EXPLORING THE MARKET OPPORTUNITIES OF ELECTRODYNAMIC TETHERS FOR DEORBITING AND IN-ORBIT-SERVICING

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ABSTRACT

ElectroDynamic Tethers (EDTs) provide a sustainable, propellant-free solution for propulsion and autonomous space deorbiting. This paper conducts a survey of interesting EDT applications, focusing on two key sectors: satellite and rocket body deorbiting, and In-Orbit Servicing (IoS). The analysis identifies significant growth in Low Earth Orbit (LEO) satellite launches projected through 2033. Currently, 74% of active LEO satellites under 70 kg lack propulsion systems. Conversely, 85% of satellites between 70-210 kg, and 96% of satellites over 200 kg, have propulsion systems. Despite propulsion availability, more than 40% of satellites as of 2022 failed to comply with the 25-year deorbit guideline. Rocket bodies showed better compliance, with only 7% not meeting regulations. However, the introduction of stricter 5-year deorbit rules in the US and Europe dramatically increases the demand for effective deorbit solutions. Within the IoS market, Life Extension Solutions represent 47% of projected revenue, while Active Debris Removal accounts for 26%. This paper explores EDTs' potential within these markets, also summarizing recent advancements in EDTs under the E.T.PACK-F and E.T.COMPACT projects.

Keywords: Electrodynaic tethers, Deorbiting, In-Orbit Servicing, Active Debris Removal.

1. INTRODUCTION

In recent years, the increasing concern regarding space debris has drawn significant attention from both governments and the space industry. The proliferation of satellites in Low Earth Orbit (LEO) has reached a point where the density of space debris now surpasses the threshold that can trigger an uncontrolled cascade of collisions. This phenomenon, widely referred to as the *Kessler syndrome* [12], presents a major challenge for sustainable space activities. Data indicates that even if all satellite launches were halted immediately, the number of objects in orbit would continue to increase due to a self-sustained cascade of collisions that have already commenced [10].

Efforts to mitigate this escalating risk have led to the introduction of stricter deorbit policies and regulations designed to minimize space debris accumulation. From 2023, the European Space Agency (ESA) has promoted the Zero Debris Charter [5], which proposes new policies to address this challenge. They propose that future satellites operating in LEO complete their deorbit phase within 5 years of reaching their End-of-Life (EOL), a significant reduction from the previously established 25-year guideline. Furthermore, ESA recommends that satellites in medium to high-risk orbits be equipped with interfaces to enable Active Debris Removal (ADR) in the event of failure. Although ESA guidelines are not legally binding, they are mandatory for ESA projects, and it is anticipated that Member States will incorporate the five-year deorbit requirement into their national regulations. In parallel, the Federal Communications Commission (FCC) in the United States has introduced the five-year deorbit rule [9], mandating that both satellites and launchers must be removed from orbit within five years of completing their mission.

The introduction of these regulations has had an immediate impact on the space sector, creating a demand for effective deorbit technologies. Consequently, new market opportunities have emerged for solutions that offer either: a) a cost-effective, autonomous, resilience and scalable deorbit system that can be integrated into satellites prior to launch; or b) In-Orbit Servicing (IoS) vehicles capable of actively removing satellites lacking onboard deorbit systems. In fact, from all the activities encompassing IoS, such as satellite repairs, Life Extension Solutions (LES) such as refuelling, In-orbit Manufacturing and Assembly (IAM), and Last Mile Delivery (LMD) including orbital transfers, ADR is projected to be the most profitable IoS activity [16].

Furthermore, IoS vehicles will achieve maximum efficiency when they can deliver multiple services within a single mission. However, their operational capabilities are often restricted by the limited amount of propellant they can carry, which imposes constraints on mission du-

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ration, manoeuvrability, and the number of tasks they can perform. This limitation encourages the search for alternative propulsion systems that can operate independently of onboard propellant, enabling IoS vehicles to extend their service range and increase overall mission efficiency.

In this context, a market study of ElectroDynamic tethers (EDTs) is presented. EDTs are conductive tapes that exploit the surrounding space environment to generate thrust or drag forces. As the tether moves through Earth's magnetic field, a motional electric field E_m is induced at the unperturbed plasma in the tether frame. Such a motional electric field drives a current along the tether if good anodic (electron collection) and cathodic (electron emission) contacts with the ambient plasma are provided. This resulting current interacts with Earth's magnetic field and generates a *Lorentz force*. In LEO, the *Lorentz force* is a drag that reduces the orbital altitude while accelerating the satellite. If needed, power for on-board use can be harvested by reducing the deorbit performance. Contrary, if on-board power is available, it can be used to make the current flow opposite to the motional electric field and generate a thrust to increase the orbital altitude. Detailed explanations of their working principles, performance characteristics, and past mission implementations can be found extensively in the literature [2], [13], [21]. Remarkably, a 20 kg and 12 U autonomous deorbit device has been developed in the framework of the E.T.PACK [22] and E.T.PACK-F [20] projects and its in-orbit demonstration is scheduled in 2026.

Building on these capabilities, EDTs leverage three key traits that make them particularly attractive for both the deorbiting and IoS markets. First, EDTs are propellantless, meaning they harness natural resources from the surrounding space environment, eliminating the need for onboard fuel. Second, they are reversible, meaning EDTs can work in both deorbiting and thrust modes. The third trait is that they are scalable, enabling their dimensions to be tailored to target plenty of objects' masses and sizes. More importantly, these working principles of EDTs enable to embed them into an autonomous deorbiting subsystem which can generate their own power and operate independently from the spacecraft's primary avionics.

