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Validation of enabling technologies for deorbiting devices based on electrodynamic tethers

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Abstract

The increasing number of man-made objects in near-earth space is becoming a serious problem for future space missions around the Earth. Among the proposed strategies to face this issue, and due to its passive and propellant-less character, electrodynamic tethers appear to be a promising option for spacecraft in low Earth orbits thanks to the limited storage mass and the minimum interface requirements to the host spacecraft.

This work presents the roadmap that the Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit (E.T.PACK) is following to develop a prototype of a deorbit device based on electrodynamic tether technology with Technology Readiness Level 4 by the end of 2022. The paper illustrates the roadmap of the activities carried out at the University of Padova, where software and hardware have been prepared to validate some of the critical elements of the deorbit device. Specifically, the software tools include: (a) the software called "DEPLOY" that allows the computation of a reference trajectory for the deployment of the tether and the completion of sensitivity analysis of the deployment trajectory to key error sources; (b) the software called "FLEXSIM" that predicts the performances of electrodynamic tethers as a function of the system configuration employed; and (b) the software called "FLEX" that includes the dynamical effects of tether flexibility and provides important information on the dynamic stability of the system during deployment and deorbiting phase. The paper describes in detail the three software tools and provides results of a simulation showing how it is possible to deorbit a 24-kg satellite from an initial orbital altitude of 600 km in less than 100 days using a 500-m long tape-like bare tether.

The team has also developed laboratory mock-ups and performed experimental activities to: (a) determine the tether mechanical properties; (b) test the functionality of mechanisms used to deploy the tether; (c) test the functionality of the attitude control assembly used during the deployment phase; and d) validate a passive damper designed for dissipating the longitudinal oscillations of the tether and thus guarantee the stability of the system during both deployment and deorbiting phase. The paper provides a description of both the laboratory setup and the experimental activities performed to validate EDT technologies, including the damping capability of a compact passive-damping mechanism, showing how it can reduce consistently the peak forces up to about 80%.

Keywords: space tethers, satellite end-of-life disposal, electrodynamic tethers, experimental tests and validation.

Acronyms and symbols

EDT	electrodynamic tethers	LEO	Low-Earth Orbits
E.T.PACK	Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit	PMD	Post Mission Disposal
E.T.PACK-F	Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit - Fligth	ADR	Active Debris Removal
DKD	Deorbit Kit Demonstrator	FET	Future Emerging Technologies
DK	Deorbit Kit	ILD	Om-Line Damper
EEM	Electron Emitter Module	s/c	spacecraft
DMM	Deployment Mechanism Module	UniPD	University of Padova

l	tether length	e^-	electron
$\dot{l}$	tether length rate	$\boldsymbol{B}$	Earth's magnetic field
θ	tether in-plane libration angle	$\boldsymbol{i}$	conventional current
$\dot{\theta}$	tether in-plane libration angle rate	$\hat{\boldsymbol{r}}$	unit vector from the host s/c to the Earth's center of mass
c	damping coefficients of the tether in-line damper	$\boldsymbol{F}_L$	Lorentz force

1. Introduction

The issues related to the presence of man-made objects in near-Earth orbits were firstly addressed by Kessler in the 70s' [1], which stated that without direct action (e.g. by reducing the in-orbit artificial objects net input) the number of in-orbit human-made objects and their fragments could increase exponentially with time, up to quickly exceed the meteoroid background environment. The qualitative description of the cascade "Kessler Syndrome" was later quantified by the author, which confirmed that we are now entering a time when the orbital debris environment will increasingly be determined by random collisions and that we should avoid leaving future payloads and rocket bodies in orbit after the end of their operational life [2]. In fact, the recent constant growth of the small satellite launch rate [3][4] as well as the on-going deployment of several large constellations [5][6] have further distressed the scientific community. In this context, Foreman et al. [7] used the NASA Orbital Debris Engineering Model software and a Monte Carlo analysis to examine the potential implications of two recent satellites constellations by OneWeb and SpaceX on the LEO environment. In addition, Olivieri et al. [8] developed a simple statistical tool for lost vehicles during large constellations life, analyzing the effects of the main parameters of the constellations on its vulnerability.

The sustainability of the access to several Low-Earth Orbits (LEO) is under discussion [9][10][11] and the increasing number of resident objects is enhancing the probability of in-space collisions [12]. It was estimated that in case of future events such as the Cosmos-Iridium collision [13] the generated fragments are not only limited to the altitudes involved but may contaminate neighbouring orbits. In this context the current orbital population is under constant scrutiny, with the development of lists of potential objects whose fragmentation might strongly influence the access to some orbits [14][15][16], the investigation of potential critical fragmentation events [17][18][19], and the definition of strategies for the long-term sustainability of space activities [20].

The scientific community is evaluating mitigation strategies, considering both the utilization of enhanced protections [21] and the implementation of Post Mission Disposal (PMD) [22] and Active Debris Removal (ADR) [23] operations and strategies [24]. In addition, responsible conducts and self-regulations are appearing as promising solutions to address the issue of space debris [25][26]. In parallel, guidelines regarding the deorbiting of all new satellites within 25 years from mission completion, if their deployment orbit altitude is below 2000 km (i.e., in LEO), have been introduced [27] and, in a few cases, they have been absorbed into the countries legal frameworks [28].

The 25 years guideline for spacecraft disposal is currently leading to the development of deorbiting strategies (i.e., by saving propellant for re-entry maneuvers) or to the installation of dedicated systems on board the spacecraft by most of the major providers. Among them, dedicated electrical [29] and chemical l[30] propulsion systems were suggested for disposal, as well as drag enhancement devices [31][32] and Electrodynamic Tethers (EDTs) [33][34][35]. In a relevant way, EDTs are a promising option that may overcome the limitations of traditional chemical and electrical propulsion and can potentially be lighter [36] and less prone to debris impact risk [37] [38] than other devices, such as neutral drag sails. In this context, the H2020 project E.T.PACK (Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit) aims at developing a deorbit kit prototype based on EDT technology [39].

The E.T.PACK consortium is formed by a mix of academia, research centers and companies specialized in the fields required to prove the feasibility of EDT technologies: Universidad Carlo III de Madrid (UC3M)(Spain), University of Padova (UniPD)(Italy), Technische Universitat Dresden (TUD)(Germany), Fraunhofer-Institut für Keramische Technologien und Systeme (IKTS)(Germany), Advanced Thermal Devises (ATD)(Spain) and SENER Aerospacial (Spain). The consortium has knowledge on Low Work function Tether (LWTs) and plasmas (UC3M), thermionic materials (IKTS), tethers and mechanisms (UniPD), electric propulsion (TUD), solid state devices (ATD) and space product development (SENER). The European Commission invited the E.T.PACK consortium to sign the Grant Agreement of a subsequent EIC Transition project named E.T.PACK-F (Flight), that will increase the TRL from 4 (for the current E.T.PACK) up to 8. A mission demonstrating the kit functionality (DKD – Deorbiting Kit Demonstration) is planned for 2025 [40], just after E.T.PACK-F will be completed, within the framework of a launch agreement signed during IAC 2021 in Dubai between SENER Aeroespacial and Rocket Factory Augsburg.

The University of Padova (UniPD) is one of the partners of the E.T.PACK and E.T.PACK-F projects consortia, both coordinated by the Universidad Carlos III de Madrid. The team at UniPD was tasked with the validation of a certain number of enabling technologies for the deorbit kit including the development of software tools to study the EDT performance and dynamical behaviour and the realization and test of hardware mock-ups and prototypes. In the remainder of this paper, the EDT technology and the E.T.PACK project are presented in Section 2. The roadmap of the University of Padova activities to validate the enabling technologies for the DKD mission is introduced in Section 3. Lastly, the software development and experimental activities are presented in Sections 4 and 5.

