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Electrodynamic Tethers In Space

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CHAPTER 1

TETHERS IN SPACE

1.1 Fundamentals of tether dynamics

The idea of having long tethers orbiting in space while attached to other structures, may seem rather odd at first sight, but it becomes immediately more practical once a basic dynamical concept (the gravity gradient force), is introduced.

Long tethers do not curl up randomly in Space as they would do on the Earth, because of the role of the gravity and centrifugal forces which causes such tethers to stretch out vertically.

Let us explain this fact which, although far from exhausting all the complexities of tether dynamics, is in any case fundamental to the comprehension of orbiting tethers in space and to many applications of space tethers.

An elementary tether system has a "dumbell" form with two masses connected by the tether. The top mass experiences a larger centrifugal than gravitational force, being higher than the orbit of the center of mass (CG), whereas the reverse occurs for the bottom mass (Fig. 1.1). On the other hand, gravity on the upper mass is smaller than on the lower mass. The center of mass, halfway between equal masses, is in free fall but the end masses are not. As can be seen from the Figure, this unbalance between forces, at the upper and lower masses, result in a tension on the tether.

The forces, related to gradients in gravitational and centrifugal accelerations, have been computed in a very simple way by Arnold [**1.1**] considering the tether as a rigid rod.

Let us choose an orthogonal reference system Oxyz with the origin at the center of mass, z along the vertical away from the Earth, x in the direction of orbital motion and y out of the plane of the orbit.

Then, the vertical force on a mass m at a distance z from the center of mass, is given by[1]

$$F_z = 3m\Omega^2 z \tag{1.1}$$

[1] The overall vertical force is composed by two parts gravity gradient and one part centrifugal gradient.

where $\Omega = GM/r^3$ is the orbital angular velocity.

The out of plane force is given by

$$F_y = -m\Omega^2 y \tag{1.2}$$

and, being negative, does not produce a tension in the tether connecting the two masses.

On the other hand, the force in the direction of motion is zero

$$F_x = 0 \tag{1.3}$$

It is worth noticing that the tension force (1.1) is far weaker than the corresponding force on the surface of the Earth.

