit period and the out-of-plane libration period. Once-per-orbit variations in the tether current, such as is caused by the diurnal variation in the ionospheric density, illustrated in Figure 8, could potentially "pump" the out-of-plane librations. Our studies, however, have found that the once-per-day rotation of the geomagnetic field with the Earth contributes to stabilize this vibration. Figure 15 shows simulation results for a Terminator Tether™ operated at 1000 km in a 50° inclination. The plot of the out-of-plane (OOP) libration angle shows that the OOP libration does increase for several days, but then damps down, with a long-scale period of four days. This long-scale variation results from the beat resonance of the orbit, Earth rotation, and libration frequencies.

At high altitudes, therefore, the currents collected by the Terminator Tether™ and their interaction with the geomagnetic field are small enough that the growth rate of the tether librations is very slow, and thus at high altitudes they are not a concern. Once the tether system drops to lower altitudes, however, the tether currents and electrodynamic forces can become quite significant, and without control over the tether dynamics, the instabilities can result in the tether "flipping over" or even beginning to rotate, with a resultant loss of deorbit efficiency and control over the tether system. This instability is primarily in the In-Plane libration, rather than the OOP libration. Consequently, the Terminator Tether™ system will require implementation of a scheme for controlling the tether dynamics. Because the Terminator Tether™ must be a low-cost system and thus cannot afford an extensive computational capability, the control scheme must based upon simple calculations using readily observable quantities as inputs. The Terminator Tether™ conceptual design has been chosen to make this feedback control of the tether dynamics possible. The fact that the Terminator Tether™ control electronics will be housed in the tether endmass will enable the system to observe the tether librations. In addition, the Terminator Tether™ will use a Field Emission Array Cathode (FEAC) to emit electrons; unlike a conventional plasma contactor, the emission current of these devices can be controlled quite accurately by varying its input gate voltage. These two choices in the Terminator Tether™ design will permit implementation of a simple feedback control scheme which will enable the device to maintain tether stability during the descent phase.

Using the TetherSim numerical model of the electrical, dynamical, and orbital behavior of the Terminator Tether™, we investigated several methods of performing feedback control on the tether current in order to stabilize the tether dynamics. The necessity for control of the tether dynamics is illustrated by Figure 16, which plots the in-plane libration angle of an electrodynamic tether with no current control as it attempts to deorbit a satellite from a 400 km, 50°

