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ON THE SURVIVABILITY OF TETHERS IN SPACE

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ABSTRACT

Tethers have been proposed for several space applications, like satellite de-orbiting or re-boost, electric energy generation, scientific research and so on. However, they may be vulnerable to orbital debris and meteoroid impacts.

The problem was assessed, to assist tether systems design, by detailed numerical computations of the average impact rate of artificial debris, taking into account the specific geometric properties of tethers as debris targets, when compared to typical satellites.

The results obtained confirm that, for single-strand tethers in low earth orbit, the probability to be severed by orbital debris and meteoroid impacts is quite significant, making necessary the adoption of innovative designs for long duration missions.

INTRODUCTION

More than forty years of space activity have produced significant quantities of artificial debris in orbit around the earth, spanning from sub-millimeter fragments to large abandoned satellites and rocket bodies. The hazard for operational spacecraft is still relatively low, but space tethers present a peculiar structure and geometry that make them particularly vulnerable to small debris (artificial and natural) impacts.

This is due to the very high relative velocities – typically close to 10 km/s – involved in the collision process in low earth orbit: even a particle smaller than ½ of the tether diameter may cut a single-strand wire, compromising its mission. A tether system is, therefore, much more vulnerable to space debris impacts than a typical spacecraft, because it can be severely damaged by a single hit of a very small particle. In addition, a long tether can increase significantly the collision probability with spent upper stages and spacecraft, including operational satellites.

To understand why a tether cannot be treated as a typical satellite, it is useful to resort to a simplified description. A stable tether of length L and diameter d, deployed along the gravity gradient, presents, for small debris particles with diameter $D << d$, an effective cross-section ~ Ld. However, for satellites of typical linear dimension $D >> d$, the cross-section becomes ~ LD, which may assume very large values, able to compensate the low spatial density of large space objects. In the intermediate debris size range, where $D \sim d$, the effective collision cross-section is ~ $L(D + d)$. Therefore, the collision flux does not necessarily decrease with larger debris, but presents a minimum at a certain debris size, which is a function of the tether diameter and debris distribution.

IMPACT RISK ANALYSIS

In order to support the mission and the system configuration design of an electrodynamic tether for satellite end-of-life de-orbiting[1], whose study was funded by the Italian Space Agency (ASI), a detailed numerical analysis was carried out at CNUCE/CNR to determine the impact probability with artificial debris. However, the results obtained can be applied to any space tether in low earth orbit.

The CNUCE orbital debris reference population[2] was significantly upgraded, introducing the possibility to re-scale the sampling factors, in order to match the measured debris flux where comprehensive radar measurements are available[3–5]. This revised debris environment model, and a specifically adapted version of the Space Debris Impact Risk Analysis Tool (SDIRAT)[6–7], were used to determine the orbital debris impact rate on cylindrical tethers in circular orbits, as a function of altitude, inclination, debris size and tether diameter. For debris sizes below the lower limit (1 mm) of the CNUCE population, an analytic estimation with the NASA's ORDEM96 model[8] was performed.

Three orbital altitudes (600, 800, 1000 km) and two inclinations (30°, 50°) were considered, in order to obtain the impact rate to be expected on the tethers proposed for satellite de-orbiting and other applications. The results are summarized in Tables 1-6, for a tether length of 1 km. The impact rates for a specific tether can be obtained by multiplying its length, in kilometers, by the entries of the applicable table.

The numbers obtained confirm that the survivability concern is justified, in particular for single-strand tethers. In fact, to estimate the probability of cutting a cable, it must be recalled that debris quite smaller than the tether diameter may obtain such a result. As an example, 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[9–10].

The altitudes below 600 km are significantly safer, but the high probability of critical impacts with artificial debris in low earth orbit will limit the mission duration of long tethers not appropriately designed.

For the largest space objects, typically spacecraft and upper stages, the expected average impact rates, per kilometer of tether length, are of the order of 10^{-2}–10^{-3} per year, in the altitude (600–1000 km) and inclination (30°–50°) intervals considered in the study. Therefore, the probability of impact of long tethers with spacecraft and upper stages is not negligible.

