Space tethers: an overview.

Luciano Iess
Dipartimento Aerospaziale, Universita' "La Sapienza", via Eudossiana 16, I-00184 Roma
Tel. +39-06-57174422, fax. +39-06-44585670, iess@hermes.ing.uniroma1.it

Abstract. Long conductive tethers orbiting around the earth or any other planet with a magnetic field develop a large potential difference between the two ends. Charging therefore occurs, and in the presence of an ionosphere significant current may flow through the wire. This basic fact can be exploited for a variety of applications, ranging from propulsion (both de-orbiting and re-boosting) to onboard power generation and scientific investigations. This brief tutorial addresses the fundamental principles of electrodynamic tethers, along with its enabling technologies, and presents past missions and future applications.

1. *How do electrodynamic tethers work*? The idea of space tethers started from the pioneering work of G.Colombo and M.Grossi more than three decades ago (see for example Grossi and Colombo, 1979, with earlier references therein). In the frame of reference of a typical satellite in low earth orbit (LEO) an electric field of about 0.2 V/m develops as a consequence of the motion in the earth magnetic field. For most satellites and structures this field has little effect, but for an electrodynamic (ED) tether (of length L) crossing the magnetic field lines at velocity $\vec{v}_o$ the potential difference

$$\Delta V = \int_0^L \left(\vec{v}_o \times \vec{B}\right) \cdot d\vec{l} \qquad (1)$$

is large. The tether acts therefore as an unipolar generator. Depending on the relative geometry of the three intervening vectors ($\vec{v}_o$, $\vec{B}$ and $\vec{L}$, assuming a rectilinear tether) such a potential difference may amount to several kilovolt for lengths of the order of 10-20 km. Note that what matters is the relative velocity between the orbiting conductor and the magnetic field lines. In the case of LEO orbits, the orbital velocity is much larger than the velocity of the magnetic field lines (in the inertial space), so that $\vec{v}_0$ very close to the orbital velocity. In the case of a tether in the Jovian system the situation is reversed: as Jupiter is a fast rotator (the period is only 10 hours) with a strong magnetic field, the velocity of the magnetic field lines exceeds the orbital velocity, so that $\vec{v}_0$ has opposite sign and is typically much larger than in the terrestrial case.

In the absence of an ambient plasma, the only effect would be an internal redistribution of charges so to ensure a null electric field in the conductor. The presence of an ionosphere and the consequent availability of free electrical charges permits the onset of a sustained current flow from the space environment through the tether. It is this interaction between the generator and the external, magnetized plasma which bears most of the scientific and technological interest.

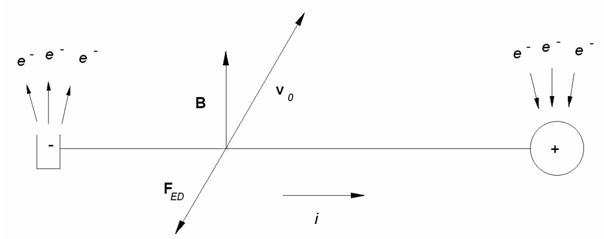

Fig. 1. *A tether in a prograde orbit attracts electron at its upper termination. Those electrons are then emitted by an active device at the lower end.*

The magnitude of the current drawn from the ionosphere depends of course on several factors, notably the electrical characteristics of the tether (electrical resistance, insulation, geometry), the density and temperature of the plasma and the available potential difference across the tether. In the simplest case (although not the most interesting one) one may consider an insulated tether which exposes its two terminations to the ambient. In order to ensure a significant current, the two ends need to be augmented by some type of device (passive or active) capable of establishing a good electrical contact with the ionosphere. This can be a rather large collector at the positive termination (to collect electrons) and some kind of active device (such as an electron gun or a plasma contactor) at the other end. This configuration was chosen for the Tethered Satellite System (TSS-1 and TSS-1R) launched by NASA and the Italian Space Agency in 1992 and 1996. Due to the large available potential difference, sheaths develop at the two ends, each one modeled by a characteristic law $V_\pm = V_\pm(i)$. For a tether of resistance R_T the total current results from the equation

$$\Delta V - R_T i = \Delta V_+(i) + \Delta V_-(i) + \Delta V_i(i) \qquad (2)$$

where the e.m.f., decreases by the closed circuit ohmic loss in the tether, is balanced by the voltage drops across the two sheaths (at the positive and negative ends) and in the ionosphere (ΔV_i). If one wishes to maximize the current, all intervening impedances (and the ohmic resistance of the tether itself) must be minimized. Were the sheath and ionospheric impedances negligible, the maximum current would be $i_{\max} = \Delta V / R_T$. In the case of the TSS ($R_T = 260\Omega$, ΔV up to 5 kV), $i_{\max} = 19$ A. In practice much lower currents can be achieved, as the sheath impedances dominate. As efficient plasma contactors are available, the cathodic termination can usually be kept to a potential very close to that of the unperturbed ambient plasma. Also, the impedance of the ionosphere is very small (ΔV_i negligible) and ultimately what matters is ΔV_+, which is usually large. For a tether in a prograde earth orbit, the anodic termination is found at the far end (higher altitude).

In the last decade the concept of insulated tethers has gradually been abandoned in favor of uninsulated, bare wires, which combine higher currents with a simpler structure. In bare tethers charge collection occurs along the whole conductor and the current is a function of the distance from the terminations. Eq. 2 becomes now a differential relation involving the local tether potential V_t with respect to the plasma, which controls the current drawn by each infinitesimal tether element of length dl:

$$dV_t = \frac{\Delta V}{L} dl - dR_t i(l)$$
$$i(l) = \int_0^l di(V_t) \qquad (3)$$

The first relation is nothing but the Ohm's law, simply stating that the potential drop dV_t across an element dl is the motion-induced potential drop diminished by the local ohmic loss. The integral relation gives (formally) the current at a distance l as the sum of all infinitesimal contributions coming from each tether element dl. In the orbital motion limit (OML), the solutions of eqs. (3) can be expressed in closed form (Sanmartin et al., 1993).

