IAC-06-B6.2.10

BENEFITS AND RISKS OF USING ELECTRODYNAMIC TETHERS TO DE-ORBIT SPACECRAFT

Carmen Pardini
ISTI/CNR, Pisa, Italy
Carmen.Pardini@isti.cnr.it
Toshiya Hanada
Kyushu University, Fukuoka, Japan
toshi@aero.kyushu-u.ac.jp
Paula H. Krisko
ESCG/Jacobs, Houston, TX, USA
paula.krisko-1@nasa.gov

ABSTRACT

By using electrodynamic drag to greatly increase the orbital decay rate, an electrodynamic space tether can remove spent or dysfunctional spacecraft from low Earth orbit rapidly and safely. Moreover, the low mass requirements of such tether devices make them highly advantageous compared to conventional rocket-based de-orbit systems. However, a tether system is much more vulnerable to space debris impacts than a typical spacecraft and its design must prove to be safe to a certain confidence level before being adopted for potential applications. To assess the space debris related concerns, a new task (Action Item 19.1) on the "Potential Benefits and Risks of Using Electrodynamic Tethers for End-of-life De-orbit of LEO Spacecraft" was defined by the Inter-Agency Space Debris Coordination Committee (IADC), in March 2001. Two tests were proposed to compute the fatal impact rate of meteoroids and orbital debris on space tethers in circular orbits, at different altitudes and inclinations, as a function of the tether diameter, and to assess the survival probability of an electrodynamic tether system during typical de-orbiting missions. IADC members of three agencies, the Italian Space Agency (ASI), the Japan Aerospace Exploration Agency (JAXA) and the US National Aeronautics and Space Administration (NASA), participated in the study and different computational approaches were specifically developed in the framework of this IADC task. This paper summarizes the content of the IADC AI 19.1 Final Report. In particular, it introduces the potential benefits and risks of using tethers in space, it describes the assumptions made in the study plan, it compares and discusses the results obtained by ASI, JAXA and NASA for the two tests proposed. Some general conclusions and recommendations are eventually highlighted as a result of a massive and intensive study.

DE-ORBITING SPACECRAFT WITH ELECTRODYNAMIC TETHERS

Over nine thousand satellites and other trackable objects are currently in orbit around the Earth, along with many smaller particles. As the low Earth orbit (LEO) is not a limitless resource, some sort of debris mitigation measures are needed to solve the problem of unusable satellites and spent upper stages.

Despite a small number of full-scale experiments made so far using space tethers[1], the possibility of de-orbiting spacecraft by means of electrodynamic tethers has been on the drawing board of theorists for almost a decade. Various conducting tether configurations have been studied and their de-orbiting performances have been extensively assessed by several authors[2-12].

The electrodynamic drag concept is based on the exploitation of the Lorentz force due to the interaction between the electric current flowing in a conductive tether and the geomagnetic field. The decelerating Lorentz force $\vec{F}$ (electrodynamic drag) depends in a complex way on the design parameters of the system, the orbit and the characteristics of the local ionosphere[3,13]:

$$\vec{F} = \int_0^L I(l)\, d\vec{l} \times \vec{B} \qquad (1)$$

where $I(l)$ is the current flowing in the tether, $d\vec{l}$ is the differential element of tether length L and $\vec{B}$ is the local geomagnetic field. The electric current in the tether is self-sustained by the induced voltage Φ, generated by the relative motion of the system across the magnetic field[13]:

$$\Phi = \int_{0}^{L} \left(\vec{v} \times \vec{B}\right) \cdot d\vec{l} \qquad (2)$$

where $\vec{v}$ is the relative velocity vector of the tether with respect to the magnetic field. The mechanical power P dissipated by the drag force can be expressed as[13]:

$$P = \vec{F} \cdot \vec{v} \qquad (3)$$

while the time Δt needed to lower a satellite in circular orbit from the radius a_2 to the radius a_1 (with $a_1 < a_2$) is given by[3,13]:

$$\Delta t = \int_{a_1}^{a_2} \frac{\mu_{\oplus}\, m}{2\, a^2\, P}\, da \qquad (4)$$

where $\mu_{\oplus}$ is the Earth's gravitational parameter, m is the satellite mass including the tether system and a is the orbital radius.

The decay rate is greater at relatively low altitudes, due to the larger currents sustained by the higher density of the ionospheric plasma. The maximum efficiency is possible for equatorial orbits, due to a combination of larger induced voltages and ionospheric densities. At high inclinations, the relative geometry of orbital motion and geomagnetic field is much less favourable, the density of ionospheric ions is relatively low and the electrodynamic drag, if any, is significantly less effective.

Another important parameter to be considered is the tether length L, whose value determines the induced voltage and, therefore, together with the impedance, the current flowing in the system. Typically, shorter tethers imply significantly longer de-orbit times, due to smaller induced voltages and currents. However, although the performances of long tethers are attractive, the price to pay in terms of mass penalty, risk of arching and space debris impact might be too high for reliable operations.

Prototypes of Electrodynamic Tether Devices

Following the Loftus' seminal idea, in June 1996, of using electrodynamic drag to remove unusable spacecraft from low Earth orbit, the American Tether Unlimited Inc. (TUI) company, founded in 1994 by Robert P. Hoyt and Robert L. Forward to develop products based on space tether technologies, took up developing a lightweight and reliable space tether system, called the Terminator Tether^{TM}. The design of the conducting tether will depend on the mass and orbit of the host satellite. For typical LEO satellites, the tether will have a length of 5-7.5 km and a mass of 1-2% of the host spacecraft. The de-orbit times computed by Hoyt and Forward[14] for a 7.5 km electrodynamic tether, with a mass of 1% of the host spacecraft, to decrease the altitude of a 1500 kg spacecraft to 250 km, are given in Table 1.

Initial Height [km]	Orbit Inclination			
	0°	25°	50°	75°
	DE-ORBIT TIME [days]			
1400	170	220	325	EDT not used
1300	140	185	280	
1200	120	155	230	
1100	95	125	185	
1000	70	95	140	375
900	55	70	110	280
800	45	55	80	200
700	30	40	55	140
600	20	30	40	80
500	15	20	25	40
400	10	15	15	20

Table 1: Time to de-orbit a 1500 kg spacecraft from a given initial altitude to 250 km with a 7.5 km Terminator Tether^{TM} with a mass of 1% of the S/C.

The concept of the Electrodynamic De-Orbiting And Re-entry Device (EDOARD) has been also jointly developed in Italy by Alenia Spazio and the University “La Sapienza” in view of potential commercial exploitations[15]. The EDOARD system is based on a 4-5 km long conductive tether, and its mass is envisaged to be less than 30-35 kg, that is between 1% and 5% of the host satellite at launch. EDOARD is conceived to be applicable to vehicles in the 600 to 4000 kg mass range, orbit altitude between 600 and 2000 km and orbital inclination up to 65°. It is intended to provide the carrier spacecraft with an electrodynamic device able to de-orbit it within a few months.

Prototypes of electrodynamic tether systems (EDTS) to de-orbit spacecraft have been also investigated by the Dutch Delta-Utec Space Research & Consultancy company[4].

As a matter of fact, for typical electrodynamic tether lengths of 5-10 km, the Lorentz force reduces the mean altitude of the tethered system orbit at rates from 2 to 50 km per day, decreasing with increasing the payload mass, inclination and altitude.

POTENTIAL BENEFITS AND RISKS OF USING ELECTRODYNAMIC TETHERS TO DE-ORBIT SPACECRAFT

Benefits: Saving the Mass

The major advantage of the tether technology compared to other propulsion systems is that it does not require any propellant. While conventional chemical thrusters need a mass allocation that is a significant fraction (10-20%) of the total mass to be disposed of, a typical electrodynamic tether system, weighting about 30-50 kg, can achieve de-orbit of spacecraft requiring only a few percent (1-5%) of the carrier vehicle mass at launch. Moreover, chemical thrusters should be able to reliably operate for mission times longer than the usual applications they were designed for. A tethered system, instead, would be inactive during the mission, while waiting for a command to de-orbit the spacecraft at the end-of-life. Therefore, by eliminating the need to launch and store in orbit for many years a large amount of propellant, electrodynamic tethers can greatly reduce the cost and improve the reliability of in-space propulsion and operations.