THE CONTRIBUTION OF METEOROIDS

The orbital debris flux has been compared with the predictions of the NASA's meteoroid model for aerospace vehicle development[11]. At 600 km, meteoroid and debris impact rates are comparable in the 0.1 mm – 1 cm size range, but in the 1–10 cm interval the artificial objects dominate the flux by one order of magnitude. In the 800–1000 km altitude shell, the impact rate due to orbital debris is about two times larger than that of meteoroids, in the 0.1–1 mm interval, and between 2 and 4 times larger, in the 1 mm – 1 cm interval. In the 1–10 cm size range, the impact rate of artificial debris dominates that of meteoroids by a factor 20-30.

Therefore, the contribution of sporadic meteoroids is important at low altitudes and for small particle sizes, but the impact rates are dominated by artificial debris in the diameter and orbital intervals analyzed in the present study. However, a tether damage assessment should also take into account the specific nature of the impacting particles. In fact, sporadic meteoroids are usually assumed to have a density of 0.5 g/cm^3 and an average impact velocity of 20 km/s. Orbital debris, on the other hand, have higher typical densities (2-8 g/cm^3), but a lower average impact velocity, close to 10 km/s.

CONCLUSIONS

Tethers represent a promising space technology. However, particularly in low earth orbit, their development and utilization may be limited by an intrinsic vulnerability to orbital debris and meteoroid impacts. On the other hand, tethers able to survive the harsh conditions of the space environment could also be used to mitigate the space debris problem, as with the already mentioned electrodynamic tether for satellite de-orbiting[1] and other similar concepts[12–13].

The detailed numerical results presented in this paper may provide useful reference data for the feasibility assessment and design of tether systems. They show that there is a survivability problem, in particular for single-strand cables. In the altitude (600-1000 km) and debris size range (≥ 0.1 mm) analyzed, the artificial particles are the main component of the impact flux; meteoroids yield comparable fluxes of particles below 1 mm, but above 1 cm they contribute 10-30 times less than orbital debris.

Yet, the results presented also demonstrate that it is possible to conceive and realize tethers for long duration missions, for instance by adopting a redundant wire, multi-strand, or ribbon-like design. However, if the number of long tethers in space at the same time were too large (several tens), the collision probability with spacecraft and upper stages – and between the tethers themselves – could not be

Table 1. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter
[Orbit Altitude = 600 km; Inclination = 30°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.128E+02	0.239E+02	0.350E+02	0.461E+02	0.572E+02
0.10 – 0.20	0.132E-01	0.185E-01	0.238E-01	0.291E-01	0.344E-01
0.20 – 0.30	0.312E-02	0.401E-02	0.490E-02	0.580E-02	0.669E-02
0.30 – 0.40	0.241E-02	0.294E-02	0.348E-02	0.401E-02	0.455E-02
0.40 – 0.50	0.372E-03	0.439E-03	0.507E-03	0.575E-03	0.642E-03
0.50 – 0.60	0.104E-03	0.120E-03	0.136E-03	0.152E-03	0.168E-03
0.60 – 0.70	0.146E-03	0.165E-03	0.185E-03	0.204E-03	0.223E-03
0.70 – 0.80	0.139E-03	0.155E-03	0.171E-03	0.187E-03	0.204E-03
0.80 – 0.90	0.939E-04	0.104E-03	0.114E-03	0.124E-03	0.133E-03
0.90 – 1.00	0.356E-04	0.390E-04	0.424E-04	0.458E-04	0.492E-04
0.10 – 1.00	0.197E-01	0.265E-01	0.334E-01	0.402E-01	0.471E-01
1.00 – 2.00	0.170E-03	0.180E-03	0.191E-03	0.201E-03	0.212E-03
2.00 – 3.00	0.781E-04	0.811E-04	0.841E-04	0.871E-04	0.901E-04
3.00 – 4.00	0.258E-04	0.265E-04	0.272E-04	0.280E-04	0.287E-04
4.00 – 5.00	0.176E-04	0.179E-04	0.183E-04	0.187E-04	0.191E-04
1.00 – 10.0	0.410E-03	0.427E-03	0.443E-03	0.460E-03	0.476E-03
10.0 – 100	0.319E-03	0.321E-03	0.322E-03	0.323E-03	0.324E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.683E+02	0.794E+02	0.905E+02	0.102E+03	0.113E+03
0.10 – 0.20	0.397E-01	0.450E-01	0.503E-01	0.556E-01	0.609E-01
0.20 – 0.30	0.758E-02	0.847E-02	0.936E-02	0.103E-01	0.111E-01
0.30 – 0.40	0.508E-02	0.562E-02	0.616E-02	0.669E-02	0.723E-02
0.40 – 0.50	0.710E-03	0.778E-03	0.845E-03	0.913E-03	0.980E-03
0.50 – 0.60	0.184E-03	0.200E-03	0.216E-03	0.232E-03	0.248E-03
0.60 – 0.70	0.243E-03	0.262E-03	0.282E-03	0.301E-03	0.321E-03
0.70 – 0.80	0.220E-03	0.236E-03	0.253E-03	0.269E-03	0.285E-03
0.80 – 0.90	0.143E-03	0.153E-03	0.163E-03	0.173E-03	0.183E-03
0.90 – 1.00	0.525E-04	0.559E-04	0.593E-04	0.627E-04	0.661E-04
0.10 – 1.00	0.539E-01	0.608E-01	0.676E-01	0.745E-01	0.813E-01
1.00 – 2.00	0.223E-03	0.233E-03	0.244E-03	0.254E-03	0.265E-03
2.00 – 3.00	0.931E-04	0.961E-04	0.991E-04	0.102E-03	0.105E-03
3.00 – 4.00	0.294E-04	0.301E-04	0.308E-04	0.315E-04	0.323E-04
4.00 – 5.00	0.195E-04	0.198E-04	0.202E-04	0.206E-04	0.210E-04
1.00 – 10.0	0.493E-03	0.510E-03	0.526E-03	0.543E-03	0.559E-03
10.0 – 100	0.325E-03	0.327E-03	0.328E-03	0.329E-03	0.330E-03

