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Development Roadmap of a Deorbit Kit Based on Electrodynamic Tether

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Abstract

Low Earth Orbit (LEO) is an environment rich of natural resources. Earth magnetic field is used to control spacecraft attitude, Earth gravity harmonics are used to control the satellite's orbit evolution and solar radiation is used to generate power. Nevertheless, today's spacecraft are not designed to use another very valuable natural LEO resource: the ionospheric plasma. Among the different devices that could take advantage of it, ElectroDynamic Tether (EDT) is the most promising one due to its passive and propellant-less character. EDT consists of a long metallic tape connected with a spacecraft. It naturally captures electrons from the plasma and an active electron emitter, or a coating with a low work-function material, emits the electrons back to the plasma to achieve a steady electrical current. The action of the ambient magnetic field on the tether current gives a Lorentz force without using propellant. The EDT physics has been already demonstrated in orbit in the 1990s, but it is not until today that the technology has found a primary application in the satellite de-orbiting. EDT technology can be more efficient than conventional chemical and electrical propulsion, resulting in the best choice for passive de-orbit systems. The promising character of this green de-orbiting system has been recently acknowledged by the European Commission that granted the FET-OPEN project entitled Electrodynamic Tether technology for PAssive Consumable-less deorbit Kit (E.T.PACK). Funded with 3M€ and started in March 2019, E.T.PACK will develop a DK based on EDT technology with Technology Readiness Level equal to 4 and aligned with the needs of a future in orbit demonstration. The DK will be a fully autonomous system designed to de-orbit satellite from 200 to 1000kg in orbits up to 1200km. DK will be bolted on customer satellite before launch. Upon activation from ground, the DK will remove spacecraft residual angular velocity, acquire a stable attitude and deploy a maximum of 3km long tape. The DK mass is expected to be less than 5% of the customer satellite mass and de-orbit a 700kg satellite from 800km altitude polar orbit in less than 1.5 years. This work presents the design of the De-orbit Kit Demonstrator (DKD), simulations of the system performances and the development roadmap. Specific goals of the DKD are to test the deployment mechanism in orbit, to evaluate the de-orbit performances and assess the maneuverability of the tether for collision avoidance.

Keywords: Deorbit Kit, ElectroDynamic, Tether, Propulsionless, Space Debris, Orbital Servicing

Nomenclature

a	semi-major axis of the orbit
B	Earth magnetic field
E_m	motional electric field
F_L	Lorentz Force
I	tether current
k_m, k_p, k_d	controller gains
L	tether length
M_s	mass of the spacecraft including the tether
m	torquerod's magnetic moment
s	tether arclength
Tc	control torque
u_t	unit vector along tether direction
$\mathbf{v}$	tether orbital velocity
$\mathbf{v}_{\mathbf{rel}}$	tether velocity relative to the plasma
w	current angular velocity
w_t	target angular velocity
θ	current Euler angle
θ_t	target Euler angle.
μ	Earth gravitational constant

Acronyms/Abbreviations

Agenzia Spaziale Italiana or Italian Space Agency (ASI)
Carbon NanoTubes (CNT)
Deorbit Kit (DK)
Deorbit Kit Demonstrator (DKD)
Deployment Mechanism Module (DMM)
ElectroDynamic Tether (EDT)
Electrodynamic Tether technology for PAssive Consumable-less deorbit Kit (E.T.PACK)
Electron Emitter (EE)
Electron Emitter Module (EEM).
Flight Model (FM).
Future Enhancing Technology (FET)
Global Navigation Satellite System (GNSS)
Hold Down and Release Mechanism (HDRM)
Hollow Cathode (HC)
Hollow Cathodes (HC)
In Orbit Demonstration (IOD)
International Space Station (ISS)
Low Earth Orbit (LEO)
Low Work-function Tether (LWT)
Low Work-Function Tether (LWT)
National Resources Laboratory (NRL)
Plasma Motor Generator (PMG)
PolyEther Ether Ketone (PEEK)
Propulsive Small Expendable Deployer System (ProSEDS)
Qualification Model (QM)
Technology Readiness Level (TRL)
Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE)
Tethered Satellite System (TSS)
Thermionic Emitters (TE)
University Carlos III of Madrid (UC3M)
University of Padova (UNIPD)

1. Introduction

In the last years, the extensive use of Low Earth Orbit (LEO) has brought back the attention on the importance of finding a solution for the space debris problem. Multiple studies have addressed the catastrophic effect of excessive space debris population density and in particular the uncontrolled cascade of collisions known as Kessler syndrome [1].

The space exploitation approach is moving from few large and reliable satellites with long life, towards mass production of small, expendable spacecraft with reduced lifetime. For instance, Starlink already launched 653 satellites of the foreseen 12000 and filed a request for 42000 satellites [2]. Starlink satellites sky pollution is already a mayor concern for astronomers [3] and is by far the mayor constellation player. OneWeb launched 74 of the 650 satellites and Amazon is planning a constellation of 3226 satellites called Project Kuiper. Other minor constellations in development include Viasat, Telesat and Galaxy Space with 288, 292 and 144 satellites respectively. To put these numbers in context, the Orbcomm LEO constellation has currently 36 operational satellites of the 62 launched from 1991 to 2015. Two Orbcomm satellites failed in orbit, from which it is calculated an unreliability of 3.2%.