But how does the circuit close outside the tether, in the ionosphere? Two fundamentally different mechanisms have been proposed, involving respectively a remote and a local closure. Let us consider the simpler case of an insulated wire in electrical contact with the ionosphere through its two ends. In the remote closure mechanism each magnetic tubes connected to the two ends provide the geometrical path for the ionospheric current. In this simplified picture the ionosphere is approximated to a medium whose conductivity is very large along B and almost zero across it. The two magnetic tubes are kept at a different potential by the motional electric field. Deep in the ionosphere, in the E-layer, the conductivity tensor changes and Pedersen and Hall currents can finally establish the electrical contact between the tubes connected to the upper and lower end of the tether. Of course, the transit time of the tether ends (of size D) across the magnetic field lines is generally small (just 10^{-4}s for a 1m collector), so that actually current pulses propagate along B, likely in the form of ion acoustic waves. Larger collectors may actually excite lower frequency Alfven waves.

The second closure mechanism involves only local currents. The necessary cross-field currents are carried by plasma waves propagating near the tether, such as whistlers. The interesting wave vectors are those forming a rather large angle with the magnetic field, as in this case the waves propagating from each termination can interfere at a relatively short distance from the tether, effectively closing the circuit. Although this interesting mechanism has been observed in laboratory experiments (Stenzel and Urrutia, 1990), whistlers are not the only waves capable of providing local closure. Lower hybrid waves have also been suggested in connection to local closure. Not only lower hybrid waves propagate across magnetic field lines, but also the characteristic excitation time of a magnetic field line by the tether termination ($\tau \approx D / v_o \approx 10^{-4}$ s) is close to the typical period of those waves.

2. The dynamics of conductive tethers. Most of the technological interest of electrodynamic tethers arises from their possible utilization in space propulsion. The interaction of the current with the earth magnetic field results indeed in a force

$$\vec{F}_{ED} = \int_0^L i(l)\left(d\vec{l} \times \vec{B}\right) \qquad (4)$$

which may be quite significant. For a uniform 1A current and a 10 km tether orbiting in LEO, $\vec{F}_{ED}$ may be as large as 0.3N. As this force is a continuous one, its action results in large momentum transfer and significant changes in the orbital elements. To be effective, however, the magnetic field must not be parallel neither to $\vec{v}_o$ nor $\vec{L}$, a condition which makes tethers much less efficient in polar orbits. The most significant effect is of course on the semimajor axis a, whose variation with time is controlled by the mechanical power

$$P = \vec{F}_{ED} \cdot \vec{v}_o = \dot{E}\,, \qquad (5)$$

equal (and opposite) to the rate of change of the orbital energy E. The power P is obviously equal to the power dissipated in the system (by ohmic losses), which in turns amounts to $i\Delta V$ for an insulated wire. This quantity can easily reach several kilowatts for a typical 10km tether. For a virialized system $E = -(1/2)GMm/a$, and decay (or re-boost) rates

$$\dot{a} = -2a\frac{P}{E} \qquad (6)$$

as high as 0.9 m/s/(W/kg) can be attained. Just to give a crude estimate, this implies that a 1000 kg mass tether system dissipating 1 kW achieves a vertical velocity as large as 80 km/day.

Whether the system undergoes a re-boost or a de-boost is determined only by the sign of the mechanical power P. In eq. (4) the sign of the electrodynamic force depends of course on the relative geometry of the vectors $\vec{v}_o$, $\vec{B}$ and $d\vec{l}$. We have already seen that for a LEO system $\vec{F}_{ED}$ is a drag force opposite to $\vec{v}_o$, causing the decay of the semimajor axis and ultimately the re-enter in the atmosphere. Orbital angular momentum (proportional to $\sqrt{a}$) has been transferred to the earth through the interaction with the magnetic field. Let us consider now a tether orbiting beyond the geosyncronous orbit and forget for a moment that $\vec{F}_{ED}$ would be very small. The sign of $\vec{v}_o$ is now reversed (opposite to the orbital velocity, as the tether lags the magnetic field lines) and so are the induced electric field and the current. Now the net force on the tether is therefore a thrust which causes an increase in the semimajor axis. Angular momentum is now transferred from the earth to the tether. The case of a tether orbiting Jupiter is also particularly interesting. As the planet is a fast rotator (the period is just 10 hours) the magnetic field lines are almost always faster than the tether. The net electric field is such that the upper part of the tether is negatively polarized (again for a prograde orbit), leading to a net thrust force.

The above considerations apply to a system in which the potential difference across the wire is not actively controlled by an external power generator. Of course an external source of energy, provided for example by solar panels, would allow to regulate the emf and eventually reverse the sign of the current and the electrodynamic force as well. An external power generator transforms the tether into a true space propulsion system. Of course achieving a given vertical velocity requires a larger power in re-boosting than in de-boosting, as in this case one needs first to reverse the naturally occurring voltage drop. As we have seen, in large current applications the required power may be quite significant.

The electrodynamic force may have important effects not only on the orbital dynamics of the system, but also on its attitude, and in this case the consequences may be catastrophic. In the absence of current, the tether is stabilized along the local vertical by gravity gradient. The center of gravity (nearly coincident with the center of mass for the lengths under consideration) moves along a keplerian orbit. Tidal force and tether tension are balanced everywhere. The upper mass rotates faster than a free flying mass at that altitude and is therefore subject to a centrifugal acceleration larger than the gravitational one. The opposite is true for the lower mass. Much like a pendulum, however, the tether can oscillate (librate) about its equilibrium position if external disturbances occur. In the limit of small oscillations, the Euler equations can be linearized, making the analysis particularly simple. The tether librates as a rigid dumbbell and the two rotational degrees of freedom (corresponding to in-plane and out-of-plane motions) are decoupled, with natural frequencies respectively equal to $\sqrt{3}n$ and $2n$ (n being the mean motion; Beletzky and Levin, 1993).

