SPIN MODULATION FOR DEORBITING WITH ELECTRODYNAMIC TETHERS

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ABSTRACT

The growing accumulation of space debris threatens the sustainability of orbital activities, particularly in low Earth orbit (LEO), where increasing satellite launches heighten the risk of collisions. This can lead to the Kessler syndrome, a chain reaction of debris creation that could render certain orbits unusable. To mitigate this risk, new regulations require satellites to deorbit within five years of mission completion, driving the need for efficient deorbiting technologies.
The E.T.COMPACT project is exploring electrodynamic tethers as a propellant-free solution, both for deorbit and reboost operations. This lightweight device (designed to occupy just a few CubeSat units) uses the Earth's magnetic field to generate Lorentz force, gradually slowing satellites for reentry. However, Sun-synchronous orbits pose challenges due to a critical magnetic field geometry. To overcome this, the project is testing a spinning strategy that increases the likelihood of optimal alignment between the tether and the magnetic field, enhancing Lorentz force generation. Using FLEX software, the project runs simulations to validate this approach, optimizing spin rates and system parameters for safe and efficient deorbiting. Different scenarios are evaluated (using one or two cathodes and various spin plane orientations) to determine the optimal approach that could be developed.

Keywords: Deorbiting; Electrodynamic Tether; Spin.

1. INTRODUCTION

The advent of space exploration marked the beginning of a steady increase in the number of objects orbiting the Earth. This growth, driven by scientific, communication, observation, and commercial missions, has led to a significant accumulation of space debris, particularly in low Earth orbit (LEO). The proliferation of orbital objects raises the risk of collisions, potentially triggering a cascade of fragmentation events, a phenomenon known as the Kessler syndrome [1, 2, 3]. This self-sustaining cycle of debris generation threatens the viability of future space operations and necessitates immediate and effective mitigation strategies. To combat the escalating space debris problem, international guidelines now recommend the removal of defunct satellites from LEO within five years of mission completion. Traditional deorbiting methods often rely on propellant-based propulsion systems, which can be costly and environmentally detrimental. Consequently, the focus has shifted toward greener alternatives that prioritize sustainability and cost-effectiveness. Among these, electrodynamic tethers (EDTs) [4, 5] have emerged as a promising solution. These propellant-less devices harness the interaction between a conductive tether and the Earth's magnetic field to generate Lorentz forces, enabling the satellite deorbiting without the need for consumable fuel.
The European E.T.PACK Initiative [6], funded by the European Innovation Council, has been at the forefront of EDT technology development. Notably, the E.T.PACK-F [7] (the transition programme) project aims to deliver a ready-to-fly deorbit device (Deorbit Kit) with a Technology Readiness Level (TRL) of 8. The system employs a deployable aluminum tether and a hollow cathode electron emitter to induce current flow, thus generating the necessary Lorentz drag to facilitate satellite reentry. Although electrodynamic tethers (EDTs) offer significant advantages, their operation still faces challenges, especially in sun-synchronous orbits, where unfavourable alignment with the geomagnetic field can hinder deorbiting efficiency. The E.T.COMPACT project [8] aims to advance the device towards higher technological maturity by introducing key improvements over previous developments, such as E.T.PACK and E.T.PACK-F, and focuses on overcoming existing challenges through the development of a miniaturized, propellant-less device capable of providing both propulsion and power generation. A key innovation under investigation is the implementation of a spinning system to improve tether alignment with the Earth's magnetic field. By inducing rotation, the tether's orientation periodically aligns with the optimal magnetic field direction, enhancing Lorentz force generation and, consequently, deorbiting performance.

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To assess the feasibility and effectiveness of this spinning approach, the E.T.COMPACT project employs FLEX software [9, 10] to conduct a comprehensive trade-off analysis. These simulations aim to determine the optimal spin rates and operational parameters and examine potential limitations related to cathode activation, ensuring an efficient execution of the deorbiting mission (reboost will be investigated in the future). The results of this analysis are critical for validating the spinning strategy and optimizing the system for future application.
This paper provides a first overview of the E.T.COMPACT project, concentrating on the development of a compact propulsion system based on an electrodynamic tether. It covers the main objectives of the project, the characteristics of the system, the dynamics of the spinning tether, and the results from the simulations which pose the basis for future investigations and requirements for the system. Section 2 defines the project's goals and scope, aiming to create a highly compact electrodynamic tether propulsion system paired with an efficient photovoltaic demonstrator. The focus is on improving the miniaturization of the system and broadening its applications for space missions, such as deorbiting and reboosting. Section 3 presents the essential features of the system, particularly focusing on the tether and cathode, and underscores the role of the University of Padova in designing the tether deployment mechanism. Section 4 offers an in-depth look into the principles of spinning electrodynamic tethers, exploring their fundamental behavior, operational features, and analyzing the spin geometry and spin-up process, both of which are critical for enhancing the system's efficiency. Section 5 presents the simulation results, while Section 6 provides a summary of the key conclusions from the work.