This value proposition distinguishes EDTs from conventional solutions. For instance, chemical propulsion systems require substantial propellant mass making autonomous operation economically unfeasible. They also deliver high thrust in a short time, which poses a fundamental challenge for the attitude control system of an autonomous device. Meanwhile, electric propulsion demands significant power levels, which necessitate deploying large solar panels to meet energy requirements. Regarding drag sails, they are not an effective deorbit solution above 800 km altitude and, although passive and simple, they do not reduce the Area $\times$ Time product which determines the collision risk of a space object. In contrast, the Lorentz drag on EDTs is a passive mechanism that provides a low force during a long time (in the order of a few month to complete the deorbit maneuver). Such a property relax the requirements on the attitude control system and, together with their propellant-less character, allows to prepare compact and autonomous deorbit devices.

Given these advantages, understanding the potential applications and market opportunities for EDTs becomes crucial. To this end, Section 2 outlines the methodology employed to analyse EDT adoption across various sectors. Section 3 studies EDTs application in deorbit scenarios, while Section 4 examines their integration into IoS solutions. Finally, Section 5 summarises the key findings and insights drawn from this study.

2. METHODOLOGY: SELECTION OF DATA AND FILTERS

To explore the potential opportunities for EDTs in the deorbiting, propulsion and IoS markets, data was gathered from multiple reliable sources to ensure accuracy, completeness, and consistency. The primary database used in this study is *Seradata* [24], which provides comprehensive information on active satellites, including their characteristics, capabilities, and mission details. This database serves as a key reference for assessing satellite populations and their technical specifications.

In addition to *Seradata*, information on satellites' latest orbital parameters was obtained from *Space-track.org* [19], a platform maintained by the United States Space Surveillance Network. *Space-track.org* provides the most up-to-date Two-Line Element (TLE) data available for active satellites, and this information was cross-referenced with *Seradata* to validate orbital parameters and ensure data reliability.

For detailed physical characteristics of both satellites and rocket bodies — such as mass, dimensions, and propulsion capabilities — data from *Seradata* was supplemented with information from *DISCOSweb* [8], a database managed by ESA. *DISCOSweb* offers extensive information on space objects, including non-functional satellites and debris. This source was particularly useful for enhancing the completeness of the dataset and ensuring consistency across the presented information. Furthermore, *DISCOSweb* served as the primary reference for data on space debris, including debris size distribution, location, and total quantity. The databases of *Seradata*, *Space-track.org* and *DISCOSweb* were combined, and duplicated objects eliminated, to construct a comprehensive and up-to-date database as of February 2025.

Moreover, to extract meaningful insights for EDT applications, a series of targeted filters were applied. These filters were designed to focus the analysis on key trends, account for EDTs operational constraints, and align with current regulatory frameworks:

First off, given the operating principles of EDTs, which rely on the surrounding plasma to sustain an electric current, their performance is dependent on ionospheric conditions. As a result, the effective operational altitude for EDTs is limited to approximately 1200 km, where sufficient plasma density exists to enable electron exchange. To reflect regulatory constraints, space objects orbiting above 500 km were identified as requiring deorbit technologies to comply with recently introduced regulation/policy mandating deorbiting within 5 years of reaching their end-of-life.

Satellite data was further categorized by mass ranges to assess market trends and identify potential EDT applications across different satellite classes. This classification was based on three mass categories: satellites below 70 kg, satellites between 70 kg and 210 kg, and satellites bigger than 210 kg. Differentiating satellites by mass range allows for a more precise evaluation of market needs, as medium- to large-sized satellites are expected to have distinct mobility and deorbiting requirements compared to small satellites or CubeSats.

Additional satellite characteristics were examined to better understand the requirements of the deorbiting and IoS markets. Specifically, data on satellites' onboard deorbiting capabilities and propulsion systems (including electric propulsion, chemical propulsion, and drag augmentation devices) were analyzed across the defined mass ranges. Furthermore, satellite design lifetimes were assessed to identify trends and variations in operational longevity across different spacecraft sizes. This data is be presented in Sections 3 and 4.

Lastly, the recent surge in LEO satellite populations, largely driven by the rapid expansion of mega-constellations, was taken into account. The *Starlink* constellation, just by itself, represents more than 58% of the total active satellite population (as of now, February 2025), significantly influencing market trends. Consequently, for some of the presented figures in this investigation, *Starlink* satellites have been filtered out to better highlight broader market patterns and trends within the active satellite population.

3. DEORBIT MARKET

3.1. Deorbit of satellites

Since the launch of the first satellite in 1957, the frequency of satellite deployments has increased exponentially. Notably, the number of satellites launched between 1957 and 2015 is equivalent to the number launched from 2015 to the present. The population of satellites in LEO continues to grow, representing today 92% of the total satellite population (as seen from data in *DISCOSweb*). Figure 1 shows the historical of the number of launched satellites to LEO per year (processed from *Seradata*), together with predictions by [14] for the next 9 years. It shows the population in LEO continues to grow, underscoring the urgent need for effective and scalable deorbiting solutions. These projections indicate that the number of LEO satellites will surpass 20,000 by 2030, largely driven by the expansion of mega-constellations such as Starlink and Kuiper.