2. Electrodynamic tethers and the E.T.PACK project

A modern EDT consists of a long conductive bare tether connecting two spacecraft, usually a host spacecraft and a tip mass. Referring to Figure 1, electrons are passively captured by the bare tether from the ionospheric plasma and

are reemitted back into the plasma by using either an active electron emitter (cathode) or a segment of the tether made of a low-work-function material using thermionic emission and photoelectric effects [41][42]. The electric current that flows in the tether interacts with the Earth's magnetic field generating a Lorentz force that, depending on the configuration of the system, can be used to either deorbit the host satellite or to reboost it.

The physics of EDTs was first demonstrated in the 1990s with three orbital missions: the two NASA-ASI Tethered Satellite System missions -- TSS-1 (1992) and TSS-1R (1996) -- and the NASA Plasma Motor Generator (PMG) mission (1993). More recently EDT projects have included: NASA's Propulsive Small Expendable Deployer System (ProSEDS) scheduled for 2003 but with the launch cancelled after the Shuttle Columbia accident, and the Naval Research Laboratory (NRL) Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE), launched successfully in 2019 [43].

Concerning the tether geometry, round tethers have been employed in several space missions of the past. However, in the last few years it was demonstrated that tape tethers have much better survivability to small debris and micrometeoroids impacts. In this context, Khan and Sanmartin [44] used NASA and ESA debris flux models to develop a simple analytical formulation that can be used as a preliminary design tool [45] for calculating tape tethers survivability per unit length as a function of taper dimensions, i.e., width and thickness, and orbit parameters, i.e., altitude and inclination. In a recent work [46], Fujiwara et al. used a two-stage light-gas gun to conduct hypervelocity-collision experiments on aluminum tape tethers to assess their survivability against debris collisions. Moreover, tape tethers have better ability for equal tether mass to collect the ionospheric electrons than round tethers, as shown by Sanmartin et al. in [47] and [48]. The ability of a bare tether in collecting electrons from the Earth's ionosphere in LEO was investigated experimentally by Siguier et al. in [49].

EDTs are now been developed in Europe, USA, Canada and Japan for the deorbiting of satellites at the end of their operational life with the final aim of mitigating space debris in LEO. Yao and Sands [50] used an EDT system with a 500 meter tether charged with a 1 Amp current to increase the orbital altitude by 250 m of a 100 kg spacecraft flying in a LEO orbit (275 km). The University of Michigan [51] is investigating the use of a short (few meters) electrodynamic tether as a technology for propellant-less drag cancellation and orbital change of smartphone-sized spacecraft. They developed the software tool called TeMPEST to predict the propulsion performance of the EDT system for picosatellites (spacecraft mass in the range 100 grams – 1 kg) and femtosatellites (spacecraft mass < 100 grams) and are developing the Miniature Tether Electrodynamics Experiment (MiTEE) technology-demonstration mission [52]. In early 2017 the mission called KITE (Kounotori Integrated Tether Experiment) [53] was conducted on the sixth H-II Transfer Vehicle (HTV-6) for demonstrating the maturity of the core technologies for EDTs. Unfortunately, the tether was not deployed due to a mechanical malfunction, but the field emission cathode operated successfully, and the mission demonstrated the maturity of this key technology for EDTs. In addition, this mission confirmed that the deployment of the tether is the first critical phase that requires extensive simulations [54] and laboratory tests [55] to verify the functionality and the reliability of the tip-mass release mechanism and the tether deployment mechanism and control algorithms.

Among the other deorbiting technologies, EDTs are an effective and promising technology able to overcome the limitations of traditional active technologies for deorbiting, i.e., chemical or electrical propulsion systems. Tether systems are mostly passive and in the configuration under development (e.g., E.T.PACK) they are designed to be autonomous and independent of the host satellite. In addition, an EDT can control the electric current by inserting a resistor with variable electric resistance between the bare tether and the electron emitter (cathode device) [56]. Moreover, if the activation of the current through the conductive tether is properly phased by electrically connecting or disconnecting the cathode device from the tether, the deorbiting profile can be controlled to avoid the collision with catalogued objects (with a characteristic size > 10 cm) [37][57]. The limitation of the current flowing in the tether is also required to limit excessive tether libration during the deorbiting phase that could lead to dynamics instability of the system (flip upside down) before its reenter in atmosphere. In addition, the probability of a tether cut due to very small debris is not a critical issue when using thin tapes as opposed to cylindrical tethers [58].

Due to those considerations, EDTs offer a solution that, specifically for LEO satellites and spent stages, is potentially very competitive among the alternative technologies currently used for end-of-life deorbiting missions, hence providing a propellant-free and fully-green device that offers a safe preservation of the space environment.

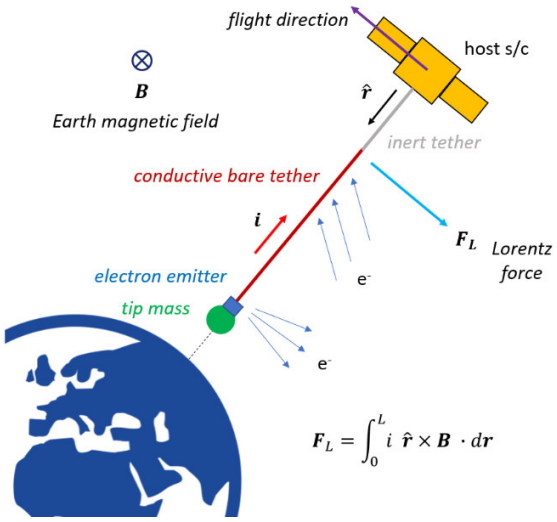

Figure 1: working principle of EDT in the configuration with an active electron emitter. The configuration shown in the figure refers to a prograde orbit (inclination < 90 deg) and i indicates the conventional current*.

The European Commission funded in 2018 with 3 M€ the project E.T.PACK, that is a 45-month H2020 Future Emerging Technologies FET-OPEN project with the objective of developing an electrodynamic-tether-based Deorbit Kit (DK) with TRL equal to 4. The E.T.PACK consortium has recently finished the design of a Deorbit Kit Demonstrator (DKD) prototype and is carrying out the manufacturing and testing phases of its elements [59]. The DKD consists of a 12U CubeSat with a total mass of 24 kg, that incorporates the key technologies to be validated in space. The flight model of the DKD (to be developed with the E.T.PACK-F project) will be launched into a circular orbit at an altitude of 600 km and a medium inclination, and it will deploy a 500-m-long tape tether. The natural deorbit time of the system from this orbit is more than 15 years (depending on solar activity) and the expected reentry time into the atmosphere using the EDT technology is less than 100 days.

The DKD consists of 2 modules connected together [59]: the Deployment Mechanism Module (DMM), that hosts the 500-m tape tether and the Deployment Mechanism (DM), and the Electron Emitter Module (EEM), that hosts the Electron Emitter, an active device that provide the emission of electrons in the plasma environment in order for the current to be established through the tether. Each module is completely independent with their own power, communication, data handling and attitude control subsystems. The mission operations include two phases: a deployment phase, during which the two modules are separated in less than an orbit to reach the nominal configuration with the tether close to the local vertical (see Fig. 1), and the deorbiting phase during which the electrodynamic functionality is enabled for deorbiting.

