Potential Benefits and Risks of using Electrodynamic Tethers for End-of-life De-orbit of LEO Spacecraft

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Benefits: Mass Savings Compared with Solid Rocket Motors [1]

The conventional chemical thrusters must be able to reliably operate for mission times much longer than the usual applications they were designed for

A solid rocket de-orbit system requires a mass allocation that is a significant fraction of the spacecraft's launch mass: a rocket stage providing a retro ΔV of 50-325 m/s is characterized by a mass fraction on the order of 0.6 to 0.75.

A rocket system with a propellant mass fraction of 0.75 will consume ~ 17% of the vehicle's launch mass to de-orbit a spacecraft from an altitude of 1500 km

An electrodynamic tether system, weighting about 30-50 kg, can achieve de-orbit of a spacecraft requiring only a few percent of the launch mass (1 to 5% for the Terminator Tether™)

Next figure shows the percent additional solid-rocket propellant mass required to drop a spacecraft from a circular orbit at the specified altitude to a new orbit with a perigee of 200 km

Benefits: Mass Savings Compared with Solid Rocket Motors [2]

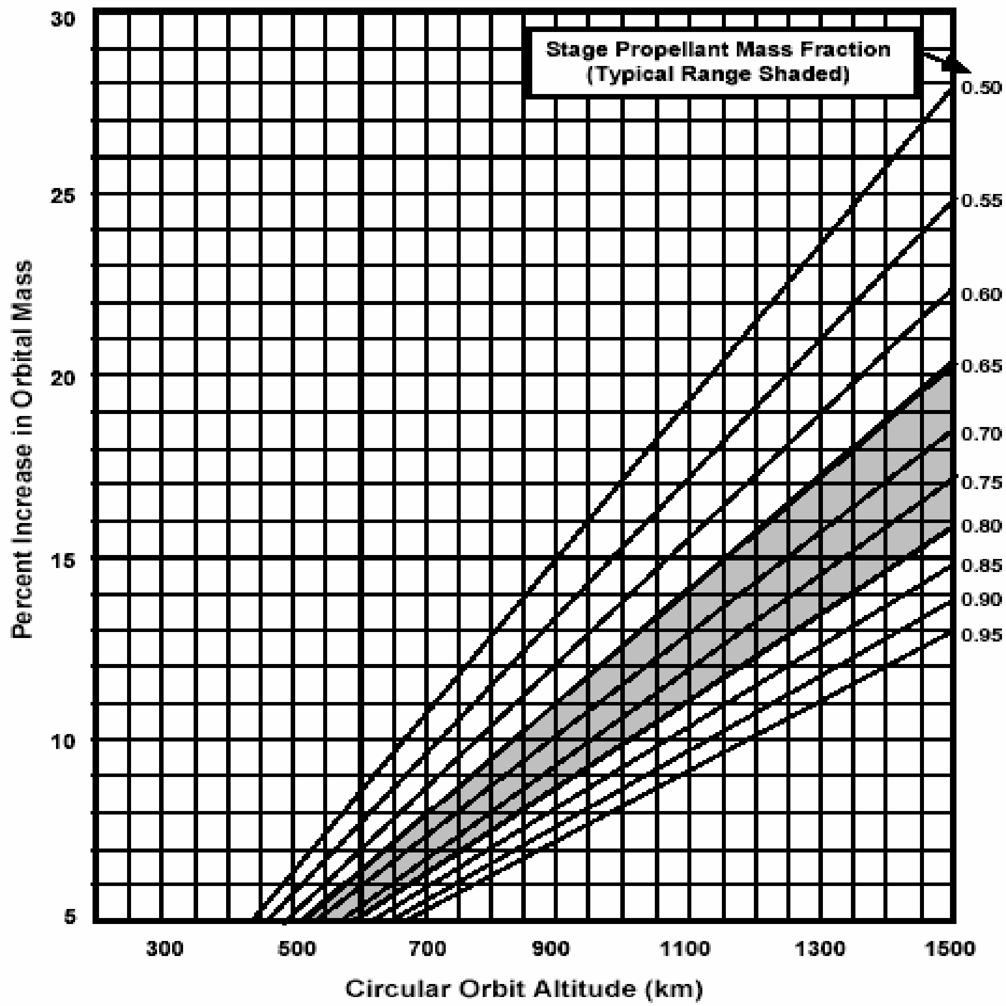


Figure 6. Conventional solid rocket motor deorbit system percent mass increase vs. altitude and stage propellant mass fraction (I_{sp}=288 sec).