Table 2. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter [Orbit Altitude = 600 km; Inclination = 50°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.137E+02	0.255E+02	0.374E+02	0.493E+02	0.612E+02
0.10 – 0.20	0.103E-01	0.144E-01	0.185E-01	0.226E-01	0.267E-01
0.20 – 0.30	0.314E-02	0.404E-02	0.494E-02	0.583E-02	0.673E-02
0.30 – 0.40	0.187E-02	0.228E-02	0.270E-02	0.311E-02	0.353E-02
0.40 – 0.50	0.283E-03	0.334E-03	0.386E-03	0.437E-03	0.488E-03
0.50 – 0.60	0.119E-03	0.137E-03	0.155E-03	0.174E-03	0.192E-03
0.60 – 0.70	0.205E-03	0.232E-03	0.260E-03	0.287E-03	0.314E-03
0.70 – 0.80	0.157E-03	0.175E-03	0.194E-03	0.212E-03	0.231E-03
0.80 – 0.90	0.917E-04	0.101E-03	0.111E-03	0.121E-03	0.130E-03
0.90 – 1.00	0.360E-04	0.394E-04	0.428E-04	0.462E-04	0.496E-04
0.10 – 1.00	0.161E-01	0.217E-01	0.272E-01	0.328E-01	0.383E-01
1.00 – 2.00	0.195E-03	0.207E-03	0.219E-03	0.232E-03	0.244E-03
2.00 – 3.00	0.809E-04	0.840E-04	0.871E-04	0.902E-04	0.933E-04
3.00 – 4.00	0.604E-04	0.620E-04	0.637E-04	0.654E-04	0.671E-04
4.00 – 5.00	0.107E-03	0.109E-03	0.111E-03	0.114E-03	0.116E-03
1.00 – 10.0	0.531E-03	0.552E-03	0.573E-03	0.593E-03	0.614E-03
10.0 – 100	0.394E-03	0.396E-03	0.397E-03	0.398E-03	0.400E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.731E+02	0.850E+02	0.969E+02	0.109E+03	0.121E+03
0.10 – 0.20	0.308E-01	0.349E-01	0.390E-01	0.431E-01	0.472E-01
0.20 – 0.30	0.763E-02	0.852E-02	0.942E-02	0.103E-01	0.112E-01
0.30 – 0.40	0.394E-02	0.436E-02	0.477E-02	0.519E-02	0.560E-02
0.40 – 0.50	0.540E-03	0.591E-03	0.643E-03	0.694E-03	0.745E-03
0.50 – 0.60	0.210E-03	0.229E-03	0.247E-03	0.265E-03	0.283E-03
0.60 – 0.70	0.342E-03	0.369E-03	0.396E-03	0.424E-03	0.451E-03
0.70 – 0.80	0.249E-03	0.268E-03	0.286E-03	0.305E-03	0.323E-03
0.80 – 0.90	0.140E-03	0.150E-03	0.159E-03	0.169E-03	0.179E-03
0.90 – 1.00	0.531E-04	0.565E-04	0.599E-04	0.633E-04	0.668E-04
0.10 – 1.00	0.439E-01	0.494E-01	0.549E-01	0.605E-01	0.660E-01
1.00 – 2.00	0.256E-03	0.268E-03	0.280E-03	0.293E-03	0.305E-03
2.00 – 3.00	0.965E-04	0.996E-04	0.103E-03	0.106E-03	0.109E-03
3.00 – 4.00	0.688E-04	0.704E-04	0.721E-04	0.738E-04	0.755E-04
4.00 – 5.00	0.118E-03	0.121E-03	0.123E-03	0.125E-03	0.128E-03
1.00 – 10.0	0.635E-03	0.655E-03	0.676E-03	0.697E-03	0.717E-03
10.0 – 100	0.401E-03	0.403E-03	0.404E-03	0.406E-03	0.407E-03