2. THE E.T.COMPACT PROJECT

The E.T.COMPACT project [8] is an EIC Pathfinder Project funded by the European Innovation Council. Its main objective is to achieve TRL 4 for a very compact propulsion module based on an electrodynamic tether. Furthermore, the team (comprising different universities and companies) will develop a bare-photovoltaic tether demonstrator with a Power Conversion Efficiency (PCE) exceeding 12%, capable of both efficient power harvesting and propellant-free propulsion (see for example [11, 12]).
Building on the experience gained in the E.T.PACK and E.T.PACK-F projects [13, 14, 15], the consortium aims to enhance the device, which is now reaching TRL 8. This improvement will focus on miniaturization, reducing its volume from 12U to 3U, while expanding its capabilities beyond deorbiting also to enable system reboost operations.
According to the physics of electrodynamic tethers [16], the condition required to generate a Lorentz force opposing the system's velocity (i.e., a drag force) is $\boldsymbol{E}_m \cdot \boldsymbol{I} > 0$, where $\boldsymbol{E}_m$ is the motional electric field and $\boldsymbol{I}$ is the current vector. Conversely, to generate thrust and reboost the system, this dot product must be negative. Therefore, to achieve both conditions, a spinning electrodynamic system is essential.
The concept, similar to the E.T.PACK-F device, involves attaching the 3U CubeSat to a host satellite before launch and deploying the tether when reboost or deorbiting maneuvers are needed. Hence, a first proposal (not the final one) of the complete system design is presented in Figure 1.

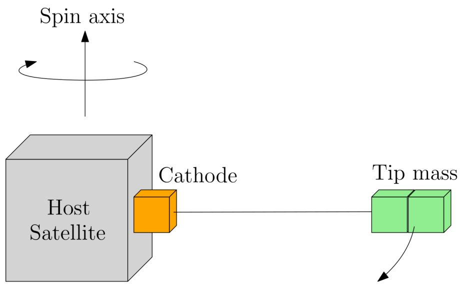


Figure 1: Complete system configuration with the host satellite and the E.T.COMPACT device. In this scenario the 3U CubeSat is divided in 1U for the cathode (orange one) and 2U for the deployment mechanism (green one).

The project started in October 2024, and hence it is now in a preliminary phase, where a series of trade-off analyses are considered, both in terms of market (possible customers) and of design and performance.
In the initial stages of the investigation, the project focuses on satellites weighing a few hundred kilograms in Sun-synchronous orbit, given the high density of commercial satellites in this region (see [17]).

3. SYSTEM CHARACTERISTICS

According to the goal of this paper, the crucial features of the system to be pointed out are the tether and the cathode characteristics.
The University of Padova is contributing to the E.T.COMPACT project through various tasks. One key responsibility is the study and design of the deployment mechanism, including an analysis of the maximum tether length that could fit within a 2U section of the device according to the desired geometry of the tether itself. The tether consists of an aluminum tape (40 μm thick, 1.25 cm wide) wound around a hollow cylinder with a diameter of 6.2 cm. A single-coil configuration is first analyzed, considering a minimum height of 7 cm for the volume hosting the mechanism to accommodate DC motors for the deployment control. Figure 2 shows tether length versus box base side (B=P, i.e., quadratic base). Tether length is calculated as a function of base side B, with height $H = Volume/B^2$ and of the packing factor, which has been experimentally determined in the E.T.PACK-F project [18, 19]. The Figure illustrates feasible volume regions and tether length variations within CubeSat dimensional constraints.
According to results in Figure 2, a total tether length of

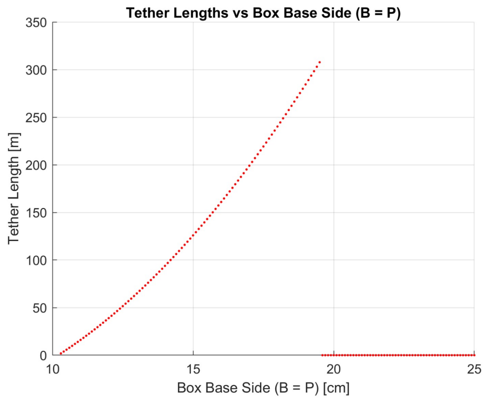


Figure 2: Maximum tether length versus box base side.

