# ASSESSING THE VULNERABILITY TO DEBRIS IMPACTS OF ELECTRODYNAMIC TETHERS DURING TYPICAL DE-ORBITING MISSIONS

**C. Pardini(1), L. Anselmo(1), T. Hanada(2), H. Hirayama(2)**

*(1) ISTI/CNR, Area della Ricerca di Pisa, Via Moruzzi 1, 56124 Pisa, Italy*
*Email: Carmen.Pardini@isti.cnr.it, Luciano.Anselmo@isti.cnr.it*
*(2) Kyushu University, 10-1 Hakozaki 6-chome, Higashi-ku, Fukuoka 812-8581, Japan*
*Email: toshi@aero.kyushu-u.ac.jp, hira@aero.kyushu-u.ac.jp*

## ABSTRACT

De-orbiting devices based on the use of conducting tethers have been recently proposed as innovative solutions to mitigate the growth of orbital debris. Electrodynamic tether drag might actually provide a cost-effective method to rapidly and safely remove spent upper stages and defunct satellites from low Earth orbits. However, 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.

In order to assess the vulnerability of electrodynamic tether systems during typical de-orbiting missions, specific work has been carried out at ISTI/CNR (Pisa, Italy) and Kyushu University (Fukuoka, Japan) over the last few years, and suitable models and methods have been specifically developed for the analysis of single and double line tethers in circular orbit and aligned along the gravity gradient. The purpose of this paper is to present the two different approaches, which have been applied to realistic de-orbiting missions of spacecraft with inclinations up to about 75 deg and initial altitudes up to 1400 km.

## 1. INTRODUCTION

The electrodynamic tether drag may provide a cost effective method for de-orbiting Low Earth Orbit (LEO) satellites in order to mitigate the growth of orbital debris. For this reason, devices based on such a principle have been proposed as an alternative solution to remove spacecraft and upper stages in LEO once they have completed their missions (Forward et al., 1998a and 1998b; Bruno et al., 2001; Iess et al., 2002a and 2002b).

The 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. Such a current is generated in a conducting tether by its orbital motion through the Earth's magnetic field and ionosphere. In fact, the natural motion of the conductor through the magnetic field induces an electric potential difference at the tether's ends, while the surrounding conducting ionosphere closes the circuit, allowing the flow of an electrical current in the system.

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 (Vannaroni et al., 1999 and 2001):

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

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 (Vannaroni et al., 1999):

$$\Phi = \int_0^L (\vec{v} \times \vec{B}) \cdot d\vec{l} \tag{2}$$

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 (Vannaroni et al., 1999):

$$P = \vec{F} \cdot \vec{v} \tag{3}$$

while the time $\Delta t$ 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 (Vannaroni et al., 1999 and 2001):

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

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

*Proceedings of the Fourth European Conference on Space Debris, Darmstadt, Germany, 18-20 April 2005*
*(ESA SP-587, August 2005)*

larger induced voltages and ionospheric densities. At high inclinations, the relative geometry of orbital motion and magnetic field is much less favorable, 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.

## 2. SPACE DEBRIS IMPACT RISK

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 fatal system failure.

During the past decade there have been several efforts to determine the impact probability of artificial and natural debris and evaluate the average useful lifetime of tethers in Earth orbit. This paper describes the progresses in the field achieved in Pisa, Italy, at the ISTI institute of the National Research Council (CNR), and in Fukuoka, Japan, at the Kyushu University. Specific methods and software tools have been developed and applied both to single and double line configurations. A detailed description is provided in the following two sections.

## 3. THE ISTI/CNR APPROACH

The Space Flight Dynamics Laboratory of ISTI (formerly CNUCE) is active in the survivability analysis of tethers subjected to space debris impacts since the beginning of 1998. This activity has been carried out in support of a proposed electrodynamic system for satellite de-orbiting (Bruno et al., 2001; Iess et al., 2002a; Anselmo and Pardini, 2005), as general basic research in the field (Anselmo and Pardini, 2000 and 2001) and in the framework of a specific task promoted by the Inter-Agency Space Debris Coordination Committee (IADC) and led by the first author of this paper (Pardini, 2003a and 2003b; Pardini et al., 2004).