3. University of Padova roadmap to validate EDT technologies

The contributions of the University of Padova (UniPD) to the E.T.PACK project are several and include both software development for EDT applications, hardware development and laboratory testing. Figure 2 shows the roadmap of the UniPD activities to validate the technologies on which the DKD prototype is based. In the next sections, the main steps of the roadmap are described in detail.

* related to the movement of positive charges, as it was believed in the 19th century.

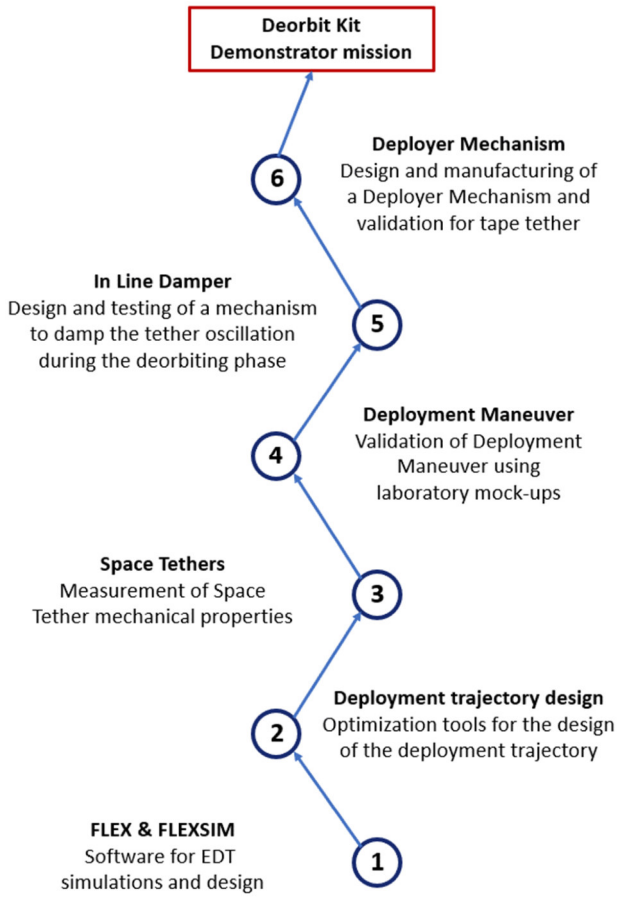

Figure 2: roadmap of the University of Padova's activities for EDTs.

4. Software tools for EDT

4.1 Deployment trajectory design tools

The deployment dynamics of a tethered system is highly nonlinear [60][61][62] and the Coriolis accelerations acting on the tip masses leads to a configuration of the tethered system with libration amplitudes that are typically in the range 40°-50° if uncontrolled [63]. Consequently, the first step in the design of a deployment trajectory is to compute tether length and velocity time profiles that bring the system from given initial conditions to a small libration amplitude at the end of the deployment maneuver. The equations of motion of a variable-length tether orbiting system are nonlinear with varying time coefficients. For this reason, we develop a software package based on optimization tools to solve a boundary value problem of the nonlinear dynamic system to find the trajectory in the system state space, i.e. tether length l, length rate $\dot{l}$, libration angle θ and libration rate $\dot{\theta}$, that the tether must track to attain the final desired state.

The reference profiles for the deployment maneuver were first obtained using the BOCOP© software [64], and then fine-tuned in the code *DEPLOY,* developed in MATLAB©, to smooth out the tether tension profile mainly at the end of deployment [65]. The equations of the deployment dynamics implemented in the software tool DEPLOY can be found in [65]. The three main steps followed to obtain the deployment reference profiles are shown in Figure 3, where the block "'Nonlinear boundary value problem" implements the differential equations describing the deployment dynamics for tethers and uses the BOCOP© software to find a reference trajectory for deployment that satisfies the following boundary conditions: initial conditions on l, $\dot{l}$, θ and $\dot{\theta}$, final conditions on l and $\dot{l}$, minimizing the final libration angle and libration rate θ_f and $\dot{\theta}_f$, respectively. Additional details can be found in [65].

During the design of the deployment trajectory both tether flexibility end effects of the environmental perturbations are neglected. Despite this, the simplified mathematical model used to compute the reference deployment trajectory can catch the key effects that actually drive the deployment dynamics and, as discussed and shown in [65], both tether flexibility end effects of the environmental perturbations can be neglected. Indeed, the tether is maintained taut during the deployment, so the tether bending and its effects on the deployment dynamics is rather limited. In addition, the

environmental forces during deployment are negligible, since: (a) the Lorentz force is null during deployment because the electron emitter (cathode) is not enabled until the following deployment phase; (b) the aerodynamic drag is negligible at an orbital altitude of 600 km; and (c) the effects of solar radiation pressure are negligible over the short deployment time, which is about 1 hour for the E.T.PACK DKD mission.

Figure 4 shows and example of reference profiles for the tether length and length rate as a function of time. Figure 5 shows an example of reference trajectory for the deployment of the DKD in the orbital plane. In addition, the UniPD team developed a MATLAB© tool to carry out a sensitivity analysis of the reference trajectory to key error sources: (a) errors in the release angle between the two modules at the start of deployment, and (b) errors in the deployer mechanism ability to follow a reference length rate profile for the deployment of the tape tether.

Preliminary experimental tests on the deployer control motor showed that it can track the reference length rate profile for the deployment of the tape with an error that can be modelled as the sum of two components: a bias component of 0.3 mm/s, which could be due to a dc offset, and a random component with a standard deviation of 1.4 mm/s, which is due to the resolution of the encoder installed on the motor and the feedback control law of the motor. This leads to a final error on the tape deployed length of 1.2 m, i.e., an error of 0.24% over 500 m of total length (Figure 6). A sensitivity analysis of both the error in the initial release angle and the errors of the deployer mechanism control showed that the reference trajectory is stable and that the post-deployment in-plane libration amplitude remains confined within 3 deg (Figure 7) off the local vertical.

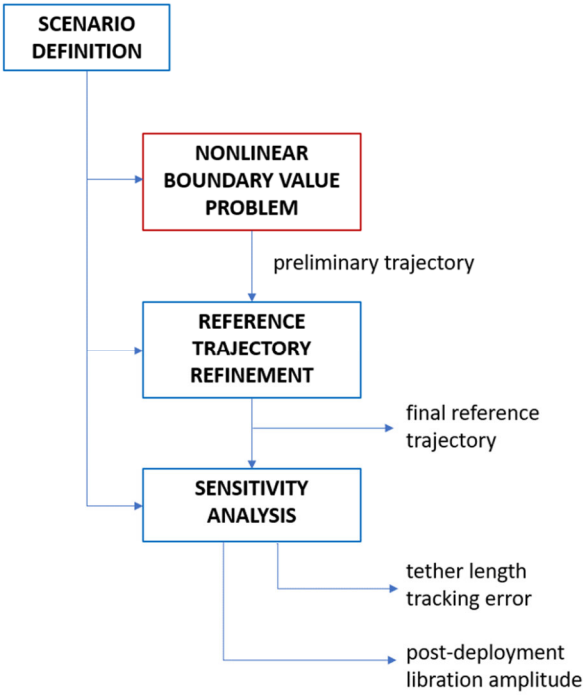

Figure 3: main steps for the design of the deployment reference trajectory.