Table 3. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter
[Orbit Altitude = 800 km; Inclination = 30°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.177E+02	0.331E+02	0.485E+02	0.639E+02	0.793E+02
0.10 – 0.20	0.510E-01	0.714E-01	0.918E-01	0.112E+00	0.133E+00
0.20 – 0.30	0.610E-02	0.785E-02	0.959E-02	0.113E-01	0.131E-01
0.30 – 0.40	0.292E-02	0.357E-02	0.422E-02	0.487E-02	0.552E-02
0.40 – 0.50	0.111E-02	0.131E-02	0.151E-02	0.172E-02	0.192E-02
0.50 – 0.60	0.620E-03	0.716E-03	0.811E-03	0.907E-03	0.100E-02
0.60 – 0.70	0.418E-03	0.474E-03	0.530E-03	0.586E-03	0.641E-03
0.70 – 0.80	0.244E-03	0.272E-03	0.301E-03	0.330E-03	0.358E-03
0.80 – 0.90	0.148E-03	0.163E-03	0.179E-03	0.194E-03	0.210E-03
0.90 – 1.00	0.123E-03	0.134E-03	0.146E-03	0.158E-03	0.169E-03
0.10 – 1.00	0.627E-01	0.859E-01	0.109E+00	0.132E+00	0.155E+00
1.00 – 2.00	0.507E-03	0.539E-03	0.570E-03	0.602E-03	0.634E-03
2.00 – 3.00	0.177E-03	0.184E-03	0.191E-03	0.197E-03	0.204E-03
3.00 – 4.00	0.725E-04	0.745E-04	0.765E-04	0.785E-04	0.805E-04
4.00 – 5.00	0.131E-03	0.134E-03	0.136E-03	0.139E-03	0.142E-03
1.00 – 10.0	0.101E-02	0.106E-02	0.110E-02	0.115E-02	0.119E-02
10.0 – 100	0.760E-03	0.763E-03	0.765E-03	0.768E-03	0.771E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.947E+02	0.110E+03	0.126E+03	0.141E+03	0.156E+03
0.10 – 0.20	0.153E+00	0.173E+00	0.194E+00	0.214E+00	0.235E+00
0.20 – 0.30	0.148E-01	0.166E-01	0.183E-01	0.201E-01	0.218E-01
0.30 – 0.40	0.616E-02	0.681E-02	0.746E-02	0.811E-02	0.876E-02
0.40 – 0.50	0.212E-02	0.232E-02	0.252E-02	0.273E-02	0.293E-02
0.50 – 0.60	0.110E-02	0.119E-02	0.129E-02	0.138E-02	0.148E-02
0.60 – 0.70	0.697E-03	0.753E-03	0.809E-03	0.865E-03	0.920E-03
0.70 – 0.80	0.387E-03	0.416E-03	0.444E-03	0.473E-03	0.502E-03
0.80 – 0.90	0.226E-03	0.241E-03	0.257E-03	0.272E-03	0.288E-03
0.90 – 1.00	0.181E-03	0.193E-03	0.204E-03	0.216E-03	0.228E-03
0.10 – 1.00	0.179E+00	0.202E+00	0.225E+00	0.248E+00	0.271E+00
1.00 – 2.00	0.665E-03	0.697E-03	0.729E-03	0.760E-03	0.792E-03
2.00 – 3.00	0.211E-03	0.218E-03	0.225E-03	0.231E-03	0.238E-03
3.00 – 4.00	0.825E-04	0.845E-04	0.866E-04	0.886E-04	0.906E-04
4.00 – 5.00	0.145E-03	0.148E-03	0.151E-03	0.153E-03	0.156E-03
1.00 – 10.0	0.124E-02	0.128E-02	0.133E-02	0.137E-02	0.142E-02
10.0 – 100	0.774E-03	0.776E-03	0.779E-03	0.782E-03	0.785E-03