LEO constellation will adopt orbits from 330 to 1400km altitude with medium and high inclinations for providing their services. Constellation satellites will use electric propulsion to deorbit after 5 years of operations [4] [5]. For satellites around 230kg in 1200km orbit, it is calculated that a full deorbit below the International Space Station (ISS) will suppose a cost of more than 7kg and 3 months of operations. A legal international framework for protecting the space environment does not exist and up to 10% of unreliability for satellite disposal is acceptable by the current regulation [6]. Assuming 3.2% unreliability value, 382 satellites of the 11926 Starlink constellation will not be able to perform deorbit manoeuvre and will increase the space debris density in crowded orbits. Table. 1 reports the orbital parameters of the foreseen Starlink constellation [7] and the assumed failures and the natural deorbit time calculated by the authors.

Table. 1. 1Starlink Natural deorbit Time

Alt. (km)	Incl. (deg)	Foreseen Satellites	Launch	Estim. Failures	Deorbit (years)
336	42.0	2493	0	80	0.20
341	48.0	2478	0	79	0.23
346	53.0	2547	0	82	0.27
540	53.2	1584	0	51	6.6
550	53.0	1584	653	51	7.5
560	97.6	520	0	17	9.0
570	70.0	720	0	23	10.0

It is clear the most effective methods to avoid the population growth are actively remove debris from densely populated orbits or passivating the spacecraft to prevent accidental post-mission explosion [8], but active debris removal is expensive and difficult to implement without affecting the competitiveness of the space sector. A solution to this problem could be found with the development of an affordable deorbit technology that would boost the future in orbit servicing market.

ElectroDynamic Tethers (EDT) is one of the most promising technologies due to its passive and propellant-less character. An EDT is a long conductor carrying a steady electrical current and it works thanks to the Lorentz drag exerted by the geomagnetic field on the tether current. This process is a much more effective mechanism in the LEO orbit of interest for the space debris problem than the aerodynamic drag used by drag augmentation devices [9]. In addition, the tether current can be turned on and off to adjust their orbit and prevent collisions.

In 2018, the European Commission awarded a H2020 FET-Open project with title “Electrodynamic Tether

Technology for Passive Consumable-less Deorbit Kit" (E.T.PACK) and reference number 828902, which is aimed at the development of a Deorbit Kit (DK) based on electrodynamic tether technology [10],[11]. This work is part of E.T.PACK activities and presents the design of the De-orbit Kit Demonstrator (DKD), aimed at demonstrating in orbit the key technologies of the future commercial deorbit kit.

The work is organized as follows. Section 2 gives a short overview of the historical evolution of electrodynamic tethers and their operation principles. Section 3 summarizes the main DKD requirements and goals. Section 4 presents the design of the main components of the demonstration, being the Deployment Mechanism Module (DMM) and the Electron Emitter Module (EEM). Section 5 contains the simulation results with the performance of the system. Section 6 contains the roadmap of the consortium and 7 the conclusions.

2. Historical evolution of electrodynamic tethers

The design of Electrodynamic Tether system started in the 80s' and the first demonstrations in 90s'. Early EDT systems were bulky with several km long wires. The first generation of tethers were **insulated.** These insulated tethers used a large anodic collector at one end and an active Plasma Contactor at the other end (see Fig. 1).

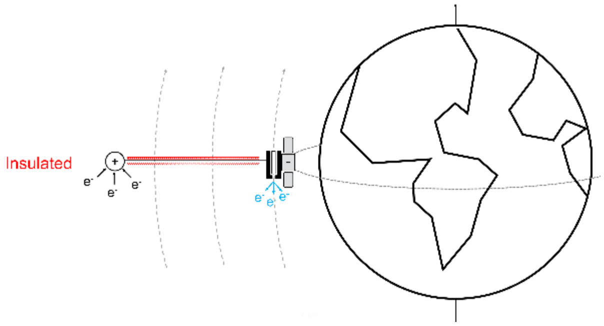

Fig. 1. Insulated Tether

Two NASA-ASI Tethered Satellite System (TSS) mission flown in 1992 (TSS-1) and 1996 (TSS-1R) carried by the Space Shuttle (STS46 and STS75 missions). In TSS missions, the electrons were captured passively by a large conductive sphere, circulated through an insulated wire and were emitted back to the plasma with an electron emitter. TSS-1R deployed a 20 km long tether and measured voltage of more than 1000V and currents of about 0.3A [12].

The NASA Plasma Motor Generator (PMG) mission in 1993 used a 500m insulated tether [13]. PMG mission flown on a Delta II second stage. PMG recorded voltages of up to 60V and currents of 0.15A. PMG also tested the use of its tether as thruster by successfully reversing the current direction using a battery and pushing 0.2A of current with -80V voltage. Active plasma contactors were placed at each end of the tether to allow both modes of operation.

The problem of the first generation of tethers were the limited current collection capability. This was solved by the **bare** electrodynamic tether. A bare tethers collect the electrons as giant Langmuir probes, thus eliminating the need for large anodic collectors. Electrons are emitted by an active device at one tether end (see Fig. 2).

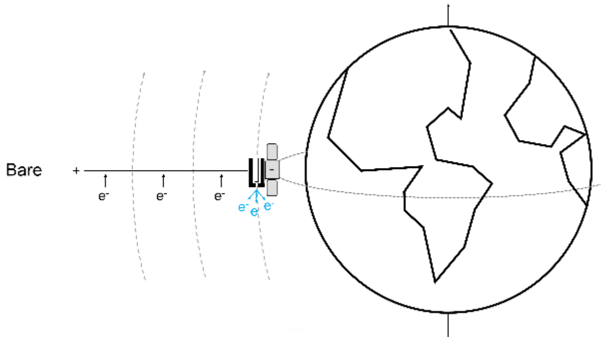

Fig. 2. Bare Tether

NASA's Propulsive Small Expendable Deployer System (ProSEDS) mission was prepared for a bare tether demonstration flight in 2003 onboard a Delta II upper stage. The mission would deploy a 5km bare tether to collect 2A. ProSEDS was cancelled after Shuttle Columbia accident one month before its launch. Afterwards, most of the tether missions have been low cost and based on cubesat technologies.