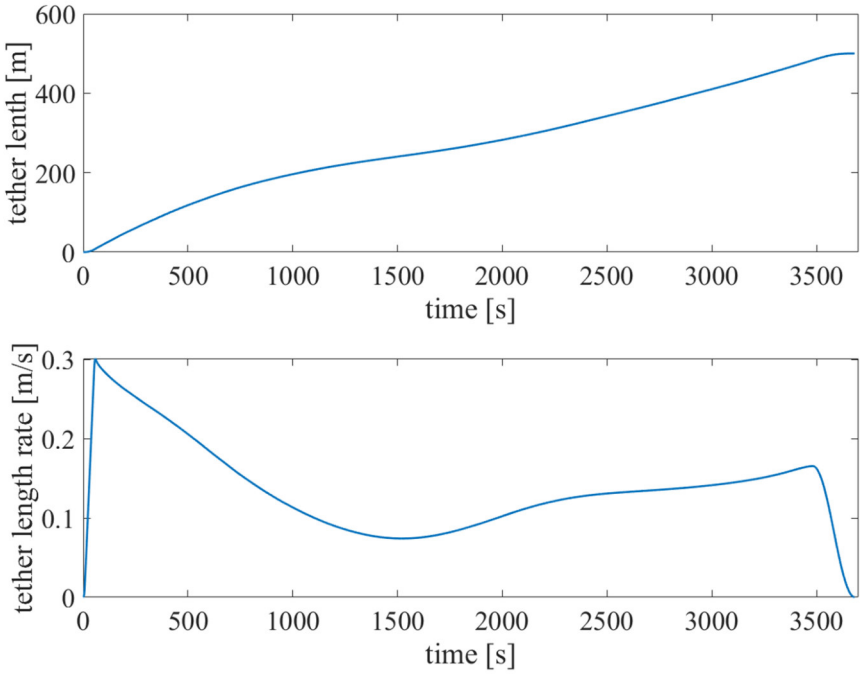

Figure 4: tether length (top panel) and length rate (bottom panel) reference profile.

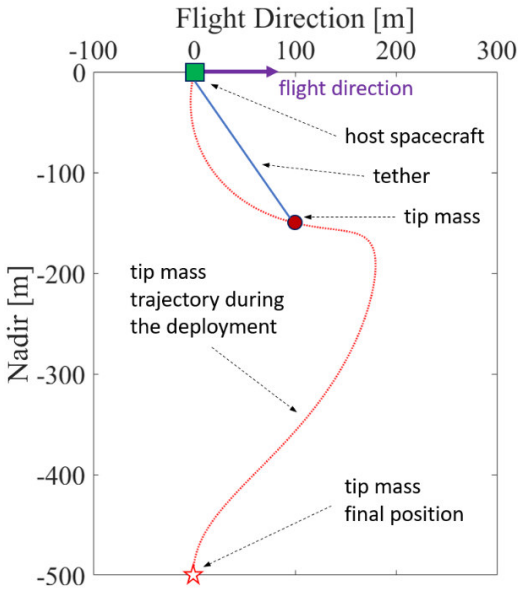

Figure 5: reference deployment trajectory in the orbital plane for the DKD demonstration mission as seen from the host spacecraft. The tip mass is the EEM of the DKD and the DMM is attached to the host spacecraft.

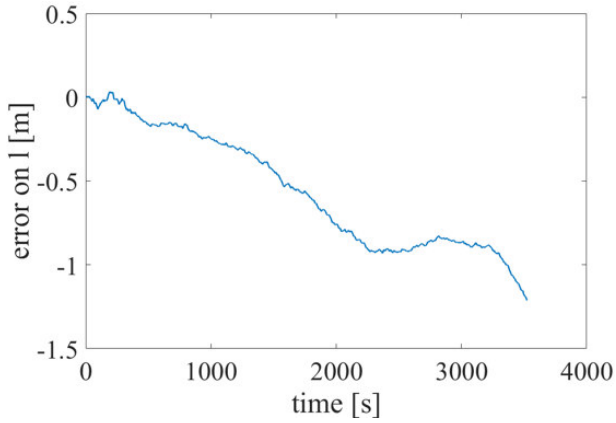

Figure 6: time profile of the deployment length error.

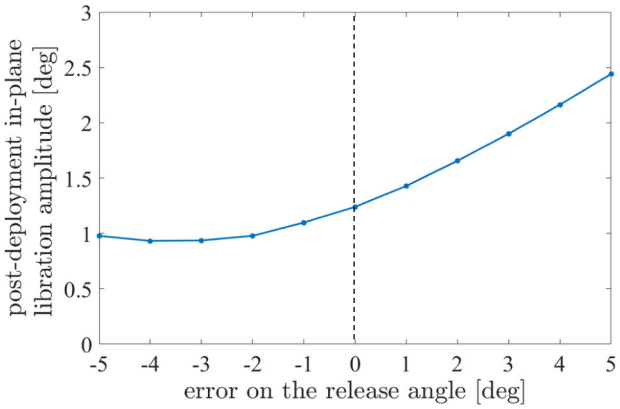

Figure 7: post-deployment in-plane libration amplitude vs. error in the release angle at the beginning of the deployment maneuver. This figure includes the effects due to errors of the deployer mechanism motor in following the reference length rate profile.

4.2 FLEXSIM and FLEX software

Two numerical software packages have been developed through the years for simulating the deorbiting performance of tethered satellite systems at Padova University: *FLEX* and *FLEXSIM*. The former has been under development since the BETs project [66], that was granted under the "FP7-SPACE program in the years 2010-2014. The latter has been developed entirely within the E.T.PACK project with the goal of obtaining faster results of the deorbiting performance of a system without taking into consideration the tether librational and flexible dynamics. Specifically, the fidelity of the simulation results is provided by FLEX, which considers both tether libration and flexibility. Since FLEXSIM has a much shorter computational time when compared to FLEX, FLEXSIM is used as a preliminary fast design tool for EDT systems, allowing to compare different system configurations, as for instance different tether lengths, in terms of deorbiting time. Once a good EDT system configuration for a given target satellite is identified, FLEX is employed to validate that configuration also considering the effects of tether flexibility and libration.

4.2.1 FLEX

FLEX is a FORTRAN simulator able to describe the dynamics and thermal behaviour of a tethered space system, including the dynamical effects of tether flexibility that are important during deorbiting. On the other hand, once the system is properly designed to provide stability and the aim of the study is the evaluation of the overall deorbiting time, the flexibility can be neglected in favour of a faster computation time.

Thanks to the incorporation of flexibility in the tether model, *FLEX* is able to provide important pieces of information on the dynamic stability of the system during the deorbiting phase. Consequently, *FLEX* is among a few simulators in the world that is able to drive the tether design (e.g., tether mass and electrical properties, tether geometry, tether optical properties and temperature) and able to confirm the long-term stability of the system configuration. An example of this type of study is shown in Figure 8 where different deorbiting times for tethered systems were evaluated after varying the damping coefficients of the in-line damper [67][68]. For all the simulations the limit height at which

deorbiting is ideally considered concluded is 250 km. However, some simulations don't reach this low altitude because the systems flip upside down at very low altitudes due to the atmospheric drag that creates a torque around the center of mass of the EDT system. Nevertheless, it is evident that, flipped or not, the systems can be treated as successfully deorbited in all cases, because below 400 km the atmospheric drag on the tethered system will complete deorbiting in a few days. Specifically, looking at the top left panel of Figure 8, it is evident that the deorbiting altitude curve is characterized by two main parts with different slopes. At the beginning of the deorbiting phase, from 600 km to about 400 km, the deorbiting rate is driven by the Lorenz force; on the contrary, when the barycenter position of the system is below 400 km, the curve experiences an evident change in slop, because the deorbiting rate is now driven by the atmospheric drag and the tethered system reenters in a few days.