300 m has been selected.
Regarding the cathode, the TUD Dresden University of Technology is responsible for its design and prototyping. They're now considering two typologies of cathodes: Carbon NanoTube (CNT) yarn field emission cathode [20] and thermionic dispenser cathode, similar to the design considered by Gasa et. al [21]. In this paper, only the CNT field emission cathode will be considered. For this initial study, it is preferable to consider the end-of-life (EOL) characteristics of the cathode to maintain a conservative approach. A single CNT field emission cathode in EOL conditions can generate a current of 2.5 mA with a potential drop of 420 V. However, by connecting 40 arrays of CNT field emission cathodes in parallel, the total current output can be increased to 100 mA while maintaining the same potential drop of 420 V.
For the simulations presented in Section 5, the main system characteristics are summarized in Table 1.

Table 1: Main system's characteristics

m_1 (Main satellite)	100 kg
m_2 (Tip mass)	1 kg
Tether length	300 m
Tether thickness	40 μm
Tether width	1.25 cm
ΔV_c	-420 V
I_c^{max}	0.1 A

Additionally, the deorbit device has been considered to be electrically connected to the host satellite. Therefore, once the host is no longer operational, the deorbit device could utilize part of the power harvested by the satellite's power system. This enhances the electrodynamic performance.

4. SPINNING ELECTRODYNAMIC TETHERS

Spinning electrodynamic tethers represent a cutting-edge solution for a variety of space applications, seamlessly integrating the advantages of rotational dynamics with the principles of electrodynamic interactions. Once extended, the tether is set into rotation [22], producing centrifugal forces that effectively stretch and stabilize the tether along a predetermined axis, ensuring it remains taut and properly oriented. This tensioning mechanism is essential for preventing the tether from becoming slack or developing unwanted oscillations, which could otherwise lead to entanglement, structural damage, or compromised system performance.
The spinning motion of the tether provides a dual benefit. Beyond merely maintaining tether tension, the rotation induces gyroscopic stability (a physical property that helps the system resist external perturbations such as gravitational gradients, solar radiation pressure, and aerodynamic drag in low Earth orbit). This enhanced stability is vital for preserving the tether's intended orientation, particularly when it should be aligned with specific directions relative to the Earth's magnetic field. A proper stable orientation can ensure consistent and efficient electrodynamic interaction with the surrounding space environment.
The fundamental working principle of EDTs revolves around their interaction with the Earth's magnetosphere and ionosphere. As the tether moves through the planet's magnetic field, it collects electrons from the ambient plasma and emits them at one end, forming a closed electrical circuit [23, 24]. This electron flow, when combined with the tether's motion through the magnetic field, generates a Lorentz force that is perpendicular to both the magnetic field and the current direction. This force can be harnessed for propellant-less propulsion, allowing spacecraft to alter their orbits without expending fuel.
At the core of this phenomenon is the motional electric field (EMF) induced in a conductor moving through a magnetic field. This can be mathematically described by the integral expression:

$$EMF = (\mathbf{v}_{rel} \times \mathbf{B}) \cdot \mathbf{u}_t \tag{1}$$

where $\mathbf{v}_{rel}$ is the velocity of the tether relative to Earth's magnetic field $\mathbf{B}$, and $\mathbf{u}_t$ is a unit vector along the tether aligned with the direction of the current. The magnitude of the induced EMF depends on the relative orientation of the tether with respect to the magnetic field and the velocity of the system as it moves through space. To maximize the induced EMF, the tether should be oriented perpendicular to both $\mathbf{v}_{rel}$ and the Earth's magnetic field lines, as this maximizes the component of $(\mathbf{v}_{rel} \times \mathbf{B})$ along the tether's direction. Conversely, if the tether is parallel to the magnetic field, the cross product $(\mathbf{v}_{rel} \times \mathbf{B})$ has no component along the tether, resulting in zero EMF. In such a scenario, no current would flow through the tether, and the electrodynamic effect would be ineffective for generating thrust or drag forces.
In the case of Sun-synchronous orbits, the optimal configuration is achieved by spinning the tether on a plane that is practically perpendicular to the orbital plane because of the geometry of the geomagnetic field, as described in Figure 3. In the case of Sun-synchronous orbits, the optimal configuration is achieved by spinning the tether on a plane that is practically perpendicular to the orbital plane because of the geometry of the geomagnetic field, as described in Figure 3.