The aim of this section is to present the methods and tools developed and used at ISTI/CNR to compute the fatal impact rate of meteoroids and orbital debris on space tethers and assess the survival probability of electrodynamic tether systems during a de-orbiting mission. These methods have been already outlined in Pardini and Anselmo (2004) and in Oishi et al. (2004).

First of all, tethers are supposed to be in circular orbit and aligned along the gravity gradient. These simplifying hypotheses are in general applicable to electrodynamic tethers used for de-orbiting, which need active libration control to avoid dynamic instability (Corsi and Iess, 2001). Two basically different designs have been considered so far (Fig. 1):

1. Single tether, with a single wire or a compact cylindrical multi-line structure;
2. Double tether, in which two cables are separated each other by a distance significantly larger than their diameter and form $N$ loops, tied together in $N$ + 1 equidistant knots.

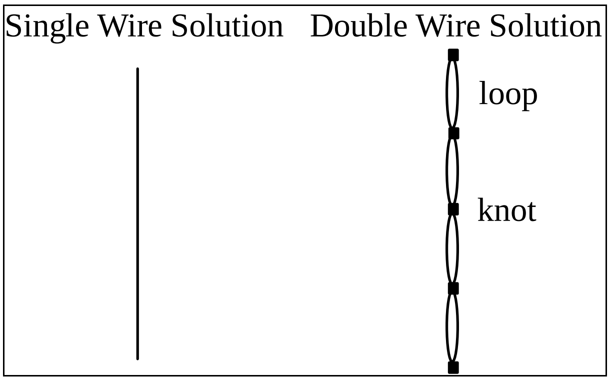

*Figure 1. Single and double tether designs considered at ISTI/CNR.*

### 3.1. Single Tether

A single tether may be severed by a space debris with a diameter $d$ larger than a certain fraction $f$ of the tether diameter $D_T$ ($d \geq d_C = f \cdot D_T$), provided that the debris edge passes within a critical distance $(1/2)D_{TC}$ from the longitudinal axis of symmetry of the tether (see Fig. 2). Assuming a circular orbit and an alignment along the local vertical, orbital debris generally impact the tether at relatively low elevation ($E$) with respect to the local horizon. Therefore, $\cos(E) \approx 1$ and the tether effective cross-sectional area $A(d)$ may be written as:

$$A(d) = L(D_{TC} + d) \tag{5}$$

where $D_{TC}$ is the critical tether diameter (Fig. 2).

Regarding meteoroids, $E$ can assume any positive value (i.e. above the local horizon). In other words, they can approach the tether from all directions, except from below, where the Earth acts as a shield. The effective tether area is in this case ¼ of that given by Eq. 5 and an appropriate Earth shielding factor must be introduced to take into account the tether geometry and orientation (Cooke et al., 2001).

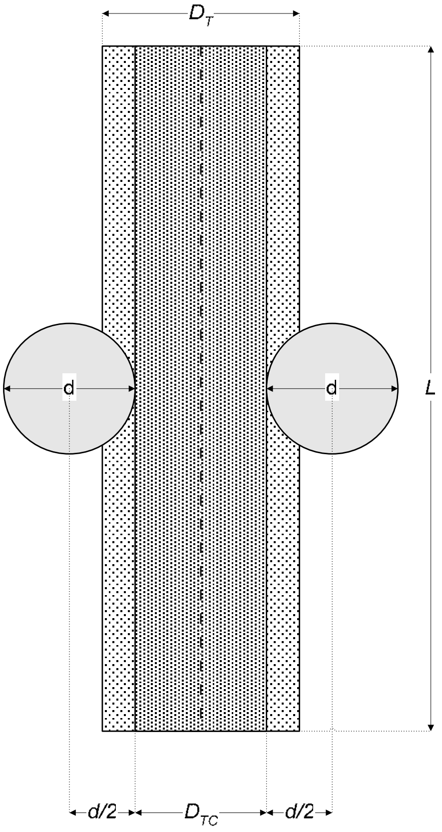

*Figure 2. Definition of the tether effective cross-sectional area with respect to the fatal debris impacts.*