Recently, the NRL launched a 3U cubesat with the Tether Electrodynamics Propulsion CubeSat Experiment (TEPCE). In November 2019 TEPCE successfully deployed 1km of round conductive tether and 5 meters of tape tether. TEPCE deorbited from 300 x 860km at 28° inclination orbit in about 3 months [14].

Bare tethers still need active electron emitters in order to reach a steady current and they require either expellant (hollow cathode emitters) or power supply (thermionic emitters). Hollow Cathodes (HC) works creating an ionized gas bridge between the emitter and the surrounding plasma while Thermionic Emitters (TE) expels electron thanks to a large potential difference, in the order of thousands of volts. Therefore, electron emitters raise the complexity of the system.

The third generation of electrodynamic tethers consists of systems without electron emitters. The tether is coated with a low-work function material emitting electrons through thermionic emission [15] and photoelectric effects [16]. In a Low Work-function Tether (LWT), a tether segment captures electrons as a conventional bare tether and the complementary segment emit them back to the plasma (see Fig. 3).

The operation of a LWT is therefore fully autonomous and passive. Several low work function materials have been identified as suitable. The most promising coating material is the electride C12A7:e- [17]. It exhibits high electronic conductivity at room temperature, it is chemically inert and its work function is extremely low.

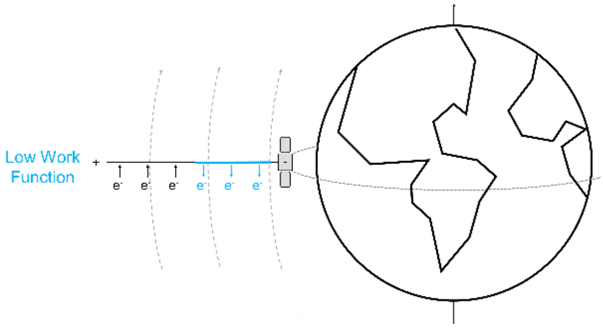

Fig. 3. Low Work Function Tether

Three active electron emitter technology are under development in E.T.PACK for their potential application on DK: heaterless HC, TE and Carbon NanoTubes (CNT). Additionally, activities on manufacturing and testing a coating based on the C12A7:e^- electride are on progress. Therefore, the project is developing in parallel the technologies to implement two types of DK: a bare tether with active electron emitter and a LWT.

Independently of the type of contact with the ambient plasma, all EDTs are based on the same physical principle. A motional electric field

$$\boldsymbol{E}_m = (\boldsymbol{v_{rel}} \times \boldsymbol{B}). \tag{1}$$

appears at the faraway plasma for an observed attached to a S/C moving at velocity $\boldsymbol{v}_{rel}$ with respect to the ambient plasma and in the presence of the Earth magnetic field $\boldsymbol{B}$. If the tether of length $\boldsymbol{L}$ has a good electrical contact with the ionospheric plasma, an electric current $\boldsymbol{I} = I(s)\boldsymbol{u_t}$ is driven in the tether by $\mathbf{E}_m$ with s and $\boldsymbol{u_t}$ the tether arclength and a unit vector along the straight tether. The Lorentz force on the tether current

$$\boldsymbol{F}_L = \int_0^L \boldsymbol{I}(\boldsymbol{s}) \times \boldsymbol{B} ds \tag{2}$$

can be used to change the orbit of the spacecraft. For instance, assuming a quasi-circular orbit, Gauss' first planetary equation shows that the semi-major axis of the orbit (a) decreases according to [12]

$$\frac{da}{dt} = \frac{2a^2}{M_s\mu}\boldsymbol{F}_L \cdot \boldsymbol{v} \approx -\frac{2a^2}{M_s\mu}E_t \int_0^L I(s)ds \tag{3}$$

with $\boldsymbol{v} \approx \boldsymbol{v_{rel}}$ the orbital velocity, M_s the mass of the spacecraft and $E_t \equiv \boldsymbol{u_t} \cdot (\boldsymbol{v} \times \boldsymbol{B}) > 0$. Typical values in mid-inclined orbits in LEO are $v_{rel} \sim 7.5 km/s$, $B \sim 10^{-5} T$ and $E_m \sim 100 V/km$. For a 400 m-long tether carrying an average current of 0.25A, the electromotive and Lorentz forces are around 40V and $5mN$.

3. Deorbit Kit demonstration requirements and goals

Initial DK requirements have been drafted based on inputs from the European Space Agency and the European spacecraft Prime contractors. Nevertheless, lack of EDT high Technology Readiness Level (TRL) has put the development team in a difficult situation in terms of gathering use case requirements from any potential customers. In order to overcome this situation, and at the same time increase the TRL, it has been decided to orient the design of the DK towards a stand-alone in orbit DK Demonstration (DKD) Mission. The DKD consist on a 12U cubesat with a maximum mass of 24kg including the DK technologies to validate in space. The DKD will be launched into a 600 km circular orbit at medium inclination where it will deploy 500m of tether to demonstrate that it can achieve the re-entry in less than 100 days. The natural deorbit time from this orbit is more than 15 years. The DKD will be scalable to satellite up to 1000kg, it will be fully autonomous, demisable and have a thrust capability of more than 5mN.