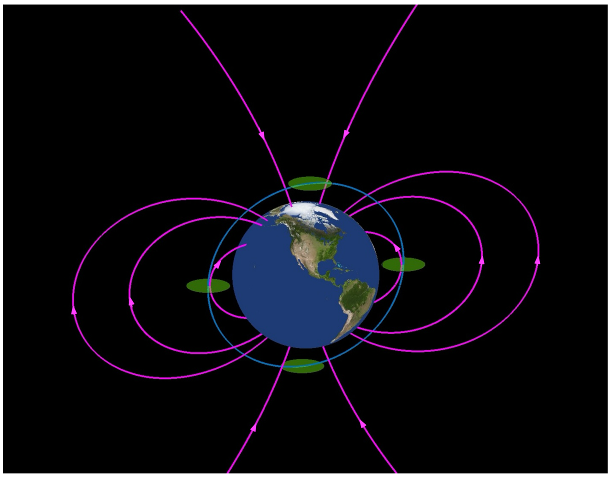


Figure 3: Tether spin planes (green disks) in different positions on a SSO (marked in blue) and magnetic field lines (marked in violet).

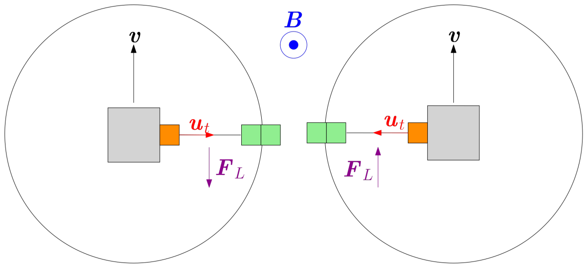
Once a current is established in the tether, its interaction with the ambient magnetic field produces a Lorentz force, which can be expressed as:

$$\mathbf{F}_L = \int_0^{L_t} \mathbf{I} \times \mathbf{B} dx \approx L_t I_{av} \left(\mathbf{u}_t \times \mathbf{B} \right) \tag{2}$$

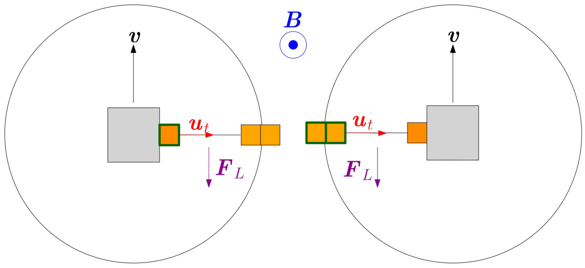
where $\mathbf{F}_L$ is the Lorentz force, I_{av} is the average current flowing through the tether, L_t is the length of the tether, and $\mathbf{B}$ is the magnetic field.

5. SIMULATIONS

These FLEX simulations aim to identify the strengths and weaknesses of a spinning EDT for deorbiting purposes. FLEX enables the discretization of the tether by modelling it with multiple lumped masses, providing an accurate representation of its dynamics. However, since the project is still in its early stages, a simplified system can be analyzed to identify the key drivers, using only two tether segments and a single lumped mass (the minimum required by FLEX).
Regarding the number of rotations per orbit, based on findings from the literature [25] and for the purposes of this preliminary analysis, a value of eight rotations per orbit has been selected.
According to this simplified model, two system configurations have been investigated, focusing on the use of one or two cathodes. The differences between the two configurations are driven by the directionality of the Lorentz force that could be generated. With a single cathode, the generated Lorentz force can act as a drag force for roughly half of the spin period, while during the other half period, it should produce a thrust effect, opposing the deorbiting objective (see Figure 4a). A dual-cathode setup, with the second cathode placed at the tip mass location shown in Figure 1, has been considered to ensure that the Lorentz force consistently acts as a drag force. By alternately activating the two cathodes during the spin (as depicted in Figure 4b), it is possible to maintain a continuous deorbiting effect throughout the entire rotation.
This behavior is illustrated in Figure 4, which shows how the system with two cathodes allows the current direction (vector $\mathbf{u}_t$ in the figure) to be reversed. Consequently, this also flips the direction of the Lorentz force, aligning it with the desired direction, i.e., opposite to the velocity $\mathbf{v}$ for deorbiting purposes.



(a) One cathode configuration.



(b) Two cathodes configuration.

Figure 4: Lorentz force generated by the two configurations in two spin positions. In the bottom panel, the active cathode is highlighted in green.

