IAC-25,A6,IP,117,x97243

HARVESTING SOLAR ENERGY FOR PROPULSION: A BREAKTHROUGH IN GREEN MOBILITY FOR SPACE APPLICATIONS

Andrea Valmorbida[a]*, Alice Brunello[b], Giulio Polato[c], Marco Ghedin[a], Enrico C. Lorenzini[a], Gonzalo Sanchez-Arriaga[d], Livia Marciano[e], Jesus Manuel Munoz Tejeda[f], Julia Martin-Fuertes Branas[g], Martin Tajmar[h], Leo Peiffer[h], Luca Sorbello[i], Andreas Zimmermann[l], Lorenzo Tarabini-Castellani[m], Rafael Perez Fragoso[m]

[a] *Department of Industrial Engineering, University of Padova, Via Venezia, 1, Padova, 35131, Italy*
[b] *Center of Studies and Activities for Space (CISAS)" Giuseppe Colombo" , University of Padova, via Venezia, 1, Padova, 35131, Italy*
[c] *Department of Physics, University of Trento, via Sommarive 14, 38126 Povo (TN), Italy*
[d] *Universidad Carlos III de Madrid, Spain*
[e] *Politecnico di Torino, Italy*
[f] *National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory, United States*
[g] *PERSEI Space S.L., Spain*
[h] *TUD Dresden University of Technology, Germany*
[i] *Homerun Energy, Viale Castro Pretorio122, 00185 Rome, Italy*
[l] *Sunplugged GmbH, Affenhausen 1,6413 Wildermieming, Austria*
[m] *INDRA DEIMOS, Ronda de Poniente 19, 28760 Tres Cantos, Madrid, Spain*
* Corresponding Author: andrea.valmorbida@unipd.it

Abstract

The rapid expansion of satellite constellations and the accumulation of debris in Low Earth Orbit can benefit from new propulsion solutions that are sustainable, scalable, and independent of onboard propellant. The E.T.COMPACT project, funded by the European Innovation Council in 2024, addresses this challenge by developing a Green-propulsion Mobility Module that merges electrodynamic tether technology with in-space solar energy harvesting.

At the core of the system is the bare-photovoltaic tether, a deployable tape tether integrating tandem thin-film perovskite–CIGS solar cells. The bare-photovoltaic tether enables both electron collection for Lorentz-force propulsion and direct solar power generation, eliminating the need for conventional solar arrays. To sustain tether current, a high-performance Field Emission Cathode provides efficient electron emission, while a bidirectional Deployment Mechanism ensures safe reel-out and reel-in, enabling dynamic tether length management. In this R&D project, the miniaturization limits of electrodynamic tether technology are explored to assess their potential use on deorbiting, orbit raising, reboosting, and station-keeping. . Building on the heritage of previous EIC-funded projects (E.T.PACK and E.T.PACK-F) on electrdynamic tethers, E.T.COMPACT shifts the focus to miniaturization and multifunctionality, with the goal of creating a low-cost and scalable subsystem tailored to small satellite constellations.

The goal of E.T.COMPACT is to reach TRL 4 through ground demonstrations of tether deployment, field emission cathode performance, and bare-photovoltaic Tether energy harvesting. These achievements lay the foundation for future in-orbit demonstrations and subsequent commercialization by the E.T.COMPACT's partner PERSEI Space, aiming to contribute to a sustainable, propellant-free space mobility. This paper introduces the system architecture, describes the project innovations, and summarizes performance simulations, highlighting the disruptive potential of solar-electrodynamic propulsion for next-generation space applications.

Keywords: Electrodynamic Tether (EDT), propellant-less propulsion, solar energy harvesting, green space mobility, space debris mitigation.

Acronyms/Abbreviations
ADCS: Attitude Determination and Control System
ADR: Active Debris Removal
BPT: Bare-Photovoltaic Tether
CIGS: Copper Indium Gallium Selenide
CNT: Carbon Nanotube
DD: Deorbit Device
DM: Deployment Mechanism
EDT: Electrodynamic Tether
EIC: European Innovation Council
E.T.COMPACT: Compact and Propellant-less Electrodynamic Tether System Based on In-Space Solar energy

E.T.PACK: Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit
E.T.PACK-F: A Ready-to-Fly Deorbit Device Based on Electrodynamic Tether Technology
FEC: Field Emission Cathode
GMM: Green-propulsion Mobility Module
IOD: In-Orbit Demonstration
IOS: In-Orbit Servicing
LEO: Low Earth Orbit
M/ODs: Micrometeoroids and Orbital Debris
PCE: Power Conversion Efficiency
PVK: perovskite
R&D: Research and Development
SSO: Sun-Synchronous Orbit
TC: Thermionic Cathodes
ThWTC: Thoriated Tungsten Sheet Beam Wire Thermionic Cathode
TRL: Technology Readiness Level

1 Introduction and background

Over decades of space activity, Earth's orbits have become crowded with defunct satellites, rocket stages, and fragmentation debris, posing serious risks to operational spacecraft, human spaceflight, and the long-term sustainability of space [1]. Collisions can generate additional debris, potentially triggering a cascade effect [2]. The IADC guidelines on space debris mitigation [3][4] are continuously updated to reflect evolving activities and technologies. Additionally, regulatory authorities have reinforced this global effort: the FCC has reduced the permissible disposal period from 25 to 5 years [5], while the FAA has introduced new rules mandating specific disposal strategies for upper rocket stages, including controlled reentry, transfer to less congested or graveyard orbits, Earth-escape trajectories, active debris removal within 5 years, or uncontrolled atmospheric reentry [6].

These measures clearly reflect the growing recognition of sustainable space operations as a global priority. In this context, Electrodynamic Tethers (EDTs) have emerged as a particularly promising propellant-less technology for spacecraft operations in Low Earth Orbit (LEO). An EDT is composed of a long conductive tape or wire deployed from a host spacecraft. The current flowing on the tether, when interacting with the geomagnetic field, produces a Lorentz force. Current direction can be chosen to generate drag for end-of-life deorbiting or thrust for orbital raising [7]. Unlike conventional chemical or electric propulsion systems, EDTs require no onboard propellant and they are a environmentally sustainable ("green") space propulsion.