Benefits: Mass Savings Compared with Solid Rocket Motors [3]

A tether de-orbiter appears to be preferable to other thrusters, unless their I_{sp} can be increased by a factor of 10, not realistically possible at present

However, many factors, such as the need to space-qualify any new system, additional complexities related to the design, dynamic effects etc. will need to be investigated

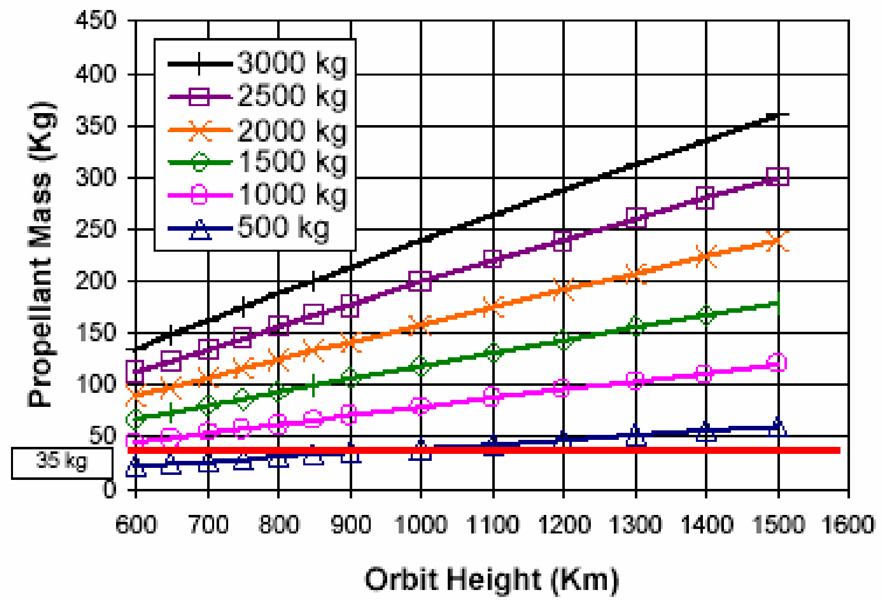


Fig. 1. Propellant mass required for spacecraft de-orbit, as a function of orbital altitude, for different classes of satellites. EDOARD, with a mass of approximately 35 kg, outperforms conventional systems in most cases.

Image from a paper of C. Bruno et al., Proceedings of the 3rd European Conference on Space Debris, ESOC/ESA, Darmstadt, Germany, 19-21 March 2001 (ESA SP-473, October 2001), pp. 707-712

Benefits: Reducing De-orbit Times

Table 1 compares the time required for a Terminator Tether to de-orbit a spacecraft to the time required for the spacecraft to de-orbit under the influence of the atmospheric drag alone (Jacchia 1977 atmospheric density model, $C_D = 2$, $A = 10\ m^2$)

A terminator Tether massing a very small percentage of the total system mass can de-orbit a satellite within a few weeks to a few months, many order of magnitude faster than the decay due to atmospheric drag alone

Table 1. Deorbit times from example constellation orbits using a Terminator Tether system with an aluminum tether massing 2.5% of the spacecraft mass.

Constellation	Altitude (km)	Inclination (degrees)	Deorbit Time, noTT (Derelict)	Initial Orbit Decay Rate (km/day)	Deorbit Time, with Terminator Tether
Orbcomm 1	775	45	100 years	44	11 days
Orbcomm 2	775	70	100 years	11.6	41 days
LEO One USA	950	50	600 years	32	18 days
GlobalStar	1390	52	9,000 years	22.3	37 days
Skybridge	1475	55	11,000 years	18.5	46 days
FaiSat	1000	66	800 years	13.5	45 days
Iridium	780	86.4	100 years	2.1[17]	7.5 months[17]
M-Star	1350	47	7000 years	27	28 days
Celestri	1400	48	9000 years	26	32 days
Teledesic	1350	~85	7000 years	1.7[17]	17 months[17]

Note: All spacecraft are assumed to have an effective drag cross section of 10 m^2.