Table. 2 summarizes the main DKD requirements (find more details in [18]).

Table. 2. DKD Requirements.

Name	Requirement
DK maximum mass	IOD DK mass shall be less than 24kg. *Rationale. 12U CubeSat Standard..*
De-orbit time	IOD DK shall be designed to de-orbit from a 600 km circular orbit with 51.5º±2º inclination in less than 100 days. *Rationale. Estimated natural deorbit time is more than 15 years.*
Scalability	IOD DK design shall be scalable to de-orbit satellite of mass from 200kg up to 1000 kg. *Rationale. Heavier satellites usually require active de-orbit. DK mass will be <5% of the spacecraft mass*
Autonomy	IOD DK shall be designed to be fully autonomous. *Rationale. The kit shall allow de-orbiting also in case of host spacecraft failure.*
Thrust level	IOD DK shall be able to generate a minimum thrust of at least 5mN at 350 km altitude. *Rationale. A minimum thrust is required to demonstrate collision avoidance capability.*
Fully demisable	The IOD DK shall totally demise when exposed to the thermal flux from an altitude of 78 km. *Note. It is defined totally demised an object when any surviving pieces impact ground with an energy lower than 15 J.*
System reliability	DK reliability shall be higher than 99.9%. *Rationale. Minimum reliability acceptable by SENER.*

The selection of a 12U standard cubesat as platform allowed the consortium to fix realistic requirements for the in-orbit demonstration mission. The main goal of the mission is to increase the TRL of the deorbit kit and in particular:

- Demonstrate the system efficiency in terms of de-orbit time.
- Qualify in orbit the deployment mechanism.
- Demonstrate the stability of the tether system during the deorbit.
- Acquire real flight data to validate and refine current EDTs models and simulators.

4. Deorbit Kit Design

The main drivers for the DK design are to keep it simple and reliable. Simple designs require a single stream approach since redundancy implies a level of complexity and costs not affordable. To ensure reliability the main philosophy is to use as much as possible qualified components and apply a complete qualification process at system level.

The DKD is designed to fit a standard 12U cubesat envelope (Fig. 4). Rails are present in each corner of the structure to interface with standard canisterized satellite dispensers [19] [20] [21] [22]. Tabs can also be implemented if required by the launcher to preload the payload inside the canister. DKD baseline launcher is Vega, nevertheless adopting a standard interface guarantees compatibility with different launchers.

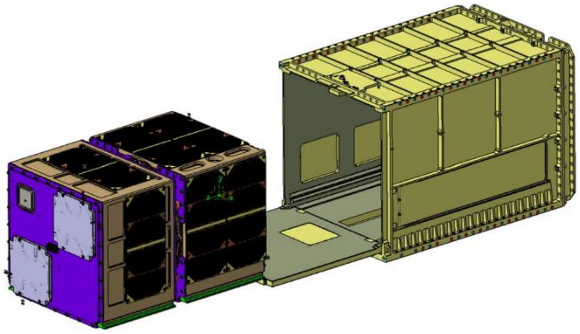

Fig. 4 DKD external mechanical interface

The DKD is composed by 2 modules connected together: the Deployment Mechanism Module and the Electron Emitter Module (Fig. 5). Each module is completely independent and they have their own power, communication, data handling and attitude control subsystems.

The DMM contains 500m of tether packed in 3 coils to optimise the volume occupation. The tether is mechanically connected at both ends with the two modules. The union between the DMM and the EEM during launch and early orbital operations is guaranteed by a means of a commercial Hold Down and Release Mechanism (HDRM). Upon activation, the DMM separates from the EEM and deploys the tether. The EEM contains the Electron Emitter (EE) and is commanded from ground to start the deorbiting operations.

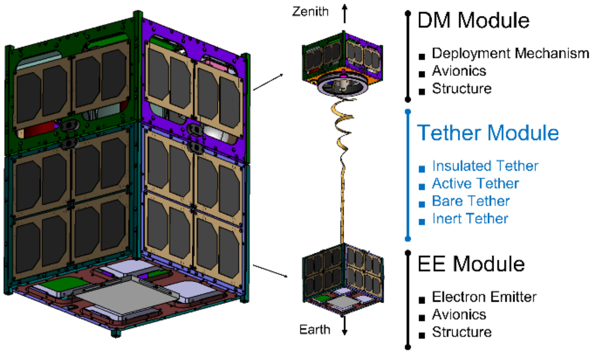

Fig. 5 Overview of the DKD

4.1 Deployment Mechanism Module

The DKD mission is organized in 5 operation modes (see Fig. 6). About 30 minutes after the separation from the launcher, DMM exits HIBERNATION mode to enter STABILIZATION mode.

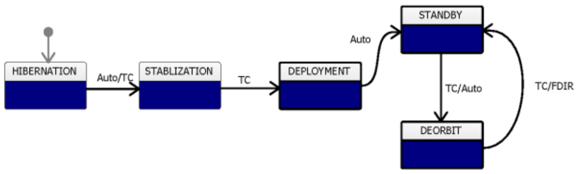

Fig. 6 DKD Operation Modes

In STABILIZATION mode DMM acquires inertial attitude and orbital position knowledge by means of a suite of sensor including 2 fine sun sensors, a gyroscope, a magnetometer and a GNSS receiver. Then it commands the 3 torque rods to remove the angular velocity below 1°/s. This is performed overall several orbits in a maximum time of 24 hours. Once removed the initial angular velocity, DMM acquires and maintains nadir pointing attitude. In this stable attitude, DMM waits for ground contact to carry out the in-orbit commissioning in preparation for the deployment. One of the tasks of the in-orbit commissioning is to acquire the attitude pointing with the accuracy required for the deployment.