The direction of the Lorentz force plays a crucial role, as it generates a torque on the tether that affects both the spin velocity and the orientation of the spinning plane. When a single cathode is used, this torque consistently acts in one direction, leading to either an increase or decrease in spin velocity. However, by alternating activation between two cathodes, the Lorentz torque can be effectively compensated. Over a full revolution of the tether, the torques in the two halves have opposite signs because the Lorentz force maintains a constant direction, while the current direction changes based on the activated cathode. This results in a balancing effect, counteracting the net torque.
From Figure 5, it is possible to deduce the torque due to the Lorentz force when the system is operating at 700 km of altitude. The plots on the right refer to the dual-cathode configuration and show time profiles of the torque components with mean values that are approximately zero. In contrast, the single cathode configuration exhibits two torque components with a nonzero mean value, demonstrating that the Lorentz force alters the spin velocity.
In addition, since the Lorentz force includes components outside the spin plane, it induces a precession of the spin axis. If continuously excited, the system could rapidly change its spin plane and, in the worst case, start liberating around the local vertical. To mitigate these effects, a duty cycle was implemented for cathode activation. The

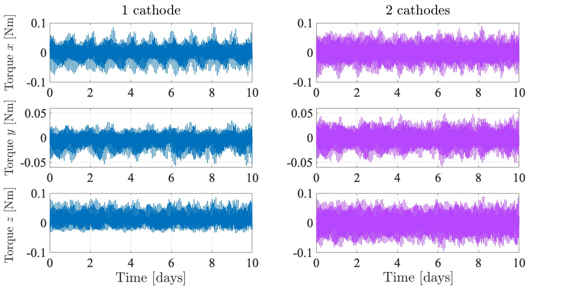


Figure 5: Lorentz torque expressed in the three inertial components when using both one (left) and two cathodes (right).

tether is designed to generate current during only one revolution per orbit, followed by an inactive period of eight revolutions before reactivating. This strategy ensures that the current generation occurs at different orbital positions rather than being concentrated in the same region.
With these assumptions, some simulations of the first stages of the missions (the most critical for electrodynamic tethers) have been performed.

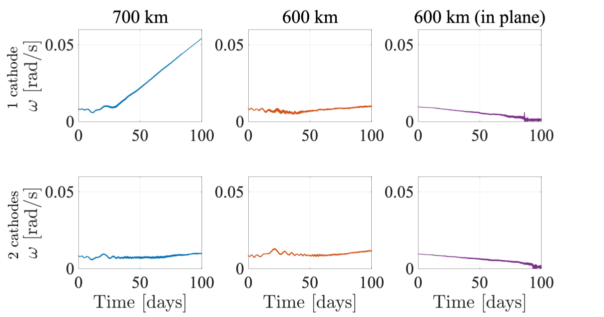


Figure 6: Tether spin velocity in different scenarios: spin plane orthogonal to the orbital plane at 700 and 600 km of altitude (left and middle panels) and with the spin plane that lies on the orbital plane at 600 km (right panel).

Figure 6 illustrates the spin velocity profiles under different scenarios. The upper row represents the system with a single cathode, while the lower one corresponds to the two-cathode configuration. The results indicate that using two cathodes allows for better spin velocity control, maintaining greater stability when the spin plane is orthogonal to the orbital plane (first two columns). In contrast, the single-cathode configuration tends to increase the rotation speed at both 700 km and 600 km altitudes. This effect is more pronounced at higher altitudes, where the Lorentz force dominates over other external forces, namely the aerodynamic drag, as shown in Figure 7.
Furthermore, when the spin plane lies on the orbital plane, the spin velocity decreases, approaching near-zero values. This suggests that, over time, the system transitions from rotation to libration.
Such a transition is due to low current production and, consequently, a weak Lorentz force. Figure 8 illustrates and confirms that for an SSO the optimal spin plane is practically perpendicular to the orbital plane. Specifically, when the dot product between $\mathbf{u}_t$ and $(\mathbf{v}_{rel} \times \mathbf{B})$ reaches its maximum, i.e., when the spin plane is approximately perpendicular to the orbital plane, in the case of Sun-synchronous orbits, the induced EMF is stronger, leading to a higher generated current.

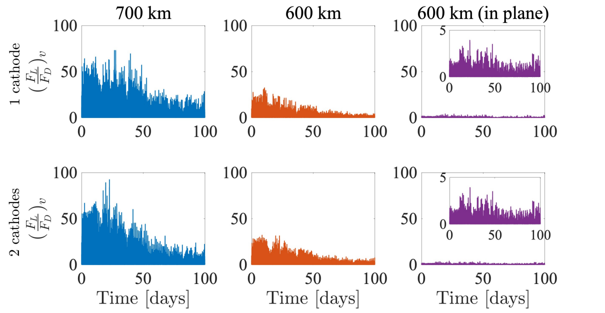


Figure 7: Ratio between the Lorentz force and the aerodynamic drag force projected along the velocity direction (i.e., the useful components for the deorbiting).