Table 4. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter [Orbit Altitude = 800 km; Inclination = 50°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.192E+02	0.359E+02	0.526E+02	0.693E+02	0.860E+02
0.10 – 0.20	0.229E-01	0.321E-01	0.413E-01	0.504E-01	0.596E-01
0.20 – 0.30	0.940E-02	0.121E-01	0.148E-01	0.175E-01	0.201E-01
0.30 – 0.40	0.332E-02	0.406E-02	0.479E-02	0.553E-02	0.627E-02
0.40 – 0.50	0.140E-02	0.166E-02	0.192E-02	0.217E-02	0.243E-02
0.50 – 0.60	0.650E-03	0.750E-03	0.850E-03	0.950E-03	0.105E-02
0.60 – 0.70	0.430E-03	0.487E-03	0.545E-03	0.602E-03	0.659E-03
0.70 – 0.80	0.385E-03	0.430E-03	0.476E-03	0.521E-03	0.566E-03
0.80 – 0.90	0.202E-03	0.223E-03	0.244E-03	0.265E-03	0.287E-03
0.90 – 1.00	0.163E-03	0.179E-03	0.194E-03	0.210E-03	0.225E-03
0.10 – 1.00	0.389E-01	0.520E-01	0.650E-01	0.781E-01	0.912E-01
1.00 – 2.00	0.545E-03	0.579E-03	0.613E-03	0.647E-03	0.681E-03
2.00 – 3.00	0.230E-03	0.239E-03	0.248E-03	0.257E-03	0.266E-03
3.00 – 4.00	0.805E-04	0.827E-04	0.850E-04	0.872E-04	0.894E-04
4.00 – 5.00	0.836E-04	0.854E-04	0.872E-04	0.891E-04	0.909E-04
1.00 – 10.0	0.108E-02	0.113E-02	0.118E-02	0.123E-02	0.128E-02
10.0 – 100	0.665E-03	0.668E-03	0.670E-03	0.673E-03	0.676E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.103E+03	0.119E+03	0.136E+03	0.153E+03	0.170E+03
0.10 – 0.20	0.688E-01	0.779E-01	0.871E-01	0.963E-01	0.105E+00
0.20 – 0.30	0.228E-01	0.255E-01	0.282E-01	0.309E-01	0.336E-01
0.30 – 0.40	0.700E-02	0.774E-02	0.848E-02	0.922E-02	0.995E-02
0.40 – 0.50	0.268E-02	0.294E-02	0.319E-02	0.345E-02	0.370E-02
0.50 – 0.60	0.115E-02	0.125E-02	0.135E-02	0.145E-02	0.155E-02
0.60 – 0.70	0.717E-03	0.774E-03	0.831E-03	0.889E-03	0.946E-03
0.70 – 0.80	0.612E-03	0.657E-03	0.702E-03	0.747E-03	0.793E-03
0.80 – 0.90	0.308E-03	0.329E-03	0.350E-03	0.371E-03	0.393E-03
0.90 – 1.00	0.241E-03	0.256E-03	0.272E-03	0.287E-03	0.303E-03
0.10 – 1.00	0.104E+00	0.117E+00	0.130E+00	0.144E+00	0.157E+00
1.00 – 2.00	0.715E-03	0.749E-03	0.783E-03	0.817E-03	0.851E-03
2.00 – 3.00	0.275E-03	0.283E-03	0.292E-03	0.301E-03	0.310E-03
3.00 – 4.00	0.917E-04	0.939E-04	0.961E-04	0.984E-04	0.101E-03
4.00 – 5.00	0.927E-04	0.945E-04	0.963E-04	0.981E-04	0.100E-03
1.00 – 10.0	0.132E-02	0.137E-02	0.142E-02	0.147E-02	0.152E-02
10.0 – 100	0.678E-03	0.681E-03	0.683E-03	0.686E-03	0.688E-03

