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SPACE DEBRIS REMOVAL WITH BARE ELECTRODYNAMIC TETHERS

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Electrodynamic tethers (EDT´s) have been proposed as one of the most promising tool for space debris removal thanks to their inherently propellantless mode of operation. Among the different technological solutions for electrodynamic tether current collection the bare tether concept has been shown to offer the best performance in terms of deorbiting capability per unit of tether mass. Although some studies have been performed by other authors to assess the capability of bare EDT´s to deorbit existing debris objects the design of the bare tether has not been optimized and often the simulation results in the literature are not reproducible. In this article we consider optimally sized bare electrodynamic tethers with tape cross section attached to existing space debris whose characteristics are provided by the DISCOS database of the European Space Agency. Simulations are performed with aluminum tape EDTs stabilized along the local vertical and assuming Orbital Motion Limited (OML) theory hence providing a lower limit in terms of deorbiting time for the objects considered. For the present design the EDT system is completely passive, i.e. it does not use onboard power in the current generation process. Considered Tether lengths and masses are 10,15,20 km and 40,60 and 80 kg. Results confirm the suitability of passive EDTs as orbital debris removing systems.

INTRODUCTION

The steadily increase of the space debris population is threatening the future of space utilization for both commercial and scientific purposes and calls for urgent measures to deal with the problem. While international policies for avoiding the accumulation of new debris are likely to become agreed upon in the near future it is argued that active disposal of existing non-operating space objects by dedicated "space debris removers" will soon become necessary. In spite of the huge technological challenge that such a task would imply some solutions have been proposed and studied in the literature. Among them stands the use of electrodynamic tethers which offer one key advantage: propellantless and controlled reentry with limited required hardware mass.

An Electrodynamic tethers (EDT) is a space apparatus which can supply power and/or propulsion to a spacecraft by exploiting the electromagnetic interaction of a conducting cable orbiting around a planet with a magnetic field and reasonable plasma density. As such interaction occurs without the need of expending fuel EDTs can be used as propellantless propulsion systems of great interest in space technology. Following its first appearance in the literature [1] the concept of electrodynamic

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tether has been studied and refined until the introduction of the higher performance bare electrodynamic tether concept in 1991 by Sanmartin et al. [2]. After a few initial studies were conducted to assess the performance of bare EDTs in different scenarios of space science and technology it became clear that these devices could be considered as a candidate solution to the problem of space debris and several articles on the subject appeared in the literature (see for example [3]). The problem with these early studies is that in most cases the EDT design considered in the simulations is far from been optimized. It is in fact known [4] that the best use of bare electrodynamic tether mass is to adopt a thin tape-like cross section for the tether and having the tether long enough in such a way to push the current collection well into the dominant ohmic effects regime for most of its orbital operation. A light multi-line high-specific-strength wire structure can then be embedded in the tape for boosting tether survivability.

In this article we perform an analysis of the deorbiting capability of optimally-designed EDTs to deorbit existing space debris, as provided by the DISCOS catalog of the European Space Agency [5] and employing the analytical approximation in ref. [6] to compute OML current collection by the EDT. The attitude motion of the EDT is considered constantly stabilized along the local vertical to provide a simpler reference model. The plasma electron density is computed according to the IRI2007 model while atmosphereic drag is here neglected being orders of magnitudes smaller than the Lorentz drag provided by the tethers. An IGRF95 model for the Earth magnetic field is employed.

TARGET SPACE DEBRIS FOR ACTIVE REMOVAL

Since the Sputnik-1 launch in 1957 thousands of satellites have been launched in orbit with a current launch rate of about 60 new satellites per year. A considerable fraction of the launched mass, more than 5000 tons, has remained in orbit producing more than 9000 trackable objects (i.e. greater than about 10 cm in size). In the current situation this number is growing not only because of newly launched satellites but also due to on-orbit explosions and accidental collisions among resident space objects. According to a study by Liou and Johnson [7], even assuming no new satellites were launched, the increase rate of trackable objects generated by accidental collisions would exceed the decrease rate due to atmospheric drag decay starting from about 2055. This trend is mostly due to large and massive objects placed in crowded orbits, that is, at an altitude between 800 and 1000 km and near-polar inclination.