Over the past decades, several missions have demonstrated the potential of EDTs for in-orbit propulsion and deorbiting [8]. Among the earliest were the Plasma Motor Generator (PMG, 1993) [9] and TSS-1R (1996) missions [10], which employed long and insulated wire tethers. PMG used two plasma contactors to make anodic and cathodic contact with the ambient plasma. TSS-1R experiment had a big end-masses to collect electrons from the surrounding plasma and a cathode to close the electric circuit. These missions significantly advanced EDT research by validating in-space current reversibility, hollow cathode operation, and the generation of effective drag and thrust forces. In more recent years, experiments such as the Tethered Experiment (T-REX) [11][12], the Space Tethered Autonomous Robotic Satellite (STARS) [13], and the Kounotori Integrated Tether Experiment (KITE) [14] have expanded upon these foundations, moving towards compact EDT systems. Theoretical studies had proposed the use of tape tethers as efficient electron collectors [15][16], and the 2010 T-REX suborbital flight mission provided the first demonstration with a 300 m tape-shaped tether folded using an "Inverse Origami" technique. The Japanese STARS series further contributed to this miniaturization effort, with STARS-II (2014) [17][18] and KITE mission (2016) [19] considering ultra-thin and multi-line bare tethers.

Most recently, the U.S. Naval Research Laboratory's TEPCE mission (2019) [20][21] employed a 1 km braided conductive tether between two 1.5U CubeSats, achieving partial deployment of 450 m. Although incomplete, the mission successfully demonstrated the capability of compact EDT propulsion systems by enabling deorbit within three months, underscoring the growing maturity and potential of EDT technology for small satellite applications.

In Europe, the E.T.PACK and the ongoing E.T.PACK-F projects have played a central role in advancing EDT [22]. The E.T.PACK project developed a 12U autonomous Deorbit Device (DD) equipped with a tape-shaped tether and a hollow cathode for electron emission, successfully reaching Technology Readiness Level (TRL) 4 in 2022 [22][23]. Building on this foundation, the follow-up project E.T.PACK-F is currently developing a flight-ready DD that incorporates a 420-meter aluminum tape tether, a robust deployment system, and high-current electron emission capability. The In-Orbit Demonstration (IOD) scheduled for 2026 can provide the first in-orbit validation of a bare EDT system equipped with a hollow cathode [22][24][25].

Building on this heritage, the E.T.COMPACT project seeks to advance the field further by combining miniaturization and multifunctionality in the design of next-generation tether systems. The miniaturization of space tethers has, in fact, become increasingly important in recent years, driven by the rapid expansion of small satellite platforms such as CubeSats and nanosatellites. The current challenge lies in validating innovative design strategies that ensure reliable deployability, robustness, and compatibility with the highly constrained CubeSat form factor. Such advances can significantly enhance the feasibility of EDT propulsion for small satellites, enabling scalable solutions for orbital maneuvering, deorbiting, and debris mitigation. Within this evolving framework, the E.T.COMPACT aims at contributing to propellant-less, scalable and sustainable mobility in LEO, by advancing key EDT technologies together with the development of a compact 3-liter Green-propulsion Mobility Module (GMM).

This paper aims to present the E.T.COMPACT project workplan and first results. In particular, Section 2 introduces the project, providing an overview of the R&D activities and the GMM primary subsystems. Section 3 presents in detail the technology developments for EDTs that are currently being advanced within the project, while Section 4 presents performance results for deorbiting and reboost scenarios across representative satellite mass classes. Finally, Section 5 offers concluding remarks.

2 The E.T.COMPACT project

E.T.COMPACT is a Pathfinder project funded by the European Innovation Council (EIC) that started in October 2024. The consortium brings together partners from academia and the space and energy industries, including Universidad Carlos III de Madrid (UC3M), Technische Universität Dresden (TUD), Università degli Studi di Padova (UNIPD), Indra-Deimos, Homerun Energy, and Sunplugged. Over its three-year duration, the project aims to reach TRL 4 (design and prototype) for the GMM: a compact, 3U-class, non-autonomous, fully propellant-free technology demonstration system that enables versatile orbital mobility for small satellites, including deorbiting, re-boosting (orbital altitude increasing), and orbital inclination changing. The GMM, with a target mass and volume of around 5 kg and 3U respectively, was selected to drive the miniaturization of electrodynamic tether technology while remaining compatible with small satellite platforms.

The performance of an EDT decreases in high-inclination orbits if the tether aligns with the nadir, as the motional electric field weakens and the Lorentz force acts mainly out of the orbital plane, leading to dynamic instability. To address this, the E.T.COMPACT includes R&D activities on spinning tethered systems, exploring alternative approaches to spin-up and analyzing the stability and controllability of the spin plane. The reference scenario therefore assumes an EDT system operating in a SSO with an initial orbital altitude up to 700 km and a spacecraft mass of up to 100 kg (Fig. 1). The R&D activities of the E.T.COMPACT project are focused on key technologies for EDTs, as summarized below and described in detail in the subsequent sections of this paper:

- Bare-Photovoltaic-Tether (BPT) [26]: a bare tape tether embedding thin-film tandem perovskite/CIGS solar cells on one side, and able to provide both current collection for propulsion and solar power generation;
- Field Emission Cathode (FEC): a high-efficiency, expellant-free electron emitter sustaining the tether current;
- Deployment Mechanism (FM): a compact mechanism capable of reel-in and reel-out of up to 300 m of tape tether, ensuring controllable and reversible operations.

In parallel, the project also includes R&D activities on printable structures for satellites, i.e., structures made of light polymeric material to optimize volume and reduce mass. Theoretical analysis of spinning electrodynamic tethers (modelling and simulation) to study dynamics, control and performance are also part of the workplan.

To help focusing on direct applicable solutions and reduce dependence, the project also pursues a stand-alone IOD mission. For this reason, in parallel with GMM development, a 6U Platform is being designed to host the GMM, providing avionics, power, and tether spin support for the flight demonstration of E.T.COMPACT (Fig. 2). The spin system also assists tether deployment and enables the platform to reach a spin velocity of about 8 revolutions per orbit. In parallel, an Attitude Determination and Control System (ADCS) is being developed to manage and control spin operations.

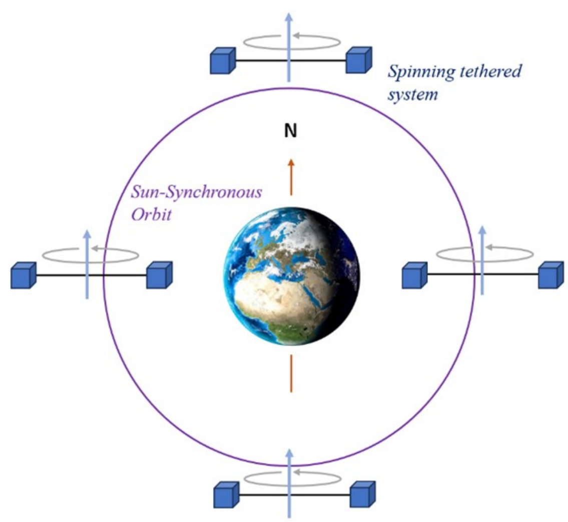

Fig. 1 – E.T.COMPACT IOD mission with two masses connected by the bare tape tether, flying in a SSO and spinning on a plane that is almost perpendicular to the orbital plane.