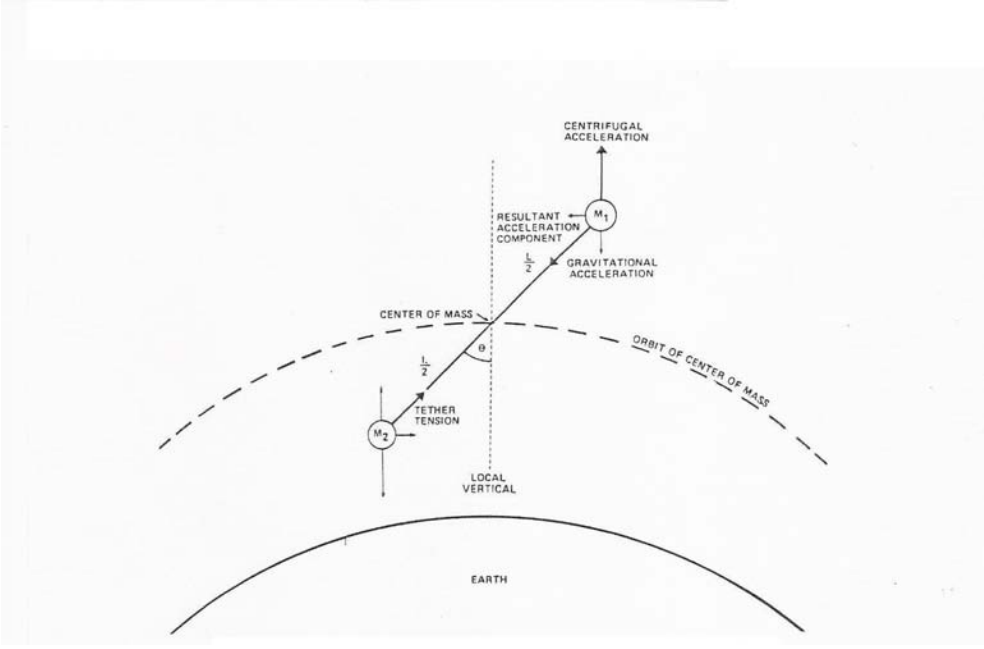

Fig. 1.1: Stabilizing forces on tethered masses

For example, the entire Shuttle, suspended from a 25 km tether, would generate a tension of only $\approx$ 0.91 kg which is 1% of the earth's weight of the vehicle. That can be supported by a Kevlar line of diameter less than 1cm. Likewise, a 500 kg satellite, suspended 100 km below the center of mass, has a tether tension of $\approx$ 18g. To sustain that, a tether with a diameter of 2 mm is sufficient.

The conclusion (see Ref.[**1.1**]), is that, displaying the system from the vertical position, generates restoring forces tending to return the system to such position.

1.2 A short history of tether flights

The basic idea of employing tethers in space dates back to 1895 when the russian engineer Tsiolkovsky, who pionereed rocket propelled flight, proposed to build a ground based tethered structure extending upwards to reach the geostationary orbit and stabilized by gravity gradient forces [**1.2**].

In 1966, the Gemini XI and XII capsules [**1.3**] were connected to several target objects by means of cables up to 30 m long: these represented the first in flight test of tether system basic dynamics.

Just about in the same years (end of sixties) science fiction writers A.C. Clarke and J. D. Isacs described a tether system, the Sky-Hook [**1.4**], which would stabilize the orbit and the attitude of a permanent space station by extending two long cables along the local vertical, one earthwards, the other spacewards.

However, a real impulse to tether studies, followed by several tether missions in space, started only in the years 1972 - 74 thanks to two italian scientists, M. D. Grossi, of the Smithsonian Astrophysical Observatory in Cambridge (USA) and G. Colombo of the University of Padua (Italy).

Indeed, in 1972 - 73, Grossi submitted to NASA a proposal [**1.5**] for using a Shuttle based tethered system as a space based ULF/ELF antenna and, subsequently, in 1974, Colombo, in a paper entitled "Shuttle born Sky-Hook: a new tool for low altitude orbital research" [**1.6**], provided the formal proof that tethers could actually be deployed and stabilized in orbit.

Following these two pioneering papers, several studies were specifically addressed to the case of conducting tethers [**1.7**, **1.8**]. These studies, and the interest they triggered on space tethers, led the way to the implementation of several space missions involving tethers, the most important of which is the TSS (Tethered Satellite System) mission.

To proceed in chronological order,, before the first TSS mission, there was the Canadian project Oedipus-A[2]. Oedipus-A was launched on January 1989 by a Black Brant X 3 stage sounding rocket from Adoya in Norway. The trajectory had an apogee at 512 km. The tether, of length L = 958 m and diameter d = 0.85 mm, was conductive (19 strand tin-coated copper with white Teflon insulation) and it was connecting two sub-payloads (of masses 84 kg) containing experiment hardware and telemetry system.

The main objective of the mission was that of using the long tether as a double probe to make observations of the auroral ionosphere and, in particular, measure the natural electric field parallel to magnetic field lines. During the 11 minutes of sub-orbital flight, the main objectives were in fact reached (see Refs.[**1.9**], [**1.10**]).

Oedipus-A was followed by a more complex, and more technological mission called Oedipus-C ([**1.11**], [**1.12**]). This was again a sounding rocket mission which took place in November 1995 from the Poker Flat Research Range in Alaska. The trajectory was higher than that of Oedipus-A (apogee at 843 km) with the consequence of encompassing a greater range of ionospheric densities. In addition, this mission carried instrumentation to measure accurately the tether dynamics. The tether (conductive) was of the same type as that of Oedipus-A but longer (L = 1173 m).