Benefits: Reducing the De-orbit Times

Another benefit of using electrodynamic tethers is that the time to de-orbit spacecraft from LEO can be many order of magnitude faster than the decay under the influence of the atmospheric drag alone. For a typical satellite above 500 km, affected by the sole natural orbit perturbations, the orbital lifetime can be tens to thousands of years. On the other hand, the Terminator Tether^{TM} or the EDOARD system might de-orbit a satellite from various LEO orbits within a few weeks to a few months.

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

The main objective of a de-orbit technology is to remove dead and unwanted spacecraft from orbit so that they cannot pose a collision threat to other operational spacecraft. Of course, the use of a long tether will greatly increase the cross-sectional area of the spacecraft system, raising, in turn, the probability that the system will suffer an accidental collision during the mission. However, this probability depends not only on the cross-sectional area, but also upon the amount of time the satellite spends in orbit. For a satellite left to de-orbit by aerodynamic drag only, the cross-sectional area is relatively small, but the amount of time needed to re-enter the Earth's atmosphere can be many hundreds or thousands of years. Nonetheless, even if an electrodynamic tether increases the satellite system cross-sectional area, the orbital decay rate is large enough to compensate the first effect and to greatly reduce the risk for the tethered system to collide with other spacecraft.

Therefore, according to Forward and Hoyt[16], the criterion to evaluate the effectiveness of a de-orbit technique is not just whether it reduces the orbital lifetime compared to the atmospheric drag decay, but whether it reduces the product of the orbital lifetime and collision cross-sectional area of the spacecraft, namely the Area-Time-Product: ATP. As a matter of fact, they also demonstrated that the Terminator Tether^{TM} can significantly reduce the ATP value for most LEO orbits[16].

Risks: Space Debris Related Concerns

Tethers are usually very long and thin, providing increased opportunities for something to go wrong.

The accidental tether severing may be due to a number of causes including manufacturing defects, system malfunctions, material degradation, vibrations, and contact with other spacecraft elements. Most of these causes can be prevented through design, quality check and active control of the tether dynamics and stability during the mission.

However, due to their peculiar characteristics, tethers in space introduce unusual problems when viewed from the space debris perspective. They present a much greater risk to operating satellites due to their considerably 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. The resulting tether remnants may pose additional risks to operating spacecraft.

Therefore, before electrodynamic tethers can be used to mitigate the problem of orbital debris, various problems have to be investigated:

1. to evaluate the impact of tethers on the space environment, i.e. to determine the tether collision risk with operating spacecraft, the risk posed by the tether remnants after severing, the chance of collision among the tethers themselves;

2. to assess the tether survivability, i.e. to evaluate the risk for a tether of being cut during the mission by orbital debris and meteoroids.

Impact of Tethers on the Space Environment

Collision Risk with Large Space Objects

The potential risk for collisions or close encounters with other space objects is a critical aspect for many space tether applications, representing a likely risk both to the tether system integrity and to the safety of operational spacecraft. The risk of impact with the largest space objects, typically spacecraft and upper stages, cannot be reduced by modifying the tether design or increasing the tether diameter[17]. Anselmo and Pardini[18] estimated the expected average impact rates, per km of tether per year, as a function of the average size of the large space objects at different orbit altitudes (H) and inclinations (I) (see Table 2). The value of 2.80 m corresponds to the average size of objects larger than 1 m, computed with the CNUCE Orbital Debris Reference model 1997[19], assuming a spherical approximation of debris particles. The values for smaller (1 m) and larger (5 m, 10 m) characteristic sizes are provided as well to take into account the possible deviation of typical objects from the spherical or box-like shape.

Tether Orbit	AVERAGE CHARACTERISTIC SIZE OF LARGE SPACE OBJECTS			
	1 m	2.8 m	5 m	10 m
H: 600 km				
I: 30°	$7.02\cdot10^{-4}$	$1.97\cdot10^{-3}$	$3.51\cdot10^{-3}$	$7.02\cdot10^{-3}$
I: 50°	$3.90\cdot10^{-4}$	$1.09\cdot10^{-3}$	$1.95\cdot10^{-3}$	$3.90\cdot10^{-3}$
H: 800 km				
I: 30°	$8.96\cdot10^{-4}$	$2.51\cdot10^{-3}$	$4.48\cdot10^{-3}$	$8.96\cdot10^{-3}$
I: 50°	$1.22\cdot10^{-3}$	$3.42\cdot10^{-3}$	$6.08\cdot10^{-3}$	$1.22\cdot10^{-2}$
H: 1000 km				
I: 30°	$1.24\cdot10^{-3}$	$3.47\cdot10^{-3}$	$6.22\cdot10^{-3}$	$1.24\cdot10^{-2}$
I: 50°	$1.24\cdot10^{-3}$	$3.47\cdot10^{-3}$	$6.21\cdot10^{-3}$	$1.24\cdot10^{-2}$

Table 2: Impact rate [$yr^{-1}\ km^{-1}$] of large space objects with tethers.

With reference to Table 2, Anselmo and Pardini concluded that if tens, or hundreds, of such systems (several kilometers long) were employed at the same time, the situation in low Earth orbit could become critical, even limiting the concern to operational satellites (in that case, the impact rates given in Table 2 should be reduced by an order of magnitude). Analytical and statistical approaches were also developed and used by other authors to determine the probability for a tether to collide with tracked objects[20-23].

All studies carried out so far confirm that the probability of impact of long tethers with spacecraft and upper stages is still small, but not negligible. Therefore, an active control of the tether during the mission is needed to prevent possible impacts with operating spacecraft.

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.

The collision probability among tethers was not estimated by the US Tether Unlimited Inc. company when conceiving the Terminator Tether de-orbiting device. This, in fact, will not be a concern until a number of tethers will be in orbit at the same time[24].

In the same way, the Dutch Delta-Utec Space Research & Consultancy company concluded that if 40 de-orbiting per year are assumed, i.e. an average of 4 tethers are in orbit at the same time, it should be possible to coordinate de-orbiting to avoid inter-tether collisions[4].

Therefore, only if many uncontrolled tethers are in orbit at the same time the collision probability among them may be far from negligible. To evaluate this likelihood, Anselmo and Pardini[17] estimated the mutual collision rate among one hundred 5-km tethers randomly distributed around the Earth, between 500 km and 1500 km, and based on the Italian EDOARD system concept. They found an average mutual collision rate of the order of 10^{-1} per year for the Italian system under study. Such a value would be far from negligible, adding further more weight to the need, for future tether systems, of the capability to control their internal and trajectory dynamics.

Tethers Survivability Concerns

Tethers are particularly vulnerable to small artificial and natural debris impacts, because – at the very high relative velocities characterizing the collisions – even a particle smaller than one half of the tether diameter may cut a single strand wire. A single hit by a very small particle may therefore produce a critical failure of the tether, while reducing its lifetime to times much shorter than the mission duration. Of course, although single line tethers lifetimes can be improved by increasing the tether diameter, this incurs a prohibitive mass penalty as well as additional operational problems. Therefore, strands with ultra high strength characteristics, together with more creative tether designs, like multi-strand structures[25], should be realized to reduce the tether vulnerability to space debris impacts.