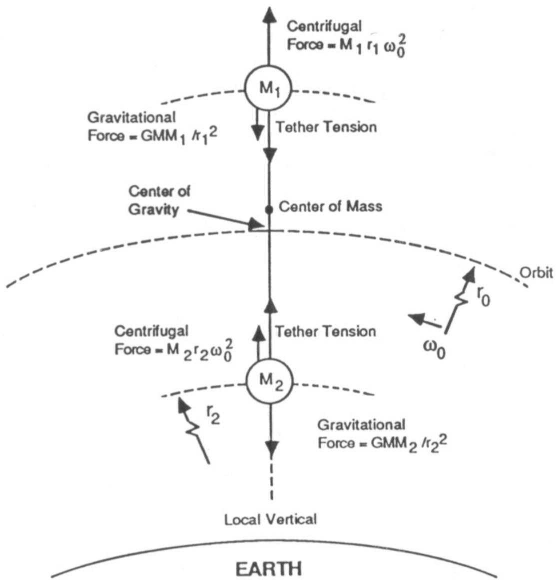

Fig. 2. The forces acting on a tether system. ω_0 *is the orbital angular velocity.*

When the electrodynamic force acts on a tether, its effects are twofold. Being orthogonal to the line element $d\vec{l}$ (eq. 4), the force bends the wire. More important, however, is the resulting torque, which tends to displace the system from the local vertical. If the electrodynamic torque is comparable or larger than the gravity gradient torque, the tether may go slack and flip its orientation, an event which must of course be avoided. The risk is even bigger as the electrodynamic torque is not constant. Indeed, even if the current were kept at a fixed value along the orbit (by means of an active control, of course), the magnetic field would change its orientation with respect to the tether, giving rise to a periodic, forcing torque. In a system where the current is determined by eq. 4, additional modulations come from the time varying plasma density and temperature. In general a forcing torque can have deleterious effects on the attitude dynamics and need to be carefully analyzed. The main source of instability comes from the large quadrupole term of the earth magnetic field, which induces a modulation of the torque at a frequency very close to the out-of-plane libration frequency (it is not exactly $2n$ due to the earth rotation). A resonance then occurs, which may soon induce tumbling if the system is not appropriately designed.

3. Charge collection by electrodynamic tethers. The use of tethers as propulsion systems requires large currents. The charge collection process from the ambient plasma is of course made easier by the large potentials developing across the tether, but when the plasma density is low (at high altitudes or nighttime), a strong decrease of the current has to be expected anyway. The need to ensure large currents entails the solution of two problems: a) how are charges collected by bodies at large potentials and b) how can the electrical contact between the system and the ionosphere be enhanced. The solutions to both problems require a combination of theoretical analysis, experimental work and technological developments.

Let us consider first the case of a large spherical collector positively biased with respect to the plasma. This was the case of the Tethered Satellite System (TSS) flown in 1992 and 1996 (see Sect. 5), where a 0.8m radius satellite (equipped with scientific instrumentation) was attached at the upper end of a 20 km wire. Larger collectors (realized by means of inflatable structures) are also currently being considered. The main limitation to electron collection by such structures is the smallness of the thermal current density $J_o = (1/4)en_o v_e$, where n_o is the unperturbed plasma density and $v_e = (8kT_e / \pi m_e)^{1/2}$ the electron thermal velocity. In the most favorable ionospheric conditions J_o does not exceed 16mA/m^2, so that effective collecting areas of the order of 100 m^2 would be necessary to provide currents of 1-2 A. Another limitation arises from the smallness of the electron Larmor radius r_e (typically 3cm) and Debye length λ_D (ranging from 1mm to 1cm in the earth's ionosphere), which determines an effective shielding of the collector's potential.

The simplest models of charge collection in the large potential regime assume that the particle motion in the sheath is collisionless. All these models neglect also the actual motion of the collecting body in the plasma, whose velocity is intermediate between the ion and electron thermal speeds ($v_i << v_o << v_e$). In the absence of a magnetic field and for large potentials), the current-voltage (I-V) characteristic follows the Alpert law (Alpert et al., 1965)

$$\frac{i}{i_o} = 1.5\left(\frac{eV_+}{kT_e}\right)^{6/7}\left(\frac{\lambda_D}{R}\right)^{8/7} \quad \text{if} \quad \frac{eV_+}{kT_e} > \left(\frac{\lambda_D}{R}\right)^{-4/3} \qquad (7)$$

$i_o = 4\pi R^2 J_o$ being the thermal current collected by a sphere of radius *R*. For a probe of radius 1m, the regime of applicability of the model starts at potentials exceeding by a factor at least 500-1000 the thermal potential kT_e / e. For larger bodies the relevant potentials become quite substantial. Note also that as the probe dimension grows, the collected current in a collisionless sheath must approach the thermal current, as the thin sheath approximation applies. The gain factor entailed by eq. 7 allows also to define a nominal sheath thickness $R_{sh} \approx R\sqrt{i/i_o}$, which in the case of the TSS may reach 2-3m for $V_+ \approx$1-2 kV.

The Alpert model has received some confirmation from TSS data (see fig. 3), as the I-V characteristic follows rather closely eq. 7. However, alternative explanations have been proposed and the available data are not conclusive. The physical mechanism underlying the charge collection process has still to be considered an open question.

The other collisionless model applicable to probes at large potentials attempts to include magnetic field effects (Parker and Murphy, 1967). The magnetic field introduces an axial symmetry and channeling effects are to be expected. In the absence of collision, a particle accelerated toward the central body conserves its energy ε and canonical angular momentum *J*. By combining the energy and angular momentum equations, an effective potential *W* appears. Introducing cylindrical coordinates, it can be shown that, given ε and *J*, the particle is allowed to occupy only the region of space for which $W(d,z) < \varepsilon$. This region has the shape of a magnetic bottle. If a particle lies in a bottle connected with the central body, it will eventually be collected, thus contributing to the current. The crucial quantity determining the enhancement over the thermal current is of course the bottle's radius at infinity. This quantity, which depends of course on V_+, *R* and *B* (or, equivalently, the electron cyclotron frequency Ω_e), determines the desired characteristic law, which turns out to be

$$\frac{i}{i_o} = \frac{1}{2} + \left(\frac{2eV_+}{m\Omega_e^2 R^2}\right)^{1/2} . \qquad (8)$$

The TSS data are in rather striking disagreement with Parker and Murphy's law (Thompson et al., 1998; Vannaroni et al., 1998). The measured currents are generally a factor of three larger than the model's prediction, although the $V^{1/2}$ dependence fits rather well the experimental points.