The fatal impact rate and the severing probability for a tether orbiting at a certain altitude are obtained by numerically integrating the differential space debris flux with respect to the debris diameter. The fatal impact rate $R_F$, i.e. the number of impacts able to cut a tether in a given time, for instance one year, can be expressed as:

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

where $d\varphi$ is the differential flux of particles with respect to the debris diameter $d$. The probability $P$ that the tether is severed in a certain time interval $\Delta t$ is therefore given by:

$$P = 1 - \exp(-R_F \Delta t) \tag{7}$$

For small debris sizes and tether diameters ($D_T$, $d \geq d_C <$ 1 mm) the use of the cumulative flux instead of the differential one may be convenient from a computational point of view. The resulting underestimation of the sever rate is in any case small with respect to the uncertainties affecting the environment models and the impact effects on the tether (Cooke et al., 2001).

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 (Eqs. 12 and 13).

### 3.2. Double Tether

In order to assess the survivability of double line tethers with the basic design outlined in Fig. 1, a numerical multi-step algorithm has been developed at ISTI. 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 $i^{\text{th}}$ height interval, characterized by a decay time $\Delta t(i)$. If $P(n, i)$ is the sever probability of a single wire in the $n^{\text{th}}$ tether loop and $i^{\text{th}}$ altitude interval, computed using Eq. 7, the sever probability of both wires in the same tether loop ($P_{SE}$) is given by:

$$P_{SE}(n,i) = [P(n,i)]^2 \tag{8}$$

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

$$P_{SU}(n,i) = 1 - P_{SE}(n,i) \tag{9}$$

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 $i^{\text{th}}$ altitude interval can be expressed as:

$$P_{SU\_T}(i) = \prod_{n=1}^{N} P_{SU}(n,i) = [P_{SU}(n,i)]^N \tag{10}$$

while the corresponding sever probability ($P_{SE\_T}$) is given by:

$$P_{SE\_T}(i) = 1 - P_{SU\_T}(i) \tag{11}$$

A said before, 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 meteoroid 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:

$$P_{SU\_M} = \prod_{i=1}^{H} P_{SU\_T}(i) \tag{12}$$

while the total sever probability during the mission ($P_{SE\_M}$) may be expressed as follows:

$$P_{SE\_M} = 1 - P_{SU\_M} \tag{13}$$

The approach and the tools described may be used with any orbital debris and meteoroid model, making possible a comparison between different representations of the environment. For meteoroids, the model adopted so far was that included in the NASA's DAS 1.5.3 tool (Kessler et al., 1994), while for orbital debris the following models have been applied: ISTI's CODRM-99R (Pardini et al., 1998), ESA's MASTER 2001 (Wiedemann et al., 2002), and NASA's ORDEM96 (Kessler et al., 1996) and ORDEM2000 (Liou et al. 2002).

## 4. THE KYUSHU UNIVERSITY APPROACH

Fig. 3 shows a conceptual drawing of a micro tethered satellite being developed at Kyushu University under the initiative of graduate and undergraduate students. This tethered satellite, named Kyushu University Tether Experiment (QTEX), consists of two identical satellites, named QTEX Public Relations (QTEX-PR), and a tether connecting them. QTEX-PR itself is a fully functional satellite to be launched stand alone and is being developed ahead of QTEX.

To estimate the survivability of QTEX against meteoroids and orbital debris, Kyushu University has developed a risk assessment model for space tethers. The following subsections present the detailed description of the Kyushu University approach.

### 4.1. Single Tether

As to the single tether solution, the Kyushu University approach is exactly the same adopted by ISTI/CNR. Therefore, no further description is provided.

### 4.2. Double Tether

Fig. 4 illustrates the detailed design of the double tether considered at Kyushu University. Unlike ISTI/CNR, Kyushu University assumes a finite distance between the two wires of a segment (i.e. the tether portion included between two knots), so that they might be severed simultaneously by a single impact. In addition, the knots have a finite volume and they too might be severed by a single impact.