The critical size of a particle able to sever the tether is affected by the tether material as well as by the tether design, and it can only be determined by the hypervelocity impact test results. However, many new resistant materials and combinations of these have not been thoroughly characterized yet for the effects of hypervelocity impacts by either meteoroids or orbital debris particles. On the other hand, only a few laboratory experiments have been carried out using aluminium tethers of normal design, proving that an aluminium, single strand, tether may be cut by a particle 1/3 of its diameter, while one of woven aluminium could be severed by particles 1/2 of its diameter[1,26]. Moreover, an adequately large space debris may sever a tether provided its edge passes within 0.20-0.35 D_T (tether diameter) of the tether's centre of axial symmetry[1].

Proposals to Reduce the Tether Vulnerability

An innovative configuration to reduce the EDOARD system vulnerability to space debris impacts was proposed by Alenia Spazio, in Italy[27]. The new design envisaged a two bare metallic strands, 0.7 mm in diameter each, forming N loops tied together in N+1 equidistant knots along the tether (Figure 1).

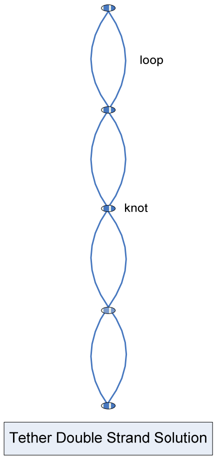

Fig. 1: Conceptual illustration of the double strand solution like that proposed by Alenia Spazio.

A similar structure was also investigated at the Department of Aeronautics and Astronautics of the Kyushu University in Japan[28]. The double tether solution was also taken into account and analysed to increase the survival probability of the Kyushu University Tether Experiment (QTEX)[29].

The US Tether Unlimited Inc. company proposed the long-life, damage-resistant tether design called Hoytether^{TM}. The Hoytether is a structure composed of multiple lines with redundant interlinking that is able to withstand many impacts[25]. Through analytical and numerical simulations, the Hoytether's designers proved that this is a fail safe long-lived structure that can replace a single strand tether imposing a minimal mass penalty.

The Probability of Severing a Single Line Tether

Due to their peculiar structure and geometry, space tethers cannot be treated as a conventional spacecraft. In fact, the thinness and orientation (practically gravity-gradient) of tethers introduce a few differences in the calculation of the flux and effective cross-sectional area. Therefore, the number of impacts to be expected (N_T) on a single line tether can be expressed in terms of the differential (with respect to size d) flux of particles ($d\varphi$) as follows:

$$N_T = \Delta t \cdot \int_{d_C}^{\infty} A(d)\, d\varphi(d) \qquad (5)$$

where $A(d)$ is the tether effective cross-sectional area, also a function of particle size, and Δt is the tether orbit lifetime. Whether d_C is the minimum size of particles able to sever the tether, N_T is the number of fatal impacts to be expected. Defining the fatal impact rate, R_F, as the number of impacts able to cut a single line tether in a given time (for instance one year):

$$R_F = \int_{d_C}^{\infty} A(d)\, d\varphi(d) \qquad (6)$$

Eq. 5 can be rewritten as:

$$N_T = R_F \cdot \Delta t \qquad (7)$$

The probability (P_n) of n fatal impacts occurring in an elapsed time Δt can be expressed by the Poisson's distribution as follows:

$$P_n = \frac{{N_T}^n e^{-N_T}}{n!} \qquad (8)$$

thus, the probability of no random particle impacts occurrences ($n = 0$) is:

$$P_0 = e^{-N_T} \tag{9}$$

and the probability for at least one collision to occur (P_1) is given by:

$$P_1 = 1 - P_0 = 1 - e^{-N_T} \tag{10}$$

Substituting Eq. 7 into Eq. 10, the probability P of severing a single filament tether in a certain time interval Δt is then computed as:

$$P = 1 - e^{-R_F \, \Delta t} \tag{11}$$

The relationships to compute the probability of severing specific tether structures, other than the single line, during typical de-orbiting missions have been developed in the framework of the IADC AI 19.1 and have been described in detail in Section 5 of the Action Item Final Report[30]. A summary of the techniques developed is also presented in this paper in the section on “Mathematical Approaches”.

STUDY PLAN FOR THE IADC AI 19.1

The electrodynamic tether drag may actually provide a cost effective method for de-orbiting low Earth satellites in order to mitigate the growth of orbital debris.

However, a tether system is much more vulnerable to space debris impacts than a typical spacecraft and its design must prove to be safe to a certain confidence level before being adopted for potential applications. As a matter of fact, a de-orbiting mission will be possible provided the tether will maintain its integrity. Therefore, since the tether-tether collision chance does not currently present a threat, the impact with operating spacecraft can be avoided by an active control of the tether during the mission, the accidental tether severing can be prevented through design, quality check and active control of the tether dynamics and stability, thus the main threat to tethers in space is from collisions with meteoroids and orbital debris too small to be detected and avoided.

For the above mentioned reasons, the study plan of the IADC Action Item 19.1 was formulated with the main objective of investigating the potential risk to the tether system integrity due to impacts with meteoroids and orbital debris.

Two tests were proposed:

1) to compute the fatal impact rate of meteoroids and orbital debris on space tethers in circular orbit, at different altitudes and inclinations, as a function of the tether diameter;
2) to assess the survival probability of a specific electrodynamic tether system during typical de-orbiting missions.

The fatal impact rate (see Eq. 6), in ($yr^{-1}km^{-1}$), was computed at different orbit altitudes and inclinations, as a function of the tether diameter, according to Table 3.

Orbit Altitudes [km]	Orbit Inclinations [deg]	Tether Diameter [mm]
1400	25, 50, 75	0.50, 0.75, 1, 2.5, 5, 10, 25, 50
1000	25, 50, 75	0.50, 0.75, 1, 2.5, 5, 10, 25, 50
800	25, 50, 75	0.50, 0.75, 1, 2.5, 5, 10, 25, 50

Table 3: Tether orbits and diameters considered in the first IADC AI 19.1 test.

Realistic de-orbiting scenarios based on the concept of the Terminator Tether, from Tether Unlimited Inc.[14], were simulated in the second AI 19.1 test. Detailed computations were carried out for typical de-orbiting missions (see Table 1) of a 1500 kg spacecraft, with initial altitudes of 800 km, 1000 km and 1400 km and orbital inclinations of 0°, 25°, 50° and 75°.

Main Study Assumptions

Space Debris Flux Models

The environment model used for the first AI 19.1 test was the NASA’s ORDEM2000 model[31], coupled with the Grün meteoroids model[32]. Figure 2 represents the total debris flux, obtained by summing the contributions of ORDEM2000 and Grün at epoch January 2003 .

For the second AI 19.1 test on the survivability analysis, two different representations of the environment were assumed:

I. ORDEM2000[31] (orbital debris) coupled with Grün[32] (meteoroids) at epoch January 2001;

II. MASTER-2001[33] (orbital debris and meteoroids). The analyst application was used to obtain more accurate debris fluxes at the reference epoch of the model, i.e. May 5th, 2001.

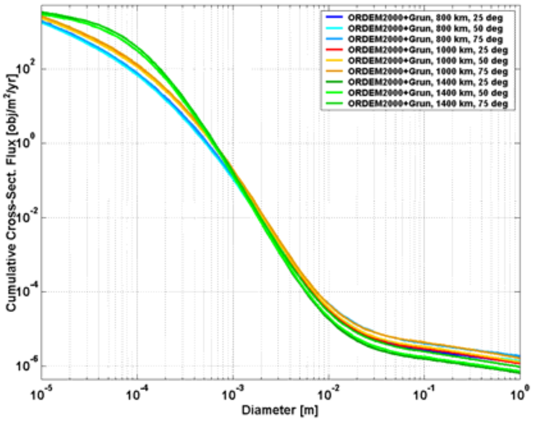

Fig.2: Cumulative flux of orbital debris (ORDEM2000) and meteoroids (Grün) at 800, 1000, 1400 km, i = 25°, 50°, 75°, versus debris diameter. Reference epoch: January 2003.

