Orbital Maneuvering with Spinning Electrodynamic Tethers

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Electrodynamic tethers produce low thrust through interaction of the electric current in the tether with the Earth's magnetic field. The thrust is comparable with that of ion rockets and Hall thrusters, and they have the added advantage that they are propellantless, allowing them to produce an order of magnitude greater velocity changes than ion rockets. However, the long conductors of such electrodynamic thrusters typically exhibit unstable behaviors with higher currents. Instability affects both libration and bending modes of tether motion and significantly limits the performance characteristics of electrodynamic tether thrusters. Previous concepts for electrodynamic tethers have proposed stabilizing them by hanging vertically under the gravity gradient, but this passive gravity-gradient stabilization severely limits the current in the conductor, and therefore limits the thrust. Two methods have been developed to stabilize electrodynamic tethers and improve their performance. First, the system spins with an average spin rate significantly higher than the orbital rate, increasing tether tension for a more robust and controllable tether system, and providing a better orientation of the tether with respect to the magnetic field for orbital maneuvering. Second, electric current variation is used to control both the tether spin parameters and the tether bending modes. It is shown that a controlled, spinning electrodynamic tether can consistently deliver a much higher thrust compared with the traditional "hanging" tether configuration. Minimum-time orbit transfers with spinning tethers can be described approximately by a set of relatively simple ordinary differential equations using Pontryagin's Principle. These techniques were developed to control the dynamics of the Spinning Electrodynamic Tether (SET) system. This uses a conductor two to ten kilometers long as an electrodynamic thruster for a low-thrust orbit transfer vehicle. The SET was simulated with a PC-based computer program to evaluate its orbit transfer capabilities. This vehicle is capable of repeated large orbit changes in low earth orbit, totaling >50 km/sec each year for several years.

Nomenclature and Acronyms

AC	=	alternating current in the conductor
DC	=	direct current in the conductor
EDT	=	electrodynamic thruster
EMF	=	electromotive force over the conductor length
LEO	=	low Earth orbit, below approximately 2000 km altitude
SET	=	spinning electrodynamic tether

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I. Introduction

As shown in Figure 1, electrodynamic thrusters (EDTs) use the electromagnetic force generated by a current through a long conductor in the earth's magnetic field to generate net forces that cause orbit changes. One end of the conductor acts as a bare-tether collector[1] to absorb electrons from the ambient plasma; at the other end is an electron emitter to eject electrons. The current generated by the solar arrays flows through the long conductor and returns through the ambient plasma around the conductor. The force on the conductor can be in either of two opposite directions, depending on the current flow direction in the conductor. If it flows with the EMF induced by orbit motion through the earth's magnetic field, then power is generated and there is orbit decay. If solar or other power is available, it can be used to create a current in the other direction. In this case, orbit boosting is obtained, and external power must supply a voltage equal to the EMF plus all other voltage drops in the overall current loop: electron collection, conduction, emission, and external cross-field conduction.

Conventional "hanging" electrodynamic tethers are stabilized near the vertical by the gravity gradient force, which provides a restoring moment if the conductor is perturbed away from the vertical by the electrodynamic force distributed along the tether length. Tether stability work by Levin[2] showed that if the average tether thrust exceeds ~10% of the gravity gradient tension at inclinations like that of ISS, then it is difficult to control tether swinging, bending, and end-mass attitude motions. This is a severe limitation on the thrust of hanging electrodynamic tethers. In addition, hanging ED tethers exert mainly E-W forces. This makes the force mainly in-plane in low-inclination orbits, and out-of-plane in high-inclination orbits. This makes some maneuvers easy, but others quite difficult.