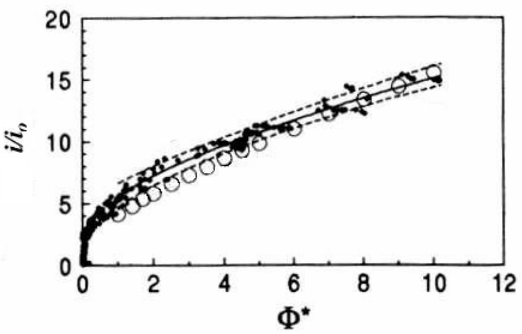

Fig. 3. The experimental I-V characteristic of the TSS satellite, in terms of the normalized potential $\Phi^* = eV / kT_e (\lambda_D / R)^{4/3}$ *and normalized current* i / i_o. *The solid dots are the data points. The circles show the fitting Alpert curve.*

Among the attempts to find a good physical reason for the missing scale factor, the conjecture of particle heating in the presheath looks particularly attractive. Indeed, it is not unlikely that a temperature increase occurs, as a consequence of the onset of waves and instabilities. Random fields developing in the sheath can strongly interact with the streaming particles and lead to anomalous viscosity. As a net effect the ordered, collisionless motion is destroyed and particles gain thermal energy. Some confirmation for this mechanism comes again from the TSS data (see fig. 4). The wave sensors recorded electrostatic random fields with rms value up to 12 V/m when the potential of the satellite was 190 V (later the sensors went into safe mode after a large charging event). The peak frequency occurs in the lower hybrid region, making particle heating even more likely (Iess et al, 1998).

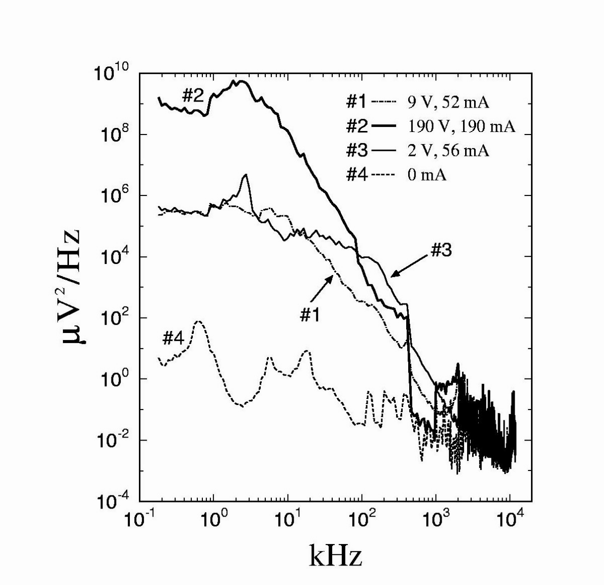

Fig. 4. Power spectra of the electric field recorded by the RETE (Research on Electrodynamic Tether effects) wave sensors in the plasma sheath of the TSS satellite, under different voltage and current levels.

Spherical collectors are severely limited in their capacity to draw electron currents from the ionosphere by the difficulty in achieving large effective collection areas. In both Alpert and Parker&Murphy models the current varies more or less linearly with the radius of the collector. However, large bodies and large potentials are needed to attain the levels required by propulsive applications. A clever workaround to these limitations exploits the tether itself as a collecting body (Sanmartin et al., 1993). The basic idea is that, even if the radius ρ of the cylinder is small, large effective collection areas are attained thanks to the huge length of the body (at least as compared to λ_D and r_e). A cylinder has the same geometrical surface of a sphere if $\rho = 2R^2 / L$, so that typical space tethers need very small diameters (typically below 1 mm) to be as effective as relatively large end collectors ($R \approx 1-5\,\text{m}$). The charge collection by a thin bare wire (of radius smaller than $4\lambda_D$) occurs in a regime limited by orbital motions (OML), with considerable simplification of the theoretical analysis. The particles cross the thick sheath without collisions, conserving energy and angular momentum, with negligible limitations by the external magnetic field. The current gain by a section of the wire at a potential V follows from classical probe theory:

$$\frac{i}{i_o} = \left(\frac{4eV}{\pi k T_e}\right)^{1/2} . \qquad (9)$$

Of course the potential changes along the wire and so is the current, but in general one has the scaling $i \sim L^{3/2}$, a more favorable dependence with respect to spheres ($i \sim L^{6/7}$ in the Alpert model and just $i \sim L^{1/2}$ according to Parker and Murphy). It must be noted however that large spheres still show some advantages when the plasma density is low. While the current decreases linearly with density for bare tethers, spheres preserve (at least in the Alpert model) their ability to collect charges, as a consequence of the increased Debye length.

4. Electron emission. Conductive tethers would be a very simple and efficient propellantless propulsion system were not for the problem of grounding the cathodic termination to the ambient plasma. In the case of a bare wire the electron current at the anode could be balanced by an equivalent ion current collected from the section biased negatively with respect to the plasma. However, as the velocity of the ions in the tether's frame of reference is much smaller than the electron thermal speed, this current would be very small and most of the tether would become negatively polarized. Fortunately simple and effective devices able to ensure adequate electron emission at the negative end have been developed and successfully tested in space, thus overcoming the inherent inefficiency of the ion collection process.

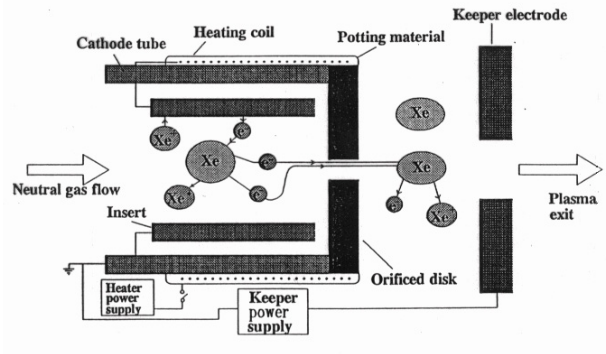

Fig 5. Schematic layout of a hollow cathode using Xe gas.