Table 5. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter
[Orbit Altitude = 1000 km; Inclination = 30°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.154E+02	0.288E+02	0.422E+02	0.556E+02	0.690E+02
0.10 – 0.20	0.608E-01	0.851E-01	0.109E+00	0.134E+00	0.158E+00
0.20 – 0.30	0.946E-02	0.122E-01	0.149E-01	0.176E-01	0.203E-01
0.30 – 0.40	0.370E-02	0.453E-02	0.535E-02	0.617E-02	0.700E-02
0.40 – 0.50	0.126E-02	0.149E-02	0.172E-02	0.195E-02	0.218E-02
0.50 – 0.60	0.619E-03	0.714E-03	0.809E-03	0.905E-03	0.100E-02
0.60 – 0.70	0.476E-03	0.539E-03	0.602E-03	0.666E-03	0.729E-03
0.70 – 0.80	0.250E-03	0.279E-03	0.309E-03	0.338E-03	0.368E-03
0.80 – 0.90	0.195E-03	0.216E-03	0.236E-03	0.257E-03	0.277E-03
0.90 – 1.00	0.184E-03	0.201E-03	0.219E-03	0.236E-03	0.254E-03
0.10 – 1.00	0.769E-01	0.105E+00	0.134E+00	0.162E+00	0.190E+00
1.00 – 2.00	0.794E-03	0.844E-03	0.893E-03	0.943E-03	0.992E-03
2.00 – 3.00	0.181E-03	0.188E-03	0.195E-03	0.202E-03	0.209E-03
3.00 – 4.00	0.445E-04	0.458E-04	0.470E-04	0.483E-04	0.495E-04
4.00 – 5.00	0.307E-04	0.314E-04	0.320E-04	0.327E-04	0.334E-04
1.00 – 10.0	0.111E-02	0.117E-02	0.122E-02	0.128E-02	0.134E-02
10.0 – 100	0.780E-03	0.783E-03	0.785E-03	0.788E-03	0.790E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.824E+02	0.958E+02	0.109E+03	0.123E+03	0.136E+03
0.10 – 0.20	0.182E+00	0.207E+00	0.231E+00	0.255E+00	0.280E+00
0.20 – 0.30	0.230E-01	0.257E-01	0.284E-01	0.311E-01	0.338E-01
0.30 – 0.40	0.782E-02	0.864E-02	0.946E-02	0.103E-01	0.111E-01
0.40 – 0.50	0.241E-02	0.264E-02	0.287E-02	0.309E-02	0.332E-02
0.50 – 0.60	0.109E-02	0.119E-02	0.129E-02	0.138E-02	0.148E-02
0.60 – 0.70	0.793E-03	0.856E-03	0.919E-03	0.983E-03	0.105E-02
0.70 – 0.80	0.397E-03	0.427E-03	0.456E-03	0.485E-03	0.515E-03
0.80 – 0.90	0.298E-03	0.318E-03	0.339E-03	0.359E-03	0.380E-03
0.90 – 1.00	0.271E-03	0.289E-03	0.306E-03	0.324E-03	0.341E-03
0.10 – 1.00	0.218E+00	0.247E+00	0.275E+00	0.303E+00	0.332E+00
1.00 – 2.00	0.104E-02	0.109E-02	0.114E-02	0.119E-02	0.124E-02
2.00 – 3.00	0.216E-03	0.223E-03	0.230E-03	0.237E-03	0.243E-03
3.00 – 4.00	0.507E-04	0.520E-04	0.532E-04	0.544E-04	0.557E-04
4.00 – 5.00	0.340E-04	0.347E-04	0.354E-04	0.360E-04	0.367E-04
1.00 – 10.0	0.140E-02	0.146E-02	0.152E-02	0.158E-02	0.164E-02
10.0 – 100	0.792E-03	0.795E-03	0.797E-03	0.800E-03	0.802E-03

Table 6. Impact rate [$yr^{-1}km^{-1}$] as a function of orbital debris size and tether diameter
[Orbit Altitude = 1000 km; Inclination = 50°]

