

ENERGY HARVESTING ON SPACECRAFT USING ELECTRODYNAMIC TETHERS

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1 Introduction

Harvesting of power and energy from the space environment using spacecraft structures offers the promise of reduction in fuel usage as well as extended mission lifetimes and/or enhanced system capability. Apart from solar cells, limited adoption of other energy harvesting devices on satellites has occurred, such as the conversion and recovery of thermal energy. Other untapped resources available to satellites include gravity, the planetary magnetic field, and the surrounding ionosphere. Electrodynamic tethers (EDTs) represent an innovative scheme to harvest energy in the orbital environment from these resources.

1.1 Space Tethers

A space tether is a long thin structure that extends from an orbiting spacecraft such as a rocket, satellite, or space station. Typically, space tethers are greater than 1 km in length, but have been as long as ~20 km (19.7 km for the Tethered Satellite System reflight [1]) or as short as 1 m. Depending on the application, a tether can be designed to withstand high tensile forces, designed to be lightweight, of low volume with high surface area, and/or to be highly survivable.

There are three broad categories of space tethers: electrodynamic, momentum exchange, and formation flying [2]. The functions of the tether in these configurations are mechanical, electrical, or both. Mechanical tethers (momentum exchange and formation flying) physically connect two masses in orbit but do not necessarily have to be conductive. Electrodynamic tethers are conductive but also generally provide structural support, although strength may come from a material that is not conductive.

EDTs can be composed of any conductive material such as aluminum, which provides suitable

conductivity and low density, or copper, which provides higher conductivity per volume but at higher mass. The material can be single stranded, a porous tape, braided similarly to electrical wiring, or braided in an innovated lattice [3] to mitigate damage from micrometeoroids and orbital debris (MMOD).

2 Electrodynamic Tether Principles

The principles behind the operation of an orbiting EDT system are fairly straightforward. In general, EDTs possess three key properties [4]: 1) the wire has an intrinsic electromotive force (*emf*) generated along it due to the orbital motion of the tether, 2) the wire provides a low-resistance path connecting different regions of the ionosphere, and 3) access to external electron and ion currents is confined to specific locations, such as the endpoint when the conductor is insulated, or collected along a length of bare tether [5].

2.1 Lorentz Force

The first principle listed above, *emf* generation along the tether, results from the Lorentz force on the electrons in the tether as the system travels through the geomagnetic field. To determine the magnitude of this *emf*, we start with the Lorentz force equation for charged particles:

$$F = q(\mathbf{E} + \mathbf{v}_s \times \mathbf{B}), \quad (1)$$

where q is the charge of an electron, \mathbf{E} represents any ambient electric field (small), and $\mathbf{v}_s \times \mathbf{B}$ represents the motional electric field as the spacecraft travels at a velocity \mathbf{v}_s through the Earth's magnetic field, represented by \mathbf{B} . Eq. (1) can be rewritten as

$$\mathbf{F} = q\mathbf{E}_{\text{tot}}, \quad (2)$$

where

$$\mathbf{E}_{\text{tot}} = \mathbf{E} + \mathbf{v}_s \times \mathbf{B} \quad (3)$$

and represents the total electric field along the tether. In order to get the total *emf* generated along the tether, we must integrate \mathbf{E}_{tot} along the entire length of the tether, l . That is, the total tether potential is

$$\varphi_{\text{tether}} = -\int_0^l \mathbf{E}_{\text{tot}} \cdot d\mathbf{l} \approx -\int_0^l \mathbf{v}_s(l) \times \mathbf{B}(l) \cdot d\mathbf{l}, \quad (4)$$

which is negative since electrons in the tether are acted upon by the Lorentz force. Because the ionospheric plasma surrounding the EDT system is generally a good conductor, the ambient electrostatic field \mathbf{E} is small and is usually ignored, i.e., $\mathbf{E} \approx 0$. The tether potential is path independent assuming a conservative resultant electric field and steady-state conditions. Thus, φ_{tether} can be calculated knowing only the relative locations of the endpoints (separation distance and orientation) and does not depend on the position of the tether between the endpoints.