The simplest device for generating dense plasma clouds is probably the hollow cathode (fig. 5). A flow of tenuous neutral gas (typically Argon or Xenon) is maintained through a short pipe, internally coated with a low work function material. The discharge is started from some initial ionization in the neutral gas induced by thermoionic emission from the heated insert. The negative sheath which develops at the walls enhances the thermoionic emission, so that the electrons achieve larger energies and are more effective in ionizing the neutral gas. The electrons generated by the ionization are then forced through an orifice by the electric field sustained by an external anode, called keeper (usually a drilled plate). Part of the ions resulting from the ionization of the neutral gas are accelerated toward the negative insert, which is therefore heated without the need of an externals energy source. After the initial warm-up (requiring an external power source of the order of 50-70 W), the discharge process becomes self-sustained ant the power supply is needed only to maintain the potential difference between the keeper and the cathode.

The hollow cathodes can provide large currents (up to 10 A) and space qualified devices are available on the market. Their use with space tethers has been demonstrated in 1993 by the Plasma Motor Generator (PMG) experiment (Cosmo and Lorenzini, 1997, p. 21), made up by a 500 m tether connecting the second stage of a Delta II with an end platform (both equipped with hollow cathodes). The I-V characteristics are usually determined experimentally (see fig. 6), but a semi-empirical exponential law fits rather well the data point in the region of interest and can be used in eq. 2 to determine the tether current (Vannaroni et al., 1992).

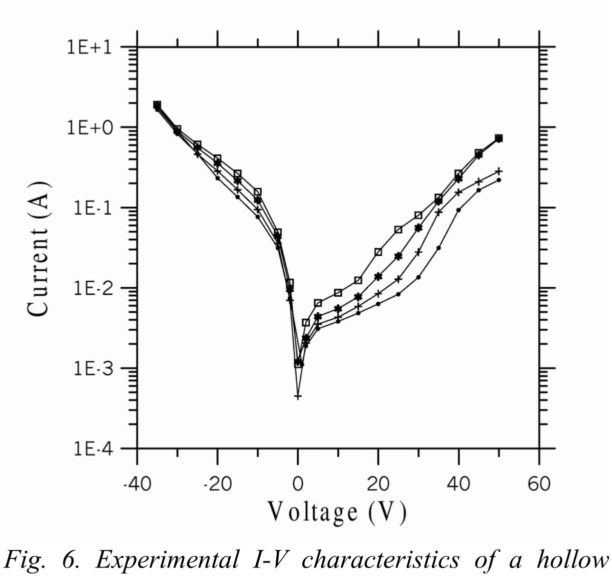

Fig. 6. Experimental I-V characteristics of a hollow cathode, under different external magnetic field.

Hollow cathodes are low impedance devices and are therefore particularly attractive for propulsive applications. The dense plasma cloud they emit creates a good electrical contact with the ionosphere, effectively grounding the negative tether termination to a potential very close to that of the ambient plasma. Indeed, hollow cathode neutralizers have been widely used in space to prevent satellite charging, also in connection to the use of electric propulsion systems.

Drawbacks of hollow cathodes are the need of consumables (the neutral gas sustaining the discharge) and power. A new type of device overcoming these difficulties and well suited to space operations has recently received considerable attention. The field emitter array cathodes (FEAC) exploit the large electric field generated between micron size cones and an anode (fig. 7). The manufacturing process relies upon precision machining of semiconductor wafers, which allows to reach tip densities up to $10^6/cm^2$. Laboratory experiments have demonstrated that each tips can emit up to 1mA with polarization voltages of about 100-200 V in high vacuum. In the ionospheric environment the emission would be considerably lower, but even with 1μA per tip a small surface would emit substantial currents. Although the required polarization voltages are a significant fraction of the available e.m.f, FEACs do not need consumables and are purely passive devices. In combination with the very low mass and size, these features make them extremely attractive for space applications.

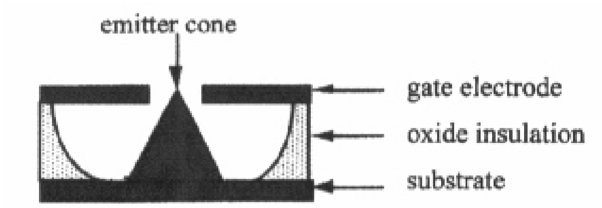

Fig. 7. Layout of a FEAC. Up to 10^6 tips can be accommodated in a 1 cm^2 silicon wafer.

5. The Tethered Satellite System. Although several space missions involving tethers have flown in the past decade (see, for example, the comprehensive Tether Handbook, Cosmo and Lorenzini, 1997), by far the most ambitious one was the Tethered Satellite System (TSS), jointly developed by NASA and the Italian Space Agency. The TSS was deployed twice from the Space Shuttle, in August 1992 (TSS-1) and February 1996 (TSS-1R, the “R” meaning “re-flight”), in a nearly circular orbit at 270 km altitude, 28 degrees inclination. Both missions were ill-fated, as failures of different nature prevented the full accomplishment of the scientific objectives. Nonetheless these missions, the second one in particular, have provided a wealth of data on the dynamics and electrodynamics of tethers, establishing a solid ground for future applications.

The TSS was made up by three elements: 1) a deployer (2027 kg mass), hosted in the Shuttle’s cargo bay, which included a 12 m deployable boom and a drum for the reeling and unreeling of the tether; 2) a 22 km length, 280 kg mass cylindrical cable (2.54 mm diameter, 260 ohm resistance) and 3) a 518 kg, 0.8 m radius spherical satellite, accommodating 68 kg of scientific instrumentation. Ten scientific investigations involving hardware both on the orbiter and the satellite were selected for the monitoring and control of crucial quantities (see for example Dobrowolny and Stone, 1994, in a special issue devoted to the TSS experiments). In order to achieve the full 20 km upward deployment, the satellite is first separated from the Shuttle by means of the 12 m boom. In-line thrusters are then activated and the tether released. At a distance of 50-100 m the tidal force is already very effective in separating the two masses and the satellite achieves a (controlled) vertical velocity of about 1 m/s. Shortly before reaching the nominal length, the tether was severed at the lower termination by an arching phenomenon across the insulating layer. Fortunately payload operations were carried out during the deployment and valuable scientific data were nonetheless collected.