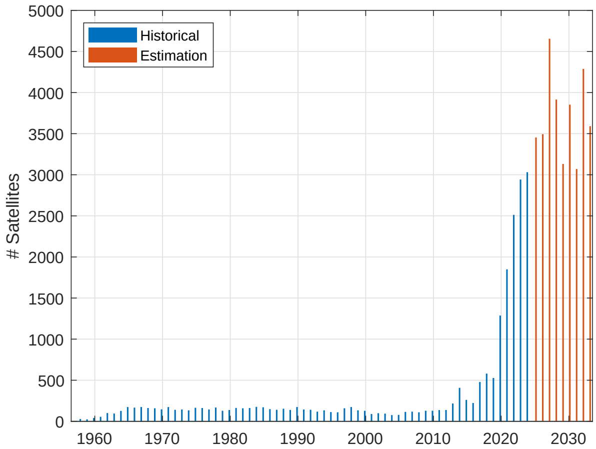


Figure 1: Historical (data processed from [24]) and Projected [14] LEO satellite launches (2010-2033)

Data processed from *Seradata* as of February 2025 shows a significant portion of active LEO satellites in orbits ranging from 500 km to 1200 km are equipped with propulsion systems (see Figure 2). Figure 3 illustrates the types of propulsion systems used in active satellites equipped with propulsion capabilities. Among satellites weighting less than 210 kg chemical and electric propulsion is equally prevalent. Larger satellites often incorporate multiple propulsion systems, utilizing different types for distinct operational purposes, which contributes to the overall distribution of propulsion methods. Notably, drag sails remain relatively uncommon for satellite deorbiting. While the presence of a propulsion system suggests potential deorbit capability, achieving successful deorbiting at EOL requires additional conditions.

The first condition is that propellant-based propulsion systems must reserve sufficient propellant mass by the end of the mission to execute a deorbit maneuver at EOL which can impact the mission objective and its lifetime. Relying on the propulsion system for deorbiting is not a simple task, as the system needs to perform its largest effort at EOL. It is also necessary for the satellite to still be operative: a failure of the propulsion system or any other critical system (communications, Attitude Control System (ACS), power...), could result in the satellite not deorbiting. Consequently, even satellites equipped with propulsion systems may fail to meet deorbiting requirements even if an adequate amount of fuel is available at EOL. Figure 4 presents the equipment group associated with spacecraft insurance claims resulting from failures occurring during the launch and in-orbit in the period 2004 to 2022. The equipment with the most related failures at 31%, is attributed to Power, emphasizing the critical role of reliable power generation in satellite operations. If the power generation fails, so does the propulsion system if it is based on electric propulsion. Engine - Thruster and Payload (including Communications) each account for 11% and 13% respectively, highlighting the significant impact of propulsion and communication systems on mission success. The elevated number of failures due to power subsystem (thus, electric engine if present), together with the failures due to the engine thruster, make it highly unlikely the development of a reliable deorbit system based in electric propulsion. The deorbit at EOL of a satellite must be performed by a system that is able to survive all the designed years of the satellite without failure, thus ideally an autonomous system would be used.

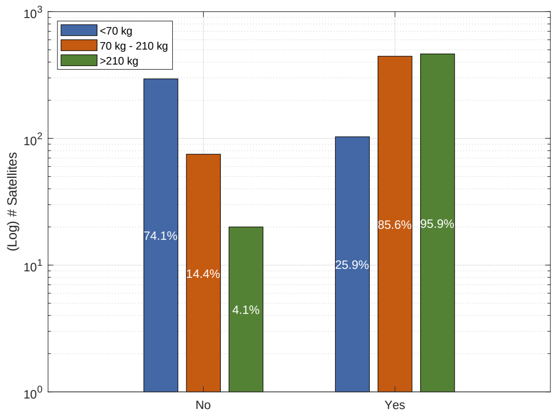


Figure 2: Active satellites with/without propulsion systems in orbits [500 km - 1200 km] by mass range (excluding *Starlink*). Data processed as of February 2025.

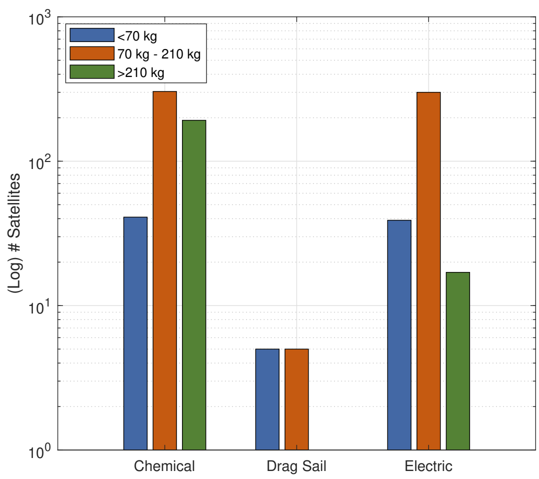


Figure 3: Type of propulsion of active satellites in orbits [500 km - 1200 km] by mass range (excluding *Starlink*). Data processed as of February 2025.

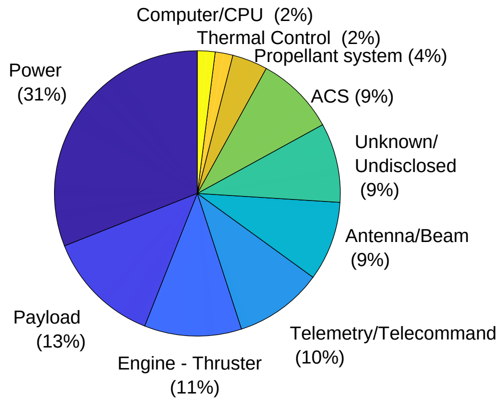


Figure 4: Spacecraft equipment group involved in in-orbit insurance loss and launch related insurance loss events 2004-2022. Data based on information from [27]

The impact of these limitations is reflected in the rate of non-compliance with deorbit regulations. As shown in Figure 5, in 2022, 42% of all satellites that reached EOL failed to comply with the 25-year deorbit rule and did not deorbit successfully [6]. Consequently, these satellites have become space debris and now require ADR services to mitigate their contribution to the growing debris population. With the recent introduction of stricter regulations, including the 5-year deorbiting rule (see Section 1), the pressure to ensure timely deorbiting is become even greater, further exposing the limitations of conventional propulsion systems and increasing the risk of non-compliance.