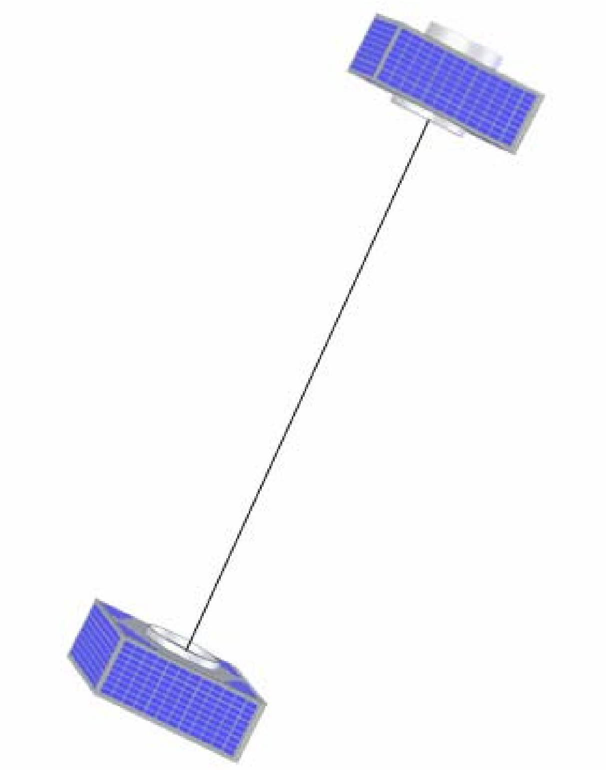

*Figure 3. Conceptual illustration of QTEX.*

Therefore, the double tether considered herein (Fig. 4) can be severed when:

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

The sever probability for a knot can be estimated as for a single tether with a length of 3.0 $D_T$ and a diameter of 2.5 $D_T$. Thus, the effective cross-sectional area of a knot ($A_{knot}$) can be expressed as:

$$A_{knot}(d) = 3D_T\left(2.5D_{TC} + d\right) \tag{14}$$

while the corresponding fatal impact rate ($R_{Fknot}$) is:

$$R_{Fknot} = \int_{d_C}^{\infty} A_{knot}(d)\,d\varphi(d) \tag{15}$$

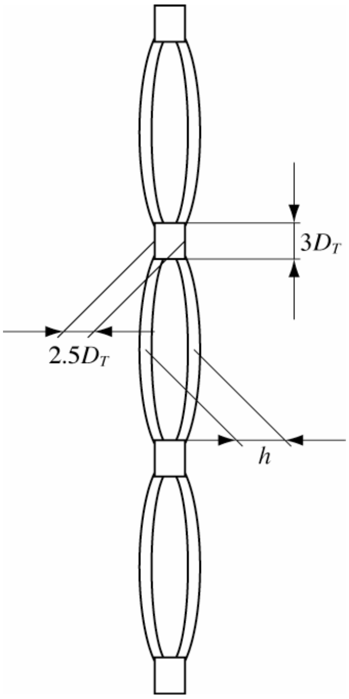

*Figure 4. Double tether design considered at Kyushu University.*

In order to estimate the probability for a tether segment to be severed by one or two impacts, the incidence angle $\theta$ of in-coming orbital debris, defined in Fig. 5, must be accounted for.

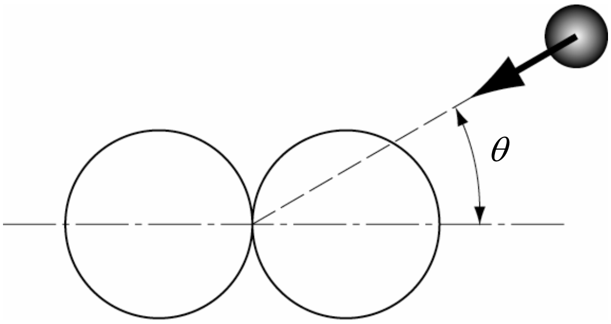

*Figure 5. Definition of the incidence angle (in-coming direction) of orbital debris with respect to a tether segment.*