Benefits: Effectiveness in Terms of the Area-Time-Product

<u>The true measure of the effectiveness of a de-orbit method</u> is not just whether it reduces the orbital lifetime compared to atmospheric drag decay, but whether it reduces the product of the orbital lifetime and collision cross-sectional area of the spacecraft

(**Area-Time-Product - ATP**)

<u>The use of ED tethers can reduce the de-orbit ATP by several order of magnitude</u>, therefore reducing the risk for a decaying satellite to collide with another satellite

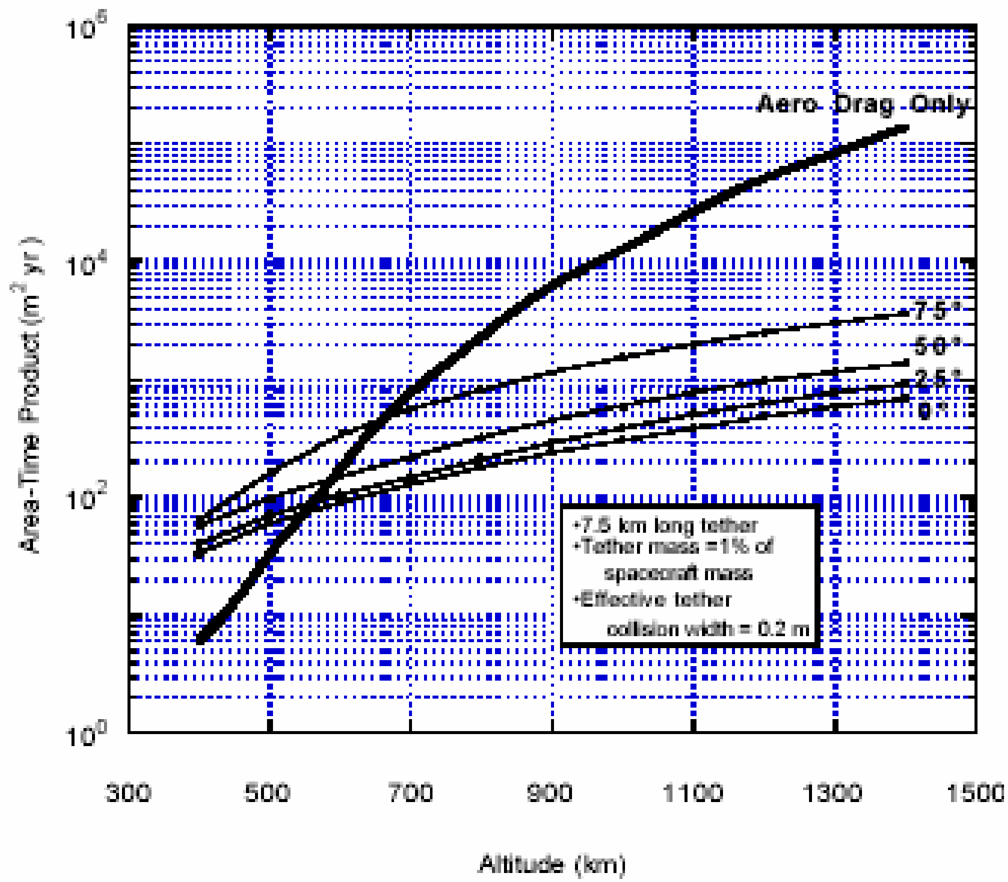


Figure 20. Area-Time-Product for Terminator Tether™ systems with tethers massing 1% of the host spacecraft mass, compared to the ATP for deorbit of the host spacecraft due to aerodynamic drag alone.

Risk Analysis [1]

Tether in space present unusual problems when viewed from the orbital debris perspective

- Space tethers present a much greater risk to operating spacecraft due to their very large collision cross-sectional area
- Because of their small diameter, tethers of normal design may have a high probability of being severed by impacts with relatively small meteoroids and orbital debris (M/OD)
- The resulting tether fragments may pose additional risk to operating spacecraft

Risk Analysis [2]

Therefore, before using ED tethers to mitigate the problem of orbital debris, the following problems have to be investigated

1. **SURVIVABILITY CONCERNS:** what is the risk of tether being cut during mission operations by M/OD?
   - What is the minimum critical impactor diameter of a particle able to sever the tether?
   - What strategies have to be adopted to reduce the tether vulnerability?
   - What are the impact and cut rates during the tether mission?