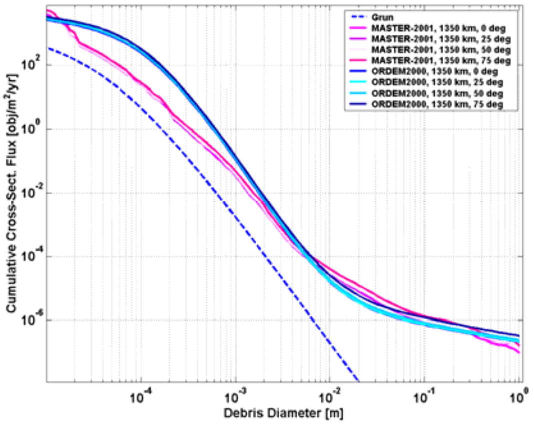

Fig. 3: MASTER-2001, ORDEM2000 & Grün cumulative flux versus debris diameter at 1350 km, i = 0°, 25°, 50°, 75°.

The debris flux was estimated in the middle of each altitude shell crossed during the de-orbiting mission, i.e. 1350, 1250, 1150, 1050, 950, 850, 750, 650, 550, 450, 325 km, and inclinations of 0°, 25°, 50° and 75°. Figures 3 and 4 exemplify some differences between the environmental models at the altitudes of 1350 km and 325 km, respectively.

Large differences exist in the flux versus particle diameter distribution computed by the ESA and NASA models, with ORDEM2000 predicting fluxes up to one order of magnitude higher than MASTER-2001 in the significant diameter region of less than 1 mm[34].

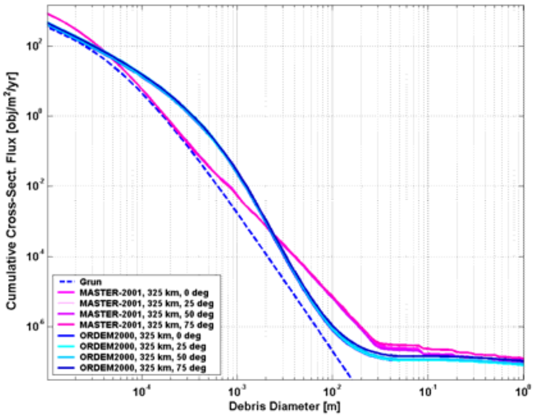

Fig. 4: MASTER-2001, ORDEM2000 & Grün cumulative flux versus debris diameter at 325 km, i = 0°, 25°, 50°, 75°.

Tether Orbital Configurations and Designs

The tethers orbital configurations and designs assumed in the AI 19.1 study plan were very simple. Tethers were supposed to be in circular orbit and aligned along the gravity gradient. Two basically different and very simple designs were considered (see Figure 5):

1) Single tether, with a single wire or a compact cylindrical multi-line structure;

2) Double tethers, in which two cables are separated from each other by a distance significantly larger than their diameter and form *N* loops, tied together in *N*+1 equidistant knots.

Tethers with a length of 5 km, 7.5 km and 10 km, of single line design, were considered in the first AI 19.1 test, adopting wires with diameters of 0.50 mm, 0.75 mm, 1 mm, 2.5 mm, 5 mm, 1 cm, 2.5 cm and 5 cm.

Tethers of length 7.5 km, with both single and double line designs, were considered in the second AI 19.1 test, adopting conducting wires with diameter of 0.5 mm and 1 mm. With regards to the double line solution, three configurations, where the length of each tether loop was 5 m, 10 m and 100 m, were simulated.

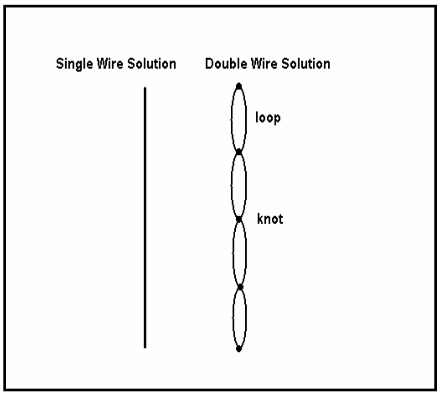

Fig. 5: Single and double line tether designs.

Tether Vulnerability to Space Debris Impacts

A single tether was assumed to be severed by a space debris with a diameter d larger than a certain fraction f of the tether diameter D_T

$$d \geq d_C = f \cdot D_T \tag{12}$$

where d_C is defined as the minimum fatal debris diameter, provided that the debris edge passes within a critical distance $D_{TC}/2$ from the longitudinal axis of symmetry of the tether (see Figure 6).

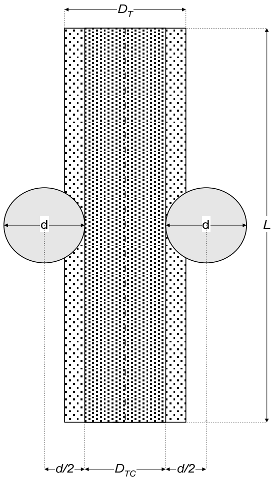

Fig. 6: Definition of the tether effective cross-sectional area with respect to the fatal debris impacts.

The following conjecture on the tether vulnerability was considered in the first test of AI 19.1:

$$d_C = 0.25 \cdot D_T \text{ and } D_{TC} = 0.7 \cdot D_T \tag{13}$$

The following two conjectures were adopted in the second AI 19.1 test:

1. $d_C = 0.25 \cdot D_T$ and $D_{TC} = 0.7 \cdot D_T$ (14)
2. $d_C = 0.33 \cdot D_T$ and $D_{TC} = 0.7 \cdot D_T$ (15)

Moreover, it was assumed that each strand in a loop of a double line system is so separated from the other that there is no chance for one piece of debris to sever both. A negligible cross-sectional area of the knots was supposed as well.

MATHEMATICAL APPROACHES

Different computational approaches were specifically developed in the framework of the IADC Action Item 19.1; other techniques, coming from past research and experience in the field, were instead revised and improved. A detailed description of the mathematical approaches developed at ISTI, Kyushu University (KU) and NASA/JSC is given in the AI 19.1 Final Report[30]. Some basic elements are provided in this paper.

The ISTI/CNR Approach

Survivability of a Single Tether

For a single line tether, the fatal impact rate is obtained using Eq. 6, expressing the tether effective cross-sectional area $A(d)$ as:

$$A(d) = L\,(D_{TC} + d) \tag{16}$$

where L is the tether length, d is the debris diameter and D_{TC} is the critical tether diameter (see Figure 6). Thus, the probability P that the tether is severed in a certain time interval Δt is determined according to Eq. 11.

Concerning the overall survival/sever probability during a full de-orbiting mission that follows a certain orbital decay profile, the same approach described at the end of the next subsection is adopted (see Eqs. 21 and 22).

Survivability of a Double Strand Tether

A numerical multi-step algorithm was developed at ISTI[35] to assess the survivability of double line tethers with the basic design outlined in Figure 5. It is based on the simplifying hypotheses of a distance between the two cables significantly larger than their diameter and a negligible volume of the knots along the tether.

For each relatively small altitude interval in which the decay profile is subdivided, it computes:

1. the sever probability of a single cable of length L/N;
2. the sever and survival probability of both lines of the same tether loop;
3. the survival and sever probability of the whole tether.