Fig. 2 – E.T.COMPACT IOD mission: render of the Platform with deployed solar panels and tether (reduced dimensions).

3 Technology Developments

This section presents the ongoing technology developments for EDTs within the E.T.COMPACT project, the technical choices being made, the performance demonstrated to date, and how each element contributes to miniaturization and multifunctionality.

3.1 Bare-Photovoltaic Tether (BPT)

While the baseline GMM utilizes a standard conductive tape tether, a key innovation being developed within the E.T.COMPACT project is a BPT demonstrator. The BPT represents a significant technological leap, aiming to create a monolithic structure that performs both propulsion and power generation simultaneously.

The BPT concept is based on integrating next-generation, flexible tandem thin-film perovskite-CIGS solar cells directly onto the surface of the conductive aluminum tether substrate (Fig. 3). This innovative integration uses the metallic tether itself as a common electrode (busbar) for the solar cells, simplifying the electrical architecture and creating a single, cohesive device. This approach is designed to produce a flexible, rollable tether that merges the functions of a solar panel and a bare tape tether for EDT applications. The primary goal of the BPT development is to produce a demonstrator that proves the viability of this integrated technology for EDT applications. The project aims to fabricate some 3 cm x 20 cm BPT samples with the following performance targets:

:

- Power Conversion Efficiency (PCE) greater than 15%;
- Power-to-Weight Ratio greater than 50 W/kg.

To reach these objectives, the project focuses on three main R&D activities: 1) band gap optimization of the solar cells, 2) optimization of the fabrication process, and 3) integration into two-terminal (2T) devices. Specifically, the solar cell band gaps were optimized to efficiently harvest the entire solar spectrum. A value of approximately 1.63 eV for perovskite (PVK) and 1.1 eV for CIGS was targeted. For the perovskite, the ratio of iodide to bromide (I−/Br−) halides was optimized to achieve the 1.63 eV band gap (Fig. 4). For CIGS, the gallium-to-indium (Ga/In) ratio was optimized to narrow the band gap to 1.1 eV.

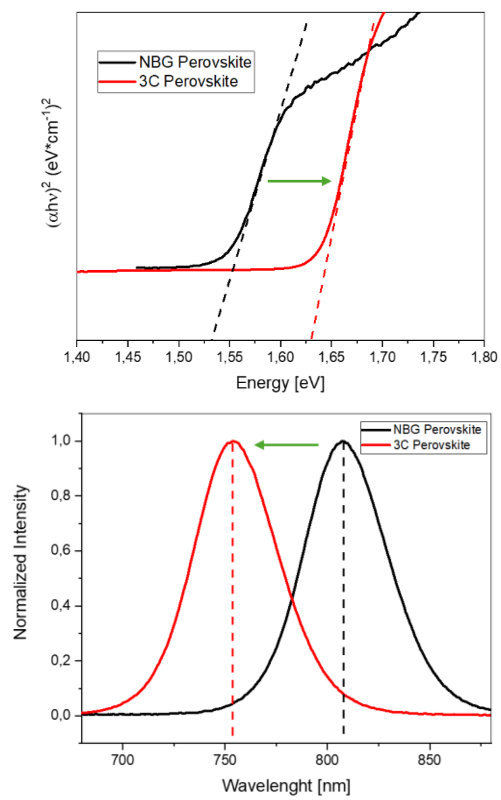

Fig. 4 – Band gap shift for PVK material at optimized I-/Br-ratio.

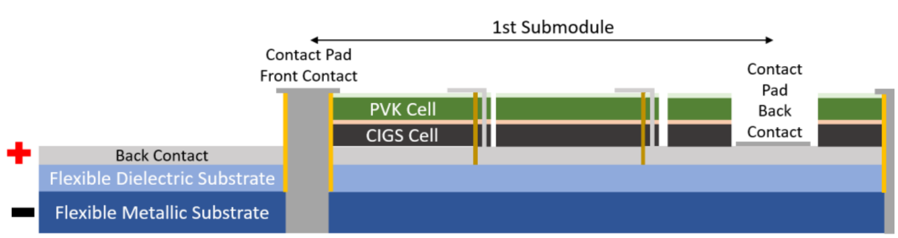

Fig. 3 – Sketch of a BPT with the modules made of 2-terminal CIGS/PVK Tandem modules. Courtesy of Sunplugged.

Concerning the fabrication process, PVK solar cells were initially fabricated in a single-junction configuration on a rough substrate to mimic the CIGS surface. This approach achieved efficiencies above 17% (Fig. 5 and Fig. 6) with a semi-transparent electrode, thanks to specific ink chemistry design and process engineering. The process was then scaled up from a laboratory environment (spin coating) to a semi-fabrication scale (blade/slot-die coating) in an ambient air environment, producing mini-modules with a substrate size of 30-35 cm^2 (Fig. 7). The optimized stack was subsequently transferred to a flexible substrate to evaluate the mechanical properties of the device before being integrated into a two-terminal (2T) device.

Building on this phase, the final integration required further optimizations, including the development of a recombination layer, defect identification, and material screening. These steps were essential to minimize optical losses and ensure high charge carrier transport between the stacked cells. Initial cell prototypes are currently under development.

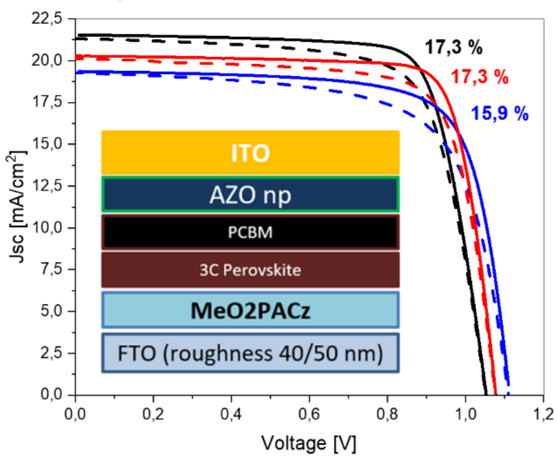

Fig. 5 – Best JV curves for optimized semi-transparent perovskite solar cells (PSCs).

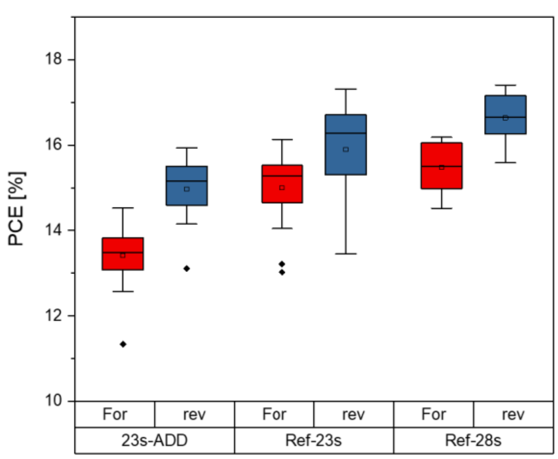

Fig. 6 – Power Conversion Efficiency (PCE) or optimized semi-transparent perovskite solar cells.