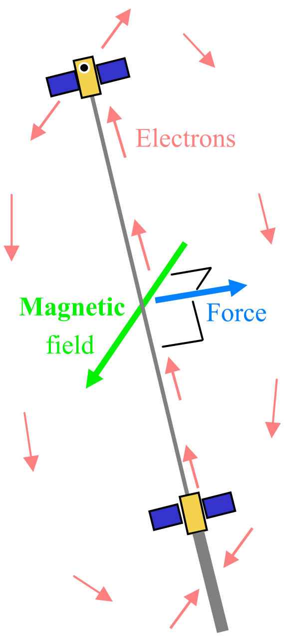

Figure 1. Electrodynamic Loop and Force

STAR Technology and Research proposed a maneuvering spacecraft concept using an electrodynamic tether in 1999. A Phase I SBIR study[3] with the Air Force Research Laboratory established the feasibility and basic design features of a spacecraft optimized for fast orbit change using electrodynamic forces. In Phase II we realized that spinning the tether provided substantial advantages. We developed a design for a spinning electrodynamic tether (SET) and developed several key system components.[4] The system design described in these limited-distribution documents is given in a published paper.[5] Spinning not only allows the tether to be driven much harder than conventional ED tethers can be driven without going unstable, but the constantly varying tether and magnetic field line orientations allow the tether to better "tack" against the magnetic field. This allows relatively efficient change of any desired combination of orbit elements, in any orbit inclination.

II. Spin Stabilization

Spinning an electrodynamic tether is a key technical advantage because it stiffens and stabilizes the tether. This does sacrifice some of the EMF on a vertical tether at low latitudes, and hence reduces boost or drag forces. Spinning tethers spend 50-75% of their time closer to horizontal than to vertical, depending on whether the spin is in or normal to the orbit plane. This reduces the EMF from a horizontal field. But as shown in Figure 2, the vertical field exceeds the horizontal field over much of the earth; so horizontal tether orientations might often be useful.

Most satellites in LEO have inclinations >70°. The average vertical magnetic field around their orbits exceeds the average horizontal field. So electrodynamic thrusters might often provide more boost or decay thrust when horizontal than when vertical. More importantly, a spinning

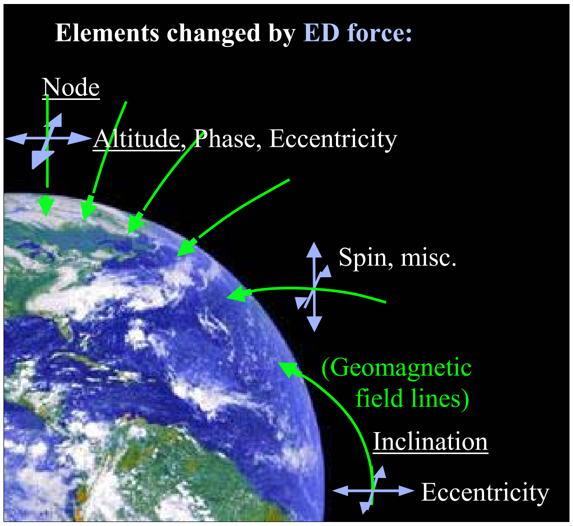

Figure 2. Possible ED Thrust Vectors

tether is far more flexible operationally: it can vary the current with spin phase to direct the net thrust anywhere in the plane normal to the local field, rather than just thrusting roughly east or west (i.e., normal to both the roughly vertical conductor and the mainly north-south magnetic field component that is normal to the conductor).

Besides allowing far higher drive levels and more flexible maneuvering, spinning also allows the system to be simpler and lighter. Hanging EDTs tend to have unstable swing dynamics if driven much harder during the day than at night. To avoid this, they need heavy batteries to power nighttime operation at power levels comparable to those used during the day. They also need more electron-collection area to collect enough current to run at night, despite factors of 3-10 reduction in plasma density at night. A spinning system does not need to run at night for stability, so it can use smaller electron collectors that are sized for the denser daytime plasmas. In addition, it does not need the heavy batteries needed by "hanging" tethers to provide power for thrusting at night. These benefits are very valuable, and they have been protected by a patent application[6]. The patent covers spinning electrodynamic thrusters to improve performance, operations, and system design.

A. Controlling the Spin Plane and Rate

Typical spin rates are of order 8 revs/orbit. This is high enough for good centrifugal stabilization, without imposing large mass penalties for tether strength reinforcement. Far higher rates may be appropriate in applications requiring artificial gravity, or release of payloads into orbits well above or below the current orbit, or designs that use ultra-capacitors or other high-rate storage devices for partial-spin energy storage.