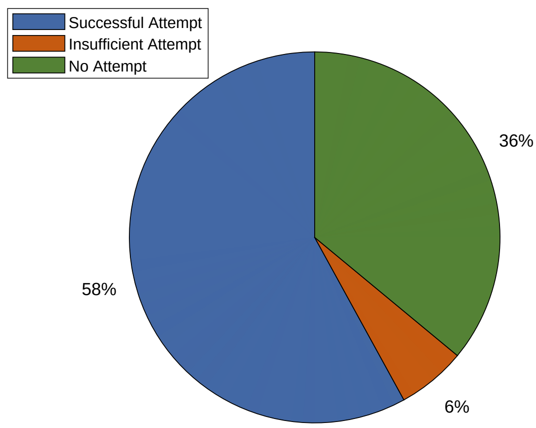


Figure 5: Satellite clearance in 2022 (compliant with 25-year deorbit rule). Graph based on information from [6]

3.2. Deorbit of rocket bodies

A significant contribution to the space debris population comes from rocket upper stages. Following the completion of their primary mission of delivering payloads to orbit, these upper stages — along with detached payload adapter pieces (if not integrated into the stage) — remain in orbit as non-functional debris. These objects are key targets for dedicated rocket body deorbiting solutions, such as the ESA ClearSpace mission planned for 2025 [4], which aims to remove the VESPA adapter from a VEGA launcher.

Rocket bodies pose a substantial threat to the space environment due to their large size and mass. As shown in Figure 6, rocket bodies account for 6% of the total number of objects in LEO as of 2023 [28]. However, while this percentage may seem modest, their contribution in terms of total mass is considerably greater. Unlike smaller debris particles, which can range from millimeters to centimeters in size, rocket bodies are typically large, often exceeding one ton in mass. This disproportionate mass makes rocket bodies particularly concerning, as they present a higher risk of initiating collision cascades.

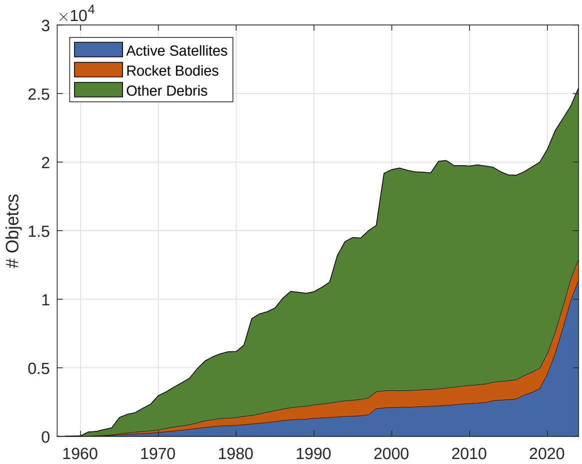


Figure 6: Evolution of number of objects in LEO. Data taken from [28]

The distribution of rocket bodies across orbital regions further exacerbates this concern. Due to the high interest in sun-synchronous orbits (SSO) for Earth observation and other satellite missions, more than half of all rocket bodies in orbit are located in this region.

As reported in ESA's Annual Space Environment Report [6], Figure 7 shows the deorbiting actions taken by rocket bodies in LEO during 2023. Rocket bodies are classified as: *Naturally Compliant* if injected into an orbit that satisfies the **25-year lifetime rule**; *Successful Attempt* if actively maneuvered to comply with this rule; *Insufficient Attempt* if the attempt to reduce orbital lifetime was unsuccessful; and *No Attempt* if no deorbiting effort was made. Despite the flexibility of the 25-year deorbit rule — which offers a relatively lenient timeframe for post-mission disposal — a fraction (7%) of rocket bodies still fails to comply nowadays. Although this scenario is more optimistic than with satellites (where 42% failed to deorbit within this regulation, see Figure 5) the more demanding regulations and policies in 2023 are set to change this landscape drastically.

Given the current challenges and limitations, EDTs also present a promising solution for the autonomous deorbiting of rocket bodies, either as the primary deorbiting system, or a backup system to ensure compliance. These ideas are further explored in the next Section 3.3.

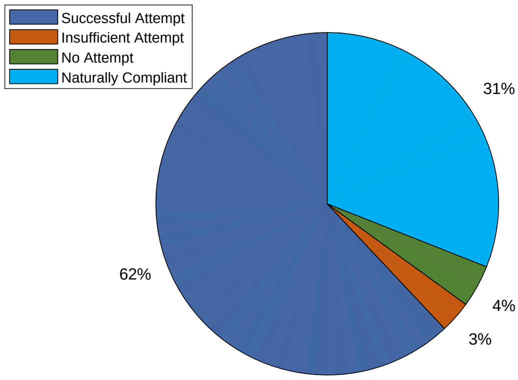


Figure 7: Rocket bodies clearance in 2023 (compliant with 25-year deorbit rule). Graph based on information [6]

3.3. EDTs for deorbiting

Based on the studies studied in previous sections, EDTs can offer a distinct advantage by providing a fully autonomous solution that eliminates the need for additional propellant and does not rely on the continued functionality of the spacecraft's critical systems. This independence makes EDTs particularly suitable for ensuring deorbiting at the end of the mission without requiring extra propellant reserves or relying on the continued operability of essential spacecraft subsystems to initiate the deorbiting process. According to the ESA Strategy 2040 report [7] on space debris:
"*Highly autonomous systems are essential, including autonomous operations for efficient debris removal and developing largescale autonomous distributed space systems, like swarm constellations*". Figure 8 shows a diagram of a satellite at EOL deorbiting with an autonomous and standalone EDT subsystem.