2. **IMPACT ON THE SPACE ENVIRONMENT:** how the tethers contribute to the growing of the orbital debris population?
   - What is the collision risk with operating spacecraft during the tether mission, i.e. during the de-orbiting phase of an unwanted satellite?
   - After a tether has been cut by impacts with M/OD, what are the risks posed to operating spacecraft by the severed tether?
   - What are the orbital characteristics of the severed tether and what is its orbital lifetime?
   - If tethers will be the way to proceed for de-orbiting, the tether-tether collisions would become an issue. Therefore, how the tether-tether collision probability may be estimated?
   - How can the threat to operating spacecraft from intact or severed tethers be minimized?

Survivability Concerns [1]

Critical Impactor Diameter

The diameter of a space debris which can cut a tether is affected by the tether material as well as by the tether design.

As an example, an aluminum, single-strand, tether may be cut by a particle 1/ 3 of its diameter, while one of woven aluminum could be severed by particles 1/ 2 of its diameter.

As a consequence, the lifetimes of conventional single-line tethers may be limited, by damage due to M/OD impactors, to times much shorter than the mission duration

Although single-line tether lifetimes can be improved by increasing the diameter of the tether, this incurs a prohibitive mass penalty as well as additional operational problems for many missions.

Therefore, different and reliable designs have to be analyzed to reduce the tether vulnerability to space debris

- **Possible involvement of the IADC Working Group 3 in this study**

Survivability Concerns [2]

How to reduce the tether vulnerability?

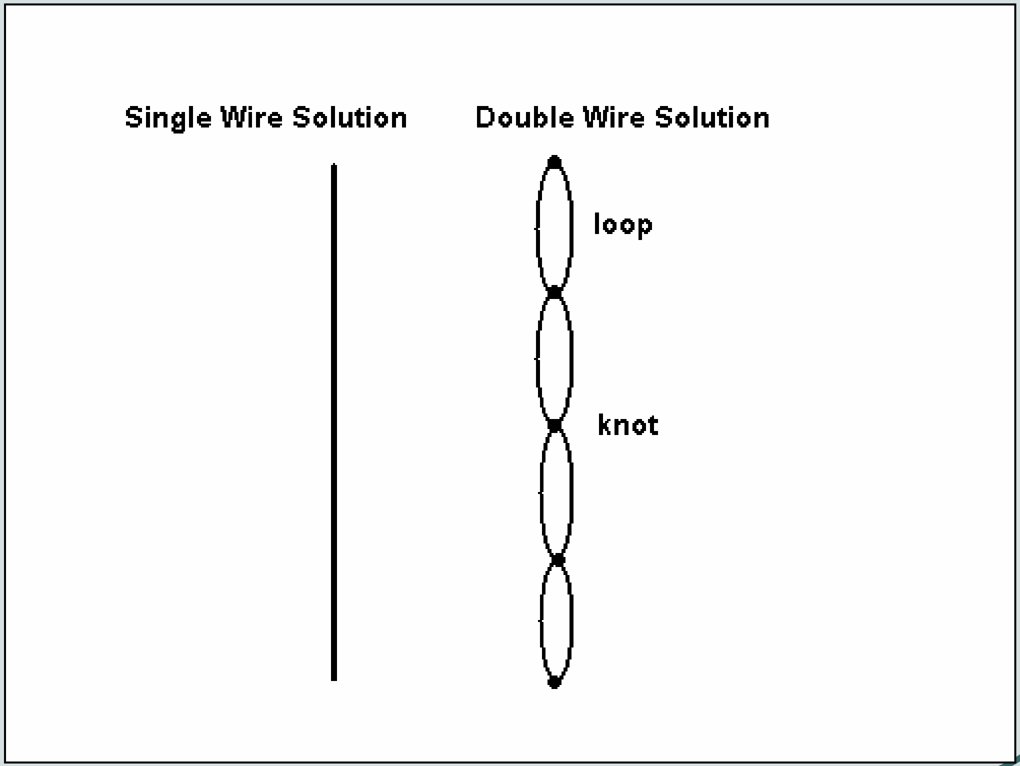
A new configuration has been proposed by Alenia Spazio (Italy) to reduce the vulnerability of the **EDOARD** system:

A double wire tether will be used

The two bare metallic cables, 0.7 mm in diameter each, will be designed to form *n* loops, tied together in *n+1* equidistant knots along the tether

A similar configuration was also investigated at the Department of Aeronautics and Astronautics of the Kyushu University, in Japan

