Electrodynamic Tether (EDT)
Summary of Student Presentation

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Tether structures are presenting an inexpensive and innovative approach in space exploration. Yet, the underlying principles behind that technology rest on some basic laws of physics, like electromagnetic induction. This paper outlines the principles of tether structures and further on examines the Electrodynamic Tether or EDT. Finally, attention is given to presenting the vast application of EDT's in space transportation, low-gravity experiments, and interplanetary exploration.

Introduction

In their general structure, tether-systems in space consist of a long, tin, high-strength rod or cable and two masses at its ends. Variations of that scheme are possible, with three-bodies and other different geometrical configurations. The tether structure is taken to low Earth orbit (LEO) or geostationary orbit (GEO) by a rocket vehicle. Once deployed and fully expanded, the basic forces that act on the tether are the Earth's gravitation and centrifugal force.

Electrodynamic tethers have a conductive cable which gives rise to high-voltage electric currents induced by the magnetic field of the Earth. Ranging in mega Watts, that current can provide enough electricity to supply on-board instruments and even human missions. Additionally, induced currents produce electromotive force (emf) which for an orbiting tether is a source of drag. On the other hand, reversing the current in the tether alters the emf and creates thrust. What is considered to be the most important tether structure for space transportation is the so called momentum-exchange (MX) and more especially the MX – electrodynamic reboost (MXER). These kinds of tethers rotate around their center of mass and can serve for taking a payload (satellite, space ship) from LEO and literally "throwing" it into GEO or to interplanetary space without the use of any fuel for propulsion.

Since the mid- 1960s numerous experiments have been conducted in space in order to validate models of tether dynamics. Nowadays, NASA and other space administrations are developing tether systems to be deployed in the near future like the ProSEDS, mission scheduled for 2005. However, there exist several constructional problems which are yet to be tackled by engineers.

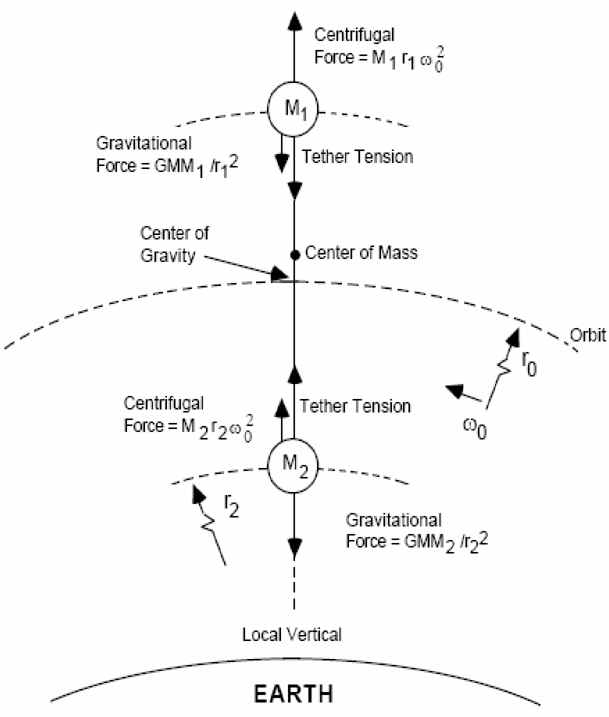

Figure 1 Forces on a "Dumbbell" tether system

Gravity gradient

This part of the paper is based on the fundamental forces experienced by the two-mass configuration tether – the so-called "dumbbell". Figure 1 shows the forces on such a configuration in orbiting velocity. It can be shown that a mass in orbit, connected to a tether has an orbital angular velocity in [s^{-1}] equal to:

$$\omega^2 = \frac{GM}{(r_0 + L)^3},$$

where L is the distance from the center of mass [m], r_0 the radius of the system's center of gravity from the center of the Earth [m], G = universal gravitational constant (6.673 x 10-11 Nm2/kg2) and M = mass of the Earth (5.979 x 1024 kg). Since the two masses are rotating around the Earth in different orbits M_1 experiences grater centrifugal and smaller gravitational force which is opposite to the situation of M_2. For the purpose of this discussion we can assume that the center of mass and the gravitational center of the system match. Furthermore, we can also consider that the two bodies are with equal mass and that the mass of the tether itself is negligible. The system in figure 1 is in a vertical position – the so called "local vertical". Any deviation of that alignment produces restoring forces (figure 2) and so the system will start librating as a pendulum until it is pointed back towards Earth. Deviations can occur due to contributions such as air drag, electrodynamic forces or solar heating.