TSS-1, which was the next tether to be flown after Oedipus-A, was a complex project (corresponding to the original idea [**1.6**] of G. Colombo et al.), consisting in the deployment from the Shuttle of a 20 km tether with attached a subsatellite. Prior to deployment, the satellite was placed on top of a boom on the Shuttle.

The tether was a conductor covered with an insulator and in electrical contact with the medium through its two terminations (i.e. the Shuttle and an upper satellite). We will describe this very complex project (indeed the most important flown with a conducting tether), in a separate chapter.

It is enough, at the moment, to recall that TSS-1, was first flown in 1992 (see Ref.[**1.13**]) on board of the Space Shuttle Atlantis STS-46. Fig.1.2, which is a picture taken from the Orbiter, shows the satellite, attached to the tether, moving away from the Orbiter. In this first flight, however, after 268 m of deployment, the reel jammed. The tether and sub-satellite were then retrieved on the Shuttle. In spite of the short deployment, a lot was learned (in the $\approx$ 20 hours of detached phase), about the dynamics of the system: the satellite could be deployed, controlled and retrieved with TSS being even

[2] Oedipus stands for Observation of Electric Field Distribution in the Ionosphere: a Unique Strategy.

more stable than predicted. On the other hand, due to the short length deployed, no relevant electrodynamic results were obtained.

TSS-1 was later reflown under the name TSS-1R (see [**1.14**]). TSS-1R was launched on February 22, 1996 on STS75 into a 300 km circular orbit at 28.5^{o} inclination. The tether was deployed to $\approx$ 19.7 km before a failure occurred due to an electrical arc (on February 27). After separation from the Shuttle, the satellite, with the tether still attached, was left in a 28.5^{o}, 400x300 km orbit. It remained in orbit for a few weeks re-entering on March 19, 1996

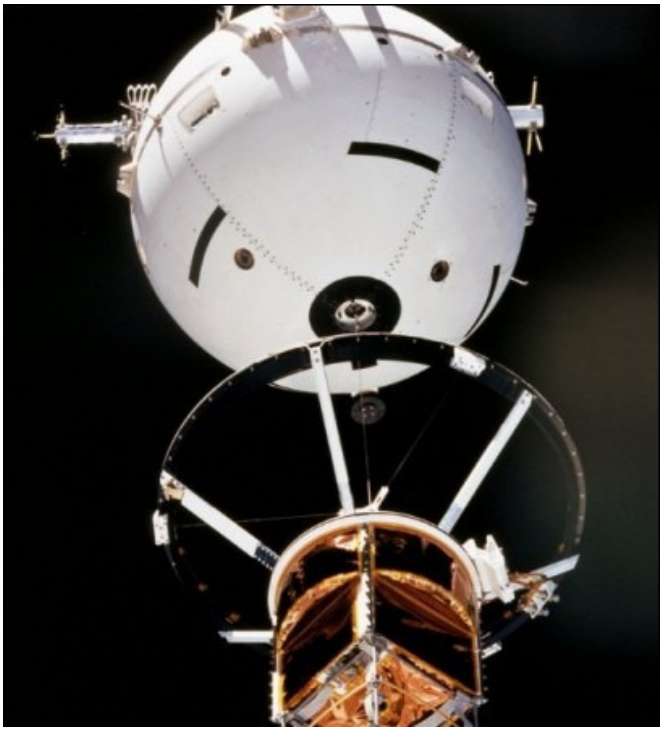

Fig.1.2: initial TSS-1 deployment
(from: http://www.satorbs.org/tss.html)

During these weeks, the system was visible from the ground like a fluorescent light travelling through the Sky. It was in fact followed by several observatories and all observations reported that the tether was hanging below the main satellite approximately along the Earth radius vector.

Fig.1.3 is a view of the broken tether during a close pass (75 km) towards the end of the mission, and, together with the determination of the tether approximate orientation, is an efficient example of gravity gradient stabilization of tethers in space.