Another example of the capabilities of *FLEX* is shown in Figure 10, where the changing tension profile of the tether at the passage form the illuminated side to the eclipse condition is captured and it shows that the transition needs to be treated accurately, even though it takes less than 30 seconds.

As it can be seen from Figure 11, the tether in *FLEX* is discretized into lumped masses connected by a series of massless springs and dampers [69] that represent the tether mechanical characteristics. Specifically, the dynamics of this discretized lumped masses model is governed by a set of ordinary differential equations that considers the resulting force $\boldsymbol{F}_i$ acting on each mass and with constraint conditions related to the continuity of the tether [70]. The resulting force $\boldsymbol{F}_i$ is the sum of the following contributions: gravitational force, aerodynamics force, Lorentz force, forces due to thermal elongation or restriction of the tether and elastic forces due to the interaction of each lumped mass with the neighboring lumped masses. In addition, FLEX computes the temperature of the tether by also implementing a thermal model that considers infrared end visible thermal fluxes due to Earth and Sun. As for the tether current evaluation, the high-bias Orbital Motion Limited law is used to evaluate the current collection by the bare segment [56].

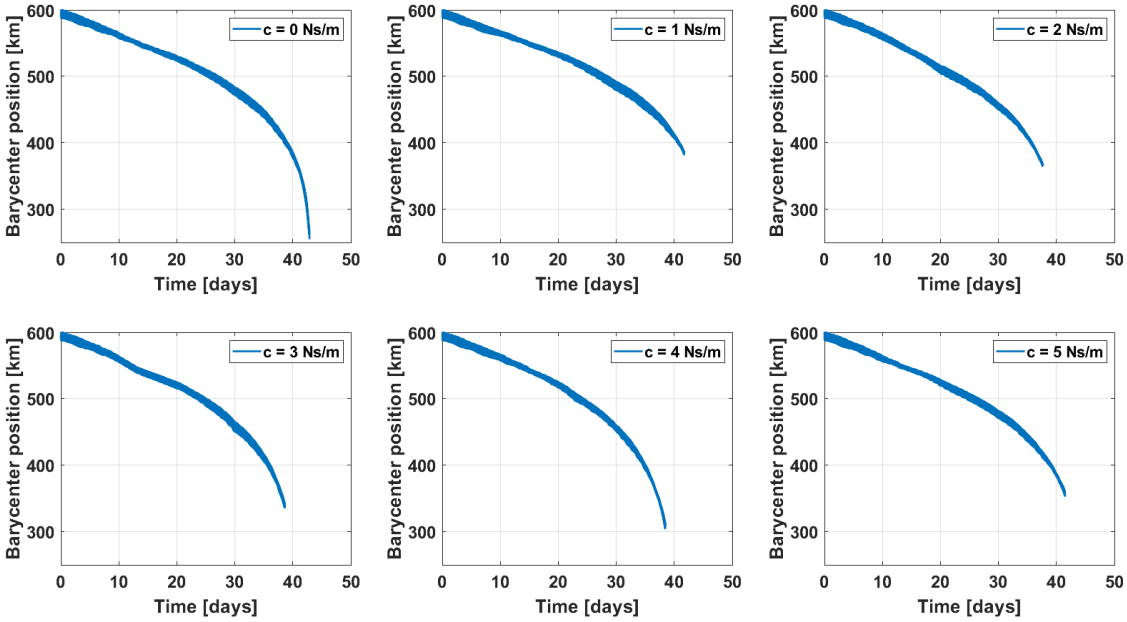

Figure 8: deorbiting time for electrodynamic tethered systems with different damping coefficients c of the tether in-line damper.

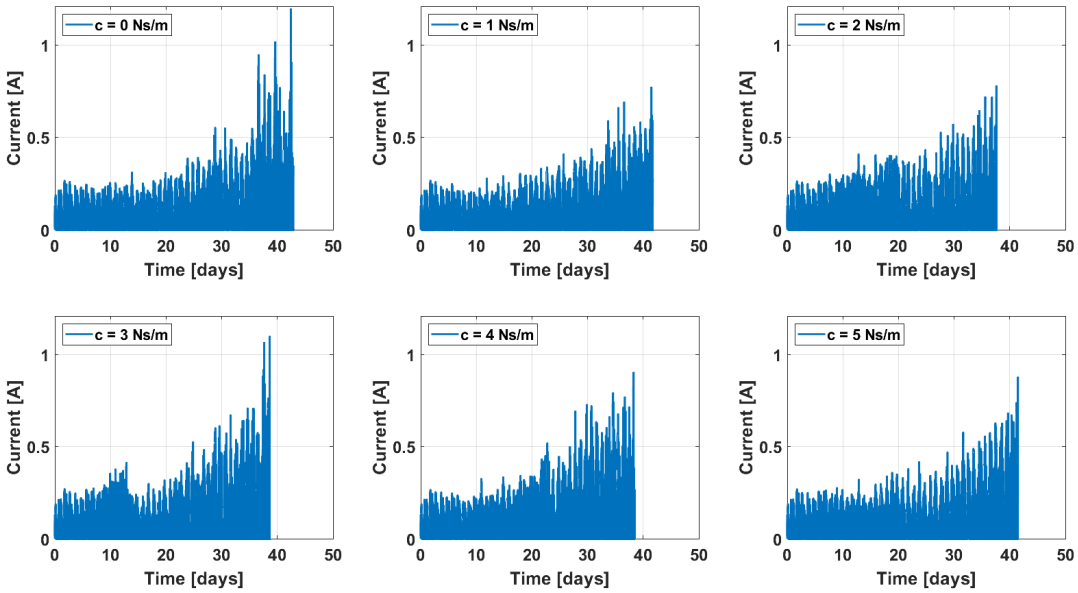

Figure 9: time profile of the mean electric current through the tape tether during the deorbiting for the six configurations of the tethered system with different damping coefficient c.

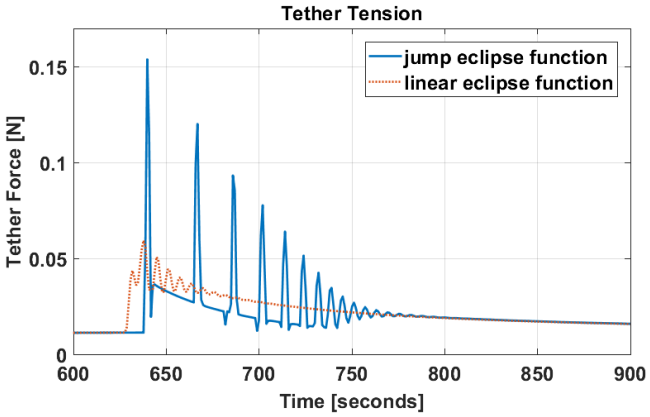

Figure 10: tension peaks due to the lit to eclipse transition. The difference is due to the different type of transitions, over a time less than 30 s.

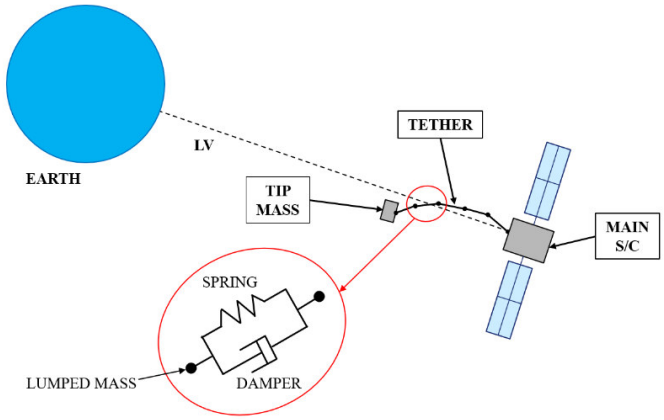

Figure 11: discretized lumped-mass model for the tether in *FLEX*.