The most obviuous counter-measure to limit this trend is to adopt postmission disposal guidelines, which are likely to become agreed upon by the international space community in the very near future. However, as pointed out by Liou and Johnson [7], these measures will be insufficient to contrain the growth of man-made space objects and active removal of existing space debris will be required.

When implementing an active removal strategy the first thing to do is to establish selection criteria to rate the objects according to their likelyhood of causing a major increase in the current debris population. In this regards important parameters to take into account can be listed in the following:

- *object mass*: a massive object is likely to generate more debris when exploding or colliding with another object
- *object cross section*: it directly affects the collision probability with another object

- *orbital elements*: they affect the collision probability of each debris with the reminder of the spacecraft population determining how crowded the debris orbit is
- *estimated lifetime*: it also affects the collision probability, as the longer a debris stays in orbit the higher is the probability of impacting with satellites at lower altitudes.
- *additional debris specifications*: for instance the presence of residual fuel, charged batteries, etc. increases the probability the debris will explode

For our preliminary analysis we will limit our target objects to spent upper stages (which have the highest likelyhood of exploding) having perigee altitude not exceeding 2000 km (we will use that as our definition of “Low Earth Orbit”) and with total mass greater than 1000 kg. After eliminating objects with less than 60 years lifetime we rate them according to a simplified hazard coefficient which is just the product of the satellite mass and the cross-sectional area:

$$H = A\,m \tag{1}$$

Note that the estimated debris lifetime has not been included given the (optimistic) assumption that the majority of existing debris will be removed from orbit in less than 60 years from now.

Using the data provided by the DISCOS database of the European Space Agency[5] we have found that there are currently* 587 spent upper stages in LEO orbit weighting more than 1 ton and with an expected lifetime exceeding 60 years. The heaviest debris found were the twenty-two 2nd stages of the Russian-Ukrainian Zenith launcher, reaching a mass of 8 to 9 tons and placed in high inclination circular orbits of 800 to 1000 km altitude. The most numerous upper stage family is the one of the Russian Kosmos launcher 2-nd stage with 264 elements in high-inclination circular orbits of mostly 800 and 1000 km altitude.

Figure 1 and 3 plots the mass of the 587 candidate upper stages according to descending hazard coefficient highlighting the most numerous upper stage families. The plot suggests that the heavy Russian and upper stages (Zenith-2) should be given the highest priority. Note that because orbit elements are not considered our simplified hazard coefficient does not fully take into account the impact probability of each debris with the reminder of the space population.

ASSESSING REMOVAL COST

Before considering any possible removal strategy it is important to introduce a way of measuring the cost related to deorbiting each of the considered space debris. A simple reasonable metric we can use is the apogee impulsive ΔV required to lower the perigee to a prescribed altitude, which can be written as:

$$\Delta V = \sqrt{\frac{2\mu}{r_a}} \left(\sqrt{\frac{r_{pi}}{r_a + r_{pi}}} - \sqrt{\frac{r_{pf}}{r_a + r_{pf}}} \right) \tag{2}$$

with μ, r_a, r_{pi} and r_{pf} the Earth gravitational constant, the apogee radius and the initial and final perigee radii, respectively.