2.2 Interactions with the Space Environment

The second and third principles are related to current flow through the tether, which occurs when a connection is made between the tether's endpoints and the surrounding ionospheric plasma. This can be accomplished via passive or active means. In the passive case, the voltages and currents in the overall system distribute themselves in a self-consistent manner, which can require the endpoints to charge to high levels in order to attract enough current. Active means generally employ an electron generator of some type, such as an electron gun or hollow cathode plasma contactor. With either method, current flows through the tether as shown in Fig. 1. In the passive case, current flows up the tether because the resultant force on the electrons is downwards. After electrons are collected at the subsatellite, they are conducted through the tether to the spacecraft where they are ejected. Current closure occurs in the ionosphere, thus making the overall circuit complete.

If current flows in the tether element, a force is generated as given by

$$\mathbf{F} = \int_0^l \mathbf{I}(l) \times \mathbf{B}(l) \cdot d\mathbf{l}. \quad (5)$$

In self-powered mode (energy-harvesting or de-orbit mode), this *emf* can be used by the tether system to drive the current through the tether and other electrical loads (e.g., resistors, flywheels, batteries), emit electrons at the emitting end, and/or collect electrons at the opposite. In boost mode, on-board power supplies must overcome this motional *emf* to drive current in the opposite direction, thus creating a force in the opposite direction (see Fig. 1) that boosts the system. Thrust levels depend greatly on applied power and typically are less than 1 N.

3 Research Methods

Our research team is investigating EDT power harvesting and propulsion on spacecraft sizes from chip-scale systems ($\sim 1 \text{ cm}^2$), to the CubeSat platform ($10 \times 10 \times 10$ -cm cubes), to larger spacecraft ($> 100 \text{ kg}$). For these various spacecraft size ranges, we are evaluating energy storage capacity of the system using EDTs and the orbital potential as the "power generator", the feasibility of using an EDT as a propulsion device for the chip-scale spacecraft, and high power generation using long tethers on large spacecraft.

3.1 Software

We employ two software tools, TeMPEST (Tethered Mission Planning and Evaluation Software Tool) and TetherSimTM, to predict the induced tether voltages and collected tether currents of our system of interest. Over the years, TEMPEST has been used to study various tethered systems and support tethered satellite system development and has evolved to include the following features:

- Precision orbital propagator (with perturbations);
- Solar and magnetic indices prediction;
- Earth magnetic field model;
- Neutral atmosphere model (up to 1000-km altitude);
- Model of ionospheric densities and temperatures (valid in the altitude range 50 km to 2000 km);
- Simple tether libration forced harmonic mode;
- Induced electromotive force (*emf*) tether voltage model; and

- Tether current collection model for bare and insulated tethers with various plasma contactors.

TEMPEST is being updated to simulate and evaluate the performance of tether systems for power generation with a limited incremental software development effort.

TetherSim is a simulation toolset developed by Tethers Unlimited, Inc. over the past 12 years to facilitate design and analysis of space and terrestrial systems that involve tethers. TetherSim's key distinguishing feature when compared to TEMPEST is that it incorporates algorithms for simulating the dynamic behavior of a tether and the bodies connected to it. Consequently, where TEMPEST is more useful for rapid exploration of a wide engineering trade space, TetherSim is more suitable for detailed analysis of system behavior, operations, and effects on the host vehicle. The TetherSim code integrates models for orbital mechanics, tether cable dynamics, and spacecraft attitude dynamics with NASA-standard environment models such as the IRI ionosphere model, MSIS neutral density model, and the IGRF magnetic field model to enable simulation of a wide range of tether systems. TetherSim has been used to simulate electrodynamic drag/power generation tethers for spacecraft deorbit applications, electrodynamic propulsion tethers for orbital maneuvering [6], momentum-exchange tethers for orbit transfer [7], formation-flight using tethers, and towing of tethered sensors from aircraft. It has been validated against flight data from the Plasma Motor Generator (PMG) experiment.