The larger the number of knots, the lower the sever probability will be



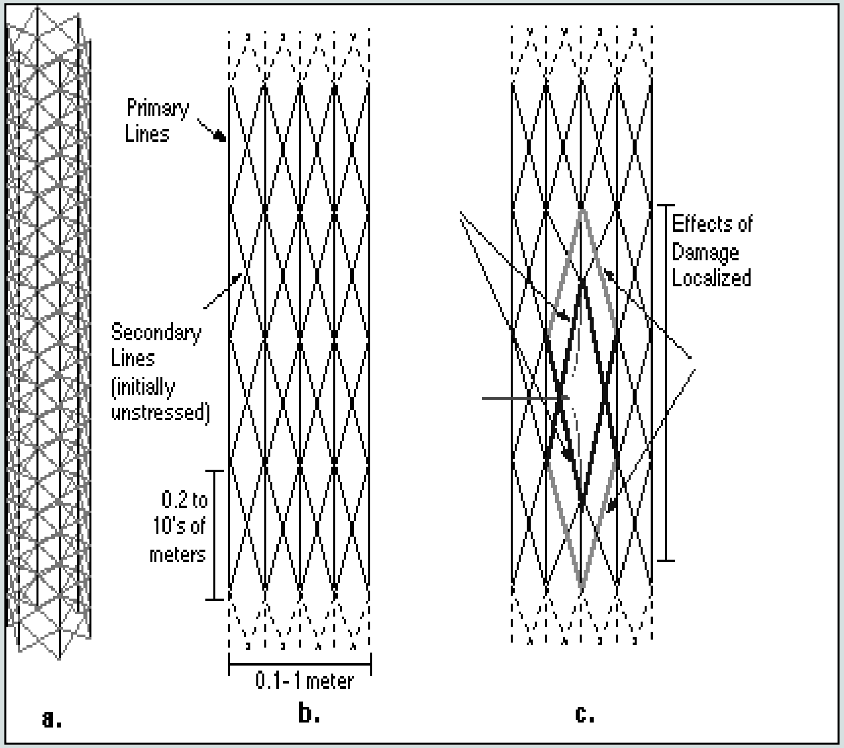
Survivability Concerns [3]

How to reduce the tether vulnerability?

Tether Unlimited Inc. proposed the long-life, damage-resistant tether design called **Hoytether™**

The Hoytether™ is a structure composed of multiple lines with redundant interlinking that is able to withstand many impacts

"Analytical modeling and numerical simulations of this design proved that this tether structure can achieve lifetimes of tens of years without incurring a mass penalty"



Ref: http://www.tethers.com/Hoytether.html

The Hoytether Solution

Questions to Robert P. Hoyt, President of TUI / ScienceOps

Is this structure too cumbersome to be deployed in space?

"No, not at all. We have successfully test-deployed both conducting and non-conducting Hoytethers in several deployment systems, including our microPET deployer and the NASA SEDS deployer"

What is the tether diameter?

The diameter of the yarns or wires used to make the tether are typically half a millimeter in diameter, but that varies greatly depending upon the linear density desired for the tether. The structural diameter also can vary. Most of the tethers we have made have been two or three primary line Hoytethers with widths of 2 to 5 cm"

Did you have done ground tests to assess the performances?

"We have done extensive testing of deployment of the tethers as well as strength testing in the laboratory"

Survivability Concerns [4]

Impact Rate

Due to their peculiar structure and geometry, space tethers cannot be treated as a typical satellite

The impact rate on a tether, i.e. the number of times a tether collides with space debris in one year, can be expressed as the product between the debris flux and the **tether collision cross sectional area**, or tether effective cross-section

a stable cylindrical space tether of length L and diameter d_T, deployed along the gravity gradient and in a circular orbit, presents the following Effective Cross-Section (ECS) to debris particles with diameter D (Anselmo & Pardini *Space Debris*, Vol. 1, No. 2, 1999, pp: 87-98)