The E.T.PACK-F project, funded by the European Innovation Council (EIC) and composed of Universidad Carlos III de Madrid, University of Dresden, University of Padova, Sener Aeroespacial, Rocket Factory Augsburg (RFA), and PERSEI SPACE is developing an autonomous Deorbit Device (DD) to demonstrate EDT technology in orbit.

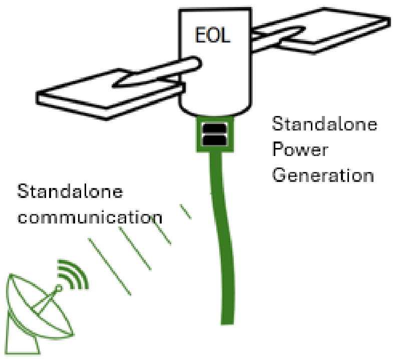


Figure 8: Diagram of a space body at the End-Of-Life deorbiting thanks to an autonomous EDT subsystem.

This In-Orbit-Demonstration (IOD), lead by the company PERSEI Space, features a 12U unit below 20kg using 430 m-long bare tether with a hollow cathode. The hardware, shown in Figure 9, is equipped with integrated solar panels for autonomous power generation and includes two primary modules: the Electron Emitter Module (EEM), which enables efficient electron emission to sustain electric current flow in the tether, and the Deployment Mechanism Module (DMM), responsible for controlled tether deployment. Both modules feature independent communication systems (S-band for the EEM and UHF band for the DMM) to ensure reliable ground communication without relying on the host object's systems.

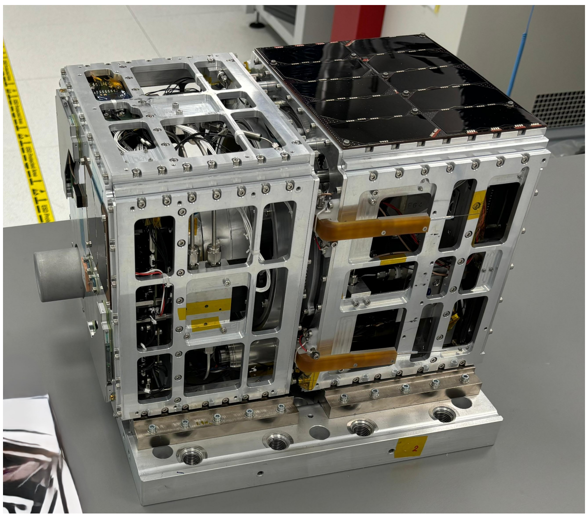


Figure 9: EQM of the Deorbit Device developed under E.T.PACK-F project [26].

Scheduled for Q2 2026 and funded by ESA and the European Commission under the Flight Ticket Initiative, this IOD aims to validate this technology in an operational environment and mark a significant step toward the commercialization of EDT technology. When successful, these systems could be deployed in the deorbit market for both satellite and rocket body deorbiting applications, as discussed throughout this paper, contributing to the broader objective of achieving a Zero Debris space environment.

4. IN-ORBIT-SERVICING (IOS): PROPULSION + DEORBIT MARKET

The IoS market is rapidly gaining momentum, driven by the growing demand for orbital adjustments, trajectory corrections, LES, and ADR technologies. This need has become increasingly critical with the expansion of satellite populations, particularly accelerated by the deployment of mega-constellations such as *Starlink* and *Amazon Kuiper*, further intensifying the demand for efficient and sustainable orbit management solutions.

In fact, the IoS market is projected to generate approximately 2 billion between 2024-2033 [15], with a Compound Annual Growth Rate exceeding 11.6% [11]. This projected revenue distribution highlights the diverse nature of this market, where distinct service categories address various industry demands (see Figure 10).

To start with, **LES** emerge as the dominant segment, accounting for nearly half (47%) of the total market value. This reflects the growing emphasis on extending satellite operational lifetimes, particularly for high-value assets and mega-constellations. As satellite operators seek to maximize return on investment, **LES** solutions are becoming increasingly attractive for reducing replacement costs and improving mission sustainability.

ADR constitutes the second-largest segment, contributing 26% of the total market. This substantial share underscores the rising urgency to address space debris, which poses a significant threat to operational satellites and future space missions. With the increasing density of satellites in orbit, particularly due to the proliferation of mega-constellations, **ADR** solutions are expected to play a crucial role in maintaining a safe orbital environment.

IAM, projected to generate 16% of the total market, reflects the growing interest in enhancing spacecraft capabilities directly in orbit. This emerging sector is driven by advancements in modular satellite design and the need for flexible, adaptive mission architectures.

Finally, **LMD**, while representing the smallest segment at 10%, addresses a vital niche in the IoS ecosystem. As satellite deployment strategies become more complex, **LMD** services are essential for efficiently positioning satellites in their designated orbits, especially in high-traffic regions like Low Earth Orbit (LEO).