* the data were retrieved in december 2009

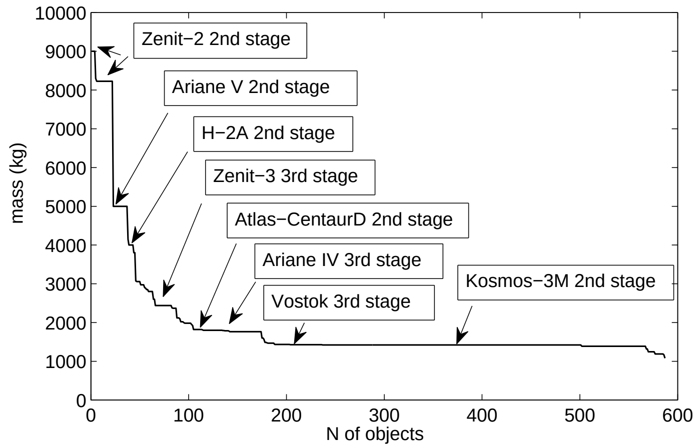

Figure 1. mass of LEO spent upper stages highlighting different families

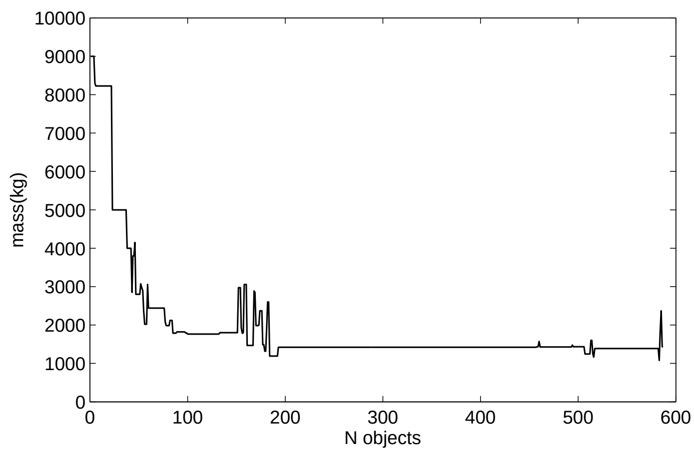

Figure 2. mass of LEO spent upper stages ordered by descending hazard coefficient (Eq. 1)

In reality, such maneuver is almost never possible, primarily due to the limited thrust available, which forces to perform multiple ΔV maneuvers on subsequent apogee passes (a description of a real space debris deorbiting operation can be found on reference [8]) so the actual ΔV needed is always somewhat greater. As far as the choice of the final perigee altitude it depends on the type of deorbiting maneuver required. According to the guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) the minimum requirement for the maneuver is to reduce the lifetime of the debris to less than 25 years in orbit, which roughly corresponds to a perigee altitude of 500 km. On the other hand the same committee recommends a *direct reentry* whenever possible which is achieved with a perigee altitude around 150 km. In some cases in which the debris could pass through the atmosphere without being fully disintegrated and/or could release harmful material on the ground a *targeted reentry* is recommended which requires a final burn resulting in a steep angle of attack reentry with respect to the dense atmosphere at ~80 km altitude and correponds to "equivalent" perigee altitude of about 50 km.

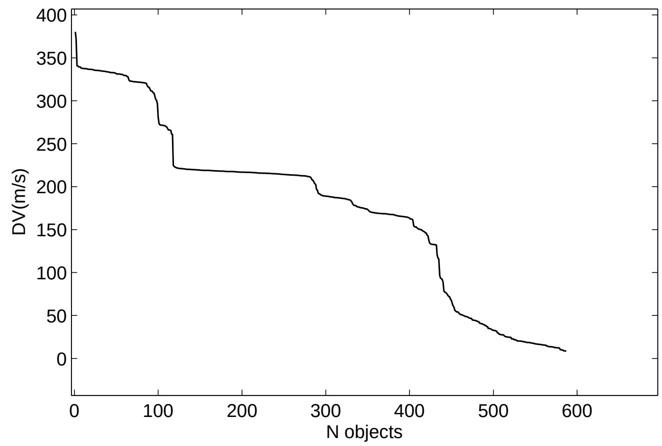

Figure 3. ΔV cost to lower the space debris perigee at 150 and 500 km altitudes with an impulsive apogee maneuver

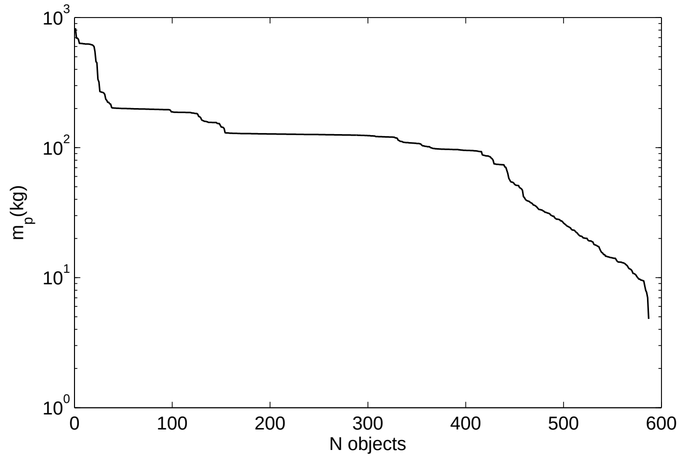

Figure 4. Propellant mass cost to lower the space debris perigee at 150 km altitude with an impulsive apogee maneuver

Figure 3 plots the ΔV required to lower the perigee of each space debris down to 150 km altitude.