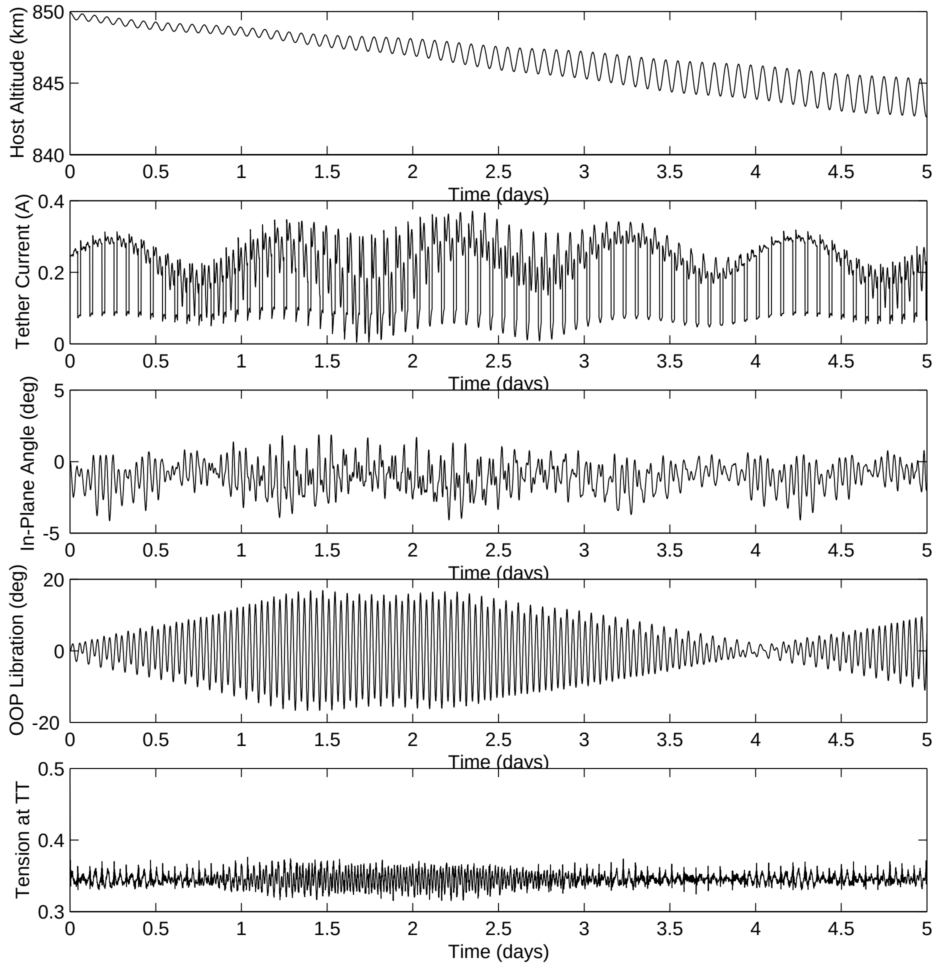

Figure 15. Data for a 5-day simulation of a Terminator Tether starting in a 850 km, 50° initial orbit.

inclination orbit. Without current control, the libration grows until the tether becomes unstable within half a day.

The Terminator Tether™ will stabilize the tether dynamics using a proprietary feedback control algorithm. The algorithm is based upon readily obtainable observables, and is computationally inexpensive. Figure 17 shows simulation results for a tether system operating with the feedback control algorithm. With this control scheme, the tether dynamics are stabilized sufficiently to enable the system to deorbit the satellite from 400 to 250 km in 14 days.

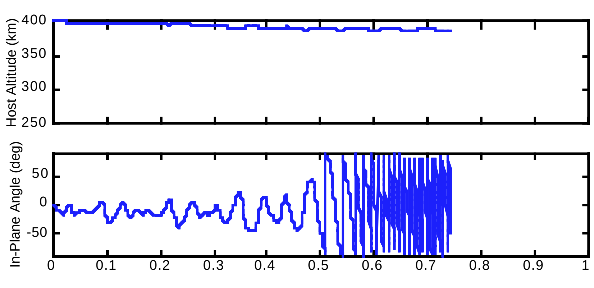

Figure 16 Host spacecraft altitude and the in-plane libration angle of the tether endmass for a 15 kg, 7.5 km long tether deorbiting a satellite from a 400 km, 50° inclination orbit with no feedback control.

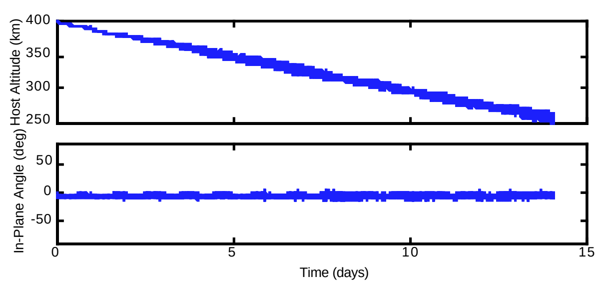

Figure 17. Host spacecraft altitude and tether in-plane libration angle with feedback control on the in-plane libration. The feedback succeeds in keeping the tether dynamics under control.

Deorbit Rate and Deorbit Times

The Terminator Tether™ Satellite Deorbit System utilizes passive electrodynamic interactions between a long conducting tether and the Earth's magnetic field to drag LEO spacecraft down out of orbit. The purpose of using such a deorbit system is to remove an old spacecraft from orbit more rapidly than it would if left to deorbit by aerodynamic drag alone, so as to minimize the collision threat the spacecraft poses to operational spacecraft. The NASA Safety Standard 1740.14, *Guidelines and Assessment Procedures for Limiting Orbital Debris*, recommends that "if drag enhancement devices are to be used to reduce the orbit lifetime [of a LEO spacecraft], it should be demonstrated that such devices will significantly reduce the area-time product of the system…." In previous work, we studied the performance of the Terminator Tether™ system using analytical techniques and found that an electrodynamic tether drag system can indeed reduce the area-time product of a satellite system by several orders of magnitude.[1]