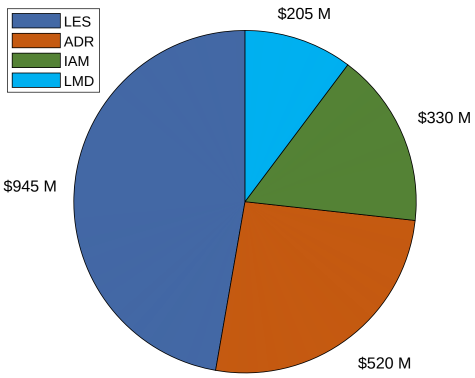


Figure 10: Estimated revenue for the IoS market for the period 2024-2033. Graph based on information from [15]

Overall, this revenue distribution reveals that while **LES** dominates in terms of market size, the combined value of **ADR**, **IAM**, and **LMD** reflects the increasing diversification within the IoS sector. This diversification aligns with the evolving needs of satellite operators, driven by both economic considerations and the growing challenge of space congestion. Consequently, sustainable and cost-effective solutions — particularly those capable of reducing debris and enhancing satellite longevity — will be pivotal in shaping the future of the IoS market.

The following subsections outline the various roles that EDTs can fulfill within this market. Section 4.1 examines how an EDT-based mobility system can enhance the capabilities of IoS vehicles in LEO by providing a propellant-free propulsion solution. Section 4.2 discusses the autonomous capabilities of EDTs, highlighting their potential for ADR vehicles to deploy EDT-based autonomous subsystems for deorbiting dysfunctional satellites. Lastly, Section 4.3 presents the latest advancements in orbital mobility for EDTs, developed as part of the EIC funded project: E.T.COMPACT.

4.1. Life Extension Solutions

The operational lifetime of LEO satellites is inherently limited by several factors, including onboard fuel capacity, component degradation, and environmental conditions such as radiation exposure and atmospheric drag. Figure 11 generated from *Seradata* database, presents the mean operational lifespan of active LEO satellites, categorized by mass ranges: satellites below 70 kg, those between 70 and 210 kg, and larger satellites ranging from 210 to 2000 kg. This segmentation reflects the typical correlation between satellite complexity and mass, which directly impacts their longevity.

Figure 12: Artistic view of an In-Orbit-Service vehicle based on tether's propellant-free technology.

Smaller satellites (below 70 kg) tend to exhibit shorter operational lifetimes, with a significant portion lasting only 1 to 3 years. This trend is often linked to their simplified designs, lower costs, and reduced redundancy. The 70–210 kg range displays a broader distribution, peaking around 7 years—primarily driven by the OneWeb constellation. Meanwhile, satellites exceeding 210 kg generally demonstrate longer operational lifespans, reflecting their higher investment, enhanced redundancy, and critical mission profiles. Despite these differences, satellites with lifespans greater than 10 years or with undefined design lives remain a minority across all categories.

All costs associated with satellite development, integration, and launch are ultimately tied to these limited operational lifetimes, typically capping their value at 10 years or less. Extending satellite lifetime is thus crucial to improving mission return on investment and reducing the need for frequent replacement missions.

To address this, IoS solutions can strategically extend satellite lifetimes. By performing tasks such as refueling, component replacement, or orbital adjustments, IoS can significantly extend the operational period of satellites beyond their original design limits.

An example of such a system is the EDT-based IoS vehicle depicted in Figure 12. This concept, first presented as ElectroDynamic Debris Eliminator (EDDE) in [17], leverages a long conductive tether that interacts with Earth's magnetic field to generate a Lorentz force for autonomous propulsion. The vehicle can execute orbital maneuvers, reposition satellites, and conduct deorbiting operations efficiently. Since the EDT system does not rely on propellant, it can provide multiple services in LEO across a wide range of orbits without being constrained by limited fuel reserves. This self-sustaining capability makes the EDT-based IoS vehicle a scalable and cost-effective solution for extending satellite lifetimes, ensuring that critical infrastructure in orbit remains operational for longer periods.