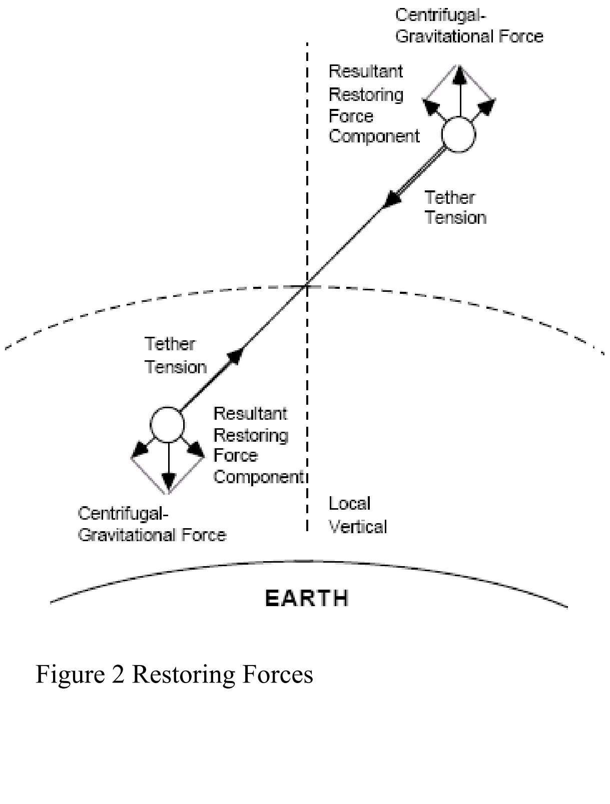

Figure 2 Restoring Forces

To approximate the value of the artificial gravity force for a body with mass *m* we can use the following relation:

$$F_{GG} \approx \pm 3Lm\omega_0^{\ 2},$$

where L is the distance from the center of mass [m] and; the plus goes for a mass above the center of gravity and minus for below.

Further on, tether system can be rotated to produce controlled gravity for a number of experimental purposes.

As we mentioned earlier in the discussion momentum exchange is one important aspect of tethers. To define angular momentum we can use the relation:

$$\vec{h} = m\vec{r} \times \vec{v} = mr^2\omega_0,$$

where h = angular momentum of system (kgm^2s^{-1}), m = mass of system (kg), r = radius vector from center of rotating coordinate system (Earth) to system center of mass (m) and v = velocity of system center of mass normal to r (ms^{-1}).

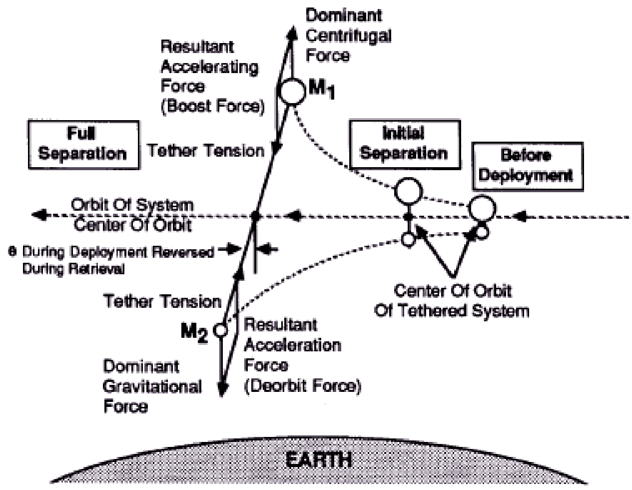

Figure 3 Tether Deployment

To illustrate momentum exchange we can consider a tether deployment situation. Initial stage begins with both masses slowly separating from each other until the length of the tether is sufficient for a gravity gradient and centrifugal forces to continue separation. If the two masses were not constrained by a tether, mass M_1 would acquire a lower orbital circular velocity and M_2 would obtain a higher orbital circular velocity in ther new orbits. Nevertheless, since the masses are constrained by a tether, they must move at the same orbital velocity. That is why M_2 will actually start "dragging" M_1. In this case, mass