Debris Diameter Interval (cm)	Tether Diameter 1 mm	2 mm	3 mm	4 mm	5 mm
0.01 – 0.10	0.166E+02	0.310E+02	0.454E+02	0.598E+02	0.742E+02
0.10 – 0.20	0.495E-01	0.693E-01	0.891E-01	0.109E+00	0.129E+00
0.20 – 0.30	0.108E-01	0.139E-01	0.169E-01	0.200E-01	0.231E-01
0.30 – 0.40	0.397E-02	0.486E-02	0.574E-02	0.662E-02	0.751E-02
0.40 – 0.50	0.133E-02	0.158E-02	0.182E-02	0.206E-02	0.231E-02
0.50 – 0.60	0.595E-03	0.686E-03	0.778E-03	0.869E-03	0.960E-03
0.60 – 0.70	0.486E-03	0.550E-03	0.615E-03	0.680E-03	0.745E-03
0.70 – 0.80	0.309E-03	0.345E-03	0.382E-03	0.418E-03	0.454E-03
0.80 – 0.90	0.227E-03	0.251E-03	0.275E-03	0.299E-03	0.323E-03
0.90 – 1.00	0.197E-03	0.216E-03	0.234E-03	0.253E-03	0.272E-03
0.10 – 1.00	0.674E-01	0.916E-01	0.116E+00	0.140E+00	0.164E+00
1.00 – 2.00	0.780E-03	0.829E-03	0.878E-03	0.927E-03	0.975E-03
2.00 – 3.00	0.171E-03	0.177E-03	0.184E-03	0.190E-03	0.197E-03
3.00 – 4.00	0.115E-03	0.118E-03	0.121E-03	0.124E-03	0.128E-03
4.00 – 5.00	0.688E-04	0.703E-04	0.718E-04	0.733E-04	0.747E-04
1.00 – 10.0	0.123E-02	0.129E-02	0.135E-02	0.142E-02	0.148E-02
10.0 – 100	0.758E-03	0.761E-03	0.763E-03	0.765E-03	0.768E-03

Debris Diameter Interval (cm)	Tether Diameter 6 mm	7 mm	8 mm	9 mm	1 cm
0.01 – 0.10	0.886E+02	0.103E+03	0.117E+03	0.132E+03	0.146E+03
0.10 – 0.20	0.148E+00	0.168E+00	0.188E+00	0.208E+00	0.228E+00
0.20 – 0.30	0.262E-01	0.292E-01	0.323E-01	0.354E-01	0.385E-01
0.30 – 0.40	0.839E-02	0.927E-02	0.102E-01	0.110E-01	0.119E-01
0.40 – 0.50	0.255E-02	0.279E-02	0.303E-02	0.328E-02	0.352E-02
0.50 – 0.60	0.105E-02	0.114E-02	0.123E-02	0.133E-02	0.142E-02
0.60 – 0.70	0.809E-03	0.874E-03	0.939E-03	0.100E-02	0.107E-02
0.70 – 0.80	0.491E-03	0.527E-03	0.563E-03	0.600E-03	0.636E-03
0.80 – 0.90	0.347E-03	0.371E-03	0.395E-03	0.419E-03	0.443E-03
0.90 – 1.00	0.291E-03	0.309E-03	0.328E-03	0.347E-03	0.366E-03
0.10 – 1.00	0.189E+00	0.213E+00	0.237E+00	0.261E+00	0.286E+00
1.00 – 2.00	0.102E-02	0.107E-02	0.112E-02	0.117E-02	0.122E-02
2.00 – 3.00	0.204E-03	0.210E-03	0.217E-03	0.223E-03	0.230E-03
3.00 – 4.00	0.131E-03	0.134E-03	0.137E-03	0.140E-03	0.144E-03
4.00 – 5.00	0.762E-04	0.777E-04	0.792E-04	0.807E-04	0.822E-04
1.00 – 10.0	0.154E-02	0.160E-02	0.166E-02	0.172E-02	0.178E-02
10.0 – 100	0.770E-03	0.772E-03	0.774E-03	0.777E-03	0.779E-03

neglected anymore. For this reason, the future tether systems in low earth orbit should also be able to control their internal and trajectory dynamics, in order to avoid collisions with operational and abandoned satellites.

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