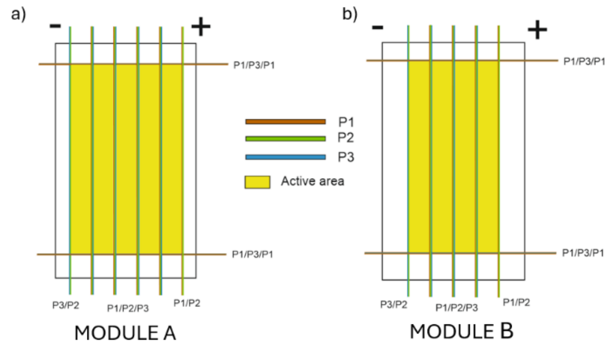

Fig. 7 – Design of PVK single junction minimodules.

3.2 Cathodes

A critical technology for enabling a truly expellant-less EDT system is the FEC, which is responsible for closing the electrical circuit by emitting electrons into the surrounding plasma without requiring an expellant. Within E.T.COMPACT, the development of the FEC is carried out by TUD and represents an ambitious task, since it is required to deliver a scalable solution applicable to a broad range of satellite classes. Consequently, the cathode is designed to meet two distinct performance targets:

- Low-Power Mode: an emission current of 10 mA with an efficiency greater than 2 mA/W, suitable for small satellites (<15 kg) with limited power (~10W);
- High-Power Mode: an emission current of 100 mA with an efficiency of 0.5 mA/W, designed for larger host platforms (70-210 kg) with more available power (~200W).

To meet these dual requirements, a trade-off study was conducted by TUD on different expellant-less emitter technologies. For the low-current, high-efficiency requirement, "cold cathode" Field Emitters were evaluated, with Carbon Nanotube (CNT) yarn technology being selected as the most promising and mature option. For the high-current requirement, "hot cathode" Thermionic Cathodes (TC) like Thoriated Tungsten were investigated due to their higher current density.

3.2.1 CNT-yarn FEC Design and Laboratory Performance

The current prototype development focuses on the CNT-yarn FEC for the 10 mA mission profile. The design consists of a compact 1U module that houses the CNT emitters, high-voltage power supplies, and control avionics, as shown in Fig. 8.

The emitter itself is composed of a CNT-yarn biased to a high negative voltage (~ –500 V) relative to a metallic extraction grid [27][28]. This high electric field extracts electrons from the yarn, emitting them into space. Laboratory testing of a cluster of four CNT-yarn prototypes has demonstrated a 10 mA current target with a total power consumption of 5 W. The emitter itself weighs only 23 g. A total module mass of approximately 1 kg is targeted, including all power electronics and housing for a redundant configuration.

3.2.2 Thoriated Tungsten Thermionic Cathode (ThWTC) for High-Current Operation

To address the high-current 100 mA requirement for larger host satellites, a Thoriated Tungsten Sheet Beam Wire Thermionic Cathode (ThWTC) also is being developed and preliminary tests were performed. Unlike the cold CNT-FEC, this "hot cathode" design uses a heater to bring a thoriated tungsten wire to a high temperature, enabling thermionic electron emission. The design, shown in Fig. 9, incorporates extractor electrodes to create the necessary electric field and a repeller electrode to focus the electron beam, maximizing the net current leaving the spacecraft. The design is based on the work by Vancil et al. [29]. The experimental prototype has confirmed its ability to achieve the 100 mA emission target current, with a current-to-power ratio higher than 1 mA/W in preliminary experiments but is still being optimized. While more power-intensive than the FEC, the ThWTC provides a reliable, high-current alternative essential for enabling faster deorbit maneuvers on larger platforms.

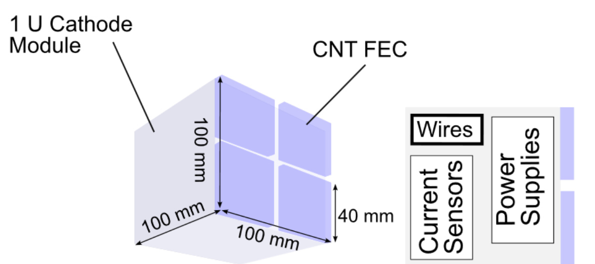

Fig. 8 – Schematic of the 1U cathode module with CNT-FEC.

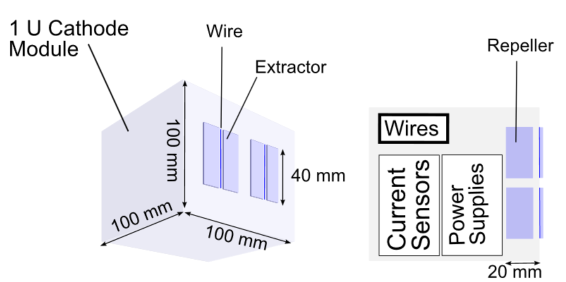

Fig. 9 – Schematic of the 1U cathode module with ThWTC.

The targeted performance metrics for both technologies are summarized in Table 1. The CNT-FEC provides a more efficient light-weight and compact solution for power-constrained missions, while the ThWTC shall offer a more robust and more mature, high-current performance needed for more demanding applications. This dual-technology solution shall ensure that the E.T.COMPACT GMM can be a versatile system, adaptable to a wide spectrum of future space missions.

Table 1 – Target Performance Metrics of the cathodes' prototypes

Quantity	**CNT FEC**	**ThWTC**
Target Current	10 mA	100 mA
Current-to-Power Ratio	> 2 mA/W	> 0.5 mA/W
Mass (cathode)	0.09 kg	0.15 kg
Mass (module)	1 kg	2 kg
Module Volume	1U	1U
Heater Power	-	20 W
Extraction Power	5 W	180 W
Total Power	5 W	200 W

3.3 Deployment Mechanism (DM)

The Deployment Mechanism (DM) is another key element of the E.T.COMPACT system, responsible for the precise, controlled, and bidirectional deployment of the electrodynamic tether. Its design was the subject of a detailed trade-off analysis to ensure reliability and compliance with the strict volume and mass limitations of the GMM.

3.3.1 System Architecture and Trade-Off

A key early decision was the selection of the overall system architecture. A preliminary trade-off study compared a simpler two-mass configuration with a more complex three-mass system. The two-mass configuration, shown in Fig. 10, comprising a primary mass hosting the DM and a secondary separable mass, was selected as the baseline. This choice was motivated by its significantly lower mechanical and control complexity, together with its more straightforward integration within the stringent 3-liter GMM volume constraint.