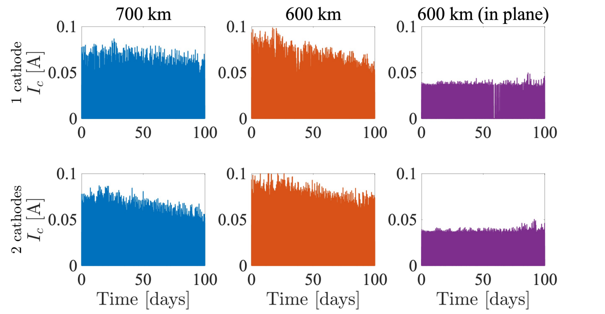
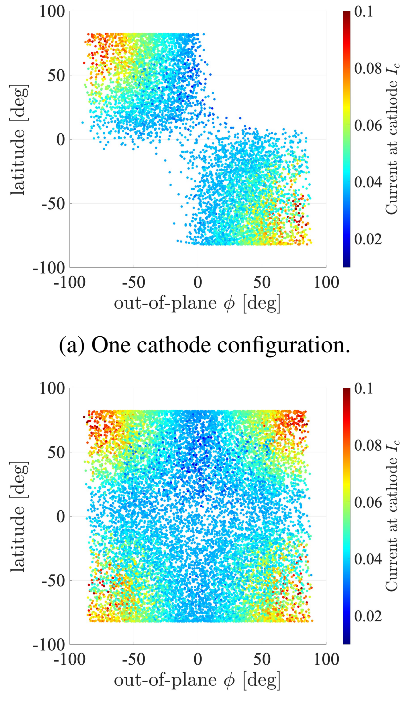


Figure 8: Generated current at the cathodic tip with the spin plane orthogonal to the orbital plane (first two columns) at altitudes of 700 km and 600 km, and with the spin plane parallel to the orbital plane (third column) at 600 km.

Additionally, Figure 9 highlights the regions where current generation is higher. Specifically, greater currents are observed when the system is positioned over the Earth poles and when the tether has a 90° out-of-plane angle. This is due to the combination of the stronger magnetic field present at the poles, which leads to a higher EMF, and an optimal geometry. Moreover, Figure 9a, unlike Figure 9b, lacks two regions where the current is generated. This is because only a single cathode is considered, making certain geometrical configurations unfeasible for producing a deorbiting Lorentz force. On the other hand, the system with two cathodes always enables current generation by appropriately activating the correct cathode. Specifically, the top-left and bottom-right corners of the plot correspond to the current produced when one cathode is active, while the other two corners represent the current generated when the second cathode is in operation.
Another indication that the two-cathode configuration is superior to the single-cathode setup is the tension in the tether. As shown in Figure 10, when using a single cathode, the tension can drop to zero in some instances, indicating a slack tether, which is undesirable. Conversely,



(a) One cathode configuration.

(b) Two cathodes configuration.

Figure 9: Generated current as function of both geographical latitude and out-of-plane angle ϕ.

the two-cathode system ensures a more taut tether due to better torque compensation. Additionally, in the single-cathode configuration, an increase in spin velocity can lead to a rise in centrifugal force and, consequently, in tether tension, as illustrated in the top-left panel. This behavior could result in tether failure if the tension exceeds the breaking point of the tape material.
Finally, the performance of the deorbit device can be evaluated by analyzing the decrease in the semimajor axis. Figure 11 illustrates the evolution of the semimajor axis over time for different scenarios. The blue lines represent the reduction in the semimajor axis when the main satellite is not equipped with the deorbiting device. As expected, this is the worst-case scenario. However,