From the previous metric we can derive the cost in terms of mass of required chemical propellant for deorbiting:

$$m_p = m_{SD} \left[exp\left(\frac{\Delta V}{c}\right) - 1 \right] \tag{3}$$

where m_{SD} is the debris mass and c the propellant exhaust velocity. Figure 4 plots the required propellant mass assuming $c = 2550\ m/s$ (corresponding to a chemical engine with 260 s of specific impulse). The total propellant mass spent to deorbit all upper stages considered is about 79 tons for a direct deorbiting.

We can see that for the majority of space debris in orbit the cost in terms of propellant can be relatively high which plays in favor of propellantless strategies as advantageous solutions for debris removal. As the typical space debris orbits are characterized by sufficiently high plasma density and magnetic field intensity electrodynamic tether systems (EDT) are potentially good candidate tools for active space debris removal.

ELECTRODYNAMIC TETHER DESIGN AND MODELING

When considering a bare electrodynamic tether working in *passive mode* the best performance in terms of thrust to mass ratio is achieved by considering an aluminum conductive tether[†] with a tape cross section of width w and thickness h designed in such a way that the following two conditions are satisfied:

1. Current collection along the tether occurs in the Orbital Motion Limited regime (OML)
2. Current collection is dominated by ohmic effects

Condition 1 imposes a limit on the maximum tape width based on local environmental conditions. More precisely the width has to be small when compared with the Debye length λ_D of the surrounding plasma in daylight conditions [9]. For instance a tape tether flying on a low earth orbit (around 300 km altitude) the upper bound on w is about 2-3 cm and increases for higher altitude orbits.

Condition 2 suggests that the tether length L should be as large as possible compared to the tape width h. More precisely the tether-plasma equivalent contact impedance should be small when compared to the conductive impedance of the aluminum tether tape. Due to tether safety constraints a reasonable lower limit for h is about 0.05 mm [‡] while a reasonable upper limit for L can be taken as 20 km. It can be easily verified that a tape tether of 20 km length and 0.05 mm thickness works in the dominant ohmic effects regime in circular orbit up to 1300 km altitude even with minimum solar illumination conditions. If we then consider 3 cm as a our tape width we end up with a tether of about 80 kg of mass.

Following the work of Bombardelli et al. [6] the maximum average current flowing through a passive EDT under orbital motion limited current collection can be written as:

$$I_{av} = \frac{3}{5}\eta_{th} I_{ch}$$

where $I_{ch}$is the characteristic tether current and η_{th} the thrust ohmic efficiency[6]. The former is defined as:

$$I_{ch} = \frac{4w}{3\pi} N_e \sqrt{\frac{2E_t}{m_e} q_e^3 L^3}, \tag{4}$$

where N_e is the local plasma electron density, q_e and m_e the electron charge and mass, respectively, and where E_t is the projection of the local motional electric field along the tether line.

The resulting electrodynamic drag force is finally:

[†] aluminum is among the materials with the highest ratio of electric conductivity to mass density and the highest malleability

[‡] a 300m aluminum tether tape of such thickness has been built and will be flown later this year onboard of a JAXA sounding rocket

$$\mathbf{F} = I_{av} BL(\mathbf{u}_t \wedge \mathbf{u}_B) \tag{5}$$

where B is the magnetic field intensity while $\mathbf{u_t}$ and $\mathbf{u}_B$ are, respectively, the tether line unit vector directed along the current flow and the magnetic field unit vector.

DEORBITING PERFORMANCE

In the following we present numerical simulation results for a tape electrodynamic tether deorbiting system applied to different families of upper stages. For this preliminary analysis only circular or almost circular orbits were considered as gravity-gradient stabilized tethers require constant attitude control when in highly eccentric orbits. In addition space debris in high-eccentricity orbits have in general a lower deorbiting cost in terms for chemical-propulsion-based maneuvers. Note that out of 587 space debris in our sample 410 have eccentricity lower than 0.015.