4 Results

4.1 Energy Harvesting

Energy harvesting was considered for the CubeSat platform, which requires that the spacecraft must be no more than 4 kg (for a 3-unit configuration) [8]. Our design allows 1.33 kg (essentially 1 unit) to be allocated to electrodynamic energy harvesting. This allocation includes the tether, endmass, electron emitter, and other associated hardware.

System designers have a number of options when selecting the EDT itself. For certain applications such as energy harvesting, a bare tether will outperform one that is fully or partially insulated when in a high electron density plasma [9]. The opposite is true for lower electron densities where a

partially insulated tether is preferred. No insulating materials were considered for this study because of their added mass.

Two conducting materials have been considered so far: copper and aluminum. A low resistivity tether, such as copper, is preferred for optimum current flow, but is not always the best choice. For a CubeSat to harvest as much energy as high efficiency solar panels mounted on all six faces, a minimum of 1300 m of 25 AWG is needed. This amount of aluminum tether has a mass of 0.558 kg, whereas an equally long and thin copper tether would have a mass of 1.848 kg, already exceeding the 1.33 kg mass allocation limit. Therefore, aluminum was chosen for this study because of its relatively high conductivity and low mass. The tether composition is determined by the power needed for the mission and by mass limitations.

The total energy capable of being harvested depends on the system configuration. Longer tethers yield more power, but weigh more. Fig. 2 shows the relationship between tether mass and the total energy that can be harvested during one day. Data for both 24 and 25 AWG are shown to illustrate the benefit of using a thinner tether to harvest more energy for the same amount of mass. There is a crossover point at 0.558 kg, at which point the total energy from the tether is equal to the best-case scenario for solar panels. System designers can look at the mass allocation for the EDT and the power budget to choose a suitable length. This is the mass-to-total-energy trade-off.

If a hybrid system of EDT and solar panels is needed because the available power from solar panels is not sufficient for the application, then the mass (and therefore length) of tether could be chosen based on the energy deficit. For example, a mission that requires 1200 J/day would require either more solar panel surface area or an addition of approximately 0.50 kg of EDT, with supporting system mass.

4.2 Simulation of High Power EDT Power Generation

While analytical models can provide first-order estimates of the power generation or propulsion capabilities of an EDT system, the system's performance depends upon a large number of complex, interrelated phenomena, including the dynamic behavior of the tether system and the

highly nonlinear characteristics of the electrical connection between the tether and the varying ionospheric plasma. Consequently, in order to study the potential performance of an ED tether power generation system and its dependence upon system characteristics and orbital conditions, we utilized the TetherSim code (described above) to simulate an ED tether in power generation mode. The simulations were run using a tether with a length of 10 km and a conductor mass of 7.6 kg of aluminum. The system configuration used an insulated tether, with hollow cathode plasma contactors (HCPCs) at each end of the system to enable electrical connection to the ionospheric plasma. The tether was set into an initial orbit of 500 km, 28.5° inclination, and the *emf* induced in the tether was allowed to drive current along the tether and through a load impedance placed in series with the tether. Figure 5 shows plots of the voltage and power dissipated across the load, tether, anode HCPC, and cathode HCPC, as well as the overall efficiency of conversion of orbital energy to electrical power in the load. The plots show that the tether system can provide conversion efficiencies on the order of 80%. The power generated by the tether varies significantly over the course of each orbit. This variation is due primarily to the large variations in ionospheric plasma density around the orbit. On the eclipse side of the orbit, the low plasma densities result in large voltage drops developing between the anodic HCPC and the ambient plasma in order to collect the electron current from the ionosphere. Additionally, the power generated varies over the course of multiple orbits as the Earth's magnetic field rotates with respect to the orbit plane. However, unlike a solar cell based power system, the tether is able to provide power throughout the entire orbit. The 10-km-long tether can provide an average of 1 kW to the load. Fig. 3 shows the variation of peak, orbit average, and minimum power generation capability as the tether length is increased.