Those calculations, however, relied on a number of simplifying assumptions to make the problem analytically tractable. They ignored the complications of tether dynamics, plasma contact resistances, tether thermal behavior, plasma density variations, and a number of other effects which could impact the performance of the system. In this study, we have employed a numerical model of the Terminator Tether™ that includes models for these phenomena to investigate the performance of the system. Using this model, we have simulated the Terminator Tether™ system operation at a variety of altitudes and inclinations so as to determine the rate at which the device can reduce the altitude of a typical satellite. Using these rates, we have estimated the total time required to deorbit a satellite, and used these values to compare the Area-Time Product for Terminator Tether™ systems to the Area-Time Product for satellite deorbit by aerodynamic drag alone.

Method

To determine the rate at which a Terminator Tether™ system can deorbit a spacecraft, we used the TetherSim numerical model to simulate the orbital, electrodynamic, dynamic, and thermal behavior of the tether system for a period of one day at various initial altitudes and orbit inclinations.[7] The tether systems modeled in this study consisted of a 15 kg aluminum tether, with a 15 kg endmass. The tether was chosen to be 7.5 km long. The host spacecraft mass was 1500 kg, so the tether massed 1% of the spacecraft mass, and the entire TT system massed 2% of the host mass. The simulations assumed that there were no load resistances in line with the tether; presence of DC/DC converters or other loads in the circuit will tend to reduce descent rates and thus increase deorbit times slightly.

In these simulations, the maximum tether current was limited to 1A, and a feedback control scheme was used to prevent the uncontrolled growth of In-Plane librations. The feedback control was initially inactive, allowing the system to generate maximum drag at high altitudes and inclinations. However, once the tether current reached 1 A or the maximum In-Plane libration angle exceeded 15 degrees, the feedback control was turned on.

Note that in these calculations we have assumed that the Terminator Tether™ has completed its mission when the host spacecraft's perigee altitude drops below 250 km. At this altitude, atmospheric drag on the spacecraft and tether will cause the satellite to deorbit and burn up in the upper atmosphere within several orbits. Furthermore, these simulations assumed a spherically symmetric ionosphere. In reality, the ionosphere has an equatorial bulge that increases the plasma density significantly near the equator. Consequently, deorbit times for equatorial orbits will be considerably lower than those shown here.

Descent Rate

The rate of perigee decay in orbits with inclinations of 0, 25, 50, 75, and 90° at various altitudes is shown in Figure 18. Comparison of the curves at various altitudes reveals the expected result that the rate of descent varies approximately as the cosine of the inclination. The descent rate does not go completely to zero at polar orbit because the Earth's magnetic dipole is tilted relative to its spin axis, and thus during some portions of the day a polar satellite will be crossing field lines; the descent rate for polar orbits, however, is very small. Following the curves from high altitude to low altitude (right to left), the descent rate in orbits with 0, 25, and 50° inclinations increases rapidly as the ionospheric plasma density increases, but then as the 1 A current limitation and the feedback control come in to play at low altitudes, the slope of the curve becomes less steep.

Deorbit Time

Total deorbit times as a function of initial altitude were calculated by integrating the inverse of the descent rates shown in Figure 18. These deorbit times are shown in Figure 19. Taking particular examples, the results indicate that a tether massing 1% of the host spacecraft mass could remove an Iridium NX spacecraft from a 850 km, 50° orbit within three months, and a SkyBridge satellite from a 1475 km, 55° orbit in about 1.2 years. These results indicate that a lightweight Terminator Tether™ system can effectively deorbit satellites in inclinations up to about 75°. In very polar inclinations, however, the tether's interaction with the geomagnetic field is much lower, and thus deorbit times with such a low-mass tether are rather high. Lower deorbit times for polar orbits could be achieved using more massive tethers.