If $d > h - D_{TC}$ (see Fig. 6), orbital debris coming from any direction can cut two wires simultaneously by a single impact, but the effective cross-sectional area for cutting two wires with a single impact ($A_{20}$) does depend on the incidence angle defined in Fig. 5 and can be expressed as:

$$A_{20}(d,\theta) = L_S\left(D_{TC} + d - h\sin\theta\right) \qquad (16)$$

where $L_S$ is the length of the tether segment. The subscripts 2 and 0 represent, respectively, the initial number of wires and the number of wires survived after a single impact. Integrating $A_{20}(d,\theta)$ with respect to the incidence angle of in-coming orbital debris and dividing by $2\pi$, the average effective cross-sectional area for cutting two wires simultaneously with a single impact is given by:

$$A_{20}(d) = L_S\left(D_{TC} + d - \frac{2}{\pi}h\right) \qquad (17)$$

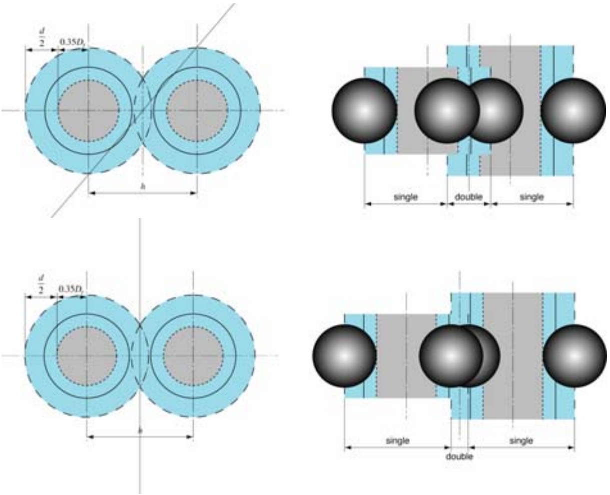

*Figure 6. Definition of the effective cross-sectional area with respect to the incidence angle $\theta$ for $d > h - D_{TC}$ (as an example, $D_{TC}$ has been put equal to $0.7D_T$).*

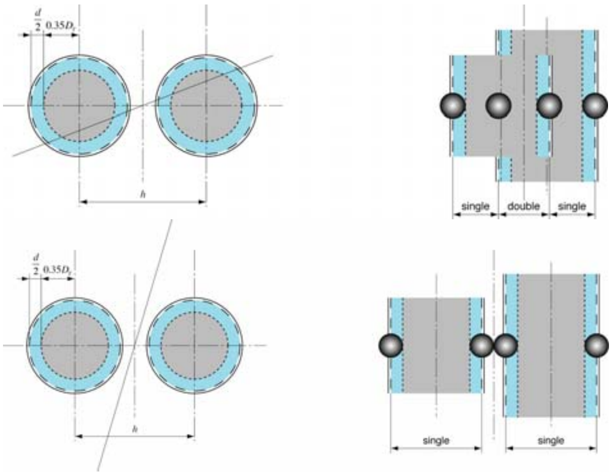

*Figure 7. Definition of the effective cross-sectional area with respect to the incidence angle $\theta$ for $d < h - D_{TC}$ (as an example, $D_{TC}$ has been put equal to $0.7D_T$).*

In the same way, the $\theta$-dependent and average effective cross-sectional areas for cutting only one wire of a segment by a single impact ($A_{21}$) are given, respectively, by:

$$A_{21}(d,\theta) = L_S \times 2h\sin\theta \qquad (18)$$

and

$$A_{21}(d) = L_S \times \frac{4}{\pi}h \qquad (19)$$

If $d < h - D_{TC}$ (see Fig. 7), orbital debris can cut the two wires of a tether segment simultaneously with a single impact when:

$$0 \le \theta \le \frac{D_{TC}+d}{h} (\equiv \theta_C) \qquad (20)$$

Thus, the $\theta$-dependent effective cross-sectional area for cutting two wires of a segment simultaneously can be expressed by:

$$A_{20}(d,\theta) = \begin{cases} L_S\left(D_{TC} + d - h\sin\theta\right) & 0 \le \theta \le \theta_C \\ 0 & \theta > \theta_C \end{cases} \qquad (21)$$

while the corresponding average effective cross-sectional area is given by:

$$A_{20}(d) = L_S \times \frac{2}{\pi}\left[(D_{TC}+d)\theta_C - h(1-\cos\theta_C)\right] \qquad (22)$$