4.3 ChipSats and Nanospacecraft

The growing success of nanospacecraft over the past decade has generated interest in exploring the potential for even smaller spacecraft, both as stand-alone satellites or as a distributed *swarm* [10]. Because of advances in integrated circuit and microelectromechanical systems (MEMS) tech-

nology, the feasibility of miniaturized spacecraft at the levels of fully monolithic semiconductor integrated circuits (10–100 mg) or hybrid integrated circuits (10–100 μ g) is being seriously investigated [11, 12]. Effectively, this architecture can be thought of as a small “satellite-on-a-chip,” or ChipSat.

Flat ChipSat wafers suffer from an inherently high area-to-mass ratio. Although this feature can be exploited for new behaviors, it can result in an undesirably short orbital life in LEO due to atmospheric drag, ranging from a few days to a few hours. While a satellite using chemical propulsion can overcome the continuous force of atmospheric drag, the volume of propellant required will increase with the satellite's intended lifetime. Thus, the use of a traditional thruster with propellant and directed flow to compensate for drag and possibly for maneuverability would increase the size, mass, and complexity of ChipSats.

To counter the drag force, a short, semi-rigid EDT for propulsion is considered, which keeps the overall ChipSat mass low and provides enough thrust to overcome drag in LEO.

A study was conducted that analyzed the ability to draw current from the ionosphere and thus generate thrust and compared this to the tether mass and material, electron emitter and collector types, and needed power to determine EDT capability of overcoming atmospheric drag forces. The study led to the development of a system concept (see Tab. 1) and mission scenario using the TeMPEST simulation tool to estimate tether voltages and currents based on tether configuration and ambient models. The results reveal that an insulated tether only a few meters long and tens of microns in diameter can provide milligram to gram-level ChipSats with complete drag cancellation and even the ability to change orbit [13, 14].

5 Summary

An electrodynamic tether can be used by satellites to harvest energy from orbital potential by using the Lorentz force interactions with the geomagnetic field. The amount of energy that can be harvested depends on the length of the tether, the type of tether, and the configuration of the plasma contactors. Satellite size sets the bounds for the configuration of the EDT system and, therefore, the magnitude of the energy budget. Large satellites

have the potential to harvest as much as kilowatts at the load. Small EDT systems the size of CubeSats have the potential to produce more energy than mounted solar panels alone. EDT systems benefit very small, ChipSat-sized satellites by enabling them to maintain orbit without a significant contribution to the satellites' size and mass or the need for expendable propellant.

EDTs provide a unique solution to satellites' energy and propulsion needs throughout the size and mass spectrum of current and future technology. An EDT structure utilizes the resources available in orbit.

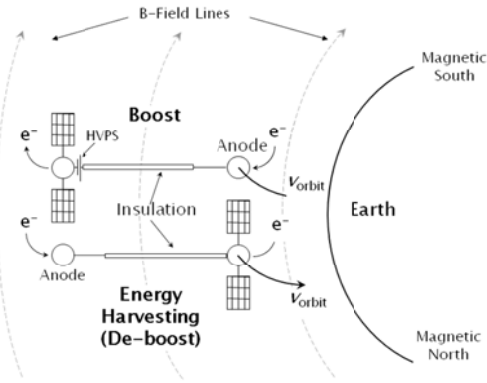


Fig. 1. EDTs can be used in an “energy harvesting” mode or a “boost” mode [9].