The stabilization mode requires a navigation function capable of acquiring the inertial position and attitude with no a-priori information and command the magnetic actuators in function of the desired actuation torque and the local Earth's magnetic field. An Extended Kalman Filter is used for the navigation function. Control torque $\boldsymbol{T_c}$ on each axis is generated from the torque rod's magnetic moment $\boldsymbol{m}$ interacting with the Earth's magnetic field $\boldsymbol{B}$

$$\boldsymbol{T_c} = \boldsymbol{m} \times \boldsymbol{B} \tag{4}$$

and $\boldsymbol{m}$ is set according to

$$\boldsymbol{m} = \boldsymbol{k_m}(\dot{\boldsymbol{B}} + \boldsymbol{w_t} \times \boldsymbol{B}) \tag{5}$$

where $\boldsymbol{k_m}$ is a vector with the controller gain, and $\boldsymbol{w_t}$ the target angular velocity equal to the orbital angular velocity on one axis and zero on the others.

The deployment of the tether is one of the most critical phases of the DKD mission. Upon reception of a telecommand from ground, DEPLOYMENT mode is entered and a sequence of operations is triggered onboard (Table. 3). Deployment is started during ground visibility to receive confirmation of the execution of the separation command sequence.

Table. 3. Deployment Sequence

Time [sec]	Events/Actions
0.0	Event. Start visibility from ground.
120.0	Action. DMM stops controlling attitude using magnetic actuators.
130.0	Action. EEM activates the cold gas system for extraction and attitude control.
132.0	Action. Activates HRDM and release the two parts.
136.0	Action. DMM activates the motor pulleys and start tether extraction while controlling its attitude.
166.0	Action. EEM stops extraction and maintains only the attitude control.
600.0	Event. End of visibility from ground.
3760.0	Action. DMM Stop motors at tether complete extraction.
3820.0	Action. DMM and EEM go to STANDBY mode

The DMM is in charge of scheduling all the deployment mode actions. It first stops the attitude control using the torque rods and then it commands the EEM to turn on the cold gas system. Two seconds later, the DMM triggers the separation of the two modules and 4 seconds later, it starts the extraction of the tape from the coil using motorized pulleys. The full deployment of the 500m of tape tether last about one hour. During the deployment, the DMM and EEM attitude is controlled using cold gas. The EEM uses a 0.2N cold gas system to aid the DMM motorised system in the extraction of the tape by maintaining a proper tension on the tether.

The motorized pulleys are required to overcome the internal friction of the deployer. The motorised system is also used to gently stop the tether deployment maintaining limited the tether libration. The cold gas system is used only during the first seconds. After that, the gravity gradient pull maintains the deployment stable. The DK deployment design is the result of an optimization process involving initial separation direction and velocity [23]. A dedicated control function was developed and verified with simulations for this purpose. The control torques $\boldsymbol{T_c}$ are given on each axis by the cold gas system according to

$$\boldsymbol{T_c} = \boldsymbol{k_p}\boldsymbol{\theta} - \boldsymbol{k_d}\boldsymbol{w}\,, \tag{6}$$

where $\boldsymbol{k_p}$ and $\boldsymbol{k_d}$ are controller gains, $\boldsymbol{\theta}$ represents the angular difference of the projections of the target direction on ZX and ZY planes of the Body Frame, and $\boldsymbol{w}$ represents the current angular velocity. Gas consumption is reduced by setting a dead band of ±20º around the target direction.

Once the separation is finished, the DMM enters into STANDBY mode and waits for the stabilization of the residual system oscillation. From this point on, the DMM tasks are to provide position and attitude information to ground to monitor the deorbiting efficiency. The tether system is designed to be passively stable during the de-orbiting.

Dedicated DKD dynamical models have been developed in Matlab/Simulink®. Using the SENERIC framework [24] and a simulation campaign has been performed to verify the algorithms for detumbling and attitude control during the deployments. Results and performances are presented in Section 6.

4.2 Electron Emitter Module

Once the deployment is completed the electron emitter is commanded from ground to enter into DEORBIT mode (Fig. 6). In this mode the EEM turns on the electron emitter and a current in the tether flows.

The DKD Electron Emitter subsystem consists of a C12A7e- Hollow Cathode (HC) fed with krypton provided by a dedicated pressurized system. The unique feature of the DKD cathode is the special low work function of the C12A7e-, which allows the operation without any heater, which in turn reduces the power consumption and simplifies the design and operation of the cathode significantly [25]. In particular, DKD will demonstrate HC power consumption and expellant flux less that of 6W and 4 sccm, respectively.

Fast and reliable cathode ignition will also be demonstrated in orbit. It is expected that the value of the current will change along the orbit in function of the plasma density and magnetic field orientation. The Electron Emitter will be turned on and off every orbit, to operate with a duty cycle of 30% of the orbital time. This will optimise on board resources and allow an extensive testing of the ignition mechanism.

During Electron Emitter operation, current and voltage generated in the tether will be monitored by dedicated sensors and provided to ground together with orbital and attitude data. The produced Lorentz force, responsible of the deorbiting, will also induce tether oscillations. Investigating tether dynamic is one of the objectives of the mission to be able to validate the design and generate high fidelity models of the tether-plasma interaction. This is particular interesting for bare and tape tethers since very few missions with this device have been flown and no in-flight data are available.