M_1 gained angular momentum equal to an identical amount lost by M_2. This amount of angular momentum transferred is equal to:

$$\Delta h = M_1 V \Delta R_1 = M_2 V \Delta R_2 .$$

If the tether is cut after the separation is finalized M_1 will acquire elliptical orbit gaining energy and M_2 will be in the reversed situation. This maneuver can actually be deployed for the space shuttle (M_1) so that it can be boosted in higher orbit at the expense of the momentum of its empty reservoirs (M_2).

Electrodynamics

Essentially, the EDT is a vertical, gravity-gradient-stabilized, conducting tether. As it rotates around the Earth it sweeps through the lines of the magnetic dipole field. In that situation electromotive force (emf) is induced in the conductor which is given by the equation:

$$V = \int \left(\vec{v} \times \vec{B} \right) \cdot d\vec{l} \ ,$$

where V = induced emf across the tether length (V), v = tether velocity relative to the geomagnetic field (m/s), B = magnetic field strength (webers/m^2) and dl = differential element of tether length - a vector pointing in the direction of positive current flow (m). For the special case where the tether is straight and perpendicular to the magnetic field lines everywhere along its length, the equation for the emf simplifies to:

$$V = \left(\vec{v} \times \vec{B} \right) \cdot \vec{L} \ ,$$

where L is the current length.

Since the direction of the orbital velocity vector is orientated with an angle θ towards the magnetic field vector we can re-write the equation in the form:

$$V = LvB \sin \theta .$$

Therefore, we can see that low-latitude orbits produce the highest emf because field lines can be considered perpendicular to the tether. The electromotive force will be pointing opposite the orbital velocity vector, thus slowing down the tether and effectively bringing it to a lower orbit. As proposed by Cosmo and Lorenzini [3], for a system in LEO the tether ends are the places of interaction with electrons from the ionosphere (figure 4). A plasma contactor (essentially a metal sphere) at the upper mass gathers the electrons which then flow through the tether due to the potential difference and are ejected back at the lower mass by a hollow cathode or an electron gun. The whole circuit configuration is closed through the ionosphere acting like a second conductor linking both ends of the tether. What is important for sustaining the tether current is that current density at the ends does not exceed the external ionospheric current density.

Alternatively, if the tether configuration is retained and the current is reversed, by applying an external source (battery, solar energy) then we have an emf which is described by:

$$\vec{F} = \int \left(I d\vec{l} \right) \times \vec{B} = I \int d\vec{l} \times \vec{B} \ ,$$

where F= force exerted on the tether by the magnetic field (N) and I = tether current (A).