The following environmental models, originally implemented in Fortran, are incorporated in the code:

1. International Reference Ionosphere IRI-95 [71];
2. International Geomagnetic Reference Field – IGRF [72];
3. NRLMSISE-00 Atmospheric Model [73].

As for the thermal model, thermal fluxes coming from the Earth and Sun are taken into consideration together with the IR emitted radiation for the computation of the tether temperature. *FLEX* has been built with an approach aiming at flexibility and modularity in order to evaluate satellite performance in a variety of scenarios. With this idea in mind, gravitational and magnetic field models with different complexity have been implemented and can be activated or deactivated based on the aim of the individual simulations. Specifically, gravitational models in *FLEX* can be simply a spherical model or a combination of this J_0-model with: (1) higher Earth's gravity harmonics up to the 4^{th} order, (2) third body gravity perturbations due to Sun, and (3) Moon. Similarly, the magnetic field model can be chosen among: (1) dipole magnetic field, (2) tilted dipole magnetic field, and (3) a full IGRF model.

Lastly, there is a feature in *FLEX* that triggers the limitation of the current flowing in the tether to limit excessive tether dynamics during the deorbiting phase.

The numerical integrator of this simulator is "RADAU5" [74], that employs an implicit Runge-Kutta method (Radau IIa) of order 5 (three stages) with step size control and continuous output. This code is typically employed for solving differential equations, such as those describing the flexible tether satellite system that involves phenomena at different time scales (i.e., orbital motion, tether librations, bending modes, and longitudinal oscillations).

4.2.2 FLEXSIM

FLEXSIM is a simulator able to describe the dynamics of a tethered space system, in which the dynamical effects of tether flexibility and librations are neglected. Figure 12 shows the configuration implemented in *FLEXSIM*: the tether is considered as a single unit, with equivalent properties computed as if the tether were perfectly aligned with the local vertical (LV). No in-plane or out-of-plane dynamics is allowed. This model does not distinguish between conductive and non-conductive portions of the tether, even though equivalent parameters are used consistently.

This code is therefore able to evaluate the deorbiting performance of the system in a much shorter computational time when compared to *FLEX* with the basic assumption that the tether was properly designed to provide stability. Depending on the orbit inclination, the results might slightly underestimate the deorbiting performance of the system evaluated by *FLEX* because the out-of-plane dynamics contributes to an increase of the motional electromotive force that drives on average a higher current flowing in the tether.

FLEXSIM has the additional feature to let the user choose between a stiff solver ("RADAU5", the same as *FLEX*) or a non-stiff solver ("DOPRI5" [75]). Further details can be found in [70].

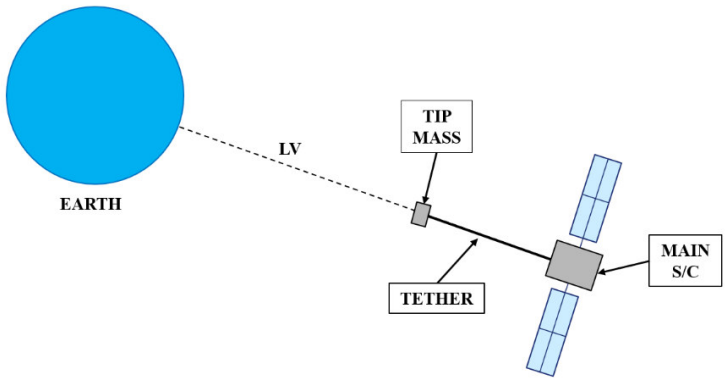

Figure 12: tethered satellite model in *FLEXSIM*: the tether dynamics is not modelled; the tether is always unstretched and aligned with the local vertical.

5. Experimental activities

To validate the main technologies involved in the E.T.PACK project, a series of experiments was performed at the University of Padova. The test activity was performed in the SPARTANS facility laboratory [76] [77], consisting of a 2-m x 3-m zero-friction testing table with a free floating module (Figure 13). The Module is composed of a translational module and a mock-up of a tether deployer and its motion is tracked by a set of IR cameras aimed at spherical IR markers placed on the module. The whole free-floating system has a mass of about 25 kg and three Degrees of Freedom (DoF), of which two translational DoF are related to its motion on the testing table and one rotational DoF associated with its rotation around the vertical axis. For the testing activities, the deployer mechanism release a tape/tether whose length is controlled by the onboard computer to follow a precomputed deployment profile. In addition, the other end of the tether is connected to a load cell constrained to the testing table structure and utilized to directly measure the tether tension during deployment.

The following subsections focuses on: (1) the determination of the mechanical properties of the tapes employed in the E.T.PACK projects, (2) the testing and validation of both deployment mechanism and maneuvers for the tether deployment mock-up, and (3) the development of an in-line damper to damp out tethers oscillations.

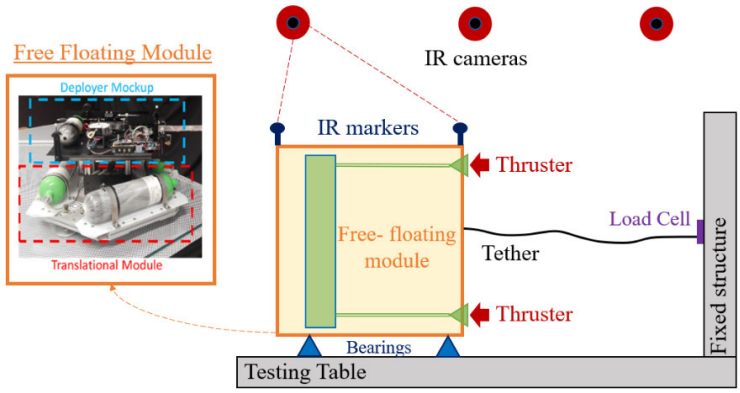

Figure 13: layout of the experimental setup with the free-floating module, the tether line, and the load cell.

5.1 Tape mechanical properties determination

The aim of this activity was the comparison of different tether materials to find valid solutions for future space tethered missions. Mission requirements, such as the survivability to hypervelocity impacts and the ability of a tether material to damp oscillations that arise during both tether deployment and deorbiting maneuvers due, in the latter case, to the continuous input of energy from the Lorentz forces, affect the tether material and its geometry. Round tethers have been employed in several space missions of the past. However, in the last few years it was demonstrated that tape tethers have much better survivability to small debris and micrometeoroids impacts.

In this work, four different tethers were investigated: a round-wire Nylon line, a Spectra braided thread, and two tape tethers respectively made of PEEK and Aluminium. The determination of their mechanical properties was carried out through a series of experiments. Specifically, tether stiffness and damping coefficients were evaluated by applying different tensile load profiles to the free-floating module of the SPARTANS facility and then measuring the tether-line dynamic response in terms of tension spike amplitude, oscillation decay, and estimation of the damping coefficient. In the experimental setup, the tether was connected to the free-floating module and to the fixed load cell, that measures the tether tension during experiment, placed between the tether and a fixed structure mounted on the testing table. Table 1 summarizes the results obtained, in term of stiffness and damping coefficient, for the four materials investigated. Further information on tapes stiffness and damping coefficients can be found in [78].