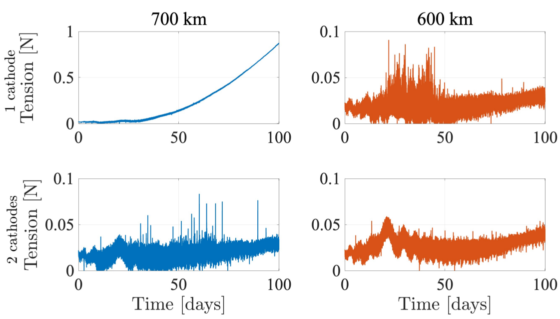
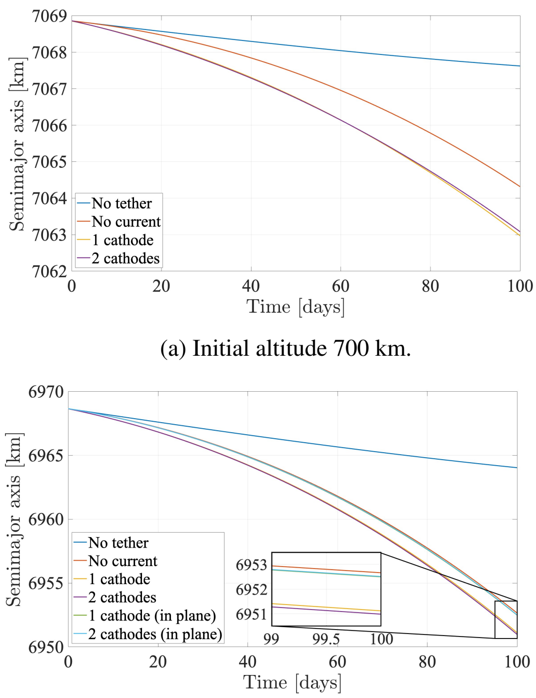


Figure 10: Tether tension when the spin plane is orthogonal to the orbital plane at altitudes of 700 km and 600 km.

even with only a simple (non-electrodynamic) tether installed (see the orange lines), the deorbiting performance improves because the tether acts as a drag sail, increasing the aerodynamic drag surface. When implementing an electrodynamic tether, deorbiting occurs more rapidly, especially when the spin plane geometry is optimal (yellow and purple lines).



(a) Initial altitude 700 km.

(b) Initial altitude 600 km.

Figure 11: Deorbiting profiles for several scenarios in the first 100 days of mission at 700 and 600 km of altitude.

6. CONCLUSIONS

With this work, a first comprehensive overview of the E.T.COMPACT project has been provided, offering an initial yet significant insight into the potential application of a miniaturized propulsion device based on an electrodynamic tether for spacecraft reboost and deorbiting. The study focuses on evaluating the best strategy to control the current generation, with one or two cathodes, for deorbiting purposes. This study highlights that spin modulation is crucial when using spinning electrodynamic tethers as deorbit devices, especially in orbital conditions that are not the optimal ones for an EDT (i.e., high inclined orbits). It emerges that the optimal conditions for current generation are achieved when the scalar product between the tether direction $\mathbf{u}_t$ and $(\mathbf{v}_{rel} \times \mathbf{B})$, where $\mathbf{v}_{rel}$ and $\mathbf{B}$ are respectively the relative velocity of the satellite with respect to the plasma and the magnetic field, is maximized. In a Sun-synchronous orbit, this occurs when the tether is perpendicular to the orbital plane. However, since this configuration is inherently unstable, spinning the tether provides a means to sustain it for as long as possible. Nevertheless, while the Lorentz force is beneficial for deorbiting purposes, it must be carefully controlled, as it also generates torques that affect the system's spin. This paper demonstrates that, when possible, adopting a system with two cathodes instead of a single one offers a better solution. The use of dual cathodes enables compensation for the torque induced by the Lorentz force, leading to a more stable spin velocity. Furthermore, this configuration allows for precise control of the spin by selectively activating or deactivating individual cathodes, generating torques that can either accelerate or decelerate the system. However, further research is needed to fully validate this approach. In particular, the development and optimization of spin control strategies (for example the duty cycle) will be crucial to improving both the efficiency and stability of the system. Investigating different spin velocities could also be beneficial in determining which values ensure good stability while minimizing the effort required to initiate the spin (e.g., reducing the need for stronger thrusters). Additionally, long-duration simulations are required to evaluate the system's behavior over time, especially in the presence of orbital perturbations.

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REFERENCES

[1] Donald J. Kessler and Burton G. Cour-Palais. "COLLISION FREQUENCY OF ARTIFICIAL SATELLITES: THE CREATION OF A DEBRIS BELT." In: *J Geophys Res* 83.A6 (1978). Cited by: 1044, pp. 2637–2646. DOI: 10.1029/JA083iA06p02637.

[2] Jakub Drmola and Tomas Hubik. "Kessler Syndrome: System Dynamics Model". In: *Space Policy* 44-45 (2018), pp. 29–39. ISSN: 0265-9646. DOI: https://doi.org/10.1016/j.spacepol.2018.03.003.

[3] Donald Kessler et al. "The Kessler Syndrome: Implications to Future Space operations". In: *Advances in the Astronautical Sciences* 137 (Jan. 2010).

[4] Gonzalo Sánchez-Arriaga, Enrico C. Lorenzini, and Sven G. Bilén. "A review of electrodynamic tether missions: Historical trend, dimensionless parameters, and opportunities opening space markets". In: *Acta Astronautica* 225 (2024), pp. 158–168. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2024.09.002. URL: https://www.sciencedirect.com/science/article/pii/S0094576524004971.