Once the baseline architecture had been defined, a subsequent trade-off addressed the DM and tether type. A single-coil, aluminum, tape-shaped tether configuration was selected over braided wire and multi-coil tape options, as it offered the most favorable balance between high survivability of the tether against micrometeoroid and orbital debris (M/ODs), superior deorbiting performance, and mechanical simplicity.

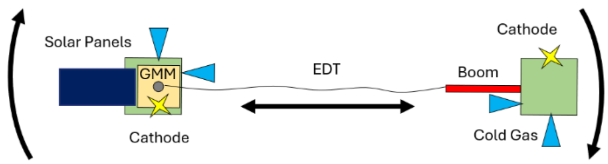

Fig. 10 – Schematic of the two-mass configuration.

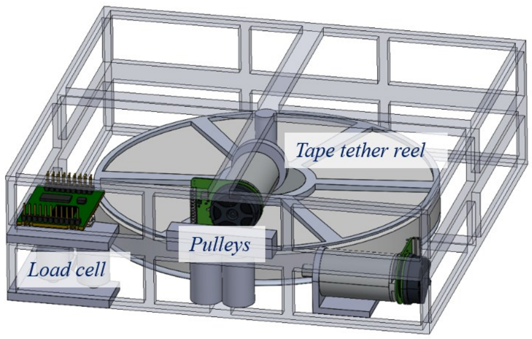

Fig. 11 – Preliminary design of the Deployment Mechanism.

3.3.2 DM Mechanical Design and Bidirectional Control

The selected DM features an active, dual-motor control system to ensure reliable bidirectional operations (Fig. 11). Specifically, the DM includes:

- Reel Motor: it operates in speed-control mode to control the velocity of the 330-meter aluminum tape tether during both deployment and retrieval;
- Pulley Motor: operates in torque-control mode, using real-time feedback from an integrated load cell; this allows the system to actively manage tether tension inside the DM, preventing slack during deployment and ensuring a tight, reliable winding with a constant tension during retrieval.

This dual-motor architecture decouples the speed and tension control, providing a robust and precise system capable of meeting the demanding operational mission requirements.

3.3.3 Deployment and Spinning Strategy

The mission requires the system to operate in a spinning configuration to enhance EDT performance. Relying on angular momentum conservation alone was found to be impractical. Therefore, a multi-stage active control strategy employing a cold gas system has been established as the baseline solution, as described in the following.

1. Initial Separation: Auxiliary deployable booms provide a controlled, rigid initial separation of the two system masses to prevent re-contact.
2. Tether Deployment: After the initial separation, the tether is fully deployed in the orbital plane, with the gravitational gradient helping to maintain the tether in tension.
3. Spin-Up: The cold gas system applies controlled thrust impulses to spin the entire assembly up to the target rate of 8 revolutions per orbit.
4. Precession: Further thrusts are used to precess the spin axis until the spin plane is almost perpendicular to the orbital plane, achieving the optimal orientation for EDT operations in a Sun-Synchronous Orbit.

3.4 Printable structures

One of the project challenges is the miniaturization of the GMM system together with the additional Platform elements to fit a 6U CubeSat. The systems required by the potential demonstration in orbit of the technology include the GMM payload and two complete satellites. Each satellite has his own processor, the communication system to send the mission data to ground, the power system including 0.5m^2 deployable solar panels, docking mechanisms, 6degrees of freedom reaction control system, magneto torquers on the 3 axes, GNSS sensor, 3 axes gyroscopes, 3 axes magnetometers and coarse sun sensors on each side.

Indra-Deimos has completed in autumn 2025 the design of the E.T.COMPACT IOD spacecraft demonstrating that the miniaturization is possible thanks to the use of fuse filament fabrication process and the development of miniature sensors, actuators, harness and connectors to be integrated during the printing. Thanks to the very complex structure geometry, the printed platform minimizes mass and volume embedding payload, equipment, harness and even piping inside the structure (Fig. 12).

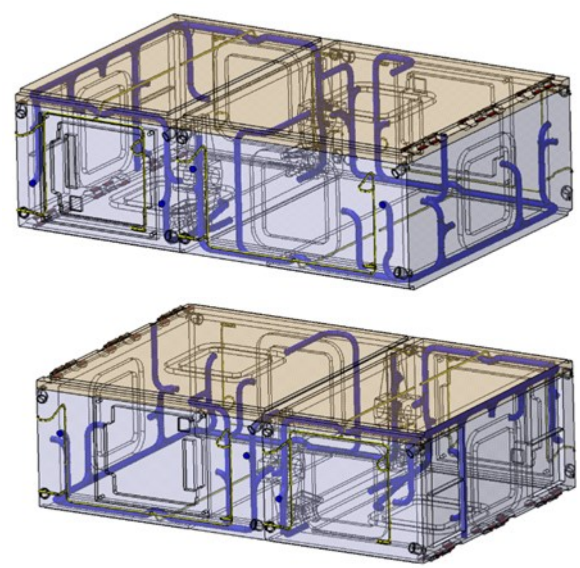

Fig. 12 – View of the 6U structure with holes and routing paths for avionics, electronics and harness integration.

For the structure prototype fabrication, Indra-Deimos selected the polymeric material ULTEM due to the good mechanical properties and the experience got with the manufacturing and flight of the 3U Neptuno spacecraft [29].

4 Performance Simulations and Analysis

As discussed in Sec. 2, a spin system has been integrated into the E.T. COMPACT IOD to enhance electrodynamic tether performance in high-inclination orbits. Preliminary simulations were carried out by UC3M to evaluate GMM performance across various mission scenarios, including deorbit and reboost maneuvers. Results were obtained using the BETsMA v2.0 tool [31] a software specifically designed for EDT mission analyses. Among the different dynamic models available in BETsMA v2.0, we here modeled the spacecraft as a punctual mass and tether dynamics was prescribed to be within a given plane (spin plane) and rotates at a prescribed angular velocity. At each time step, the software incorporates instantaneous values of ambient variables from numerical models such as IRI, IGRF, and NRLMSISE, and propagates the satellite orbit accounting for gravitational forces, aerodynamic drag, and Lorentz perturbation forces. Tether current, which appears in the Lorentz force, was found by using a bare tether model [16][32]. It includes a power supply between the tether and the cathode (find details in Ref. [31]) and it takes into account the instantaneous attitude of the spinning tether when computing the motional electric field.