Table 1. Space tether mechanical properties determined experimentally.

Materials	Stiffness	Damping coefficient
Nylon	167.6 N/m	8.2 Ns/m
Spectra™	753.4 N/m	35.1 Ns/m
Al-1100	24734.3 N/m	48.2 Ns/m
PEEK	1810.9 N/m	0.37 Ns/m

5.2 Validation of early deployment maneuvers

Following the heritage and the experience collected in past projects on tether deployment systems [79][80], a deployer mock-up was designed for the SPARTANS facility to validate in the laboratory scaled deployment maneuvers based on the E.T.PACK reference profiles [65]. We must point out that the deployer mechanism that was tested employed a rotating reel from which the tape tether is extracted using a drive-pulleys system. Although this deployment mechanism is not the one finally chosen in the DKD of E.T.PACK, the drive-pulleys system is representative of the tether deployment dynamics, because the dynamics of the tether outward of the drive-pulleys system is decoupled from the internal dynamics of the rotating reel. A first configuration of the deployer mechanism is sketched in Figure 14. It consists of a Cold Gas Actuator (CGA) propulsive unit, employing two nozzles, a pressurized tank, the associated fluidic system, and a deployment and reel-in subsystem, composed by a rotating reel, a system of drive pulleys to control the tape deployment, and a motor coupled to the reel to keep the inner part of tether taught during deployment and retrieve it during reel-in operations. In the laboratory configuration, the whole module can act as tip mass during deployment, as well as to perform the reel-in operations by switching the motor function [81].

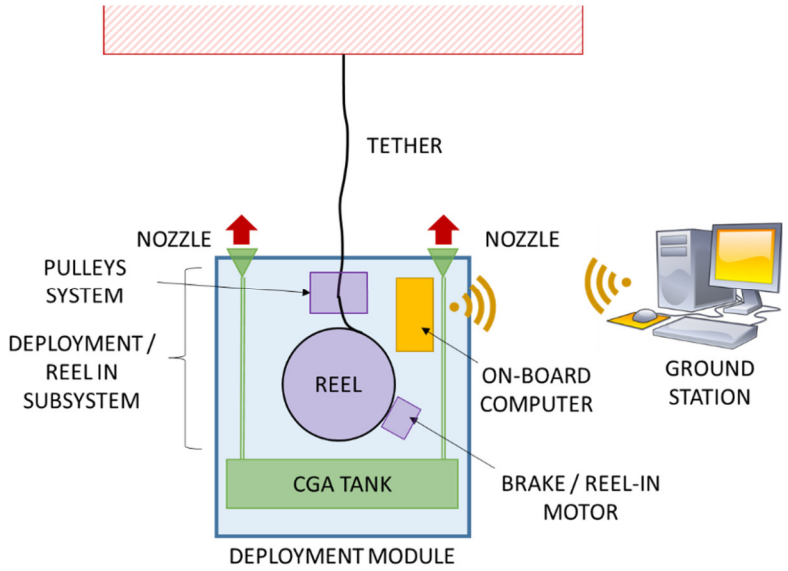

Figure 14: sketch of the lab deployment module [81].

The following activities were performed with the mock-up in the SPARTANS facility. First, a controlled deployment test demonstrated the system capability to reel-out the tape following a reference trajectory during the early separation phase As expected, the angular acceleration of the tape coil affected the attitude of the deployment module but did not influence the deployment profile. Similarly, a reel-in test (Figure 15) demonstrated the capability of the proposed system to retrieve the tape [81].

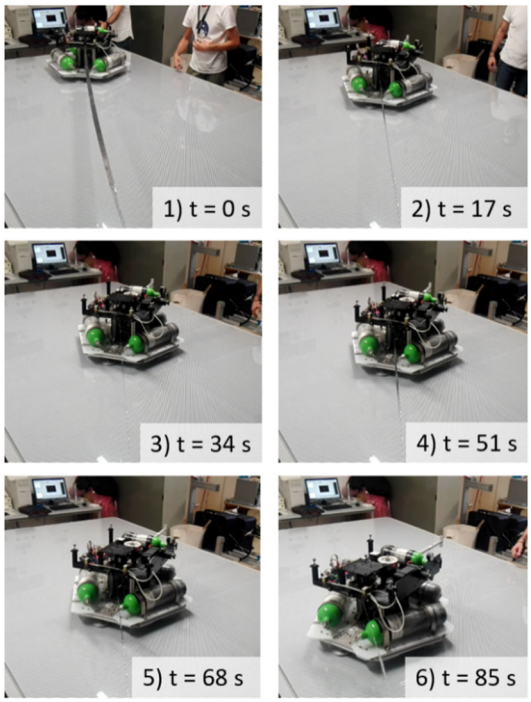

Figure 15: pictures from the tested reel-in procedure [81].

To overcome the issue of attitude deviations, dedicated attitude thrusters were actuated for controlling the module. The deployment procedures were replicated while keeping the module aligned with the tether deployment direction within a dead band of ±10 deg [82]. Figure 16 compares the reconstructed deployment procedures for the original uncontrolled scenario and the system with the attitude control operating. It can be noted that the system is capable of maintaining the alignment and performs the maneuver; further details on the system can be found in [82].

Lastly, the facility was employed to test a prototype of a passive in-line damper developed by the University of Padova for reducing the oscillations of the tape tether during the deployment maneuver [65]. Tests showed that the prototype can smooth out impulsive loads and damp transient events, allowing for smoother operations by dissipating oscillations.

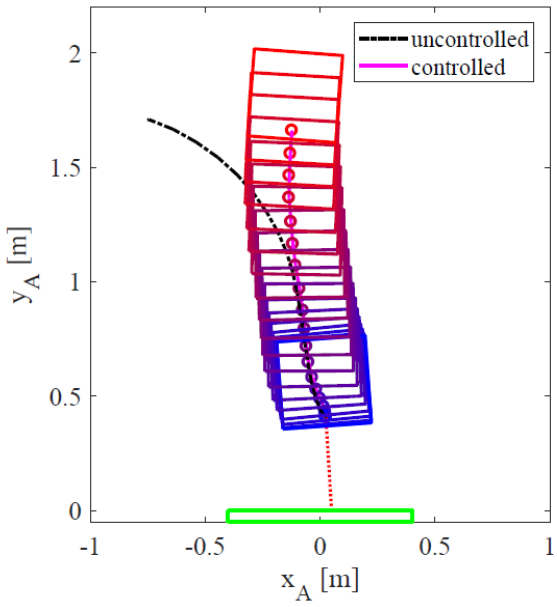

Figure 16: comparison of deployment procedures without and with the attitude control [82].

5.3 Development of an in-line damper

The dynamical stability of a tethered system can be strongly affected by the deployment strategies [83] and environmental disturbances during deorbit [84][85][86]. Consequently, it is necessary to implement energy dissipation strategies to reduce the amplitude of the tether oscillations to guarantee the stability of the system during both deployment and deorbiting phases. Among the possible solutions for passive dissipation, elastic damping materials are incorporated in series to the metallic tape; the E.T.PACK DKD is expected to include a section of 100 m of PEEK to reduce libration and oscillations. To further dampen the tether dynamics, it is planned to include an in-line damper (ILD), consisting in a small mechanism utilizing viscous-elastic devices. For the DKD, the University of Padova is proposing a compact ILD suited for CubeSat-sized tethered systems, to be placed between the tip mass and the tether and designed to absorb and smooth out tensile loads transmitted by the tether [67]. The ILD is designed to fit on board the DKD. The device has a volume of 50x35x10 mm^3; in addition to its damping capability, it provides an electrical connection between the tether and the module at the tip. A drawing and a picture of the ILD can be seen in Figure 17. A patent application was submitted in 2021 for this device.