[5] Juan R. Sanmartin, Enrico C. Lorenzini, and Manuel Martinez-Sanchez. "Electrodynamic Tether Applications and Constraints". In: *Journal of Spacecraft and Rockets* 47.3 (2010), pp. 442–456. URL: https://doi.org/10.2514/1.45352.

[6] https://etpack.eu/acerca-de/ (last access: 25.02.2025).

[7] https://etpack.eu/e-t-pack-f/ (last access: 25.02.2025).

[8] https://etpack.eu/e-t-compact/ (last access: 25.02.2025).

[9] Gabriel Borderes-Motta et al. "Cross-verification and benchmarking analysis of electrodynamic tether simulators". In: *Acta Astronautica* 208 (2023), pp. 381–388. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2023.04.015.

[10] R. Mantellato, L. Olivieri, and E.C. Lorenzini. "Study of dynamical stability of tethered systems during space tug maneuvers". In: *Acta Astronautica* 138 (2017), pp. 559–569. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2016.12.011.

[11] Giovanni Anese et al. "Bare Photovoltaic Tether characteristics for ISS reboost". In: *Acta Astronautica* 229 (2025), pp. 34–42. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2024.12.031.

[12] A. Brunello et al. "Optimal design and current control strategies of an electrodynamic tape for ISS station-keeping". In: *Acta Astronautica* 223 (2024), pp. 621–629. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2024.07.024.

[13] L. Tarabini Castellani et al. "Deorbit kit demonstration mission". In: *Journal of Space Safety Engineering* 9.2 (2022), pp. 165–173. ISSN: 2468-8967. DOI: https://doi.org/10.1016/j.jsse.2022.01.004.

[14] G. Sánchez-Arriaga et al. "The E.T.PACK project: Towards a fully passive and consumable-less deorbit kit based on low-work-function tether technology". In: *Acta Astronautica* 177 (2020), pp. 821–827. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2020.03.036.

[15] Giulia Sarego et al. "Deorbiting Performance of Electrodynamic Tethers to Mitigate Space Debris". In: 2022. URL: https://api.semanticscholar.org/CorpusID:252924184.

[16] Juan Sanmartin, Manuel Martinez-Sanchez, and Eduardo Ahedo. "Bare wire anodes for electrodynamic tethers". In: *Journal of Propulsion and Power - J PROPUL POWER* 9 (May 1993), pp. 353–360. DOI: 10.2514/3.23629.

[17] https://discosweb.esoc.esa.int,(last access: 25.02.2025).

[18] Alice Brunello et al. "Deployment Functional Tests of an Electrodynamic Tape for Space Debris Mitigation". In: *73rd International Astronautical Congress IAC2022, Paris*. 2022.

[19] A. Brunello et al. "The Deployment Mechanism of the E.T.PACK Deorbit System: Functional and Qualification tests". In: *Acta Astronautica* 226 (2025), pp. 39–47. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2024.11.008.

[20] Georg Hentsch and Martin Tajmar. "Development of High-Current Compact Radial Field Emission Cathodes for Space Applications". In: June 2024.

[21] Klevis Gasa et al. "Experimental Characterization of a Low Current Dry Neutralizer". In: June 2024.

[22] H. Lu et al. "Stability analysis and motion control of spinning electrodynamic tether system during transition into spin". In: *Acta Astronautica* 177 (2020), pp. 871–881. ISSN: 0094-5765. DOI: https://doi.org/10.1016/j.actaastro.2019.11.032.

[23] Sanjurjo-Rivo M., Sánchez-Arriaga G., and Peláez J. "Efficient Computation of Current Collection in Bare Electrodynamic Tethers in and beyond OML Regime". In: *Journal of Aerospace Engineering* 28.6 (2025/03/06 2015). DOI: 10.1061/(ASCE)AS.1943-5525.0000479. URL: https://doi.org/10.1061/(ASCE)AS.1943-5525.0000479.

[24] Claudio Bombardelli, Jesus Pelaez, and Manuel Sanjurjo. "Asymptotic Solution for the Current Profile of Passive Bare Electrodynamic Tethers". In: *Journal of Propulsion and Power* 26.6 (2010), pp. 1291–1304. DOI: 10.2514/1.46808. URL: https://doi.org/10.2514/1.46808.

[25] Jerome Pearson et al. "Orbital Maneuvering With Spinning Electrodynamic Tethers". In: 3 (Aug. 2004), p. 8. DOI: 10.2514/6.2004-5715.