In the same way, the $\theta$-dependent and average effective cross-sectional areas for cutting only one wire of a tether segment with a single impact are given, respectively, by:

$$A_{21}(d,\theta) = \begin{cases} L_S \times 2h\sin\theta & 0 \le \theta \le \theta_C \\ L_S \times 2(D_{TC}+d) & \theta > \theta_C \end{cases} \qquad (23)$$

and

$$A_{21}(d) = L_S \times \frac{4}{\pi}\left[(D_{TC}+d)\left(\frac{\pi}{2} - \theta_C\right) + h(1-\cos\theta_C)\right] \qquad (24)$$

Note that the average effective cross-sectional area $A_{20}$ can be expressed as:

$$A_{20}(d) = A_S(d) - \frac{A_{21}(d)}{2} \qquad (25)$$

where $A_S$ is the effective cross-sectional area of one of the wires of length $L_S$ (see Eq. 5), characterized by a fatal impact rate $R_{FS}$ (see Eq. 6). Thus, the fatal impact rate for cutting two wires of a segment simultaneously, $R_{F20}$, is given by:

$$R_{F20} = R_{FS} - \frac{R_{F21}}{2} \qquad (26)$$

where the fatal impact rate for cutting only one wire of a tether segment, $R_{F21}$, is given by:

$$R_{F21} = \int_{d_C}^{\infty} A_{21}(d)\, d\varphi(d) \qquad (27)$$

Since it should be treated as a stochastic process, the probabilistic state variables $X_i(t)$ were introduced to describe the survivability of the tether segments. The subscript $i$ represents the number of wires survived in a segment after a certain time $t$. Relationships among the probabilistic state variables $X_i(t)$ can be expressed as a set of simultaneous differential equations:

$$X_2'(t) = -(R_{F20} + R_{F21})X_2(t) \qquad (28)$$

$$X_1'(t) = R_{F21}X_2(t) - R_{FS}X_1(t) \qquad (29)$$

Eqs. 28 and 29 can be solved to give:

$$X_2(t) = X_2(0)\exp\left[-(R_{F20}+R_{F21})t\right] \qquad (30)$$

$$\begin{aligned} X_1(t) = {} & X_1(0)\exp[-R_{FS}t] \\ & + 2X_2(0)\exp[-R_{FS}t](1-\exp[-(R_{F21}/2)t]) \end{aligned} \qquad (31)$$

Expressing the survival probability for a knot by:

$$X_{knot}(t) = X_{knot}(0)\exp\left[-R_{Fknot}t\right] \qquad (32)$$

then the survival probability of the entire double line tether system ($X_T$) is described by the following relationship:

$$X_T(t) = \left(X_1(t) + X_2(t)\right)^N \left(X_{knot}(t)\right)^{N+1} \qquad (33)$$

As mentioned earlier, this approach assumes a finite distance between the two tether wires and a finite volume of the knots. However, to make easier the comparison with the results obtained with the ISTI/CNR method, Kyushu University may assume an infinite distance between the two wires and may ignore the volume of the knots. When the distance between the two wires approaches the infinite, Eqs. 17, 19, 22 and 24 become:

$$A_{20}(d) = 0 \qquad (34)$$

$$A_{21}(d) = 2L_S\left(D_{TC}+d\right) = 2A_S(d) \qquad (35)$$

Thus, $X_1(t)$ and $X_2(t)$ can be expressed as:

$$X_2(t) = X_2(0)\exp\left[-2R_{FS}t\right] \qquad (36)$$

$$X_1(t) = X_1(0)\exp[-R_{FS}t] + 2X_2(0)\exp[-R_{FS}t](1-\exp[-R_{FS}t]) \quad (37)$$

Finally, the survival probability of the entire double line tether system ($X_T$) becomes in this case:

$$X_T(t) = (X_1(t) + X_2(t))^N \quad (38)$$

## 5. TEST RESULTS

The approaches described in this paper, developed at ISTI/CNR and Kyushu University, have been applied to realistic de-orbiting scenarios based on the concept of the Terminator Tether, from Tethers Unlimited Inc. (Forward et al., 1998b). Detailed computations and thoroughly comparisons have been carried out for simulated de-orbiting missions of a 1500 kg spacecraft, with initial altitudes of 800, 1000 and 1400 km, and orbital inclinations of 0, 25, 50 and 75 deg.