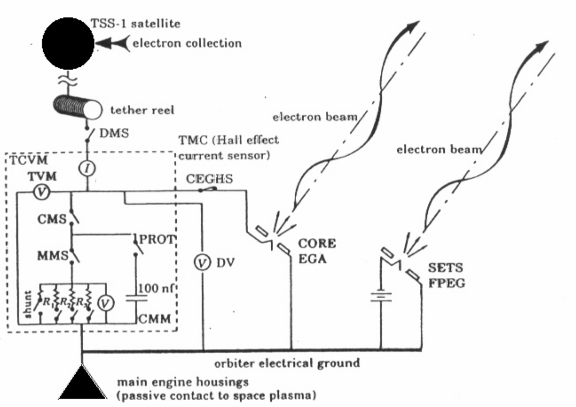

Fig. 8. The electrical configuration of the Tethered Satellite System.

In order to achieve a better control of the tether current, an electron gun (EGA) rather than a hollow cathode was used onboard the shuttle as electron emitter (Bonifazi et al., 1994). The filament of the gun was electrically connected to the wire, while the anode was grounded to the Shuttle (see fig. 8). A high voltage switch (DMS) could be commanded to separate electrically the gun and the Shuttle from the tether. When forced into the saturation region, the each of the two EGA heads was capable of ensuring nearly constant current levels independently of the induced tether voltage and external plasma conditions (density and temperature), up to a maximum of 0.35 A. Different currents were attained by controlling the filament temperature. In addition to the EGA, a second electron gun (FPEG) was connected to the tether by means of a series of resistors.

During the deployment the gun was commanded at different current levels in order to determine the I-V characteristic of the system and carry out particle and wave measurements. At a distance of 19.3 km, only 700m from the completion of the nominal 20 km deployment (two km less than the available length) the tether snapped, rapidly separating from the Shuttle. The atmospheric re-entry occurred a month later, due to the large area/mass ratio of the object. The tether break and the following events were indeed of considerable interest.

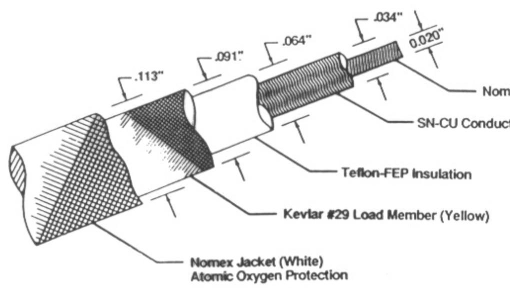

Fig. 9. The internal structure of the TSS-1 tether.

The failure occurred when no current was flowing in the wire (the DMS was open). In this condition the satellite was at its floating potential (about 1 V), while the lower tether termination reached large voltages with respect to the plasma. An insulating Teflon layer was intended to prevent ion collection and current flow (see fig. 9 and 10). However, due to the presence of small metallic and non-metallic debris in a short section of the cable (about 20 m), a pinhole was probably produced in the Teflon, effectively exposing the underlying Sn-Cu conductor to the plasma. An intermittent discharge followed, with currents reaching 1.2 A, anti-correlated with the measured tether voltage (a clear indication of a short). The break occurred about 12 seconds after the onset of the discharge, as a consequence of the large power dissipated in a tiny section of the cable.

Fig. 10. Left: the TSS-1 tether, with the Teflon layer involved in the arching. Right: the tether after the break, at the end of the Shuttle's deployable boom.

After the break the scientific instruments onboard the satellite continued to record data. Surprisingly, a large current (about 1.2 A) was still flowing along the tether, indicating that a dense plasma was generated at the lower end of the tether. This phenomenon went on rather continuously for a few minutes, with only a short interruption followed by a restart. The phenomenon can be traced to the ionization of the neutral gas trapped in the tether (inside the Teflon layer), which was flowing through the broken end (Gilchrist et al., 1998). Once the neutral gas pressure became too low, the discharge stopped. It is also possible that the material of the tether itself, heated by the large dissipated power, could be the source of the neutrals required to sustain the discharge. Understanding which mechanism was involved is quite important in view of future applications. The failure of the TSS-1R mission is now attributed to the tether manufacturing process, which was not carried out in a sufficiently clean environment.

6. Future applications. The TSS missions were designed for a thorough characterization of the behavior of long conductive tethers under high voltage conditions. The analysis of the scientific data from the various experiments was intended to pave the way to technological applications, such as propulsion and power generation. Since 1996 no electrodynamic tether has been flown, but an important project is under way. Pro-SEDS, funded by NASA for a 2002 launch, is based on the concepts developed and tested by the SEDS missions (Small Expendable Deployer System) in 1993 and 1994, but with a conductive tether (Johnson and Balance, 1998). The technological objective is a full-scale demonstration of propulsion and power generation by means of a 20 km tether system attached to the upper stage of a Delta II rocket. The tether itself is made up by a 5 km long bare copper section at the lower end (Delta II) and a 15 km non-conductive part which connects the bare section with a ballast mass. The total mass of the tether is about 50 kg. Both the ballast mass and the non-conductive cable are required to stabilize the system under the effect of the electrodynamic torque. The electrical contact of the lower termination with the plasma is ensured by a hollow cathode. The deployment will start from a circular orbit at 400-500 km altitude. The batteries of the upper stage will provide enough power to support operations for a few orbits. For the remaining part of the mission power will be supplied by the tether system itself, which will be also used to recharge secondary batteries.