In spite of the above failure, during the mission TSS-1R, large EMF potentials were reached due to the almost nominal length of deployment and, correspondingly, high currents were measured. Thus TSS-1R, as we will detail more in a subsequent chapter, gave important results on the performance and behaviour of electrodynamic tethers in space.

Other, simpler, tether missions were flown in the years between TSS-1 and TSS-1R.

Fig.1.3: An image of TSS-1R before re-entering the Earth's atmosphere (from: http://www.satorbs.org/tss.html)

An hardware package called SEDS (Small Expendable Deployer System) was developed with the purpose of deploying a 20 km tether in space. As the name says, this system (contrary to TSS-1), was expendable i.e. it was going to be cut at the end of the mission. The deployer system was completely passive with springs ejecting initially the tether from the reel and, from then on, deployment proceeding only under the action of the gravity gradient force.

The tether of the SEDS package, which is non conducting, was braided from 8 individual polyethylene fibers with commercial name Spectra 2000. The final tether diameter was d = 0.75 mm.

Two SEDS missions were flown[3], both as secondary payloads on Delta II launches of GPS satellites. A description of SEDS, as well as the results of the two SEDS missions, is found in Ref.[**1.15**]. Fig.1.4 is a picture of SEDS-1 anchored to the Delta second stage and with an end payload attached.

The first SEDS mission (SEDS-1), took place in March 1993. The orbit had an inclination of 34^{o}, a perigee altitude of 190 km and an apogee at 720 km..

SEDS-1 mission objectives were to demonstrate that SEDS hardware could be used to deploy a payload at the end of a 20 km tether and study its re-entry after cutting the tether. The end payload, equipped with accelerometers, a tensiometer and a magnetometer, was weighting 26 kg.

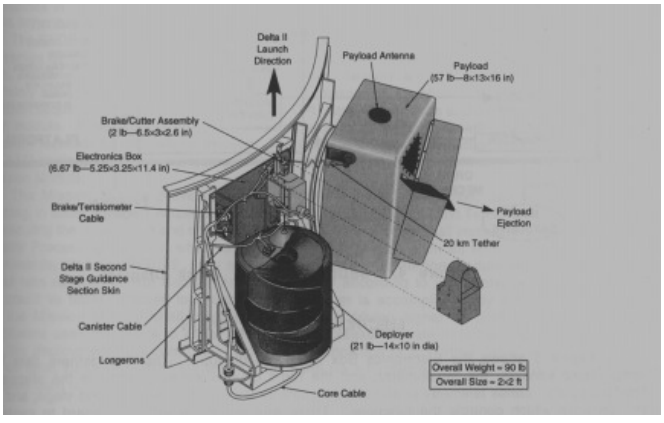

Fig.1.4: SEDS-1 attached to the Delta second stage
(from Ref.[1.8])

[3] A SEDS package was also employed in the Plasma Motor Generator (PMG) tether experiment and in the TIPS mission.

SEDS-2 was flown on March 1994 in a circular orbit at 350 km of altitude. The main objectives (more demanding than those of SEDS-1), were now to show the feasibility of deployment along a predetermined trajectory with a final position close to the vertical (within 10^o). A secondary objective was that of studying the long term evolution of the tethered system.

The primary objective was reached but the secondary objective was not because the SEDS-2 tether was probably cut by a micrometeorite (or debris) after five days. We refer to [**1.15**] for more details on the SEDS flights.

A very significant electrodynamic tether experiment, called PMG (Plasma Motor Generator), was flown in 1993 and deployed a 500 m tether with electrical contact at the terminations ensured by plasma sources of the hollow cathode type (see [**1.16**]). In this experiment which, like TSS-1, will be described in more detail in Chapter 4, the current flow was succesfully reversed between power and thrust generation modes.

I must say that, after TSS-1R, no tether mission of comparable importance has been flown although several projects have been the object of studies to different levels. This is undoubtedly related to the fact that, although the basic theories concerning power generation and propulsion from electrodynamic tethers, were confirmed, half of the missions flown at this point encountered tether failures.