The results were obtained with an in-house EDT simulator employing the IRI2007 and IGRF Earth ionosphere and magnetosphere models, respectively, and assuming the tether is constantly aligned along the local vertical. An aluminium tape tether of 0.05 mm thickness and 3 cm width was considered. Simulations where performed for different tether length (10, 15 and 20 km) as well as for minimum and maximum solar activity.

Zenith 2nd Stage

Among the different 2nd stages in the Russian-Ukrainan Zenith family the ones with higher collision hazard coefficient are all in almost circular orbits with altitudes spanning between 650 and 1000 km altitude with the majority of them around 850 km, and inclination mostly around 71 deg and in a few cases around 98 deg. They weight approximately 9 tons.

In order to demonstrate the EDT deorbiting capability we picked two samples, one in in a 997-km-altitude 99-deg-inclination orbit the other in an 845-km-altitude 71-deg-inclination. Note that the first sample is the most difficult debris to deorbit, with a required 830 kg of hydrazine for lowering its perigee to 150 km altitude.

H-2A 2nd Stage

In the Japanese H-2A rocket family there is one second stage in quasi circular orbit with a mass of about 4 tons and an estimated lifetime of 125 years. Its present orbit has 790 km altitude and 98 deg inclination with an associated cost of about 260 kg of hydrazine for deorbiting.

Kosmos-3M 2nd Stage

Even if with a lower impact hazard coefficient the Kosmos 2nd stage family is significant as it is the most numerous among all upper stages. More than 260 members of this family with expeted

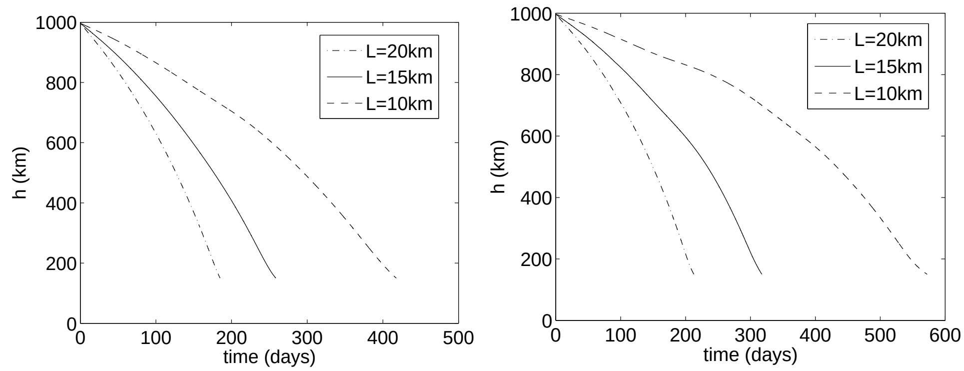

Figure 5. Deorbiting curves for a Zenith 2nd-stage (m=9 tons) starting from a circular 997-km-altitude 99-deg-inclination orbit, using a $3cm \times 0.05mm$ tape electrodynamic tether of different length (L) under maximum (left) and minimum (right) solar activity.

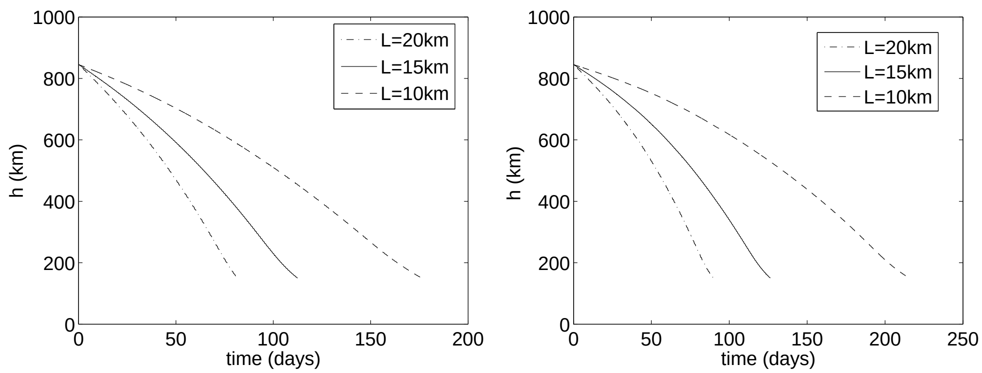

Figure 6. Deorbiting curves for a Zenith 2nd-stage (m=9 tons) starting from a circular 845-km-altitude 71-deg-inclination orbit, using a $3cm \times 0.05mm$ tape electrodynamic tether of different length (L) under maximum (left) and minimum (right) solar activity.