The fatal impact rate is estimated in the middle of every i^{th} height interval, characterized by a decay time $\Delta t(i)$. If $P(n, i)$ is the sever probability of a single wire in the n^{th} tether loop and i^{th} altitude interval, computed using Eq. 11, the sever probability of both wires in the same tether loop (P_{SE}) is given by:

$$P_{SE}(n,i)=\left[P(n,i)\right]^2 \qquad (17)$$

while the corresponding survival probability (P_{SU}) is:

$$P_{SU}(n,i)=1-P_{SE}(n,i) \qquad (18)$$

The tether is severed if both wires of at least one of its loops are cut. On the other hand, the tether survives if all loops maintain at least one intact line. Therefore, the survival probability of the whole tether (P_{SU_T}) in the i^{th} altitude interval can be expressed as:

$$P_{SU\_T}(i)=\prod_{n=1}^{N}P_{SU}(n,i)=\left[P_{SU}(n,i)\right]^N \qquad (19)$$

where N is the number of loops along the tether, while the corresponding sever probability (P_{SE_T}) is given by:

$$P_{SE\_T}(i)=1-P_{SU\_T}(i) \qquad (20)$$

The altitude of an electrodynamic tether for satellite de-orbiting changes during the mission, and with it also the debris fatal impact rate. In order to take into account the orbital debris and meteoroids flux variation, as a function of the decreasing altitude, the overall altitude range traversed by the tether is subdivided in H relatively small altitude intervals, in which the space debris flux can be assumed constant. Because the tether – single or double line – survives during the de-orbiting mission only if it survives in each altitude interval, the overall survival probability during the mission (P_{SU_M}) is given by:

$$P_{SU\_M}=\prod_{i=1}^{H}P_{SU\_T}(i) \qquad (21)$$

while the total sever probability during the mission (P_{SE_M}) may be expressed as follows:

$$P_{SE\_M}=1-P_{SU\_M} \qquad (22)$$

The Kyushu University Method

Single Tether

Kyushu University uses the same ISTI relationships to express the tether effective cross-sectional area (see Eq. 16) and the fatal impact rate (see Eq. 6). However, KU introduces a probability state variable $X(t)$ to describe the survival probability. Thus, the probability that the tether survives after a certain time t is expressed as:

$$X(t)=X(0)\exp\left[-R_F t\right] \qquad (23)$$

where $X(0)$ denotes the initial condition. Details to numerically estimate the fatal impact rate, R_F, are provided in Ref. 30.

Double Tether

Unlike ISTI/CNR, Kyushu University assumes a finite distance between the two wires of a loop, so that they might be severed simultaneously by a single impact. In addition, the knots have a finite volume and they also might be severed by a single impact. Therefore, the double tether considered herein (see Figure 7) may be severed when:

1. a knot is severed by a single impact;
2. both wires of a same loop are severed together by a single impact;
3. both wires of a same loop are severed independently by two impacts.

As shown in Figure 7, a knot is simplified by a circular cylinder with a length of 3.0 D_T and a diameter of 2.5 D_T so that the sever probability for a knot can be estimated as for a single tether.

The status of a loop of the double tether considered herein can be characterized in three different ways depending on the number of wires that survive in the loop itself (see Figure 8), namely:

Status 2: both two wires survive;
Status 1: one wire survives but the other is severed;
Status 0: both two wires are severed.

At the beginning of a mission, the status of the loop may be "Status 2." The status may transit from "Status 2" to "Status 0" through "Status 1," or directly from "Status 2" to "Status 0." The former transition process means that two wires of the loop are severed independently by two impacts, whereas the latter transition process means that both two wires of the loop are severed together by a single impact. The aforementioned status transition progressions are herein treated as a stochastic process.

Let status variables $X_2(t)$, $X_1(t)$ and $X_0(t)$ represent the probability that the status will be, respectively, “Status 2”, “Status 1”, and “Status 0” at the time t. Thus, the sum of the probabilistic status variables is unity. Denoting the transition rate from “Status i” to “Status j” by R_{Fij} (here the subscripts i and j refer, respectively, to the initial number of wires and the number of wires survived after a single impact), then the relationships among the probabilistic status variables can be expressed as a set of simultaneous differential equations[30]:

$$\frac{dX_2(t)}{dt} = -(R_{F20} + R_{F21})X_2(t) \tag{24}$$

$$\frac{dX_1(t)}{dt} = R_{F21}X_2(t) - R_{F10}X_1(t) \tag{25}$$

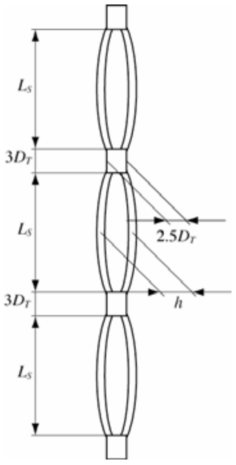

Fig. 7: Double tether design considered at Kyushu University.

Eqs. 24 and 25 are solved assuming constant transition rates[30]. Thus, the probability that the loop survives after a certain time t is computed by the sum of $X_2(t)+X_1(t)$.

Finally, if $X_{knot}(t)$ denotes the survival probability for a knot, the survival probability of the entire double line tether system, $X_T(t)$, is expressed by the following relationship:

$$X_T(t) = \left(X_1(t) + X_2(t)\right)^N \left(X_{knot}(t)\right)^{N+1} \tag{26}$$

where N is the number of loops along the tether.

Eq. 26 is solved after evaluating the transition rates, R_{Fij}, as described in the AI 19.1 Final Report[30]. In order to estimate the transition rates from “Status 2” to “Status 1” and from “Status 2” to “Status 0,” the in-coming direction of orbital debris was taken into account as well[30].

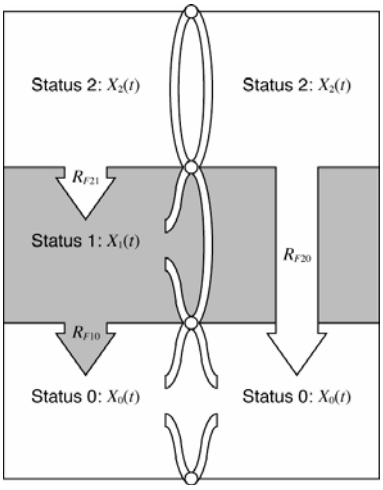

Figure 8. Status of a loop of the double tether characterized in three different ways depending on the number of wires that survive in the loop itself.

Modifications of the KU Method According to the AI 19.1 Requirements

To fulfil the AI 19.1 requirements for the double line tether design, i.e. the two cables are separated from each other by a distance significantly larger than their diameter and the knots have a negligible cross-sectional area, Kyushu University may assume an infinite distance between the two wires and ignore the volume of the knots. With these assumptions, the survival probability of the entire double line tether system at a given altitude becomes:

$$X_T(t) = \left(X_1(t) + X_2(t)\right)^N \tag{27}$$

The Kyushu University method can also be applied, with some specific additions, to the survivability assessment of an electrodynamic tether during de-orbiting missions. To make this, the altitude range traversed by the tether is split into a number of relatively small altitude bins where the space debris flux may be assumed constant.

Denoting the transition rates at the h-th altitude bin by R_{Fij}^{h}, the total time to descend the h-th altitude bin from the initial altitude by t_h, and the duration necessary to descend the h-th altitude bin by Δt_h, then the probability that each loop survives after the completion of the mission is expressed by:

$$X_2(t_H) + X_1(t_H) = \left(2 - \exp\left[-\sum_{h=1}^{H} R_{F10}^{h}\,\Delta t_h\right]\right)\cdot \exp\left[-\sum_{h=1}^{H} R_{F10}^{h}\,\Delta t_h\right] \tag{28}$$

where H is the total number of altitudes intervals crossed during the mission. Eventually, the overall survival probability of the entire double line tether system is computed as follows:

$$\left(X_2(t_H) + X_1(t_H)\right)^N \tag{29}$$

The NASA/JSC Method

The JSC method has been developed starting from the interim geometric model proposed by Anz-Meador[36] to evaluate the probability of severing a tether once it is struck by a meteoroids or orbital debris particle. This model combined with the AI 19.1 specified test conditions results in a NASA/JSC methodology that is essentially the same as that of ISTI/CNR.