There are several ways to apply electrodynamic torques to adjust the spin plane or rate. For example, collecting electrons near the middle of a wire and driving them out to emitters at both ends of the wire causes little net force but a large torque. The torque direction varies with orbit phase, so selective operation in this mode can change the spin plane and/or rate as desired. (One can reverse this torque without needing an electron emitter in the middle of the wire, by waiting until the field direction reverses.) If the system has a heavy payload at one end, so its center of mass is far from the middle of the wire, then any current along most of the length will impose a torque. Then a DC component has a secular effect on spin, while an AC component at one cycle per turn will induce little torque but large translational forces. Here too, one can vary the DC component around the orbit, to get any desired net torque by adding or subtracting torques available at different points in the orbit.

B. Effects of Different Spin Planes

In high-inclination orbits, in-plane spin is useful primarily when fast node and/or inclination changes are desired, rather than altitude changes. Spin normal to the orbit allows faster boost or decay, whether the spin is horizontal near the pole or near the equator. The spin plane will also affect the output of solar cells, if they track only around the tether axis, so power issues may affect spin-plane selection. It appears that the tether should usually spin either close to the orbit plane or nearly normal to it, because then little effort is required to maintain a fixed spin axis. A tilted spin requires more effort to maintain, and may be useful mainly while going between in-plane and normal spins. (With spin rates of ~8/orbit, such transitions can be done in hours rather than days, and spin axis nutation is acceptable then.)

C. Modifying Orbit Parameters

Careful consideration of Figure 2 will allow insight into the best conductor position and orientation to affect the different orbit elements:

Inclination:	tether vertical, near equator
Node:	align w/velocity vector, near pole
Altitude:	tether normal to orbit, near pole, or vertical at low inclination
Phase:	change altitude; wait; change back
Eccentricity and Apsides:	boost and drag once each orbit, or align tether E-W near equator

The effectiveness of the above strategies often varies with the cosine of the position and spin phase offsets. Two strategies operating in quadrature can often be 71% as effective as if only one were done at a time. This means that it is often most efficient to change two or more orbit elements at the same time (i.e., at different times in the same spin or the same orbit).

III. Active Control

D. Dynamics Model

We developed a tether dynamics model based on the theory of motions of space tether systems[2]. The model considers motions with small deflections of a massive tether. Our geomagnetic field model is based on the World Magnetic Model developed by DOD, and includes harmonics up to the 12^{th} order. We model the modules and payload as point masses. The orbit of the mass center evolves slowly under the effect of electrodynamic forces distributed along the conductor. The goal of control design is to stabilize the resulting dynamics of the conductor, while making a required orbit change as fast as possible. The orbit change may involve inclination, altitude, eccentricity, apsides, and phase, and also matching the moving ascending node of a desired target object.

E. Tether Dynamics Simulation

To test and verify various control concepts, we developed suitable dynamics simulation software. The software allows graphic visualization of the evolution of various characteristics of conductor motion. The model and the simulation software allow for differences in system behavior between forward and reverse current modes, to allow modeling of asymmetrical designs. We developed an approximate altitude profile of plasma density for the model, and a model to determine the effects of plasma variability on dynamics and control. We also developed models of voltage-dependent electron and ion collection by a narrow tape at an angle to the local magnetic field. Finally, we developed model variants for both hanging and spinning electrodynamic thrusters, including variations in available power, allowing for the use of simple one-axis solar-array tracking (around the tether axis).

F. State Estimation

The real key to controlling the spinning tether is being able to estimate its state from easily and reliably observable phenomena. This is needed to determine both how it deviates from a desired state, and to evaluate the effects of current changes. Our work shows that measurements of system drive voltage, current, and plasma properties allow estimation of the EMF, and that occasional additional voltage measurements at zero or low current allow refinement of EMF estimates. A one-orbit history of EMF appears to allow adequate estimation of spin dynamics. With hanging tethers, EMF variations generally indicate out-of-plane dynamics fairly well, but not in-plane dynamics. For in-plane dynamics, it appears very useful to also measure acceleration or tension. Measuring acceleration or tension appears unnecessary with spinning tethers, and the estimator can usually provide more accurate state estimates than feasible with hanging tethers. These are additional advantages of spinning the tether.