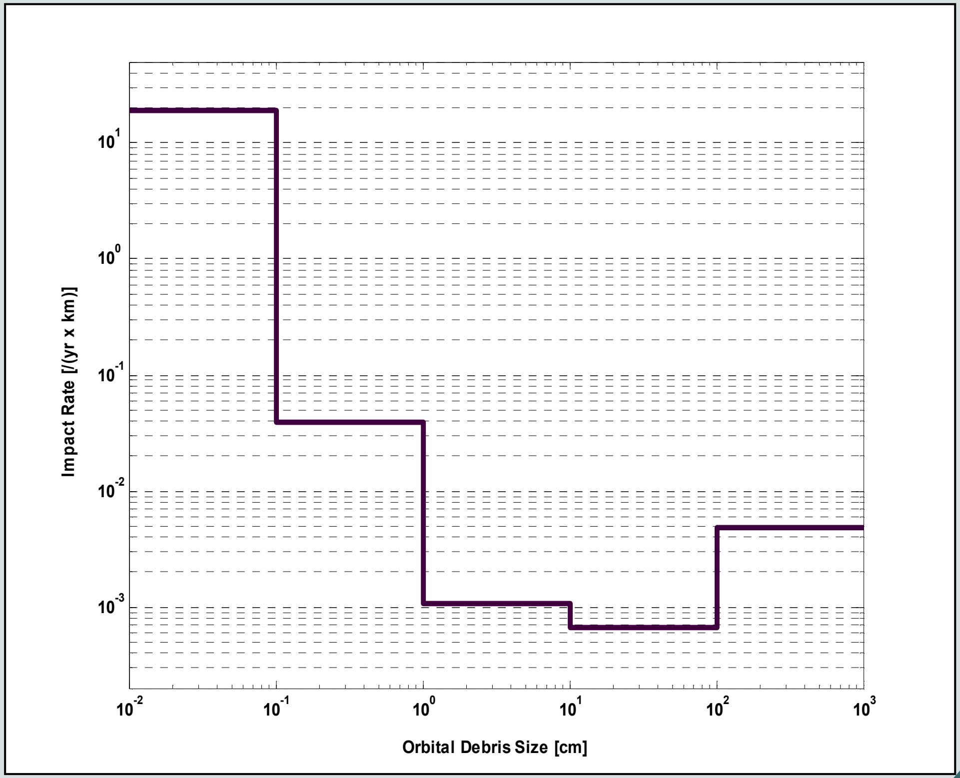
- $D << d_T$: ECS ~ $L\, d_T$ [small debris particles]
- $D >> d_T$: ECS ~ LD [satellites of typical linear dimension D]
- $D \sim d_T$: ECS ~ $L(D + d_T)$ [intermediate debris size range]

Survivability Concerns [5]

Impact Rate

The differential impact rate does not necessary decrease when larger and larger space objects are considered, but presents a minimum at a certain intermediate size, which is a function of the tether diameter and debris distribution

For tethers with d_T > 1 cm the risk to be severed does not decrease by increasing the diameter because the contribution of large orbital debris to the cutting process begins to dominate



Differential impact rate as a function of orbital debris size (tether diameter = 1 mm; altitude = 800 km; inclination = 50°)

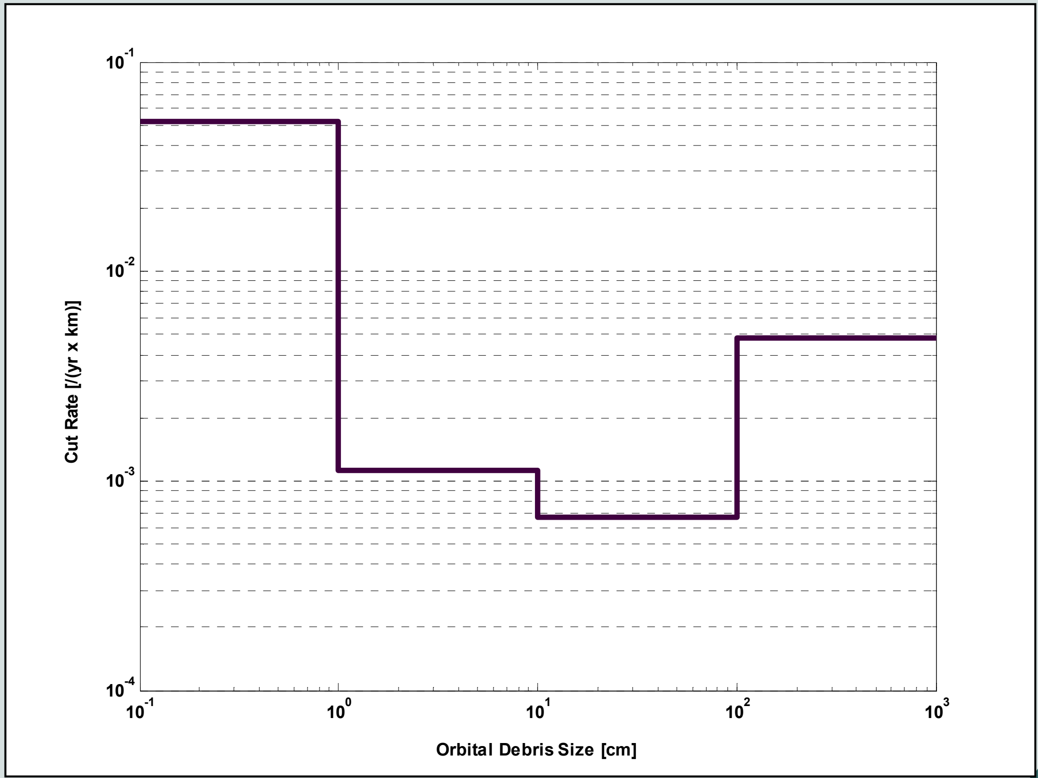
Survivability Concerns [6]