The performance of the EDT system was evaluated for two types of orbital maneuvers: a deorbiting scenario (Section 4.1) and a reboost scenario (Section 4.2). The analyses considered satellites with masses of 70 kg and 100 kg, representing light and nominal payloads, as well as a 12 kg satellite relevant for a potential IOD mission. All satellites are initially placed in a SSO at 600 km of altitude with an inclination of 98°. The GMM, integrated within the spacecraft, receives 200 W of power when the cathode needs to be turned on to produce the desired change in the orbital element (deorbiting or reboost), except for the 12 kg satellite, in which the power is limited to 10 W. The tether is assumed to be made of aluminum, with a length of 330 m, a width of 1.25 cm, and a thickness of 50 µm. The EDT is assumed to be straight and rotates at 0.09 rpm (approximately 8 revolutions per orbit) within a fixed spin plane. Finally, two types of cathodes were considered: 1) CNT cathodes for the 12 kg satellite simulations, with a potential drop of V_c = -500 V, and 2) ThWTC cathodes for the heavier satellites, with V_c = -2000 V. In all the simulations the normal of the spin plane makes an angle of 12º with the axis of rotation of the Earth, which is the optimal orientation found in Ref. [33]. Simulation parameters are summarized in Table 2.

Table 2 – BETsMA v2.0 simulation parameters

Parameter	Value
Initial Date	1/1/2009
Perturbations	Lorentz force, Aerodynamic drag, 4th Harmonics
Satellite mass	12 kg (scenario 1) 70 kg, 100 kg (scen. 2-3)
ThWTC FEC (scen. 2-3)	V_c = -2000 V, P = 200 W
CNT FEC (scen. 1)	V_c = -500 V, P = 10 W
Initial altitude	600 km
Initial inclination	98º
Spin plane angle	12°
EDT cross-section	1.25 cm x 50 µm
EDT Length	330 m
Ballistic Coefficient	50 kg/m2

4.1 Deorbiting scenario

Deorbiting is considered complete once the satellite reaches an altitude of 350 km, as below this threshold the natural re-entry time is less than one week.

Simulation results are summarized in

Table 3. For all spacecraft masses considered, the deorbit time meets the 5-year requirement and the cut probability is less than 1%. Additionally, the simulations provide key data for cathode technology development, including the number of activations and total operational time.

As an example, detailed simulation results for the 12 kg spacecraft scenario are presented below. The figures illustrate the evolution of key mission parameters, and specifically:

- Fig. 13 shows the altitude decreasing from 600 km to 350 km, with a deorbiting time of less than 1 year;
- Fig. 14 presents the evolution of the orbital eccentricity (e) and inclination (inc); as shown, the mean values of eccentricity and orbit plane inclination remain almost constant;
- Fig. 15 depicts the tether current, including the average current in amperes (I_{av}) and the cathode current ($I_{cathode}$);
- Fig. 16 shows the Lorentz force component normal to the tether.

Table 3 – Results of the deorbit maneuver scenario

Mass (kg)	No. cathode activations	Cathode operation time (hours)	Tether cut probability (%)	Maneuver time (days)
12	34630	4444	0.3	286
70	68628	8807	0.54	575
100	92021	11809	0.74	771

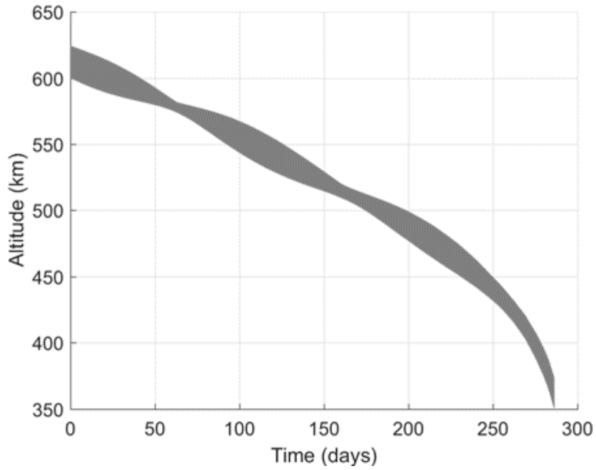

Fig. 13 – Altitude decrement for a 12 kg satellite – deorbiting scenario.

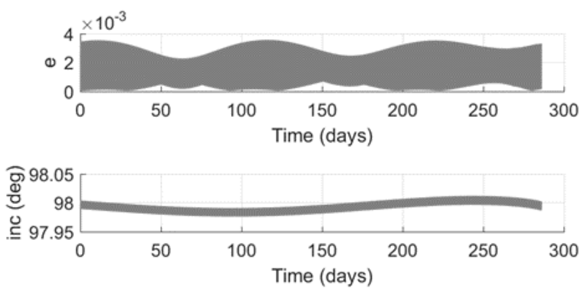

Fig. 14 – Evolution of orbital parameters eccentricity e (top panel) and inclination inc (bottom panel) for 12 kg satellite – deorbiting scenario.

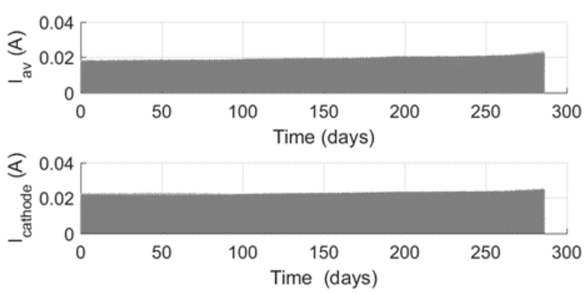

Fig. 15 – From top to bottom: average current (I_{av}) and cathode current ($I_{cathode}$) for a 12 kg satellite – deorbiting scenario.

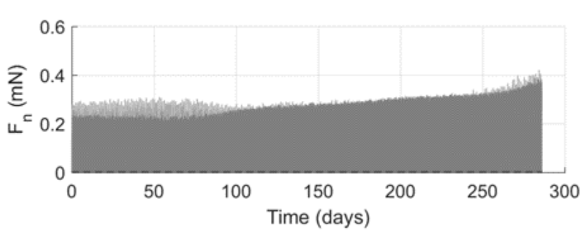

Fig. 16 – Lorentz force component normal to the tether for a 12 kg satellites – deorbiting scenario.

4.2 Reboost scenario

The reboost maneuver is simulated to raise the orbit up to 700 km for the different satellite masses. Results, summarized in Table 4, indicate that the orbit-raising maneuver can be performed at a mean rate ranging from 3.2 to 9.1 days per kilometer, depending on the satellite mass. Detailed simulation results for a 70-kg satellite are provided in Fig. 17, Fig. 18, Fig. 19 and Fig. 20, as a representative case of a reboost scenario.