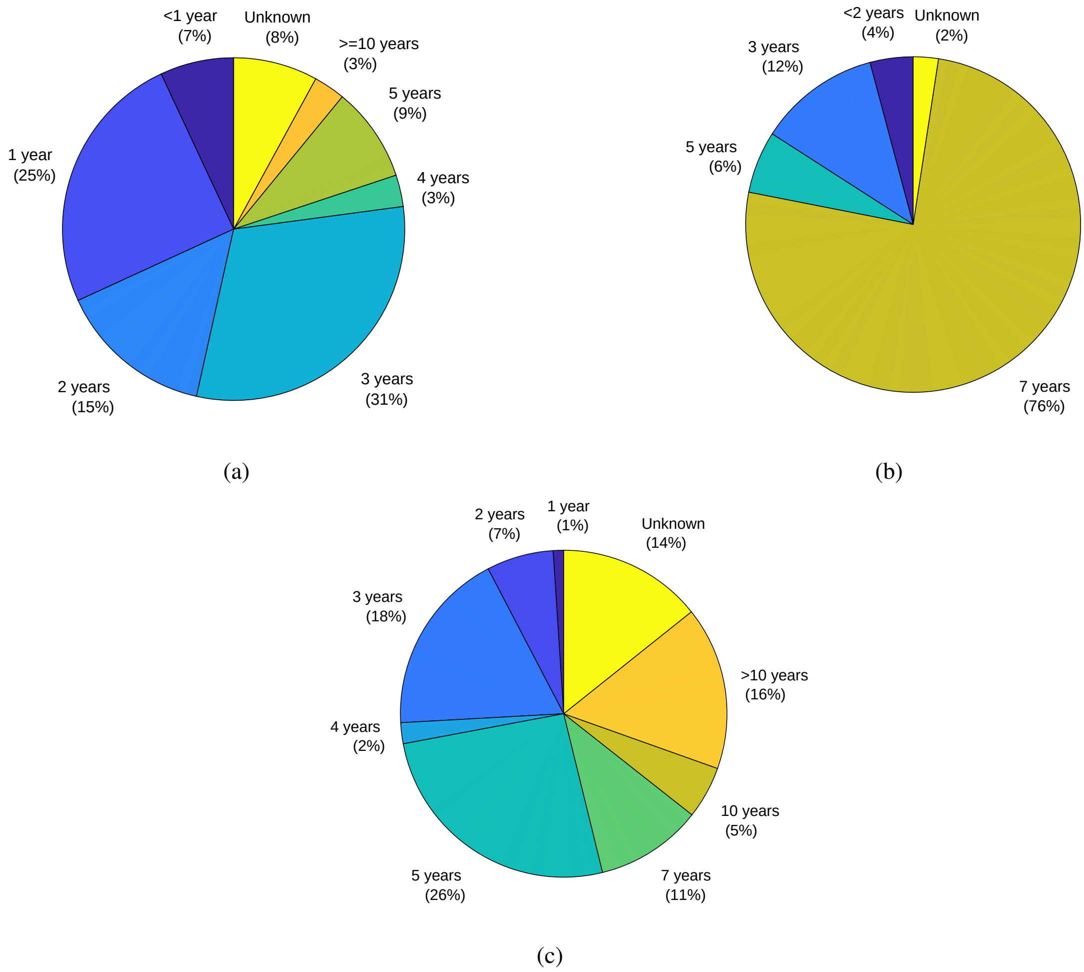


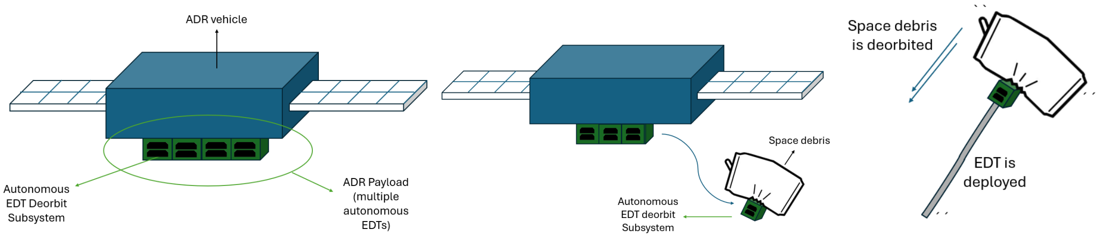
Figure 11: Lifetime of active satellites in orbits with altitude 500 km to 1200 km. Panels (a), (b) and (c) correspond to satellites with mass below 70 kg, between 70 and 210 kg, and above 210 kg, respectively. Data processed as of February 2025.

4.2. Active Debris Removal (ADR)

Conventional ADR missions, such as RemoveDEBRIS [1] and ClearSpace-1 [18], adopt different approaches. To start with, the RemoveDEBRIS mission demonstrated various ADR technologies, including net and harpoon capture systems, as well as a drag augmentation device for deorbiting. While these technologies successfully showcased debris removal capabilities, they typically require the IoS vehicle to actively manage the debris object during the deorbit phase. Similarly, the ClearSpace-1 mission, scheduled for launch by ESA in 2025, aims to capture and deorbit the VESPA payload adapter from a VEGA launcher using robotic arms. This method also relies on the IoS vehicle to actively maneuver the debris into a lower orbit.

Another approach to ADR is presented in [3], which describes the concept of operations of a mission involving an IoS vehicle equipped with multiple deorbiting devices that utilizes a robotic arm to attach them to debris objects. Following this approach, an application of EDTs for ADR is discussed in [23]. In this method, an IoS vehicle performs ADR by transporting autonomous EDT subsystems as payloads and installing them on space debris. Once an autonomous EDT subsystem is securely attached to a debris object, the IoS vehicle can disengage and proceed to its next target, allowing the EDT system to independently perform the deorbit maneuver. Unlike conventional ADR approaches, EDT-based solutions offer a distinct advantage by enabling autonomous deorbiting without the need for continuous intervention or control from the IoS vehicle.

As shown in Figure 13, the process unfolds in three key steps. In Step 1, an IoS vehicle equipped with multiple autonomous EDT subsystems deploys one of these units onto a dysfunctional space object. In Step 2, thanks to the EDT's autonomy, the IoS vehicle is free to disengage and proceed to its next target without further involvement in the deorbit process. Finally, in Step 3, the attached EDT subsystem autonomously generates a drag force by interacting with Earth's magnetic field, gradually reducing the debris' altitude until atmospheric reentry is achieved.



(a) Step 1 (b) Step 2 (c) Step 3

Figure 13: Diagram of an In-Orbit-Service vehicle providing autonomous EDT systems to dysfunctional objects in space for their deorbiting: Step 1: ADR Vehicle with a payload composed of autonomous EDT deorbit devices. Step 2: ADR vehicle rendez-vous a dysfunctional space debris and attach an EDT subsystem. Step 3: The space debris deorbits thanks to the EDT subsystem.

This self-sustaining process eliminates the need for continuous intervention, enhancing mission efficiency and scalability.