Our estimator uses simpler environmental and tether models than the simulator model. This represents expected limitations in the actual flight software, and also mimics biases and differences between estimated and actual data. The estimator uses its internal model of the system to integrate the equations of conductor motion backward in time, to find what present tether state most closely fits the last orbit's worth of measured data when projected backward. It then integrates the equations of motion forward in time from the present estimated state, to develop a current schedule that fits the orbit and spin change priorities and required damping adjustments.

The controller uses the new electric current schedule until the next call to the estimator. During this interval, new voltage, current, and possibly tension data are collected. The updated last-orbit data is submitted to the estimator, along with the time and orbit elements. The process repeats at uniform intervals. In typical missions, the flight computer might cycle through this sequence at roughly one-minute intervals.

G. Damping Strategy

Electrodynamic thrusters develop instabilities when energy is pumped into conductor dynamics. This can occur even at constant current[1,7], but is usually worse due to current variations forced by the environment. Further, the magnetic field is seldom aligned exactly as needed, so modulating current to obtain a desired effect usually excites undesired modes. Limiting the undesired dynamics requires persistently draining energy out of the system.

Our feedback control strategy starts with an ideal reference frame moving and rotating with the ideal tether motion we want (no bending, an ideal spin rate and plane, etc.). This motion need not be exactly realizable by the tether; it just needs to be computable. We then take the tether state inferred by the estimator, predict the tether motion relative to the ideal reference frame, and compute the "error EMF" caused by motion relative to the ideal frame. If that error EMF actually drove the current, then we would get passive eddy-current damping of the undesired motion. But the actual EMF is not the same as the error EMF, so we must actively mimic the effect of an error EMF. We do this by specifying a current schedule that correlates with the error EMF. This correlation need not be perfect, and can be subject to power, current, voltage, or other limitations; the better the correlation, the faster the damping.

Constraints on ED force direction limit how much each mode can be driven or damped each instant, but on timescales >1/4 orbit, all modes are accessible. The main goal is a long-term trend of damping any dynamics with effects large enough to observe. All large dynamics are clearly observable, including skip-rope. The required control current is usually small. The slow growth rate of most of the dynamics and the cumulative nature of damping makes this strategy very tolerant of periods when problems with the power, data acquisition, or control systems make active stabilizing control temporarily unavailable. Control of the tether dynamics is more effective than previous methods.[8]

Our design does not require large batteries for night-time operation. We could use smaller high-rate batteries for fractional-spin storage, but the benefits may not justify the added complexity and failure modes. As a result, we have a "use it or lose it" power usage strategy, where the tether is generally being driven in one direction or the other with all available power (solar plus tether EMF when that is favorable). The performance penalty due to control currents is least if current reductions or reversals occur near switching times, when the electrodynamic force may be large, but the force component in the desired direction is smallest. The control effect is hence typically simply a series of modest adjustments in current-switching time, superimposed on that which would nominally give the fastest desired orbit and spin changes.

H. Control Summary

Our technique for active libration and flexible tether mode control uses a secondary conductor current superimposed on the drive current, phased to suppress libration and vibration of the tether, and converted into a push-or-pull current direction decision. This method eliminates the limitation on the current in the conductor imposed on passively hanging tethers, and opens the way to very high power electrodynamic tethers; patents have granted recently by the U.S. Patent Office for the method[9] and for the apparatus.[10] Performance of LEO propulsion systems based on our SET design parameters is limited only by their power to mass ratios.

IV. Performance Analysis

We developed a computer program to allow mission planners to evaluate particular configurations and specific orbit transfer missions. We call this mission-planning program the Navigation Tool. It finds the fastest way to get an electrodynamic thruster from an initial low earth orbit to any other low earth orbit, using Pontryagin's principle. The strategies it selects often seem counter-intuitive at first. For example, changes in ascending node are often the most time-consuming part of an orbit change, because they range over 360^o, whereas popular inclinations range over a much narrower range (mostly 50^o to 100^o). The tool will often change inclination and/or altitude the "wrong way" at the start of a maneuver, to increase differential nodal regression compared to the target orbit and hence reduce the overall duration of the orbit change. For simplicity and speed, the tool does not simulate the detailed tether dynamics but rather just the long-term evolution of the orbit as it can be affected by electrodynamic thrust.