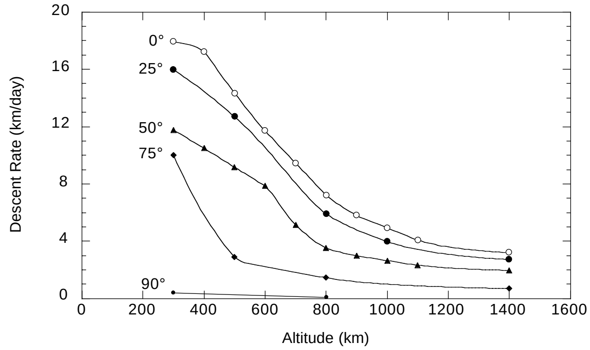

Figure 18. Rate of descent for a 7.5 km, 15 kg aluminum tether with a 15 kg endmass, deorbiting a 1500 kg spacecraft at various inclinations and altitudes.

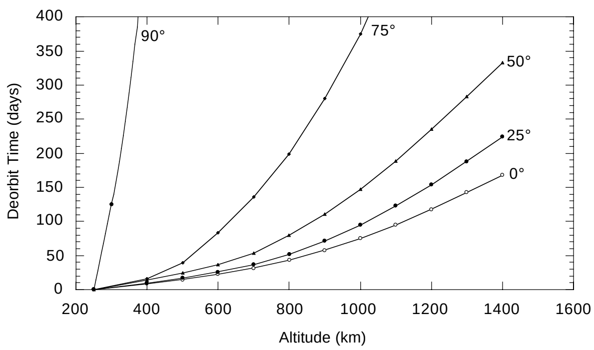

Figure 19. Time for a Terminator Tether™ with a 7.5 km, 15 kg aluminum tether and 15 kg endmass to decrease the perigee altitude of a 1500 kg spacecraft to 250 km. Note that deorbit time can be decreased by using longer or more massive tethers.

Area-Time Product

The primary purpose of the Terminator Tether™ technology is to remove unwanted spacecraft from orbit so that they cannot pose a collision threat to other spacecraft. Yet, when Terminator Tether™ system deploys a multi-kilometer tether from a satellite, it greatly increases the cross-sectional area of the satellite system. This, in turn, increases the chances that the system will suffer a random collision within a fixed time period. However, the chance of a collision between the spacecraft and another satellite depends not only upon the cross sectional area, but also upon the amount of time the satellite spends in orbit. For a satellite left to deorbit by aerodynamic drag only, its collisional cross-sectional area is relatively low, but because aerodynamic drag is so slight, the amount of time it spends in orbit can be many hundreds or thousands of years. So, although the Terminator Tether™ increases the cross-sectional area of a satellite system, it can still greatly reduce the chances of a random collision because it can reduce the amount of time the satellite spends in orbit more than enough to

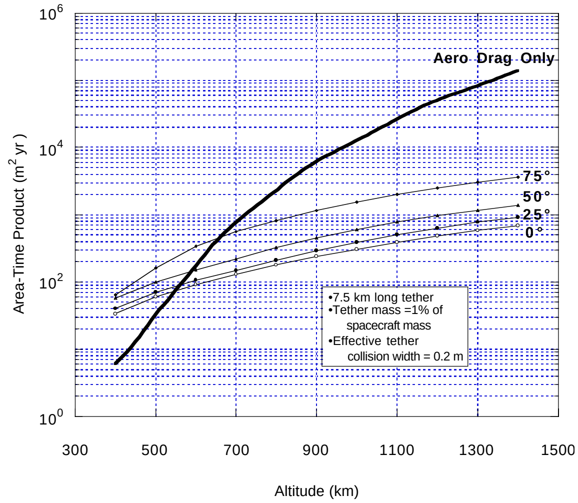

Figure 20. Area-Time-Product for Terminator Tether™ systems with tethers massing 1% of the host spacecraft mass, compared to the ATP for deorbit of the host spacecraft due to aerodynamic drag alone.

compensate. Figure 20 compares the area-time-product for satellites deorbited by Terminator Tethers™ with the area-time-product for satellites deorbiting due to aerodynamic drag alone.

Summary

Using analytical and numerical modeling, we studied the behavior and performance of Terminator Tether™ electrodynamic drag devices for deorbit of LEO spacecraft. We found that the tether lengths of 5-10 km are sufficient to enable the tether control electronics to draw several tens of watts of power from the tether circuit without severely impacting the deorbit rate. Thus the Terminator Tether™ system can derive its power from the tether current, and does not require input power from the host vehicles or dedicated solar cells. Using the same simulation tools, we modeled the performance of the device for deorbiting typical communications satellites from various LEO orbits, and found that tether systems massing less than 2% of the host vehicle mass can provide rapid disposal capability for satellites in low and moderate (<75°) inclinations. In order to solve the problem of the inherent instability of electrodynamic tethers, we developed a simple feedback control scheme based and verified its performance using simulations.