Following the Anz-Meador model, the probability, $P_C(d)$, of the tether being cut by a particle with diameter d may be expressed as:

$$P_C(d) = \left(1.0 - 2\cdot\alpha\cdot[1.0+\beta]^{-1}\right)\cdot\Theta(\beta-\alpha) \tag{30}$$

where α can be considered as a "gouging factor", and is defined as the decimal percentage of the tether's width, or diameter (D_T) for a cylindrical wire, which must be removed from the edge to sever a tether under tension, and β is the ratio between the debris diameter (d) and the tether diameter (D_T).

Herein, the parameter α is obtained as a corollary of the critical tether diameter (D_{TC}) defined in the AI 19.1 study plan (see Fig. 6 and Eqs. 14, 15) and it is computed as follows:

$$\alpha = \frac{\left(D_T - D_{TC}\right)}{2\cdot D_T} \tag{31}$$

In Eq. 30, Θ is the Heaviside function defined as being zero (0) for negative arguments and one (1) for positive arguments. The tether cross-sectional area, $A_T(d)$, is expressed in terms of the tether's length (L), the tether's diameter, (D_T) and the debris diameter (d) as follows:

$$A_T(d) = L\cdot\left(D_T + d\right) \tag{32}$$

Thus, the **e**ffective cross-sectional area for severing the tether, $A_{TS}(d)$, is given by:

$$A_{TS}(d) = P_C(d)\cdot A_T(d) \tag{33}$$

with $P_C(d)$ computed by Eq. 30.

The impact rate of space debris on a tether at a given orbit altitude and inclination is computed for each size bin of the debris flux file generated with the environmental model. Thus, if $\Delta\varphi_i$ is the differential debris flux corresponding to the i-th debris size bin (Δd_i), the impact rate per diameter bin, $R_I(\Delta d_i)$, in the interval of time Δt can be expressed as:

$$R_I(\Delta d_i) = \Delta\varphi_i\cdot A_T(d_i)\cdot\Delta t \tag{34}$$

where d_i is assumed to be the debris diameter at the beginning the i-th size bin. The fatal impact rate, $R_{IF}(\Delta d_i)$, in the same debris size bin is computed as follows:

$$R_{IF}(\Delta d_i) = P_C(d_i)\cdot R_I(\Delta d_i) \tag{35}$$

Single line tether

The sever probability of a single line tether at a given altitude and inclination is computed for each debris size bin using the Poisson's distribution (see Eq. 8) for a single severing collision event (i.e. n = 1). Herein, the number of fatal impacts to be expected (N) is computed as:

$$N = P_C(d_i)\cdot R_I(\Delta d_i) \tag{36}$$

So, the probability of a single severing event for diameter bin (Δd_i), is $P_{SEV}(\Delta d_i)$:

$$P_{SEV}(\Delta d_i) = P_C(d_i)\cdot R_I(\Delta d_i)\cdot \exp\left[-P_C(d_i)\cdot R_I(\Delta d_i)\right] \tag{37}$$

The survival probability of the tether in the same size bin, $P_{SUR}(\Delta d_i)$, is then computed as:

$$P_{SUR}(\Delta d_i) = 1 - P_{SEV}(\Delta d_i) \tag{38}$$

At this point, the JSC's model assumes that if the tether survives the impact of debris in each size bin, then it survives the impact of all debris. Therefore, the total survival probability of a single line tether at a given altitude and inclination, $P_{SUR\_ST}(h)$ may be expressed as:

$$P_{SUR\_ST}(h)=\prod_{i=1}^{I} P_{SUR}(\Delta d_i) \tag{39}$$

The variable I is the total number of debris size bins considered, from the first one to the last within the debris flux file.

The survival probability of a single line tether during a de-orbiting mission (P_{SUR_STM}) is evaluated using the same ISTI/CNR approach, i.e., the tether is supposed to survive during the mission if it survives in each altitude interval. Using the JSC symbols, Eq. 21 can be rewritten as:

$$P_{SUR\_STM}=\prod_{h=1}^{H} P_{SUR\_ST}(h) \tag{40}$$

with H as the total number of altitude intervals crossed during the mission.

Double line tether

Like ISTI, JSC assumes that each strand in a loop (see Figure 5) is so separated from the other that there is no chance for one piece of debris to sever both. Moreover, the sever events for each strand are independent of any other strand and the tether is supposed to be severed if one loop (two adjacent strands) is cut.

For a double line tether with N loops, each strand of each loop is considered in turn. Thus, Eqs. 32, 33, are applied to compute the effective cross-sectional area of each loop's strand with length $L = L_S$, and Eqs. 37, 38, 39 are used to compute the sever/survival probability of a strand at a given orbit altitude and inclination. Afterwards, if $P_{SUR\_Strand1}(h,l)$ and $P_{SUR\_Strand2}(h,l)$ are, respectively, the survival probabilities of the first and second strand of a loop l, computed according to Eq. 39, the survival probability of a loop, $P_{SUR\_Loop}(h,l)$, can be expressed as:

$$P_{SUR\_Loop}(h,l)=P_{SUR\_Strand1}(h,l)\cdot P_{SUR\_Strand2}(h,l) \tag{41}$$

The survival probability of the whole double line tether, $P_{SUR\_DT}(h)$, at a given altitude and inclination is then computed by multiplying the survival probabilities for each tether loop considered along the tether itself, i.e.:

$$P_{SUR\_DT}(h)=\prod_{l=1}^{N} P_{SUR\_Loop}(h,l) \tag{42}$$

Eventually, the survival probability of a double line tether during a de-orbiting mission, P_{SUR_DTM}, is evaluated as in the case of a single tether (see Eq. 40) as follows:

$$P_{SUR\_DTM}=\prod_{h=1}^{H} P_{SUR\_DT}(h) \tag{43}$$

RESULTS OF THE FIRST IADC AI 19.1 TEST

The approaches developed at ISTI, KU and JSC for a single line tether were applied to compute the fatal impact rate of meteoroids and orbital debris on space tethers in accordance with the first AI 19.1 test requirements.

Using the ORDEM2000+Grün model to represent the meteoroids and orbital debris fluxes, and adopting the tether vulnerability conjecture described by Eq. 13, the fatal impact rate, in ($\text{yr}^{-1}\text{km}^{-1}$), was computed for each selected orbit altitude and inclination, as a function of the tether diameter, according to Table 3. Thus, the severing rates and the orbital lifetimes of a 5 km, 7.5 km and 10 km long single line tether were evaluated for all the orbital configurations and tether diameters proposed. A detailed description of the results obtained is given in the AI 19.1 Final Report[30]. Herein, the main outcomes are summarized.

A general good agreement was found among the ISTI, JSC and KU results, leading to the following conclusions:

- single line tethers with diameter smaller than 1 mm may survive intact for less than 10 days for all orbital configurations and tether lengths assumed in the study;
- increasing the tether diameter to 2.5 mm results in an average lifetime of nearly 40-50 days for a 5 km tether at 800 km, reducing to less than one month at 1000 km and 1400 km. Of course, the longer is the tether, the shorter its lifetime;
- diameters larger than 5 mm may cause a reduction of the tether vulnerability to space debris impacts. However, a 5 mm single line tether may survive intact for less than 1 year

in all orbital and tether scenarios hypothesized;

- above 1 cm, the impact with space debris could not be longer a threat for a number of potential missions using tethers. At 1 cm, a 5 km tether may survive intact for a long while, ranging from a minimum of 3.5 years, at 1000 km and inclination of 75˚, to a maximum of 7.2 years at 1400 km and inclination of 25˚. The lifetime of a 7.5 km tether may vary between 2.3 and 4.8 years in correspondence of the previous orbital conditions, while the expected survivability time of a 10 km tether may range from 1.7 to 3.6 years;
- much more massive tethers with diameters of 2.5 cm and 5 cm may operate for relatively long times, ranging from a few decades to more than a century, depending on the orbital scenario and tether length.

In conclusion, provided the tether vulnerability conjecture and the space debris flux model considered in this study are reasonable, a single line tether with a diameter of 2.5 cm, or larger, may certainly survive the space debris environment for a moderately long time to assure the feasibility of a number of missions.