4.3 Tether longitudinal structure

The design of the DKD tether is based on the consortium experience and on an extensive simulation and trade-off activity. Simulations have been run to calculate the deorbit time for different configurations and evaluate the stability of the tether during the deorbiting. The resulting tether design is the optimum compromise between representativeness of the final DK, limited mass/volume and affordable technology risk. The DKD tether is made of different segments of 2.5cm width and different length and thickness (Table. 4 and Fig. 7).

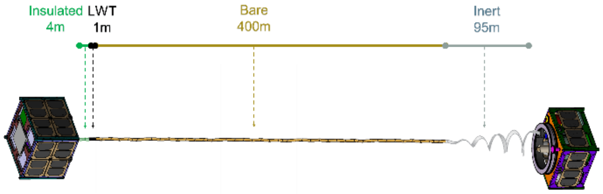

Fig. 7 DKD tether segments (not in scale)

Table. 4. DKD tether

Length	Segment Name and function
4m	Insulated. Prevent arcing and electrical contact.
1m	LWT. Demonstrate low work function tether performances.
400m	Bare. Collect electrons and generate Lorentz force.
95m	Inert. Stabilize the tether oscillations thanks to the gravity gradient.

The EEM is connected to 4m of insulated conductive tape. Insulation is required to avoid arcing and electrical contact in case of accidental connection with the body of the spacecraft. The insulated segment is connected to the LWT that will demonstrate electron emission. LWT consists of a titanium substrate tape coated with a thin layer of C12A7e-. Given the very experimental nature of this technology and the laboratory manufacturing process, only 1m of LWT segment is foreseen to be used. The objective of this segment is to demonstrate the achievable performances of a fully passive deorbit tether system. The use of this reduced segment does not prevent the need of using an electron emitter in this demonstration.

The following segment is the bare aluminium tether responsible of collecting electrons and generating most of the Lorentz force. Aluminium thickness of 30µm has been selected according to the maximum loads during the mission. The length of this segment is strictly connected to the required Lorentz force and, therefore, the produced current. For the selected orbit, currents in the order of 0.1A require 400m of bare tether. Finally, passive tether stabilization is achieved by an inert segment of 95m of PEEK. Being inert, PEEK segment increases the tension in the tape and the restoring torque provided by the gravity gradient.

5. Performance of the Deorbit Kit Demonstration

At the current stage of the project, the design has been verified by simulation. In particular 3 simulation software tools, previously developed by the partners, have been used iteratively. SENER used the SENERIC framework to simulate the spacecraft initial stabilization, the attitude control during the tether deployment and the attitude evolution during deorbiting. The tether mission analysis software BETsMA [26] was used by UC3M to find optimal tether dimensions and investigate the performance in a broad range of scenarios. UNIPD used FLEX [27] to validate the tether dynamic stability during deployment and deorbiting. Table. 5 reports the main simulation data used by the different tools.

Table. 5. Simulation Data

Parameter	Value
Orbit altitude:	600 km
Orbit Inclination:	51.5º circular
Bare tether	400m x 2.5cm 30um
Peek tether	100m x 2.5cm 50um
DMM Mass (without tether)	11.3kg
EMM Mass	10.8kg
Tether Mass	1.2 kg
Cathode Potential Drop	30V
Cathode Duty cycle	100%

The following sections report the main results of the simulation and the foreseen performances

5.1 Initial Stabilization

After releasing from the launcher, the DKD autonomously enters into STABILIZATION mode. The spacecraft uses 3 torque rods with a magnetic dipole of 0,24 Am^2 aligned along the main geometrical axes. In this mode a dedicated attitude control is designed to remove the initial angular velocity of the spacecraft.

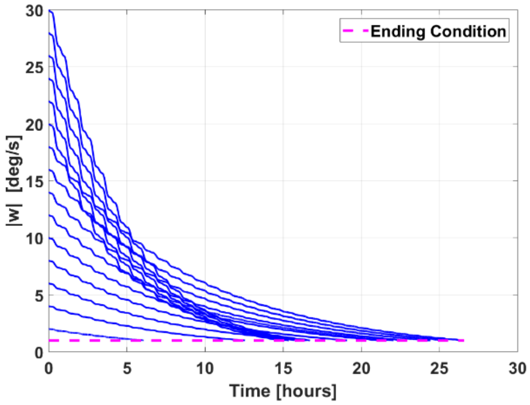

Fig. 8 Initial stabilization analysis

Typical launcher release angular velocity is in the order of 5º/s, considering a maximum of 6σ dispersion, parametric simulation with initial angular velocity of up to 30º/s are performed to verify the robustness of the control law and assess the performances. The angular velocity is reduced below 1º/s in less than 1 day for all initial conditions as reported in Fig. 8.

5.2 Controlled Deployment

During the tether deployment, the attitude of the DMM and the EEM shall be controlled within a cone of 20º semi-angle in order to maintain the proper tension in the tape. Both modules rely on cold gas systems to control their attitude during the deployment. Only 4 thrusters are needed on each module. The thrusters are commanded in pulse width modulation with a dead band of ±20º to minimize the consumption.

Table. 6 provides the details of the gas systems on EEM and DMM.