The main goal of the mission is however the exploitation of the electrodynamic force to de-orbit the heavy upper stage, thus demonstrating for the first time the use of tethers as propulsion systems. The atmospheric reentry should occur in about 15-20 days, a very short time as compared to a predicted lifetime of about six months due to atmospheric drag. Indeed, in one of the simplest and most promising applications, tethers are used as de-orbiting systems for end-of-mission disposal of satellites and upper stages (Forward et al., 1998; Iess et al., 1998). This concept is particularly interesting as the need to reduce space debris will probably force space agencies and industrial companies to equip a large class of satellites with a de-orbiting propulsion system. The accumulation of spent objects in orbit already poses a non-negligible threat to space operations. This threat will increase considerably if a collision between large objects will occur. Indeed, the resulting cloud of fragments could indeed initiate a cascade of collisions ending up with the inoperability of entire regions of circumterrestrial space. The Inter-Agency Debris Coordination Committee (IADC) has already issued a directive, strongly recommending the end-of-life disposal of every LEO object with an expected lifetime larger than 25 years.

Tethers have at least two main advantages over conventional propulsion systems: a) they usually require a much lower mass and b) they do not require an operational satellite to carry out their task. The Δv needed to de-orbit a LEO spacecraft amounts to a few hundreds m/s, which implies storing a significant fraction (about 10%, given the typical specific impulses) of propellant for many years. Larger satellites pay a larger mass penalty (fig. 11). On the contrary, a tether system develops a continuous thrust and is therefore capable of de-orbiting objects of arbitrary mass, provided that time is not a constraint. The time needed to de-boost an object of mass m between two circular orbits of radius a_1 and a_2 can be computed by integrating eq. 6:

$$[\Delta t]_{a1}^{a2} = \int_{a1}^{a2} \frac{G M_{\oplus} m}{2a^2 P} da \,, \qquad (10)$$

For an insulated tether $P = i\Delta V$. Tethers pay therefore a time rather than mass penalty in de-orbiting heavier objects, but of course time is generally a much cheaper resource.

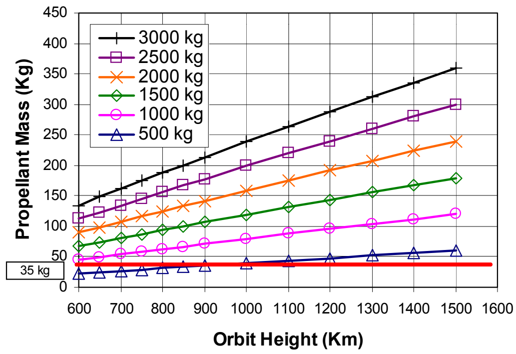

Fig. 11. Mass of chemical propellant required to de-orbit objects of different masses, as a function of the orbital altitude. A 35 kg tether system outperforms chemical propulsion in most cases.

Industrial projects are under way both in the USA and Europe (Hoyt and Forward, 1999; Bruno et al., 2001), with the goal of developing a light and simple device easily accommodated on a variety of satellites. These projects have to face three crucial requirements, namely 1) minimizing the de-orbiting time, 2) ensuring the dynamical stability of the system and 3) ensuring the survivability of the wire to impacts from micrometeoroids. Fulfilling the latter requirement involves a careful design of the tether structure, usually relying upon a number of multiple, redundant filaments, spatially separated from each other. More complex is the task of simultaneously fulfilling the first two conditions. Indeed the need of a fast reentry requires large currents (i.e. large electrodynamic drags), which in turn imply large perturbing torques. The problem is particularly serious as the tether systems envisaged in this kind of applications is necessarily unbalanced, with a center of gravity very close to the heavy satellite. The gravity gradient is therefore small and the large electrodynamic torque can easily feed a fast dynamical instability (see Sect. 2). In general an active control is required in order to decrease the rotational energy of the tether, for example by phasing the current (Corsi and Iess, 2001). In general the problem arises at low altitudes, when the large plasma density allows the flow of significant currents.

At high altitudes, where the plasma is much more tenuous, the main difficulty is the enhancement of the electromagnetic drag, which may well be as low as 5-10 mN. At low densities bare tethers become less efficient and the addition of a large collector, obtained for example from an inflatable structure, may substantially reduce the de-orbiting time (see Sect. 3). In general, a typical 5km long tether, of mass 15 kg (plus an additional 20 kg for the deployer system and control electronics), may de-orbit a 1000 kg satellite from a zero inclination circular orbit at 1300 km altitude in a time ranging from 40 to 120 days, depending on the electrical and mechanical configuration.

Orbital re-boosting is another promising application of propulsive tethers. As indicated in Sect. 2, if an external energy source is available the naturally occurring potential difference across the tether can be reversed, resulting in a thrust rather than a drag. In a typical configuration, the tether is deployed downward, while the electron emitter (most likely a hollow cathode) is kept at the object to be raised. In order to increase the net force, longer wires are considered (10-20 km), made up by a mostly insulated tether with an exposed section at the lower termination, where a ballast mass is also attached. A 10 km system may provide about 700 W of mechanical power (corresponding to a net force of about 0.1 N at a 500 km altitude). Such a concept has been considered since a long time in connection with the International Space Station, whose large area/mass ratio requires quite significant amounts of propellant for orbit keeping. It has been shown that the use of a tether propulsion system may indeed result in huge mass savings over the planned lifetime of the facility.

In the far future tethers may find useful applications also in other planetary systems. Jupiter, with its strong magnetic field, is the best candidate, and the concept has been indeed proposed especially for future missions to Europa (Gallagher et al., 1997). Tether propulsion could be exploited to perform orbital maneuvers in the vicinity of the planet and to generate power in alternative to the use of RTGs. The operation of tethers at Jupiter poses however new problems. First, the small gravity gradient would require a different method of stabilization, based upon artificial gravity generated by a rotation of the system. Second, the plasma density in the Jovian system is extremely low, so that artificial plasma sources and/or very long wires (up to 100 km) have probably to be considered. However Jupiter, with its fast rotation, induces large potential differences, which enhance the charge collection process. A preliminary analysis indicates that powers up to 1 MW can be attained, surely an encouraging indication.