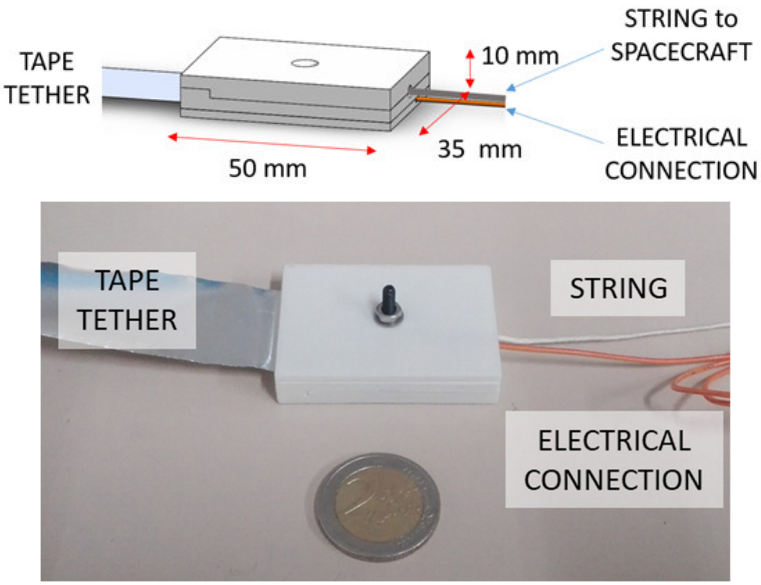

Figure 17: external case of the ILD with the main connection elements

The ILD was subjected to a number of tests [67] with the SPARTANS facility to verify its mechanical characteristics in terms of stiffness and damping coefficient. During the test campaign, the ILD was fixed to the SPARTANS module (see Figure 13) and a string of known length connected the ILD to the load cell constrained to the fixed structure. In all experiments the string was slack at the start of experiment, to allow an initial acceleration of the free-floating module pushed by the cold gas unit. A first test investigated the response to a single impulse by switching the thrusters on for a short time (about 1 second) and switching them off before the string could be stretched. A second set of experiments was performed to assess the response of the system to a step load given by leaving the thrusters switched on; a third test investigated the response to pulsed loads given by continuously switching on and off the thrusters. All cases were compared to experiments without the ILD, indicating a consistent reduction in peak forces: from about 80% for single impulse tests to about 30% for pulsed loads experiments. A selection of the tests results in terms of load measured by the load cell can be seen in Figure 18. From the analysis of the experiments data, the resulting values of the ILD stiffness and damping coefficient were respectively 160 N/m and 43.0 Nm/s.

Last, the tether deployment manoeuvre tested in section 5.2 was replicated placing the ILD close to the fixed load cell. Results [67] showed a consistent reduction in transient loads peaks, confirming the capability of the ILD to dampen transient loads.

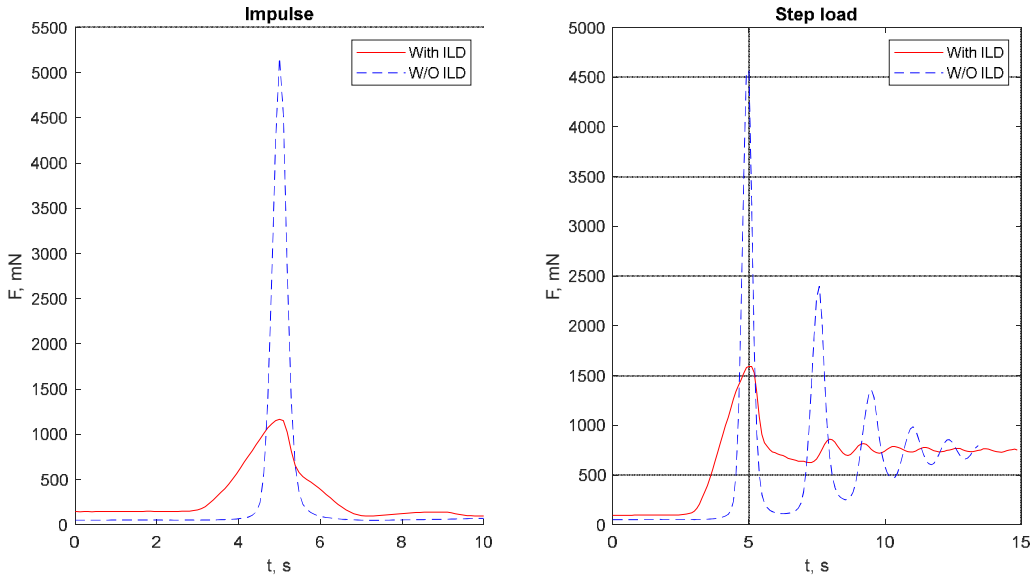

Figure 18: load cell measurement: comparison of tests without (dashed blue line) and with ILD (solid red line) for the response to a single impulse (left) and to a step load (right).

6. Conclusions

This article explains the roadmap of the activities conducted at the University of Padova to validate the technologies on which the Deorbit Kit Demonstrator (DKD) prototype of the E.T.PACK project is based. The contributions include software development for Electrodynamic Tether (EDT) applications, hardware development and laboratory testing that validate experimentally the technologies required in the phases of deployment and deorbiting of an EDT system.

Concerning software development, two kind of software tools were developed. The first one, DEPLOY, is utilized to compute the reference trajectories for the deployment phase of the DKD mission, and also to run a sensitivity analysis to errors on both the initial release angle and the capability of the deployer mechanism to track the reference profile. The second set of software tools includes FLEX and FLEXSIM simulators that contributed to defining the proper design of an EDT system, compute the deorbiting performance, and provide essential information on the dynamic stability of the system during the deorbiting phase. Specifically, FLEX is a high-fidelity simulator for EDT systems that implements: a) the orbital dynamics of the tether, b) the libration dynamics and the flexibility of the tether, c) the thermal fluxes on the tether due to infrared and visible radiations in orbit, allowing the computation of the tether temperature, d) the exchange of electrons between the tether and the ionosphere, permitting the evaluation of the electric current through the tether during the deorbiting phase, and e) the interaction with the Earth magnetic field for the generation of the Lorentz force.

Concerning the experimental activities performed to validate EDT technologies, the E.T.PACK team of the University of Padova carried out laboratory tests in order to first estimate the mechanical properties of the tapes employed in the E.T.PACK prototype in terms of elastic modulus and damping coefficients. A reliable estimation of the mechanical properties of the tether materials are very important, because they contribute to influence the stability of the tether during the deployment and the deorbiting phases. In addition, a laboratory mock-up was developed and employed to validate the design of a drive-pulleys system used during the early and critical phase of deployment. This technology was tested using a free-floating module and the low-friction facility called SPARTANS of the same institution that reproduces the microgravity environment typical of satellites in orbit. Moreover, the same team developed a compact passive-damping mechanism used to increase the stability of the tethered system during both deployment and deorbiting phases. The damping capability of this compact mechanism was tested using the low-friction facility and the experimental tests showed that the in-line dumper can smooth out impulsive loads and damp transient events, reducing consistently the peak forces, from about 80% for single impulse tests to about 30% for pulsed loads experiments.

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