This poses safety concerns. Should a tether fail (due, for example to a micrometeroid impact), a few km away from the Shuttle or the International Space Station, the resulting recoil and entanglement would surely implicate some risk.

In 1996, several Naval Research laboratories initiated a space experiment, called TIPS (Tether Physics Survivability Experiment) to test dynamics and long duration survivability of tethers in space. The experiment was jettisoned from a host spacecraft on June 20, 1996 and the tether deployment (with SEDS hardware), occurred shortly after jettison.

TIPS consisted of two end masses connected by a tether flying in a circular orbit at an altitude of $\approx$ 1000 km with 63.4^o of orbital inclination. The tether, of length L = 4 km , had an outer layer of Spectra 2000 braid for strength, with an acrylic core yarn for a total diameter d = 2 mm. The relatively large cross section (larger than that of tethers previously flown), was meant to improve the tether resistance to debris and micrometeoroids.

Important dynamic studies were done by monitoring TIPS from the ground [**1.17**]. Lots of information about this project, the dynamic data and pictures of the tether in flight, can be found on an NRL Web page [**1.18**].

The survivability objective of this project was indeed fully reached as TIPS survived for 10 years[4].

In 1999, NRO performed a follow up of TIPS, designated ATEX (Advanced Tether Experiment). ATEX was a payload element of the NRO satellite STEX (Space Test Experiment).

The tether of ATEX was of a new conception. It was in fact a tape 6 km long and 3 cm wide with reinforcements consisting of fiber strands running down its length. However, the experiment failed as the tether started its deployment at a too low velocity. After 22 m of deployment, STEX had to eject the ATEX package.

Several efforts for tether flights were also undertaken in Europe in recent years. They are due to the initiative of a small Dutch company (Delta/Utec) and ESA/ESTEC[5].

In 1997 ESA launched the first Young Engineer Satellite (YES), of mass $\approx$ 200 kg, into a GTO orbit with a 35 km double-strand tether, and planned to de-orbit a probe (of mass $\approx$ 11 kg) by rotation of the tethered system ([**1.20**]). The experiment was however cancelled due to late changes in the launcher's orbit (Arianne 5) combined with an increased collision risk with satellites in Low Earth Orbit.

A second tethered satellite project (YES-2) was coordinated by ESA and the Russian Space Agency and the satellite was launched, from a Soyuz rocket, in September 2007. It was supposed to deploy a 30 km tether with attached a small capsule (called FOTINO), 40 cm in diameter and only 6 kg of weight. The total mass of YES-2 was only 36 kg and the tether, with a diameter of 0.5 mm, was made of superstrong polyetelene fibers called Dyneema. The system was designed to re-enter and soft-land the FOTINO capsule.

Tether deployment was indeed completed and, from the mission data ([**1.21**], [**1.22**]), it was seen that the capsule was released into a near nominal re-entry trajectory. However, no signal from the capsule was received after landing.

It must be stressed that the YES satellites were entirely built and qualified by students and young engineers with expert support.

On the line of tether survivability, we must recall the proposal [**1.23**] of a multiple line tether structure. This so called Hoytether[6] was actually

[4] This long life (besides the large cross section of TIPS), can also be due to the orbit much higher (with respect to the tether experiments previously mentioned) and the diminished risk of micrometeoroid impact at this higher altitude .

[5] For these activities go to the Delta Utec web site [**1.19**].

[6] Patented by Tether Unlimited Inc.

implemented in a low cost mission called MAST (Multi-Application Survivable Tether). MAST was launched in LEO orbit on April 17, 2007. The experiment consisted of three picosatellites, stocked for launch in a very small volume and equipped with Gps receivers . Once in orbit, two of the satellites would separate deploying a 1 km tether . The third picosatellite (named Gadget), was supposed to slowly crawl along the tether length to monitor any possible damage to the tether.