7. Conclusions. Electrodynamic tethers are deceivingly simple systems. The physics of charge collection and the dynamics of large flexible structures are closely coupled and generate a variety of complex phenomena, whose understanding is crucial for future developments. Past missions have provided a vast data set paving the way to a variety of applications. Among those, the use of tethers as propellantless propulsion system is particularly promising, especially in the de-boosting and re-boosting of space platforms. Further studies are of course needed, but confidence in tethers can only be built by successful demonstration missions, based upon simple systems to be developed in short times and flown at low cost.

Acknowledgements. I am grateful to L.Anselmo, J.Corsi, R.Licata, E.Lorenzini and G.Vannaroni for many useful discussions over the past years. This work was supported in part by the Italian Space Agency and the University “La Sapienza”.

References.

Alpert, Y.L., Gurevich, A.V, and Pitaevskii, L.P., “Space Physiscs with Artificial Satellites”, Consult. Bureau, New York, 1965.

V. Beletzky, E. Levin, “Dynamics of Space Tether Systems”. Advances in the Astronautical Sciences, Vol. 83, 1993.

Bonifazi, C., Svelto, F., and Sabbagh, J., “TSS Core equipment, electrodynamic package and rationale for system electrodynamic analysis”, *Il Nuovo Cimento*, 1994, 17C, p.13.

Bruno, C., Bussolino, L., Iess, L., Licata, R., and Schirone, L.: EDOARD: A Tethered Device for Efficient Electrodynamic De-Orbiting of LEO Spacecraft, CP552, Space Technology and Applications International Forum-2001, M. S. El-Genk ed., 2001 American Institute of Physics, p.433

Corsi, J., and Iess, L., "Stability and Control of Electrodynamic Tethers for De-orbiting Applications", *51th International Astronautical Congress*, Rio de Janeiro, Oct. 2000, paper IAF-00-S.6.06, 2000.

Cosmo, M.L., and Lorenzini, E.C., "Tethers in Space Handbook", Third Edition, 1997, Smithsonian Astrophysical Observatory.
Dobrowolny, M., and Stone, N.H., "A Technical Overview of TSS-1: the First Tethered-Satellite System Mission", *Il Nuovo Cimento*, 1994, 17C, p.1.

Forward, R. L., Hoyt R. P., and Uphoff C., "Application of the Terminator Tether™ Electrodynamic Drag Technology to the Deorbit of Constellation Spacecraft", Paper AIAA 98-3491, 34th Joint Propulsion Conference, Cleveland, OH, 13-15 July 1998.

Gallagher, D.L., Bagenal, F., Moore, J., and Johnson, L., "An Overview of Electrodynamic Tether Performance in the Jovian System", Proc. of Tether Technology Interchange Meeting, Huntsville, AL, Sept. 9-10, 1997, NASA/CP-1998-206900, 1998, p. 335.

Gilchrist, B.E., Bonifazi, C, Bilen, S.G., Raitt, W.J., Burke, W.J., Stone, N.H., and Lebreton, J.P., "Enhanced electrodynamic tether currents due to electron emission from a neutral gas discharge: Results from the TSS-1R mission", *Geophys. Res. Lett.*, 1998, 25, p.437.

Grossi, M. D., and Colombo, G., "Interactions of a tethered satellite system with the ionosphere", Proc. of the UAH/NASA Workshop on the Uses of a Tethered Satellite System, edited by S. T. Wu, University of Alabama, Huntsville, 1979.

R. Hoyt, R. Forward, "Performance of the Terminator Tether™ for Autonomous De-orbit of LEO Spacecraft". 35th AIAA-ASME-SAE-ASEE Joint Propulsion Conference and Exhibit, AIAA 99-2841, June 20-24 1999/Los Angeles, California.

Iess, L., Harvey, C., Vannaroni, G., Lebreton, J.P., Dobrowolny, M., Manning, R., Cerulli-Irelli, P., Onelli, A., and De Venuto, F. "Plasma Waves in the Sheath of the TSS-1R satellite", *Geophys. Res. Lett.*, 1998, 25, p.17.

Iess, L., Bruno, C., Ulivieri, C., and Vannaroni, G., "Satellite De-orbiting by Means of Electrodynamic Tethers: System Configuration and Performances", *49th International Astronautical Congress*, Melbourne, Sept. 1998, paper IAF-98-S.6.06, 1998.

Johnson, L. and Ballance, J., "Propulsive Small Expandable Deployer System (ProSEDS) Space Demonstration", Proc. of Tether Technology Interchange Meeting, Huntsville, AL, Sept. 9-10, 1997, NASA/CP-1998-206900, 1998.

Parker, L.W., and Murphy, B.L., "Potential build-up on an electron-emitting ionospheric satellite", *J. Geophys. Res.*, 1967, 72, p. 1631.

Sanmartin, J.R., Martìnez-Sanchez, M., and Ahedo, E., "Bare Wire Anode for Electrodynamic Tethers", *J. Propulsion and Power*, 1993, 9, p.353.

Stenzel, R.L., and Urrutia, J.M., "Currents between tethered electrodes in a magnetized laboratory plasma", *J. Geophys. Res.*, 1990, 95, p. 6209.

Thompson, D.C., Bonifazi, C., Gilchrist, B.E., Williams, S.D., Raitt, W.J., Lebreton, J.P., Burke, W.J., Stone, N.H., and Wright, K.H. Jr., "The current-voltage characteristics of a large probe in low Earth orbit: TSS-1R results", *Geophys. Res. Lett.*, 1998, 25, p.413.

Vannaroni, G., Dobrowolny M., Melchioni E., De Venuto F., Giovi R., Characterization of the interaction between a hollow cathode source and an ambient plasma. *J. Appl. Phys.,* 1992, 71, p.4709.

Vannaroni, G., Dobrowolny M., Lebreton J. P., Melchioni E., De Venuto F., Harvey C. C., Iess L., Guidoni U., Bonifazi C., Mariani F., "Current-voltage characteristic of the TSS-1R satellite: Comparison with isotropic and anisotropic models", *Geophys. Res. Lett.,* 1998, 25, p.749.