RESULTS OF THE SECOND IADC AI 19.1 TEST

The survival probability of tethers during typical de-orbiting missions was assessed for the second AI 19.1 test. Tethers of length 7.5 km, with both single and double line designs, were considered, adopting conducting wires with diameters of 0.5 and 1 mm. With regards to the double line solution, three configurations, where the length of each tether segment was 5, 10 and 100 meters, were simulated. Moreover, two different conjectures on the tether vulnerability were considered, that of limiting the minimum fatal debris diameter to 1/4 and 1/3 of the tether diameter. Two different environmental models were adopted to compute the meteoroids and orbital debris flux: MASTER-2001 and ORDEM2000 coupled with the Grün's meteoroids flux. Realistic de-orbiting scenarios, based on the concept of the Terminator Tether[14] from the US Tether Unlimited Inc. company, were simulated. In particular, detailed computations and thorough comparisons were carried out for de-orbiting missions of a 1500 kg spacecraft, with initial altitudes of 800 km, 1000 km and 1400 km, and orbital inclinations of 0°, 25°, 50° and 75°.

Very similar conclusions were obtained by ISTI, JSC and KU for all the single line tether solutions herein analyzed. They state that[30, 37]:

- independently of the space debris flux model adopted, the single line electrodynamic tethers prescribed for this study (Length = 7.5 km, Diameters = 0.5 mm and 1 mm) cannot be safely used for de-orbiting from the altitudes and inclinations considered.

Therefore, trying to increase the probability that the tether will survive the meteoroids and orbital debris environment for the de-orbiting mission duration, the double line solution was considered as well. The ISTI double line results were very close to those obtained by JSC for both the MASTER-2001 and ORDEM2000+Grün environments. On the other hand, the KU outcomes showed a much lower survival probability in general, which was justified by the different approach used to estimate the overall survival probability of the mission[30]. However, according to ISTI, JSC and KU it resulted that:

- the survival probability grows considerably for a double line design with a sufficiently high number of knots and loops;
- the survival probability increases in the double loop configurations with number of loops and minimum fatal debris diameter;
- survival is also more likely from lower initial altitudes and inclinations.

Moreover:

- all results are strongly dependent on the orbital debris/meteoroids model adopted, with much higher survival probabilities obtained overall from the lower MASTER-2001 fluxes.

CONCLUSIONS AND RECOMMENDATIONS

De-orbiting devices based on the use of conducting tethers have been recently proposed as innovative solutions to mitigate the growth of orbital debris. However, tethers in space introduce unusual problems when viewed from the space debris perspective. To assess the space debris related concerns, a new task (Action Item 19.1) on the "Potential Benefits and Risks of using Electrodynamic Tethers for End-of-life De-orbit of LEO Spacecraft" was defined by the Inter-Agency

Space Debris Coordination Committee at the 19th IADC plenary meeting, in March 2001. The task was assigned to the IADC Working Group 2, on “Environment and Data Base”, and a study plan was successively formulated with the main objective of investigating the potential risk to the tether system integrity due to impacts with space debris.

Two tests were proposed:

1. to compute the fatal impact rate of meteoroids and orbital debris on space tethers in circular orbit, at different altitudes and inclinations, as a function of the tether diameter;
2. to assess the survival probability of an electrodynamic tether system during typical de-orbiting missions.

IADC members of three agencies (ASI, JAXA and NASA) volunteered to participate in the study and different computational approaches were specifically developed in the framework of this IADC task.

In both tests,

- very simple tether orbital configurations and designs were assumed. Tethers were supposed to be in circular orbit and aligned along the gravity gradient;
- specific tethers vulnerability conjectures were adopted.

The results of both tests prove that:

- the lifetimes of conventional single line tethers may be limited, by damage due to meteoroids and orbital debris impacts, to times much shorter than the mission duration;
- single line tethers lifetimes can be improved by increasing the tether diameter. However, this might incur a prohibitive mass penalty as well as additional operational problems for many missions;
- resorting to different and creative designs is necessary to reduce the tether vulnerability to space debris;
- the double line solution actually reduces the tether vulnerability, but the survival probability decreases with the distance between the two strands in each single loop[30]. However, an upper limit of such distance exists above which the result do not change any more. For the specific case analysed in the Final Report[30], this limit corresponds to a distance between strands of about 5 cm.

In conclusion, electrodynamic tethers have strong potential to become effective mitigation measures, but various problems are still to be solved before this technique can be practically adopted. From the space debris perspective, resorting to creative tether designs is necessary to increase the tethers survivability, but:

- considerable differences are still existing in the flux of small particles predicted by the environment models, e.g. MASTER-2001 and ORDEM2000. Thus, additional efforts should be done to possibly define a common standard model;

- 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 a consequence, vulnerability conjectures other than those considered might result. Thus, new hypervelocity impact experiments, using tethers of different material and design, should be necessary to identify appropriate ballistic equations.

It must be stressed that the mathematical approaches developed for this study can be applied to any available environmental model and tether vulnerability condition, thus allowing more precise evaluations as the accuracy of the environment and tether models improves. Moreover, the Kyushu University method can also be applied to real tether designs, like that of the Japanese QTEX experiment, where the volume of knots cannot be neglected any longer and the two cables in a loop may be separated by a distance varying with the tether’s construction details. But these mathematical methods can only be applied to tethers which are in circular orbit and are aligned along the gravity gradient. However, these simplifying hypotheses should be in general applicable to electrodynamic tethers used for de-orbiting, which need an active libration control to avoid dynamic instability. An active control during the mission should be also guaranteed to prevent the tether from impacting with large space objects. In fact, while the danger represented by particles smaller than 1 cm may be overcome by increasing the tether diameter and/or resorting to creative designs, the risk of impact with spacecraft and upper stages cannot be reduced by modifying the tether design.

In highly eccentric orbits, like GTO, a tether system is not longer stable or librating, but will start to rotate at pass of perigee. Thus, the mathematical approaches developed for this study should be revised and modified, while major challenges of the current electrodynamic tether designs, like the Terminator Tether^{TM} and the EDOARD systems, should be introduced.