In order to obtain reasonable de-orbiting times (Oishi et al., 2004), tethers with a length of 7.5 km, of both single and double line designs, have been considered in the survivability analysis, adopting conducting wires with diameters of 0.5 and 1 mm. Regarding the double line design, the computations have been carried out for three configurations, with $L_S$ = 5, 10 and 100 m. Concerning the tether vulnerability to impacts, the following conjectures have been adopted: $d_C = 0.25D_T$ and $D_{TC} = 0.7D_T$. Moreover, for double line systems (see Fig. 4), a negligible cross-sectional area of the knots and $h >> d_C$ have been assumed.

The complete results obtained will be presented in detail in an ensuing paper. The analysis carried out has confirmed that the survivability concern is fully justified for a single line tether. In other words, no de-orbiting mission is possible, from the altitudes and inclinations considered, using a single line tether with a diameter below a few (~ 5) millimeters.

The survival probability may significantly grow for a double line configuration with a sufficiently high number of knots and loops. However, the results strongly depend on the debris model adopted, the more pessimistic estimations being obtained with the ORDEM2000 environment.

In this case, in fact, no de-orbiting mission with a survival probability greater than 95% is possible if each tether wire has a diameter of 0.5 mm. If the length of the loops is reduced to 10 m and the diameter of each wire is 1 mm, survival probabilities greater than 95% have been obtained by ISTI/CNR for the de-orbiting from 800 km, up to an inclination of 50 deg. At an initial altitude of 1000 km, the same applies only on the equatorial plane.

The Kyushu University results based on ORDEM2000 are even more pessimistic. Also with a length of the loops of 5 m, survival probabilities greater than 95% have been obtained only for de-orbiting missions in the equatorial plane with an initial altitude of 800 km.

Using the MASTER 2001 environment model, with all orbital debris and meteoroid sources included, the outcome is substantially more encouraging. In this case, the computations carried out at ISTI/CNR have found survival probabilities greater than 95% even for double line tethers with 0.5 mm wires and $L_S$ = 10 m. More specifically, this has been found up to an inclination of 25 deg for an initial altitude of 1000 km, and up to 50 deg for a de-orbiting from 800 km. The same conclusions have been reached with $L_S$ = 5 m.

Increasing the diameter of the wires to 1 mm, ISTI/CNR has found survival probabilities greater than 95% even for double line tethers with $L_S$ = 100 m. Equatorial de-orbiting has been found possible up to 1000 km, while inclinations up to 50 deg are acceptable at 800 km. With $L_S$ = 10 m, survival probabilities greater than 95% have been found for initial orbits up to 1400 km and 25 deg, 1000 km and 50 deg, and 800 km and 75 deg. The same situation basically applies with $L_S$ = 5 m, even though also the de-orbiting from 1400 km and 50 deg is practicable in this case.

The Kyushu University results based on MASTER 2001 are very similar to those obtained by ISTI/CNR, with tether survival probabilities equal or slightly smaller (at most by a few percent). Practically the same results were also obtained by ISTI/CNR using ORDEM96 and the meteoroid model adopted for the design of the International Space Station (Kessler et al., 1994).

## 6. CONCLUSIONS

The methods developed at ISTI/CNR and Kyushu University to assess the impact survival probability of single and double line space tethers have been presented in detail. In addition to domestic projects (Italian and Japanese), they have been applied to realistic de-orbiting scenarios with electrodynamic tethers, in order to assess the survivability of such systems during typical missions to remove satellites from space at the end of their operational life.

The results obtained have confirmed that single line electrodynamic tethers with diameters of a few millimeters, or less, cannot be safely used for de-orbiting from the altitudes and inclinations considered.

The survival probability may considerably grow for a double line design with a sufficiently high number of knots and loops.

In general, there is a reasonable agreement between the survival probabilities derived with the ISTI/CNR and Kyushu University approaches. However, the results strongly depend on the orbital debris model adopted, the more pessimistic estimations being obtained with the NASA's ORDEM2000 environment.