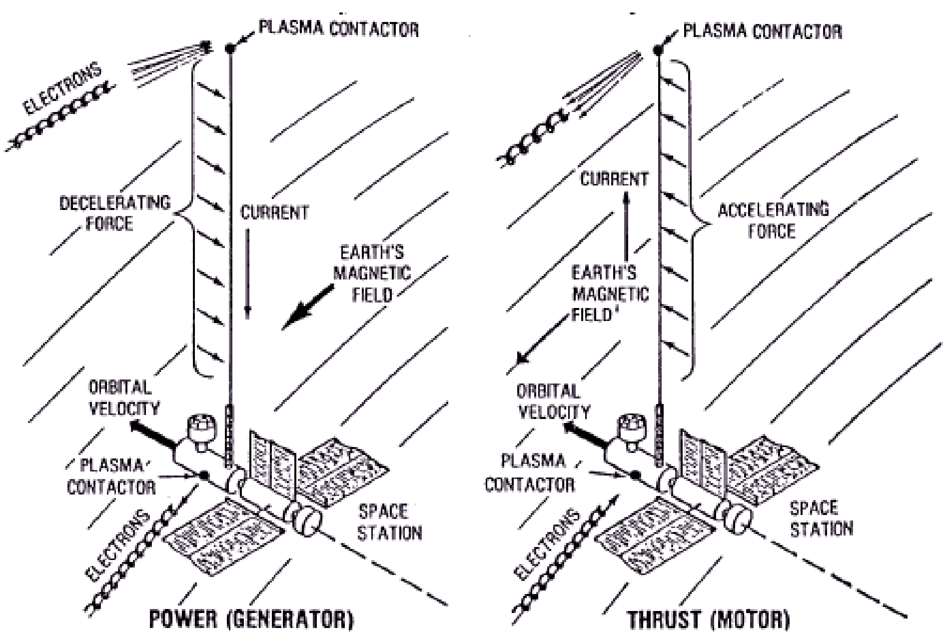

Figure 4 Power and thrust generators with an Electrodynamic tether

Analogically, in the case of a straight tether the emf is equal to:

$$F = ILB\sin\theta$$

The difference here is that the emf vector is parallel to the velocity of the system, thus acting like a thrust generator and effectively placing the tether at a higher orbit. The electron collection is in a reversed, but consisting of the same elements as in the first case. In figure 4 we can see an example of such an EDT. This thrust generation comes at the expense of the tether energy though, since it requires an external current source.

The basic equation of the current loop (circuit) is:

$V_{IND} = IR + \Delta V_{LOW} + \Delta V_{UP} + \Delta V_{ION} + \Delta V_{LOAD}$,

where V_{IND} = emf induced across the tether (volts), I = tether current (A), R = resistance of tether (Ohms), ΔV_{LOW} = voltage drop across the space charge region around the lower plasma contactor (volts), ΔV_{UP} = voltage drop across the space charge region around the upper plasma contactor (volts), ΔV_{ION} = voltage drop across the ionosphere (volts) and ΔV_{LOAD} = voltage drop across a load (volts).

The problem with EDTs is that ionospheric models are still not sufficiently exact, impedances of the charge regions around the tether ends are complex, nonlinear, and unknown functions of the tether current. The impedance of the ionosphere has not been clearly determined although is has been calculated that it is in the order of 1 to 20 Ohms.

Characteristic for a EDT system is that by modifying the emf at appropriate moments it is possible to manipulate all of its orbital parameters and not only the radii (figure 5). We have to note that EDTs can only be positioned above a minimum altitude of roughly 300 km, because aerodynamic drag may approach or exceed the thrust, while above 600-1200 km (depending on the 11-year solar activity cycle) low plasma density seriously limits electron collection and hence thrust.

Summary of past missions [7]

Many short and long tethers have flown in space. There have been both manned experiments

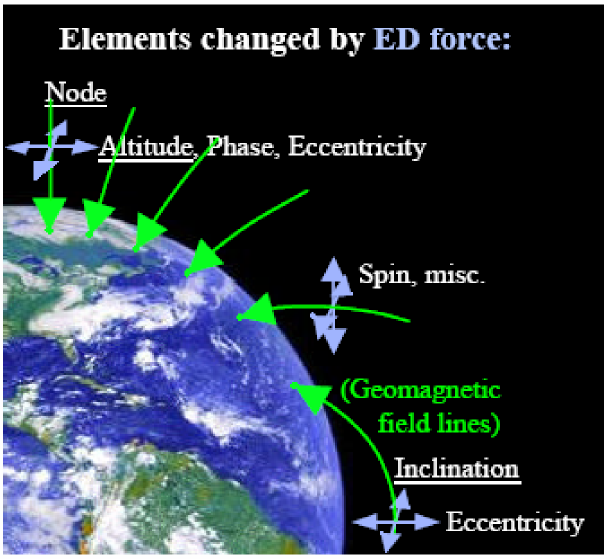

Figure 5 Possible ED Thrust Vectors vs. Latitude

Gemini XI and XII deployed 30-meter tethers between the Gemini and the Agena stages they docked with), and unmanned ones (mostly sounding rocket tests involving wires <1 km long).