Table. 6. Cold Gas System Data (axis in Body Frame)

Parameter	EEM Value	DMM Value
Thrusters	4 directed on Z axis	4 directed on Z axis
Canting	15º around the X axis	55º around the X axis
Thrust Value	50mN	10mN
Specific Imp	34s	59s

Fig. 9. shows the simulation results and in particular the angular deviation from the ideal direction of the tether during the deployment. The simulator includes the tension of the tape with its application point and the environmental perturbations.

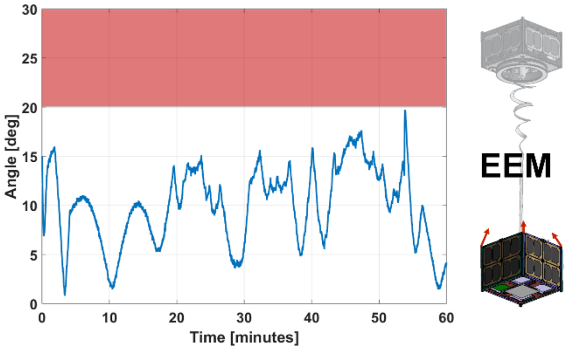

Fig. 9. EEM deployment attitude control performances

The error is properly contained within 20º with a mean value lower than 8º. The first part of the deployment is characterized by a smoother EEM control activity due to the positive effect of the initial separation velocity. This velocity, is only required at the beginning of the deployment since the gravity gradient pull grows with the separation of the DKD modules. Starting from minute 19 control pulses clearly appears to contain the error as spikes in the image.

Fig. 10. shows the results of the DMM attitude deployment control. The DMM dynamics does not account for initial propulsion but includes the rotating dynamics of the tether deployment mechanism. Moreover, the tether tension application point is not fixed and centred like in the EEM but it moves with a time-varying angular velocity (up to 8 rad/s) at 80 mm from the longitudinal axis of the module. Despite the complex dynamics, the controller behaviour is good, maintaining the error below 22º with mean value around 9º. The impact of the maximum attitude error is currently under investigation, but it is expected not to be critical since it occurs for a limited time.

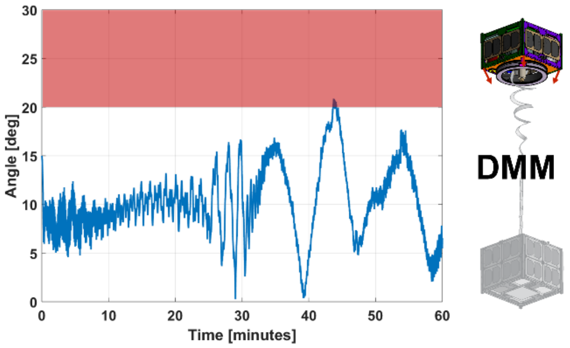

Fig. 10. DMM deployment attitude control performances

The control effort required by the DMM is higher than the one required by the EEM given the nature of the perturbations. The computed EEM cold gas consumption for the control is around 1g while the DMM consumption for the attitude control is roughly 2.5g.

5.3 Deorbit Performances with BETsMA

The DKD deorbit performances has been calculated using the BETsMA v.2 tool considering a 24kg spacecraft deploying a tether of 500m with 400m of bare tether.

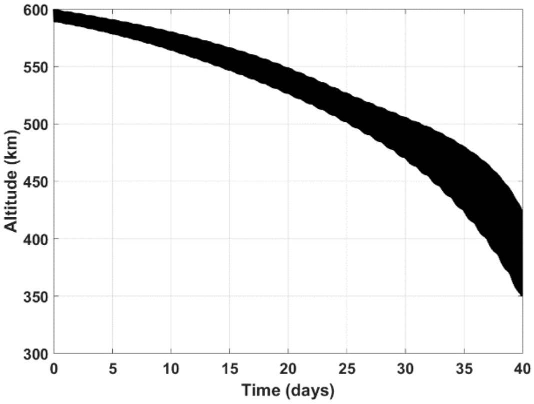

Fig. 11. DKD deorbit performances (BETsMA)

The performances are addressed assuming that the tether is aligned along the local vertical and with continuous operation of the hollow cathode. It is expected that higher performance will be obtained with a slightly oscillanting tether and final deorbit time will be also affected by the duty cycle operations. BETsMA provided interesting information like forces, tether cut probability by small debris, tether temperature and ATOX exposure, etc. The deorbit time from 600 km circular orbit is 40 days. Deorbit is considered when the perigee reaches 350km altitude. The altitude evolution along the mission is depicted in Fig. 11.

Fig. 12a displays the current at the cathode calculated considering a 30V drop due to the cathode operation. The current level increase as the orbit altitude decreases. There are two repeating trends with two different frequencies. The first trend has an orbital frequency (high frequency) and the second has a daily frequency (low frequency). It is possible to identify peaks for every orbit and peaks for every day.

The orbital pattern depends on the relative geometry between the orbital velocity and the magnetic field ($\mathbf{v_{rel}} \times \mathbf{B}$) while the daily pattern is linked to the plasma density. The current increases as the orbit decreases since the lower the orbital altitude the higher the plasma density and the motional electric field (Fig. 12 b).

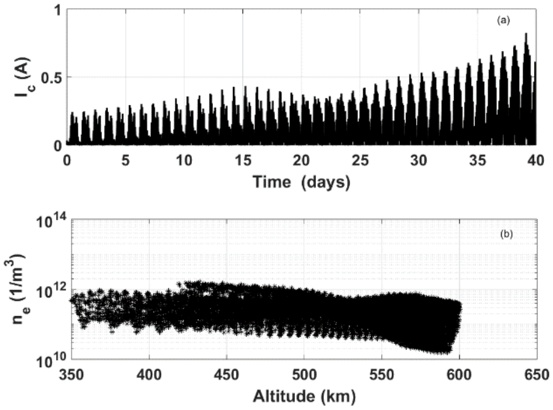

Fig. 12: Current at the cathode along the deorbit (a) and Plasma density in function of the orbital altitude (b).