A typical output is shown in Figure 3. It illustrates a common feature, which is a tendency to quickly go to a low or high altitude, loiter there to maximize passive differential nodal regression compared to the destination orbit, actively change inclination and node, and then move to the desired altitude at the end of the maneuver.

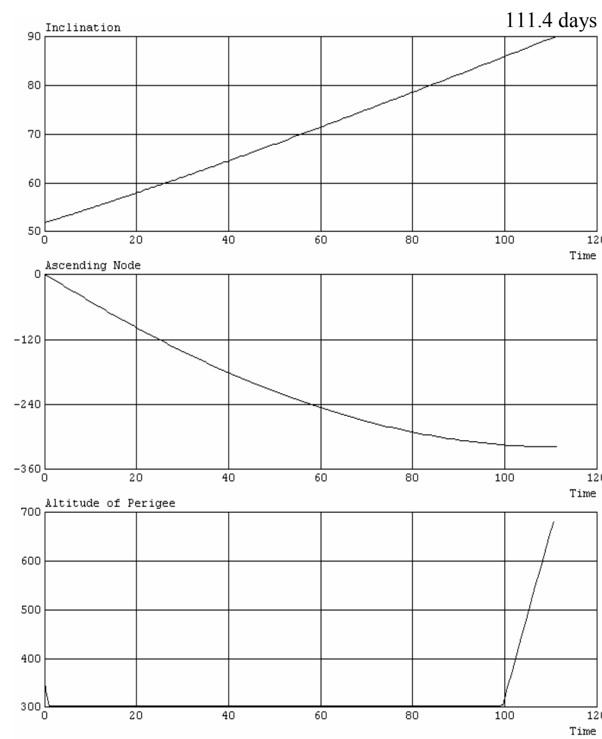

Figure 3. Orbit Transfer, ISS to Polar, Calculated by Navigation Tool

The Navigation Tool provides all necessary facilities to make the process of estimating orbit transfers user-friendly and efficient. The program is designed for Windows PCs.

I. SPINNING ED THRUSTER PERFORMANCE VERSUS ION ENGINES

The Spinning Electrodynamic Thruster (SET) provides force without using propellant, but its hollow cathodes use a small flow of xenon gas. This makes it difficult to quote a specific impulse for fair comparison with other types of electric thrusters. One measure is the "specific stage impulse" or total impulse (thrust times duration) divided by full stage mass. This has units of N·s/kg, which is equivalent to a velocity in m/s. Table 1 compares the SET with other electric propulsion systems, using our best estimates of key parameters.

The run times of the electric rockets are limited by the amount of propellant available, but the run time of the SET is determined by the lifetimes of the components in the space environment. Atomic oxygen and UV radiation will cause degradation of the solar arrays and coatings, and the risk of cut by debris or micrometeoroids determines the likely lifetime of the conductor. For our baseline design of a 30-mm wide tape, the conductor is expected to survive for the 5 years used in Table 1, and provide ~60 km/s of velocity change per year. For comparison, the Naval Research Laboratory TiPS tether, 2 mm in diameter and 4 km long, has lasted 8 years at an altitude near 1000 km, a region of higher-than-average debris density.

Table 1. Comparison of the SET with Other Orbit Transfer Propulsion Systems

System	Fluid Mass kg	Dry Mass kg	Thrust mN	Specific Power kW/N	I_{sp}, seconds	Run time months	Specific Stage Impulse, Ns/kg
NH_3 Arcjet	500	200	2000	13	800	1	6K
*SPT-100	72	25	78	17	1600	8	12K
†DS-1 Ion	82	253	92	27	3100	14	7K
10 kW Hall	400	250	450	22	3000	13	18K
‡SET	15	85	500	20	-	60	295K

* SPT-100 is a Stationary Plasma Thruster.
†DS-1 is The Deep Space One spacecraft.
‡SET thrust is for typical orbit changes; all run times are in calendar months for daylight operation.

V. Conclusions

The spinning electrodynamic thruster (SET) is significantly more capable and versatile than conventional hanging electrodynamic tethers. Because of the active control of attitude and flexible body modes, its thrust is not limited by the weakness of gravity gradient forces, and the operational flexibility added by spinning frees the thrust from the mostly-east-or-west forces available to hanging ED tethers. The SET can provide an order of magnitude higher total specific thrust than other electric thrusters.

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