The first long tether experiment in orbit was TSS-1, flown on the Space Shuttle and deployed in early August 1992. This was a large and complex system. The deployer jammed after 1% of the tether deployed, due to mechanical interference caused by late hardware modifications. The successful long orbiting tether experiments have mostly involved SEDS, which Tether Applications developed under NASA MSFC funding. SEDS-1 was a secondary payload on a Delta II/GPS launch on 29 March 1993. SEDS-1 deployed a 26 kg mass on a 20 km long non-conducting tether, and released them into a controlled reentry trajectory.

Three months later, NASA JSC's Plasma Motor Generator (PMG) flew on another Delta/GPS. It deployed 500 m of insulated 18 AWG copper wire from a SEDS-like deployer developed by Tether Applications. PMG demonstrated current flow both with and against the motion-induced voltage, using hollow cathodes at each end of the tether to create "plasma balls" to couple to the ambient plasma.

A third Delta/GPS secondary payload, SEDS-2, flew in March 1994. It demonstrated that the simple SEDS deployer could stabilize a 20 km tether very close to vertical (i.e., a residual swing amplitude of only 4^o). The end-mass and 2/3 of the tether separated 4 days after deployment, apparently due to micrometeoroid impact. The remaining 7 km length of tether survived for another 53 days until stage re-entry, without another length change being observed visually or by unexpected changes in orbit decay rate. Under good viewing conditions, the 0.8 mm diameter braided white SEDS-2 tether was surprisingly visible from the ground, from distances up to 1000 km. Amateur observers obtained videos of about 20 viewing passes during the SEDS-2 mission. The tether remained close to the vertical throughout the 6-week period when dawn or dusk views were available in the US.

The TSS was re-flown on the shuttle as TSS-1R in February 1996. The tether deployed to a length of 19.7 km without problem, but then an intermittent arc started from the deploying tether to the deployer hardware. As the arc moved away from the deployer, it continued directly to the ambient plasma. The arc burned through the tether in ~10 seconds. Data sent back by the now-free satellite showed that the arc continued for ~1 minute after separation, and then stopped near the time the satellite went into eclipse.

In June 1996, the Naval Research Lab deployed the "Tether Physics and Survivability" (TiPS) flight experiment. TiPS was a 2 mm diameter, 4 km long non-conducting SEDS tether launched into a 1024km circular orbit. TiPS has traveled a billion miles in 7 years without being cut by micrometeoroids or orbital debris. Tether Applications designed the TiPS tether for enhanced impact resistance, using highstrength Spectra braided around a puffy acrylic "sweater yarn" core.

In 1999 NRL launched the Advanced Tether Experiment (ATEx). ATEx was intended to deploy a 6 km long fiber-reinforced plastic tape and test active libration control. ATEx ended early when optical departure-angle sensors indicated a large bend in the tape, seconds after the 20m length of deployed tape came into the sun. ATEx automatically ejected itself from the host spacecraft to keep the tether from fouling on the host.

The ProSEDS experiment (for "Propulsive SEDS") was designed to verify that electrodynamic forces could cause observable reductions in the orbit altitude of the Delta/GPS second stage launching it. The ProSEDS experiment will start with ejection of a 20 kg student satellite called Icarus. Icarus is ejected energetically enough to pull out the first ~1 km of a 10 km non-conducting "pilot" tether. Then gravity gradient forces are enough to deploy the rest of the pilot tether and then a heavier 5 km wire. The wire consists of 7 strands of AWG 28 aluminum wire twisted around a braided Kevlar core. ProSEDS is currently scheduled for launch in 2005.

This tether flight experience highlights some of the practical problems of tethers. TSS experienced both jams and arcing failures during its 2 deployments. In addition, two SEDS experiments have been scrubbed shortly before flight due to potential impact risks with high-value spacecraft. There are also issues specific to ED tethers, including limitations on available ED thrust direction from the magnetic field, tendencies toward dynamic instability.

Conclusions

The development of tethers is currently limited by material strength, cost and numerous engineering problems. Still, there is no doubt this technology is going to be the leading one in all kinds of space exploration. That is why international work and cooperation in designing and testing tethers in space should follow a steady pace and soon solve most of the challenges ahead.

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