Things, however, did not go as expected, as some problems on the tether reel prevented the tether from being deployed.

1.3 Conclusive remarks

After this short review of tether flights, let me add some final remarks which point out what we need to continue research with tethers in space.

In spite of some failures (TSS-1, ATEX, YES), it is fair to say that much has been learned from the past experience.

Deployment of tethers has been successfully demonstrated and, actually, with the SEDS packages, it was shown that no active reeling is required. After initiation of deployment by ejection springs, a tether will be simply drawn from a spool by the gravity gradient.

Concerning conducting tethers and their applications, the most important mission (TSS-1R), when the tether was lost, had already achieved most of its goals. This mission demonstrated, first of all, the capability of conducting tethers to generate electrical power (with currents measured above those expected).

In the same way, the PMG experiment, although reduced in time and scope, with respect to TSS-1R, has proved the importance of using hollow cathodes as good plasma contactors at the two tether terminations to obtain currents higher than those obtained with ionospheric charge collection.

One thing that has been learned, after the big effort on the TSS project, is that, to acquire experience with tethers in space and their applications, one has rather to plan missions of low cost and more limited in scope. PMG and YES-2 are significant examples.

A very significant electrodynamic mission (ProSEDS, standing for Propulsive Small Expendable Deployer System), devoted to study of propulsion and electrodynamic de-orbiting, was also to be deployed (as a secondary payload) from a Delta II stage (like PMG). This mission was long studied [**1.24**] and was about to fly but, at the last moment, it was cancelled

due to concerns that the tether might break and then collide with the International Space Station.

This brings us to the other important issue which has come out from the experience of tether flights, which is that of tether survivability against micrometeoroids or debris impact. This would be a problem, in particular, for electrodynamic applications, which should last months or years, whereas near term mechanical applications (like sample return), last hours or, at most, days.

If a tether breaks, the application for which it was designed, obviously fails. In addition, broken tethers can be a collision risk for other satellites[7].

The TIPS project, in orbit for 10 years, has shown that it is possible to have long lived tethers. However, more experimentation on materials and tether structure is certainly needed.

In conclusion, although we have learned quite a bit from the past tether flights, it is clear that we need to continue to acquire experience if we want to be able to manage with tether applications in space. As we said already, this is probably best done by designing low cost missions with a restricted but well defined scope.

[7] The risky part of any orbit is the time spent below 2500 km altitude where the satellite density is highest.

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An electrodynamic tether is essentially a long conducting wire extended from a spacecraft. The gravity gradient field (also known as the "tidal force") will tend to orient the tether in a vertical position. If the tether is orbiting around the Earth, it will be crossing the Earth's magnetic field lines at orbital velocity (7-8 km/s!). The motion of the conductor across the magnetic field induces a voltage along the length of the tether.Â Its objectives on this flight are to demonstrate the ability to deploy and control satellites on long tethers in space and to conduct space plasma experiments that include the generation of electrical power. The TSS-1 first flew on STS-46 in 1992, but a mechanical problem allowed the satellite to be deployed only to height of 840 feet. Tethers In Space Handbook. Edited by. M.L. Cosmo and E.C. Lorenzini Smithsonian Astrophysical Observatory.Â Before an operational electrodynamic tether reboost system for the ISS can be designed, a series of ground and space-borne experiments and computer simulations must be performed. In addition, thorough systems analyses must be performed to determine the physical integration and operational issues associated with its implementation on the ISS. The Momentum-Exchange/Electrodynamic-Reboost (MXER) Tether System could pick payloads up from a reusable launch vehicle in low Earth orbit and toss them to geosynchronous orbit. This idea could act as a Hypersonic Airplane Space Tether Orbital Launch system, or be utilized to handle other launch systems other than hypersonic airplanes. (Image: Â© Tethers Unlimited, Inc.) An EDT can generate electric current flow towards the planet; this can provide enough electricity to run experiments on board a satellite; this also causes the tether to experience a force from the planet's magnetic field