Cut Rate

The differential cut rate can be estimated by only considering the space debris able to sever the tether:

an aluminum single-strand tether may be cut by a particle 1/3 of its diameter,

moreover, an adequately large meteoroid or debris may sever a tether provided its edge passes within 0.20-0.35 d_T of the tether's center of axial symmetry.



Differential cut rate as a function of orbital debris size (tether diameter = 3 mm; altitude = 800 km; inclination = 50°)

Survivability Concerns [7]

The results obtained at ISTI/CNR, former CNUCE (Italy) and at the Department of Aeronautics and Astronautics of the Kyushu University, in Japan, confirmed that the survivability concern is justified.

As an example, it was estimated at ISTI that for a high altitude (1500 km) large satellite requiring about 12 months to de-orbit, the survivability of a single-strand 5-km long tether with a diameter of less than 1 mm is as small as 10-15%

The danger represented by particles smaller than 1 cm may be overcome by increasing the tether diameter and/or resorting to a creative design. As a matter of fact, an adequate survivability (95%) has been estimated for the previous example by adopting a double strand tether structure, with a number of knots along the wire

However, a lot of work has still to be done to improve the current deployment technologies before implementing new reliable tether designs

Collision Risk with Large Space Objects [1]

Unfortunately, the risk of impact with large space objects, namely spacecraft and upper stages, cannot be reduced by modifying the tether design

It was estimated at ISTI that the expected average impact rates, per kilometer of tether length, are of the order of

- 10^{-2} - 10^{-3} per year

in the altitude (600-1000 km) and inclination (30º- 50º) intervals considered

Therefore, the probability of impact of long tethers with spacecraft and upper stages is not negligible

Important questions to be asked in this contest are:

- Will a tether impact be able to disintegrate a satellite, such as a compact piece of debris might do?
- What might be the level of damage for a spacecraft impacting a tether?

This task could require an involvement of the IADC WG3

Collision Risk with Large Space Objects [2]

Anselmo L. & Pardini C., Assessing the Impact Risk of Orbital Debris on Space Tethers, *Space Debris,* Vol. 1, No. 2, pp. 87-98, 1999

Impact rate [$yr^{-1}km^{-1}$] of large space objects with tethers

TETHER ORBIT	**AVERAGE CHARACTERISTIC SIZE OF LARGE SPACE OBJECTS**			
	1 m	**2.8 m**	**5 m**	**10 m**
Altitude: 600 km **Inclination: 30°** **Inclination: 50°**	7.02×10^{-4} 3.90×10^{-4}	1.97×10^{-3} 1.09×10^{-3}	3.51×10^{-3} 1.95×10^{-3}	7.02×10^{-3} 3.90×10^{-3}
Altitude: 800 km **Inclination: 30°** **Inclination: 50°**	8.96×10^{-4} 1.22×10^{-3}	2.51×10^{-3} 3.42×10^{-3}	4.48×10^{-3} 6.08×10^{-3}	8.96×10^{-3} 1.22×10^{-2}
Altitude: 1000 km **Inclination: 30°** **Inclination: 50°**	1.24×10^{-3} 1.24×10^{-3}	3.47×10^{-3} 3.47×10^{-3}	6.22×10^{-3} 6.21×10^{-3}	1.24×10^{-2} 1.24×10^{-2}

Collision Risk with Large Space Objects [3]

Chobotov V.A. and Mains D.L., Tether Satellite System Collision Study,

***Space Debris*, Vol. 1., No. 2, pp. 99-112, 1999**

- Analytical and statistical approaches were used to determine the tether collisions with tracked objects. The results of the two approaches were found to be in good agreement:

  - A study was performed to compute the probability of collision of the TSS (tether length = 19,700 m) after it broke away from the Space Shuttle orbiter, in February 1996. The estimated probability of collision with large objects in orbit was estimated to be on the order of 10^{-3} per month

Patera R.P., A Method for Calculating Collision Probability between a Satellite and a Space Tether, Paper AAS 01-116, AAS/AIAA Space Flight Mechanics Meeting, Santa Barbara, CA, 11-15 February 2001

- A method was developed to compute the collision probability between an orbiting object and a space tether. The methodology employed an efficient computational scheme that was successfully used in predicting the collision hazard for asymmetrical satellites. Numerical test results indicated collision probabilities significantly higher than satellite-satellite collision probabilities

Tether-tether Collisions

If many long tethers were put in space at the same time, another area of concern would be represented by the possibility of collision between them

- Tether Unlimited Inc.: tether-tether collision probabilities have not been estimated for the Terminator Tether being not a concern until a number of tethers will be in orbit at the same time
- Delta-Utec: assuming 40 de-orbiting per year, i.e. an average of 4 tethers in orbit at the same time, it should be possible to coordinate de-orbiting to avoid inter-tether collisions
- ISTI/CNR: if one hundred 5-km long tethers will be randomly distributed around the earth, between 500 km and 1500 km, an average yearly mutual collision rate of the order of 10^{-1} was estimated for the Italian EDOARD system. This value is far from negligible, therefore adding the necessity to accurately control the tether and trajectory dynamics

Lifetime of Severed Tethers [1]

Bade A., Reynolds R.C., Kessler D.J., Tethers For Power Generation On The International Space Station Alpha: Micrometeoroid And Orbital Debris Impact Study, JSC 27362, NASA/JSC, April 1996

The tether orbital evolution after severing and the orbit lifetime of a severed tether were evaluated

- Assuming a circular orbit of the tether system, the orbit of the tether including the end mass will be elliptical after the tether is cut. The longer the tether, the more eccentric the new orbit will be
- The **orbit lifetime** of the tether plus end mass depends on the tether cross-sectional area, A_T, the end mass cross section, A_E, the tether mass, M_T and the mass of the end mass, M_E..
  The tether parameters are dependent on the location of the tether cut. If the tether is cut at a distance ε from the host spacecraft (ISSA in the referenced report), then the cross sectional area and the mass of the tether fragment will be:

$$A_T(\varepsilon) = D_T(L_T - \varepsilon) = A_T(1 - \varepsilon / L_T)$$

$$M_T(\varepsilon) = (\pi \cdot D_T^{\,2} / 4 \cdot L_T \cdot \rho) \cdot (1 - \varepsilon / L_T)$$

Where D_T, L_T, and ρ are the tether diameter, length and density, respectively. The area-to-mass ratio of tether fragment plus end mass will be

$$\left(\frac{A}{M}\right)(\varepsilon) = \left(\frac{A_E + A_T(\varepsilon)}{M_E + M_T(\varepsilon)}\right)$$

Lifetime of Severed Tethers [2]

A roughly estimate of the orbital lifetime of a severed tether from different altitudes can be obtained using the area-to-mass ratio for specific configurations of tether fragment plus end mass

Conclusions [1]

An electrodynamic space tether can remove unwanted spacecraft from LEO rapidly and safely

Their low mass requirements make them highly advantageous compared to conventional rocket-based de-orbit systems

However,

Conductive tethers have out-of-plane components in their dynamics caused by the earth's magnetic field. Additional oscillations are due to the day-night effects on magnetic field, ionosphere and temperature. The dynamic instability increases with inclination and current and can be identified as one of the major items affecting the ED tether performances

Due to a very small diameter, a tether is much more vulnerable to space debris impacts than a typical spacecraft. Preliminary analyses confirm that the survivability concern is fully justified. The collision risk can be contained with multi-wire structures, but the deployment mechanisms have still to be proved in space for tethers like that proposed for EDOARD of for the Terminator Tether (Hoytether)

Conclusions [2]

Also the impact with operating spacecraft is not negligible during the de-orbit phase, so an active control from ground will be required in order to avoid collisions of the tether with large tracked objects

Also an improvement of the observational techniques, as well as orbit determination and prediction of the tethered systems, will be crucial at this point

The tether-tether collision probability does not currently represent a threat, but will become significant as soon as tens or hundreds of tethers are orbiting in space at the same time

Severed tether fragments will pose a threat to operating spacecraft