This "deploy and leave" capability, combined with the scalable design and propellant-free operation of EDTs, positions them as a highly effective solution for large-scale debris removal campaigns. By eliminating the need for continuous intervention and control, EDT-based ADR solutions can enhance mission efficiency and reduce operational complexity.

4.3. Advancements in EDTs for Propulsion + Deorbit

Section 4.1 delved into the potential of IoS vehicles utilizing the reversible property of EDTs, which can enable both deorbiting (generating power) or propulsion (if power is supplied). This scenario presents a plethora of potential applications. For instance, it can greatly benefit long-term missions, where a satellite orbiting Earth for years can maintain continuous propulsion without relying on finite propellant reserves. This capability allows the satellite to perform station-keeping, execute orbital adjustments, and effectively carry out collision avoidance maneuvers.

These capabilities are now being explored in the context of a mobility module for satellites thanks to the EIC-funded project E.T.COMPACT [25], with the potential to extend their application to in-orbit service vehicles in the near future. E.T.COMPACT involves a consortium of partners including Universidad Carlos III as the coordinator, alongside DEIMOS, University of Padova, Technical University of Dresden, PERSEI Space, Sunplugged, and Halocell Energy.

The key development under E.T.COMPACT is a miniaturized space-mobility subsystem known as Green Mobility Module (GMM). This compact system is designed to fit within a 3U volume, as represented in Figure 14. In this way, GMM targets host objects ranging from 70 kg to 200 kg.

Note that, unlike traditional EDT systems that rely heavily on orbital inclination for optimal performance, GMM employs a spinning tether design. This concept reduces the dependency on orbital inclination by dynamically adjusting the tether's orientation to optimize its interaction with the geomagnetic filed, enhancing the tether's overall performance.

An additional innovative feature of GMM is its Bare Photovoltaic Tether (BPT), which incorporates a segment covered with Perovskite/CIGS solar cells. This design enables the tether to generate power, which can be utilized onboard or to reverse the current direction for propulsion control.

This development represents a major advancement in EDT technology for both propulsion and deorbiting applications. Interested readers are referred to Ref. [25] for the latest updates on the E.T.COMPACT project and its contributions to advancing EDT-based mobility systems.

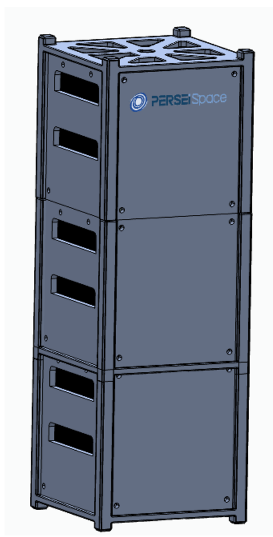


Figure 14: Artistic representation of a product based on the E.T.COMPACT Green Mobility Module (GMM).

5. CONCLUSIONS

EDTs offer a compelling value proposition as **Autonomous DDs**, capable of addressing the growing need for effective deorbiting solutions. This capability stems from their two distinctive traits: being propellant-free, as they interact with Earth's magnetic field and ionosphere rather than relying on onboard fuel, and autonomous DDs based on an EDTs have lower power needs compared to other technologies such as electric propulsion systems. These characteristics enable to prepare autonomous DDs based on EDTs, operating independently from the host spacecraft's power, avionics, or communication systems. This autonomy positions EDTs as a robust solution for ensuring deorbiting compliance, even when host spacecraft experience subsystem failures or have depleted their propellant reserves.

The need for such solutions is underscored by the projected growth in LEO satellite launches, projected in this investigation until 2033. Notably, 74% of LEO satellites under 70 kg currently lack onboard propulsion systems, while larger satellites show higher adoption rates — with 85% of those between 70-210 kg and 96% of those exceeding 210 kg equipped with propulsion. Despite this, compliance with deorbiting regulations remains a concern. As of 2022, over 40% of satellites failed to meet the 25-year deorbit rule, highlighting the gap in effective end-of-life strategies. Rocket bodies have demonstrated better compliance, with only 7% failing to meet this rule. However, the introduction of stricter 5-year deorbit mandates in both the US and Europe significantly amplifies the demand for reliable deorbiting technologies. Given their independence from spacecraft subsystems and ability to function without fuel, EDTs stand out as a promising solution to meet these evolving regulatory requirements.

The E.T.PACK-F project represents a significant step in validating EDT technology for deorbiting applications. Led by PERSEI SPACE, this initiative aims to demonstrate a 430 m-long bare tether equipped with a hollow cathode in orbit, aimed at spacecraft between $200-2000$ kg. The upcoming demonstration, scheduled for Q2 2026, is expected to be the stepping stone for the commercial deployment of this technology.

In addition to deorbiting, EDTs demonstrate strong potential for enhancing IoS capabilities. In this case, the tether is using its deorbit and propulsion capabilities effectively acting as a propellant-free mobility module. This integrated system enhances the capabilities of IoS vehicles, not restricted to the amount of propulsion onboard, thereby improving mission duration and maneuverability. Advancements in deorbiting and propulsion technologies for EDTs are currently under investigation in the EIC-funded project E.T.COMPACT. This project is developing GMM, a compact version of the E.T.PACK-F project, aimed at providing both deorbit and propulsion capabilities for smaller spacecraft ($70-200$ kg).

Another promising application is ADR, where an IoS vehicle — equipped with multiple autonomous EDT subsystems — can independently attach these units to debris objects. Once deployed, each EDT system autonomously performs the deorbit maneuver, allowing the IoS vehicles to immediately provide a service to another customer.

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