Table 4 – Reboost maneuver results

Mass (kg)	No. cathode activations	Cathode operation time (hours)	Tether cut probability (%)	Maneuver time (Days)
12	N/A	N/A	0.61	342
70	38892	4991	0.58	321
100	53795	6904	0.79	444

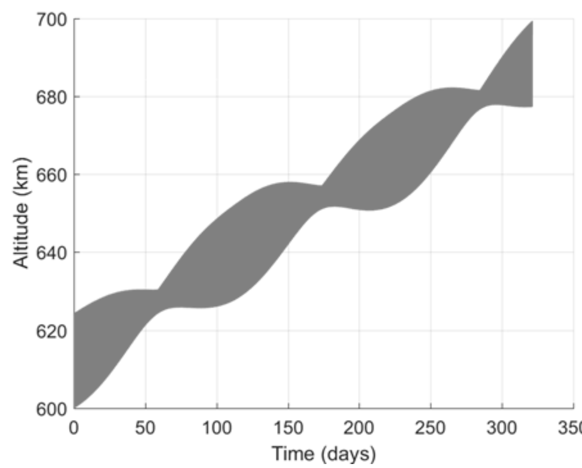

Fig. 17 – Altitude increment for a 70 kg satellite – reboost scenario.

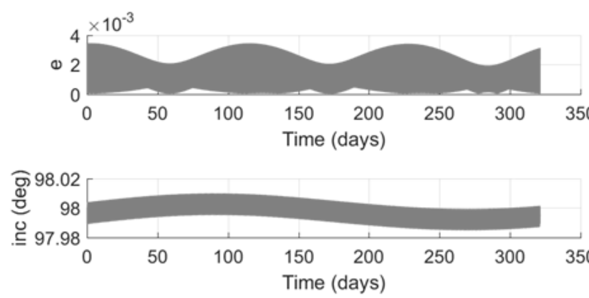

Fig. 18 – Evolution of orbital parameters eccentricity e (top panel) and inclination inc (bottom panel) for a 70 kg satellite – reboost scenario.

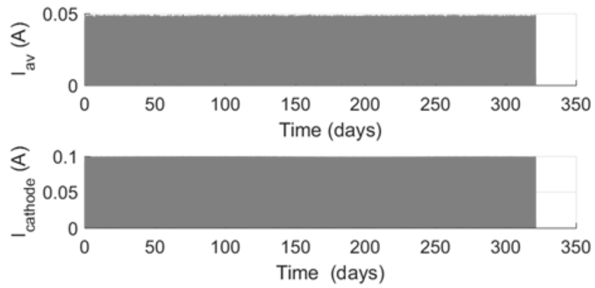

Fig. 19 – From top to bottom: average current (I_{av}) and cathode current ($I_{cathode}$) for a 70 kg satellite – reboost scenario.

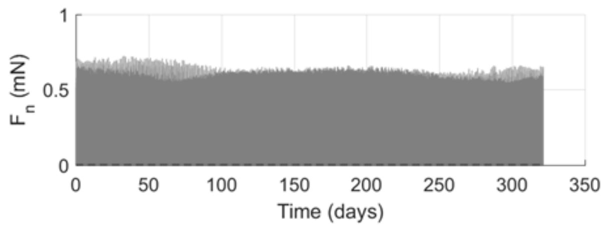

Fig. 20 – Lorentz force component normal to the tether for a 70 kg satellite – reboost scenario.

5 Conclusions

This paper presented the R&D activities currently being carried out in the EIC-funded E.T.COMPACT project, aimed at advancing EDT technologies in Europe, with a focus on their miniaturization and multifunctionality. Specifically, the ongoing developments include three core technologies that are fundamental for EDT systems. First, by integrating flexible tandem thin-film perovskite-CIGS solar cells with bare tape tethers, the BPT concept represents a unified system that is able to perform both propulsion and power generation at the same time. Samples of BPT are being developed with a target power conversion efficiency above 15% and a power-to-weight ratio exceeding 50 W/kg. The first requirement has been achieved through an optimization of the ratio of iodide to bromide (I−/Br−) halides the perovskite. Second, the project is pursuing a dual expellantless-cathode strategy to address diverse power budgets: a CNT FEC for low-power missions (~10W) and a thermionic ThWTC FEC for high-current operations (~200W). Third, a compact Deployment Mechanism with bidirectional functionalities (reel-in and reel-out) is being developed, designed to deploy and retrieve approximately 300 m of aluminum tape tethers.

In addition, advances in the technology of printable satellite structures by employing lightweight polymeric materials such as ULTEM are in progress. The filament-based fabrication process allows the production of very complex structure geometry, enabling the integration of miniaturized components (e.g., sensors, equipment, or even piping) directly into the structure. This approach is resulting in optimized volume utilization and reduced mass.

Furthermore, a 6U autonomous satellite has been designed to pave the way for a future IOD of the E.T.COMPACT technologies. At the core of this IOD mission is the GMM: a non-autonomous, fully propellant-free technology demonstrator. The GMM is designed to fit within a 3-liter volume and accommodates: (a) ~300 m of aluminum tape tether, (b) a miniaturized bidirectional deployment mechanism, and (c) a high-current field emission cathode.

Preliminary performance analyses showed that the five-year deorbit requirement can be meet for representative satellite mass classes (12–100 kg), using a 330 m tape tether and providing 10 W of power to the cathode for a 12 kg satellite, and 200 W for higher satellite mass classes. Feasible timelines can also be achieved for reboost maneuvers while maintaining tether cut probabilities within acceptable limits, providing evidence that the approach scales across multiple platforms and use cases.

The technologies under development within this project can either be combined with non-miniaturized systems or scaled up, enabling the creation of versatile green mobility architectures. These solutions can be adapted to various satellite mass classes and tailored to a wide range of customer needs, such as orbit maneuverability and mission flexibility.

Acknowledgments

This work was supported by the Horizon Europe EIC Pathfinder Program under Grant Agreement No. 101161603 (E.T.COMPACT).

References

[1] Online Source: ESA's Annual Space Environment Report, ESA Space Debris Office, 2023.
[2] Kessler, D.J. and Cour-Palais, B. G., Collision Frequency of Artificial Satellites: The Creation of a Debris Belt, Journal of Geophysical Research, Vol. 83, No. A7, 1 Jun. 1978, pp. 2637-2646.
[3] Online Source: https://orbitaldebris.jsc.nasa.gov/library/iadc-space-debris-guidelines-revision-2.pdf
[4] NASA safety standard: Guidelines and assessment procedures for limiting orbital debris. Technical report, August 1995. NSS 1740.14. Office of Safety and Mission Assurance, Washington D.C.
[5] Online Source: https://www.fcc.gov/document/fcc-adopts-new-5-year-rule-deorbiting-satellites-0
[6] Online Source: https://www.faa.gov/newsroom/Orbital-Debris_NPRM Issuance.pdf
[7] M. L. Cosmo, E.C. Lorenzini. Tethers in Space Handbook. Resource Online: https://www.nasa.gov/centers/marshall/pdf/337451main.
[8] G. Sánchez-Arriaga, E. C. Lorenzini, S.G. Bilén, A review of electrodynamic tether missions: Historical trend, dimensionless parameters, and opportunities opening space markets. Acta Astronautica, Volume 225, 2024, pages 158-168. doi: 10.1016/j.actaastro.2024.09.002.