Acknowledgments

This research was supported by NASA/MSFC SBIR Phase I Contract NAS8-98108 and Phase II Contract NAS8-99092, Technical Monitor Les Johnson. TUI would like to acknowledge Nicole Meckel and Doug Smith of Primex Aerospace for their assistance in the design of the Terminator Tether™ deployment mechanism.

References

1. Forward, R.L., Hoyt, R.P., Uphoff, C., "Application of the Terminator Tether™ Electrodynamic Drag Technology to the Deorbit of Constellation Spacecraft", AIAA Paper 98-3491, *34th Joint Propulsion Conference*, July 1998.

2. Sanmartín, J.R., Martínez-Sánchez, M., Ahedo, E., "Bare Wire Anodes for Electrodynamic Tethers," *J. Propulsion and Power*, 7(3), pp. 353-360, 1993.

3. Drell, S.P., Foley, H.M., Ruderman, M.A., Drag and Propulsion of large satellites in the ionosphere: An Alfvên Engine in space", *J. Geophys. Res.,* 70(13), pp. 3131-3145, July 1, 1965.

4. Estes, R.D., "Alfvên waves from an electrodynamic tethered satellite system", *J. Geophys. Res*., 93 (A2), pp 945-956, Feb. 1, 1988.

5. Forward R.L., Hoyt, R.P. "Failsafe Multiline Hoytether Lifetimes," AIAA paper 95-2890, *31st AIAA/SAE/ASME/ASEE Joint Propulsion Conference*, San Diego, CA, July 1995.

6. Spindt, C.A., *et al.*, "Field Emitter Arrays for Vacuum Microelectronics," *IEEE Transactions on Electron Devices*, Vol. 38, No. 10, p. 2355, Oct. 1991.

7. Hoyt, R.P., Forward, R.L., *The Terminator Tether™: A Low-Mass System for End-of-Life Deorbit of LEO Spacecraft*, Tethers Unlimited, Inc. Final Report on NASA/MSFC SBIR Phase I Contract NAS8-98108, October 9, 1998.

8 . Kim, E., Vadali, S.R. "Modeling Issues related to Retrieval of Flexible Tethered Satellite Systems," J. Guid. Contr. & Dyn., 18(5), 1995, pp 1169-76

9. Carroll, J.A., Personal Communication.

10. Battin, R.H., *An Introduction to the Mathematics and Methods of Astrodynamics*, AIAA, 1987, p. 447.

11. Barton, C.E., International Geomagnetic Reference Field: The Seventh Generation, *J. Geom. Geoelectr.* 49, 123-148, 1997.

12. Carroll, J.A., "Aerodynamic Drag", p 160 in *Tethers In Space Handbook, 3rd Edition*, Cosmo and Lorenzini, editors, Smithsonian Astrophysical Observatory, 1997.

13. Sanmartín, J.R., Martínez-Sánchez, M., Ahedo, E., "Bare Wire Anodes for Electrodynamic Tethers," *J. Propulsion and Powe*r, 7(3), pp. 353-360, 1993

14. Spindt, C. A., C. E. Holland, P. R. Schwoebel, and I. Brodie, "Field-Emitter-Array Development for Microwave Applications," *Journal of Vacuum Science and Technology -B,* Vol. 14, No. 3, pp 1986-89, May/June 1996.

15. Hoyt, R.P., *Moon & Mars Orbiting Spinning Tether Transport (MMOSTT) Architecture, Fourth Monthly Report,* Tethers Unlimited, Inc Progress Report on NIAC Phase II contract 07600-034, January 10, 2E3.

16 Hoyt, R.P., Forward, R.L., *High Strength-to-Weight Tapered Hoytether for LEO to GEO Payload Transport*, Final Report on NASA Phase II SBIR Contract NAS8-97025, 18 Nov 1998, Appendix C.