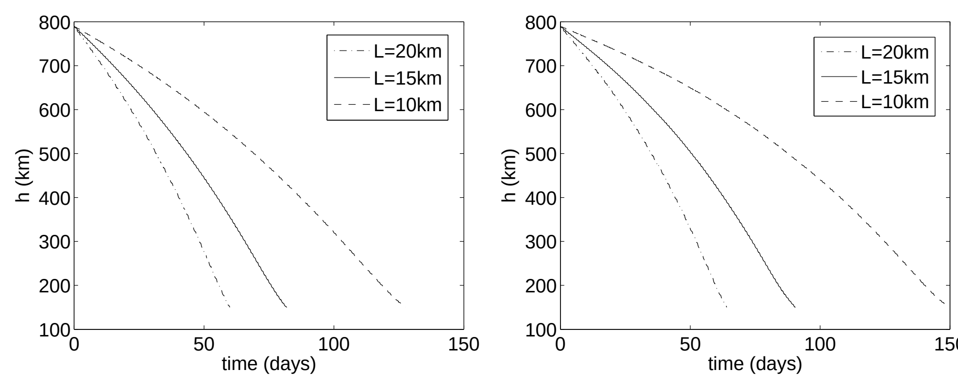

Figure 7. Deorbiting curves for an H-2A 2nd-stage (m=4 tons) starting from a circular 790-km-altitude 98-deg-inclination orbit, using a $3cm \times 0.05mm$ tape electrodynamic tether of different length (L) under maximum (left) and minimum (right) solar activity.

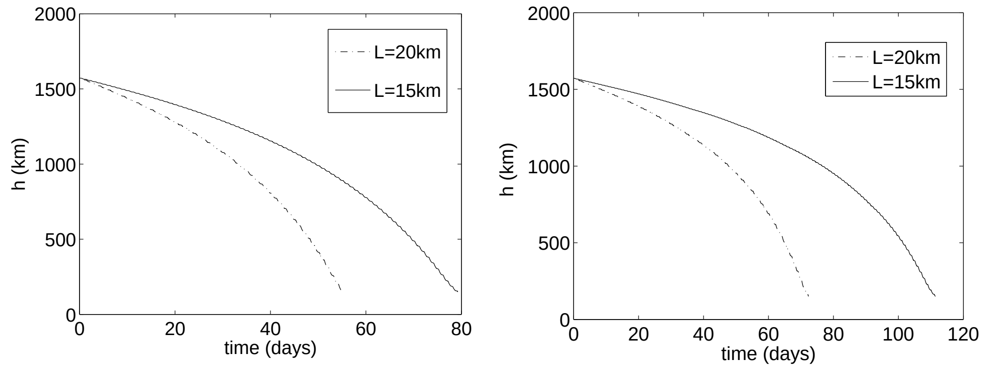

Figure 8. Deorbiting curves for a Kosmos-3M 2nd-stage (m=1.4 tons) starting from a circular 1572-km-altitude 74-deg-inclination orbit, using a $3cm \times 0.05mm$ tape electrodynamic tether of different length (L) under maximum (left) and minimum (right) solar activity.