REFERENCES

1. Cosmo, M.L. and E.C. Lorenzini (eds.), "Tethers in Space Handbook", Third Edition, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts, USA, 1997.
2. Forward, R.L., R.P. Hoyt and C. Uphoff, The Terminator Tether: A Near-Term Commercial Application of the NASA/MSFC ProSEDS Experiment, Proceedings of the Tether Technology Interchange Meeting, NASA CP-1998-206900, Marshall Space Flight Center, Huntsville, Alabama, USA, page 109, 1998.
3. Vannaroni, G., M. Dobrowolny and F. De Venuto, Deorbiting with Electrodynamic Tethers: Comparison Between Different Tether Configurations, *Space Debris*, Vol. 1, No. 3, pp. 159-172, 2001.
4. Van der Heide, E.J. and M. Kruijff, Tethers and Debris Mitigation, *Acta Astronautica*, Vol. 48, No. 5-12, pp. 503-516, 2001.
5. Iess, L., C. Bruno, C. Ulivieri. U. Ponzi, M. Parisse, G. La Neve, G. Vannaroni, M. Dobrowolny, F. De Venuto, B. Bertotti and L. Anselmo, Satellite De-Orbiting by means of Electrodynamic Tethers Part I: General Concepts and Requirements, *Acta Astronautica*, Vol. 50, No. 7, pp. 399-406, 2002.
6. Iess, L., C. Bruno, C. Ulivieri. And G. Vannaroni, Satellite De-Orbiting by means of Electrodynamic Tethers Part II: System Configuration and Performance, *Acta Astronautica*, Vol. 50, No. 7, pp. 407-416, 2002.
7. Gilchrist, B., B. Lim, N. Meckol, R. Masse and S. Williams, The use of Electrodynamic Tethers for Orbit Maintenance and Deorbit of Large Spacecraft: a Trade Study of the NASA GLAST Mission, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference Meeting & Exhibit, Paper AIAA 2002-4044, Indianapolis, IN, 7-10 July 2002.
8. Pearson, J., J. Carroll, E. Levin, J. Oldson and P. Hausgen, Overview of the Electrodynamic Delivery Express (EDDE), 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference Meeting & Exhibit, Paper AIAA 2003-4790, Huntsville, AL, 20-23 July 2003.
9. Ishige, Y., S. Kawamoto and S. Kibe, Study on Electrodynamic Tether System for Space Debris Removal, *Acta Astronautica*, Vol. 55, pp. 917-929, 2004.
10. Yamaigiwa, Y., E. Hiragi and T. Kishimoto, Dynamic Behavior of Electrodynamic Tether Deorbit System on Elliptical Orbit and its Control by Lorentz Force, *Aerospace Science and Technology*, Vol. 9, pp. 366-373, 2005.
11. Kawamoto, S., Y, Okawa, S. Yoshimura, F. Terui, A. Nakajima and S. Kitamura, Development Status of an Active Space Debris Removal System, Paper IAC-05-B6.3.03, 56th International Astronautical Congress, 17-21 October 2005, Fukuoka, Japan.
12. Kawamoto, S., T. Makida, F. Sasaki, Y. Okawa, and S. Nishida, Precise Numerical Simulations of Electrodynamic Tethers for an Active Debris Removal System, *Acta Astronautica*, 59, pp. 139-148, 2006.
13. Vannaroni, G., M. Dobrowolny, F. De Venuto and L. Iess, Electrodynamic Tethers for Deorbiting Applications, 50th International Astronautical Congress, Toulouse, France, Paper IAA 99-6.6.08, 4-8 October 1999; published in *Space Debris 1999*, Volume 100, Sciences and Technology series, Univelt Inc., San Diego, California, pp. 287-298, 2001.
14. Hoyt, R. and R. Forward, Performance of the Terminator Tether^{TM} for Autonomous Deorbit of LEO Spacecraft, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Paper AIAA 99-2839, Los Angeles, CA, 20-24 June 1999.
15. Bruno, C., L. Anselmo, L. Bussolino, L. Iess, R. Licata, L. Schirone and L. Somensi, EDOARD: An Electrodynamic Tether Device for Efficient Spacecraft De-Orbiting, Proc. Third European Conference on Space Debris, European Space Operation Center (ESOC), Darmstadt, Germany, 19-21 March 2001 (ESA SP-473, October 2001), pp. 707-712, 2001.
16. Forward, R. L. and R. P. Hoyt, Terminator Tether^{TM}: A Spacecraft Deorbit Device, *Journal of Spacecraft and Rockets*, Vol. 37, No. 2, pp. 187-196, 2000.
17. Anselmo, L. and C. Pardini, The Survivability of Space Tether Systems in Orbit Around the Earth, *Acta Astronautica*, Vol. 56, pp. 391-396, 2005.
18. Anselmo, L. and C. Pardini, Assessing the Impact Risk of Orbital Debris on Space Tethers, *Space Debris*, Vol. 1, pp 87-98, 2000.
19. Pardini, C., L. Anselmo, A. Rossi, A. Cordelli and P. Farinella, A New Orbital Debris Reference Model, *The Journal of the Astronautical Sciences*, 46, No. 3, pp. 249-265, 1998.
20. Chobotov, V. A. and D. L. Mains, Tether Satellite System Collision Study, *Space Debris*, Vol. 1, No. 2, pp. 99-112, 1999.

21. Patera, R.P. A Method for Calculating Collision Probability between a Satellite and a Space Tether, *Journal of Guidance, Control and Dynamics*, Vol. 25, No. 5, pp. 940-945, 2002.
22. Cooke, W.J., D.B. Spencer, B.J. Anderson and R.M. Suggs, Tether Survivability and Collision Avoidance: Is LEO the Right Place for Tethered Systems?, Space Technology and Applications International Forum (STAIF-2001), Albuquerque, New Mexico, USA, February 11-14, 2001.
23. Hoyt, R. and J. Buller, Analysis of the Interaction of Space Tethers with Catalogued Space Objects, Web site: "http://www.tethers.com/TUPubs.html" of Tether Unlimited Inc., 2005.
24. Hoyt, R.P., Personal Communications, March 2003.
25. Forward, R. L., R.P. Hoyt, Failsafe Multiline Hoytether Lifetimes, AIAA paper 95-28903,1st AIAA/SAE/ASME/ASEE Joint Propulsion Conference*,* San Diego, CA, July 1995.
26. Bade, A., R.C. Reynolds and D.J. Kessler, Tethers for Power Generation on the International Space Station Alpha. Micrometeoroids and Orbital Debris Impact Study, Report NASA/JSC 27362, Lyndon B., Johnson Space Center, Houston, Texas, USA, April 1996.
27. Anselmo, L., and C. Pardini, On the Survivability of Tethers in Space, in: J. Bendish (Ed.), Space Debris 2000, Science and Technology Series, Vol. 103, Univelt Inc., San Diego, California, USA, pp. 137-146, 2001.
28. Nishimine, A., Debris Collision Analysis for Tethers, 23rd International Symposium on Space Technology and Science, Paper ISTS 2002-s-29, Matsue, Japan, May 26 – June 2, 2002.
29. Pardini, C., L. Anselmo, T. Hanada and H. Hirayama, Assessing the Vulnerability to Debris Impacts of Electrodynamic Tethers During Typical De-Orbiting Missions, 4th European Conference on Space Debris (Darmstadt, Germany, 18-20 April, 2005). Proceedings, Vol. ESA SP-587, pp. 353-360. D. Danesy (ed.), European Space Agency (ESA) Publications Division, 2005.
30. Pardini, C., T. Hanada and P.H. Krisko, Potential Benefits and Risks of Using Electrodynamic Tethers for End-of-life De-orbit of LEO Spacecraft, Final Report of IADC Action Item 19.1, Document No. IADC-06-02, 27 April 2006.
31. Liou, J.C., M.J. Matney, P.D. Anz-Meador, D. Kessler, M. Jansen, J.R. Theall, The New NASA Orbital Debris Engineering Model ORDEM-2000, NASA/TP-2002-210780, Johnson Space Center, Houston, Texas, USA, May 2002.
32. Grün, E., H.A. Zook, H. Fechtig and R.H. Giese, Collisional Balance of the Meteoritic Complex, *Icarus*, Vol. 62, p. 244, 1985.
33. Bendisch, J., K. Bunte, H. Klinkrad, H. Krag, C. Martin, H. Sdunnus, R. Walker, P. Wegener, C. Wiedemann, The MASTER-2001 Model, *Advances in Space Research*, Vol. 34, No. 5, pp. 959-968, 2004.
34. Beltrami, P., Comparison of Debris Flux Models, Final Report of IADC Action Item 19.2, Document No. IADC-05-03, April 2005.
35. Pardini, C. and L. Anselmo, Methodology Used at ISTI/CNR to Assess the Sever Probability of Space Tethers, Proceedings of the 22nd IADC Plenary Meeting, Published and distributed by ASI on CD-ROM, Abano Terme, Italy, April 19-22, 2004.
36. Anz-Meador, P.D., Tether-Debris Interactions in Low Earth Orbit, Proceedings of the American Institute of Physics Conference, Vol. 552, Issue 1, pp. 525-531, February 2, 2001.
37. Pardini, C., T. Hanada, P.H. Krisko, L. Anselmo and H. Hirayama, Are De-orbiting Missions Possibile Using Electrodynamic Tethers? Task Review from the Space Debris Perspective, Paper IAC-05-B6.3.01, 56th International Astronautical Congress, 17-21 October 2005, Fukuoka, Japan.