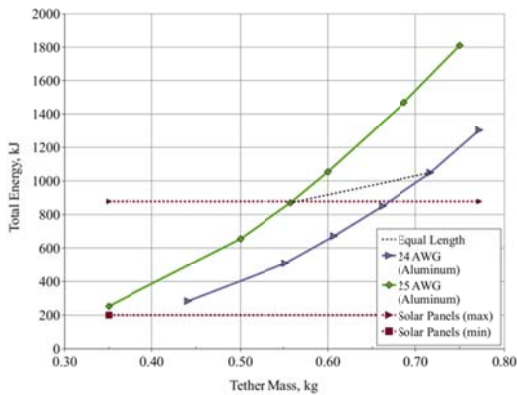


Fig. 2. Trade-off between total energy harvestable and tether mass

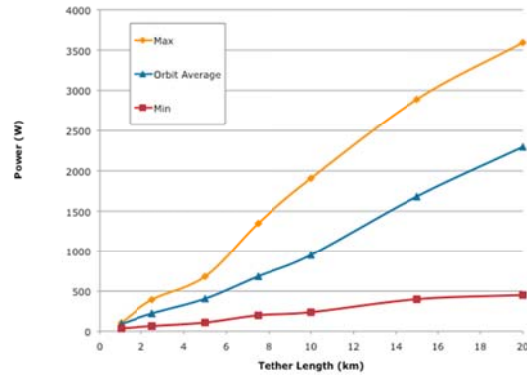


Fig. 3. Variation of power generated by an electrodynamic tether upon the tether length.

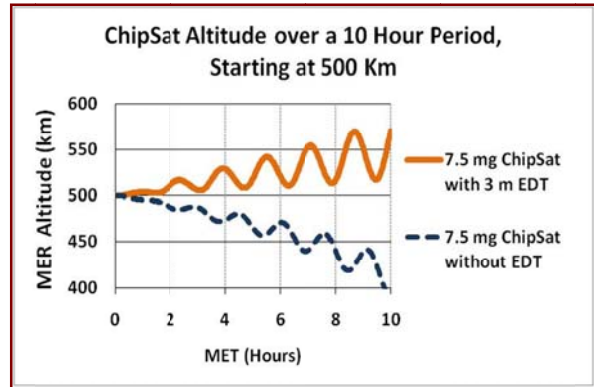


Fig. 4. TeMPEST simulation results of ChipSat orbit with and without the electrodynamic tether.

Tab. 1. Parameters for a ChipSat and miniature electrodynamic tether concept.

Parameter	Value
ChipSat Dimensions	7.5 mg, 1cm × 1cm × 25 μm
Altitude	500 km, circular orbit
ChipSat Orientation	“Ram”, i.e., large dimension perpendicular to velocity
Tether Width	~50 μm
Tether Current	~100 μA
Tether Resistance	~3 kΩ
Collector V_{bias}	+200 V
Electron Collector	6.6 mm diameter sphere

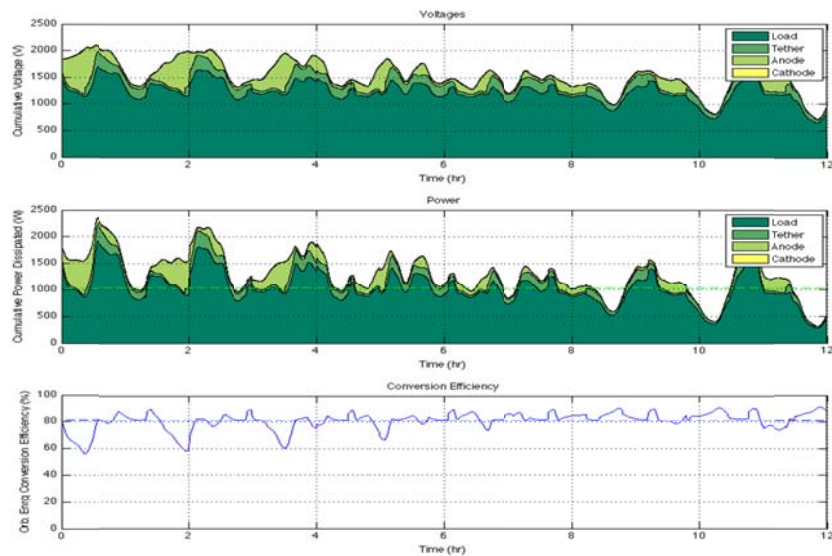


Fig. 5. Plots of system voltages, power, and conversion efficiency for a 10-km-long EDT system in a 500 km, 28.5° orbit, simulated over a half-day period using the TetherSim code [14].

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