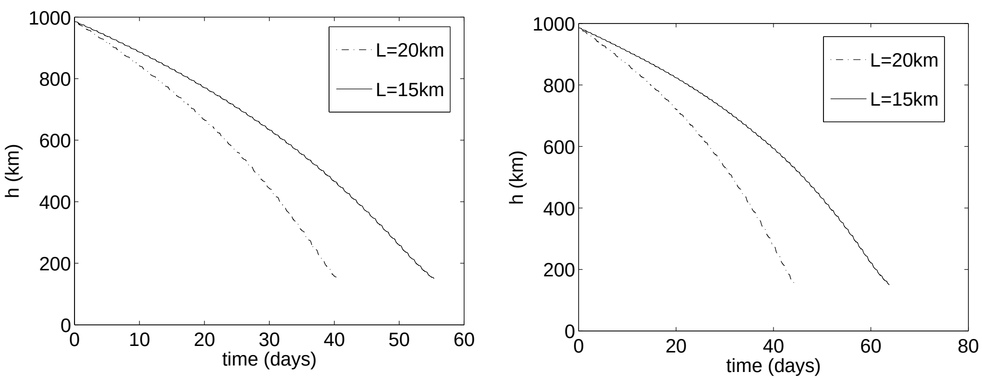

Figure 9. Deorbiting curves for a Kosmos-3M 2nd-stage (m=1.4 tons) starting from a circular 986-km-altitude 83-deg-inclination orbit, using a $3cm \times 0.05mm$ tape electrodynamic tether of different length (L) under maximum (left) and minimum (right) solar activity.

lifetime exceeding 60 years are currently in orbit. The great majority of them are in almost circular orbits around 74 and 82 deg inclination and altitude mostly in the 700 to 1000 km band. The mass of this upper stage is about 1.4 tons and the deorbiting cost is estimated to be around 200 kg of hydrazine. Notably, they all have a very high expected lifetime (from a few hundred years to more than a millenium).

ADDITIONAL REMARKS AND FUTURE WORK

The aim of the present analysis is to estimate the capability of a gravity-gradient stabilized tape EDT as deorbiting system for different classes of space debris objects. Issues like tether attitude dynamics, tether deployment and stabilization, as well as debris identification, rendevous and docking systems will need to be addressed in more details in the future. For the time being, it suffices to say that considerable work has been done towards the design of efficient control algorithms to tackle the librational instability of electrodynamic tethers [10] while self-balanced EDT design solutions have been proposed [11], [12], [13]. Nevertheless, as the tether librational motion is likely to affect the deorbiting performance a more refined dynamic model accounting for this effect will be needed for a complete assessement of the system capability.

As far as tape-tether deployment is concerned a suborbital demontration of a 300 m EDT system on board of the JAXA S520-25 sounding rocket is scheduled for this year and carries an innovative "fold-away" tape tether deployment system. Ground experiments of this deployment technique have been carried out[**?**].

Ultimately, the most challenging technological aspects of the EDT debris remover concept is probably related to the debris rendevous and docking maneuver, although the presence of the tether does not seem to complicate the matter significantly. In fact, if the electrodynamic tether would appear, at first sight, "less maneuverable" due to its elongated shape, enhanced capabilities related to target identification and debris capturing when using km-long tethers were pointed out by a recent NASA-funded study[**?**].

A last but important remark has to be made concerning the reusability of orbiting EDT systems for multiple space debris deorbiting tasks. EDT can in fact have their orbit reboosted at the end of each debris desposal operation by switching to thrust mode for a later rendezvous with another target debris. This fact represents a key advantage with respect to propellant-based solution. An evaluation of the self-reboosting capability of EDT would then be needed to completely assess the effectiveness of a multiple debris removal strategy. Note that for such case the debris deorbiting maneuver would need to be analyzed in light of the presence of a power supply unit which adds mass to the EDT system but at the same time allows to boost the tether current by increasing the plasma-tether bias. Future studies will address these topics.

CONCLUSIONS

Results from this preliminary analysis show that EDTs are effective against debris object up to 1500 km altitude and exhibit the highest performance in less inclined and lower altitude orbits. By using 20-km-long aluminum tape tethers of less than 80 kg one can deorbit the heaviest debris currently in orbit in a matter of weeks even during minimum ionosphere density conditions. Shorter and lighter tethers (10 km and 40 kg) can still be effective for average size existing debris.

Future analysis can be done to refine the calculations provided here by adding more complex feature in the tether dynamics such as librational motion, which is expected to add a small reduction in deorbiting performance provided that some level of control or clever design solutions are implemented to stabilize the tether dynamics.

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