## 7. REFERENCES

Anselmo L. and Pardini C., Assessing the Impact Risk of Orbital Debris on Space Tethers, *Space Debris*, Vol. 1, 87-98, 2000.

Anselmo L. and Pardini C., On the Survivability of Tethers in Space, in: J. Bendisch (Ed.), *Space Debris 2000*, Science and Technology Series, Vol. 103, Univelt Inc., San Diego, California, USA, pp. 137-146, 2001.

Anselmo L. and Pardini C., The Survivability of Space Tether Systems in Orbit Around the Earth, *Acta Astronautica*, Vol. 56, 391-396, 2005.

Bruno C., et al., EDOARD: An Electrodynamic Tether Device for Efficient Spacecraft De-orbiting, *Proceedings of the Third European Conference on Space Debris*, ESA SP-473, Vol. 2, Darmstadt, Germany, pp. 707-712, October 2001.

Cooke W. J., et al., 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.

Corsi J. and Iess L., Stability and Control of Electro-dynamic Tethers for De-orbiting Applications, *Acta Astronautica*, Vol. 48, 491-501, 2001.

Forward R. L., Hoyt R. P. and Uphoff C., 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, p. 109, 1998a.

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

Iess L., et al., Satellite De-orbiting by Means of Electrodynamic Tethers. Part I: General Concepts and Requirements, *Acta Astronautica*, Vol. 50, 399-406, 2002a.

Iess L., et al., Satellite De-orbiting by Means of Electrodynamic Tethers. Part II: System Configuration and Performance, *Acta Astronautica*, Vol. 50, 407-416, 2002b.

Kessler D. J., et al., Space Station Program Natural Environment Definition for Design, International Space Station Alpha, NASA SSP 30425, Revision B, NASA Space Station Program Office, Houston, Texas, USA, 1994.

Kessler D. J., et al., A Computer-Based Orbital Debris Environment Model for Spacecraft Design and Observations in Low-Earth Orbit, NASA TM-104825, Johnson Space Center, Houston, Texas, USA, 1996.

Liou J. C., et al., The New NASA Orbital Debris Engineering Model ORDEM2000, NASA/TP-2002-210780, Johnson Space Center, Houston, Texas, USA, May 2002.

Oishi A., et al., Assessment of Collision Risk to Electrodynamic Tether Used for De-Orbiting, Paper IAC-04-IAA.5.12.2, 55th International Astronautical Congress, Vancouver, Canada, October 4-8, 2004.

Pardini C., De-orbiting Spacecraft with Electrodynamic Tether Devices, *Proceedings of the 21st IADC Plenary Meeting*, published and distributed by ISRO on CD-ROM, Bangalore, India, March 10-13, 2003a.

Pardini C., Potential Benefits and Risks of Using Electrodynamic Tethers for End-of-Life De-orbit of LEO Spacecraft, *Proceedings of the 21st IADC Plenary Meeting*, published and distributed by ISRO on CD-ROM, Bangalore, India, March 10-13, 2003b.

Pardini C. and Anselmo L., 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.

Pardini C., et al., A New Orbital Debris Reference Model, *The Journal of the Astronautical Sciences*, Vol. 46, 249-265, 1998.

Pardini C., et al., Space Tethers Survivability Concerns, *Proceedings of the 22nd IADC Plenary Meeting*, published and distributed by ASI on CD-ROM, Abano Terme, Italy, April 19-22, 2004.

Vannaroni G., et al., Electrodynamic Tethers for Deorbiting Applications, Paper IAA-99-IAA.6.6.08, 50th International Astronautical Congress, Amsterdam, The Netherlands, October 4-8, 1999.

Vannaroni G., et al., Deorbiting with Electrodynamic Tethers: Comparison between Different Tether Configurations, *Space Debris*, Vol. 1, 159-172, 2001.

Wiedemann C., et al., MASTER 2001 – Meteoroid and Space Debris Terrestrial Environment Reference Model, CD-ROM, ESA SD-CD07, Release 1.0, ESA/ESOC, Darmstadt, Germany, December 2002.