[9] Grossi, Mario D., Plasma Motor Generator (PMG) electrodynamic tether experiment, Report NASACR-199523, 1 Jun 1995, papers presented at Fourth International Space Conference on Tethers in Space, Washington, DC, April 1995). Retrieved 8 June 2016.

[10] C. George, Tethered Satellite System Reflight (TSS-1R) Post-Flight Engineering Performance Report, Marshall Space Flight Center, Huntsville, Ala, USA, 1996.

[11] Spaceref, JAXA's Tether Technologies Rocket Experiment (T-REX) Launched, 4 September 2010.

[12] Online Source: Takeo Watanabe et Al, (2010). T-Rex: Bare Electro-Dynamic Tape-Tether Technology Experiment On Sounding Rocket S520, https://oa.upm.es/23248/1/A101.pdf.

[13] Online Source: Kagawa satellite development project STARS (English) Archived 27 March 2014 at the Wayback Machine.

[14] Ohkawa, Y., Review of KITE - Electrodynamic tether experiment on the Japanese H-II Transfer Vehicle, 2020, Acta Astronautica, Vol. 177, pp. 750- 758. https://doi.org/10.1016/j.actaastro.2020.03.01

[15] R.D. Estes, E.C. Lorenzini, J. Sanmartin, J. Pelaez, M. Martinez-Sanchez, L. Johnson, Bare Tethers for Electrodynamic Spacecraft Propulsion. Journal of Spacecraft and Rockets, Vol. 37, No. 2, 205-211, (2000) URL https://doi.org/ 10.2514/2.3567

[16] J. R. Sanmartin, M. Martinez-Sanchez, E. Ahedo, Bare wire anodes for electrodynamic tethers, Journal of Propulsion and Power, 1993, 353-360, 9, 3. doi: 10.2514/3.23629

[17] Herbert J. Kramer , STARS-II, eoPortal.

[18] M. Nohmi, Initial Orbital Performance Result of Nano-Satellite STARS-II, International Symposium on Artificial Intelligence, Robotics and Automation in Space (I-SAIRAS), Montreal, Canada, 17–19 June 2014.

[19] Online source: Review of KITE – Electrodynamic tether experiment on the H-II TransferVehicle.

[20] S. Coffey, B. Kelm, A. Hoskin, J. Carroll, and E. Levin, Tether elctrodynamic propulsion CubeSat experiment (TEPCE), in Proceedings of Air Force Orbital Resources Ionosphere Conference, pp. 12– 14, 2010.

[21] S. Coffey, C. Crippa, G. Dutchover, M. D. Brunner, Z. Sibert, S. Kindl, I. Galysh, C. L. Enloe, J. Carroll. TEPCE: A Tethered Electrodynamic Propulsion CubeSat Experiment. Report of U. S. Naval Research Laboratory Washington, NRL/8230/FR--2022/1

[22] Online Source: http://www.etpack.eu

[23] A. Valmorbida, L. Olivieri, A. Brunello, G. Sarego, G. Sánchez-Arriaga, E.C. Lorenzini, Validation of enabling technologies for deorbiting devices based on electrodynamic tethers, Acta Astronautica, 2022, doi: 10.1016/j.actaastro.2022.06.013. PDF.

[24] G. Sanchez-Arriaga, A. del Pino, G. Sharifi, L. Tarabini Castellani, S. García-Gonzaléz, A. Ortega, D. Cruces, A. Velasco, S. Orte, A. Ruiz, J. Matabuena, B. Martin, J.P. Wulfkuehler, C. Drobny, J. Hertel, R. Nerger, M. Tajmar, A. Valmorbida, S. Chiodini, G. Polato, G. Anese, A. Brunello, G. Colombatti, E.C. Lorenzini and D. Hubert. The E.T.PACK-F Project: towards a flight-ready deorbit device based on electrodynamic tether technology, AIAA 2024-0639. *AIAA SCITECH 2024 Forum*. January 2024.

[25] A. Brunello, G. Anese, S. Chiodini, G. Colombatti, G. Polato, S. Salmistraro, A. Valmorbida, E.C. Lorenzini, The Deployment Mechanism of the E.T.PACK Deorbit System: Functional and Qualification tests, Acta Astronautica, Volume 226, Part 2, 2025, Pages 39-47. PDF.

[26] M. Tajmar, G. Sánchez-Arriaga, A bare-photovoltaic tether for consumable-less and autonomous space propulsion and power generation, Acta Astronautica, Volume 180, 2021, pages 350-360. doi: 10.1016/j.actaastro.2020.12.053.

[27] T. Reichelt, G. Hentsch, L. Peiffer, R. Nerger and M. Tajmar, Design and Testing of a Planar CNT Array for Space Application, 2025 38th International Vacuum Nanoelectronics Conference (IVNC), Reykjavik, Iceland, 2025, pp. 1-2, doi: 10.1109/IVNC65669.2025.11120897.

[28] G. Hentsch, M. Tajmar, Development of high-current compact radial field emission cathodes for space applications, Journal of Electric Propulsion, 4, 17 (2025). doi: 10.1007/s44205-025-00119-z.

[29] B. Vancil, V. Schmidt, C. Kory, J. Rossano, N. Paschalidis, D. Chornay, T. Cameron. Miniature Sheet Beam Electron Gun. 1-2. 2024 10.1109/IVECIVESC60838.2024.10694845.

[30] Krebs, Gunter D. Neptuno (NEPT 1). Gunter's Space Page. Retrieved September 12, 2025, from https://space.skyrocket.de/doc_sdat/neptuno.htm

[31] G. Sanchez-Arriaga, G. Borderes-Motta, L. Chiabò, A code for the analysis of missions with electrodynamic tethers, Acta Astronautica 198 (2022) 471–481. doi:10.1016/j.actaastro.2022.06.021

[32] J. Sanmartin, A. Sanchez-Torres, S. Khan, G. Sanchez-Arriaga, M. Charro, Optimum sizing of bare-tape tethers for de-orbiting satellites at end of mission, 2015, Advances in Space Research. 56. 1485-1492. 10.1016/ j.asr.2015.06.030.

[33] J. Simón-Aznar, G. Sánchez-Arriaga, B. Vatankhahghadim, Performance, Navigation and Control of a Spinning Electrodynamic Tether System, 2025, Proceedings of the 9th European Conference on Space Debris. European Space Agency.