The orbital current peaks during the first day of the deorbit range from 13 to 240mA. The orbital peaks of the last days of the deorbit start from 65mA and reach to 820mA. These numbers are quite relevant for the sizing of the cathode operation since the cathode needs at least 100mA to work. The cathode operations are triggered by the on board computer as a function of a predefined mission plan that is uploaded from ground. It is important to mention that there is a large uncertainty on the plasma and magnetic field models (in the order of 20%), therefore in orbit commissioning of the deorbit operations should be performed. The tether will work as a giant Langmuir probe increasing the knowledge of our space environment and providing relevant information for the performance optimisation of the final DK.

5.4 Deorbit Performances with FLEX

Similar results have been obtained by FLEX that, unlike BETsMA, simulates the tether attitude dynamics. The tether is simulated with an approximation of 10 segments. The tether and the EMM and DMM dynamics are affected by gravity, atmospheric drag and Lorentz force. Fig. 13 shows the $\boldsymbol{E_m}$ generated on the tether during the deorbit in line with the values estimated by the equations in section 2.

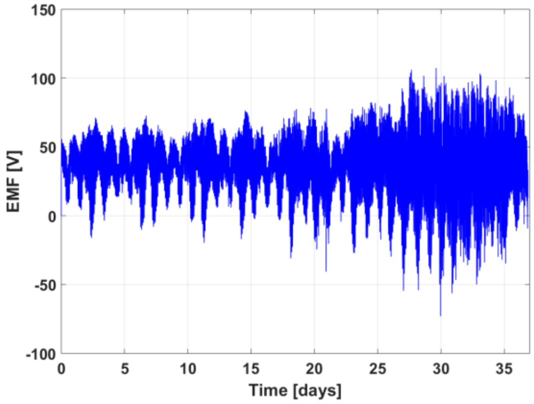

Fig. 13: EMF generated during the deorbit.

Figure 14 shows the evolution of the altitude where a much smother orbital oscillation behaviour is observable with respect to Fig. 11. As expected the computed deorbit time is lower than the one calculated in section 5.3. The resulting deorbit time is 35.3 days to reach 350km altitude and 1.6 days more to arrive to 250km. FLEX results validate the tether design previously sized with BETsMA.

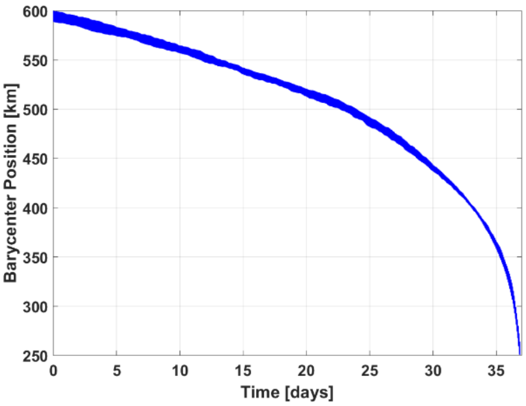

Fig. 14. DKD deorbit performances with 30V drop (FLEX)

6. Deorbit Kit Roadmap

The objective of the consortium is to leverage on the ETPACK project to develop a commercial Deorbit Kit. The following evolution of the DK development is foreseen during and after the ETPACK project.

The manufacturing of the DKD breadboard will start at the end of 2020. The subsystems will be validated independently and integrated into the breadboard in the second half of 2021. Full functional test of the DKD including mechanical tests will be performed in 2022. The objective is to achieve TRL4 at the end of the ETPACK project and continue in 2023 with the manufacturing and testing of the DKD Qualification Model (QM) and Flight Model (FM). The launch of the DKD mission is foreseen for 2024 and the first DK production by 2025.

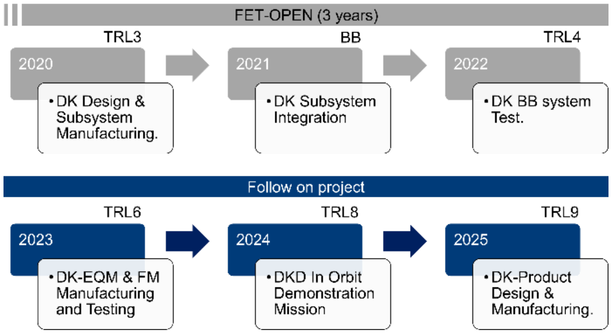

Fig. 15. DK Product evolution Logic

7. Conclusions

This work presents the design and performances of a Deorbit Kit Demonstrator fitting a 12U cubesat. DKD will be launched in 600 km altitude orbit and will re-enter in less than 100 days. The DKD goal is to demonstrate in orbit the deorbit kit technologies paving the road for the commercialization of the kit. The technology at the base of the DKD is the electrodynamic tether that allows propellant-less deorbit.

DKD is composed by two independent modules: the Deployment Mechanism Module is in charge of deploying a 500m long tether while the Electron Emitter Module is responsible of “turning on” the tether current by emitting electron. The selected emitter is a heatherless hollow cathode to fit the tight power requirements. Passive electron emission will be demonstrated on a tether segment coated with the C12A7e-.

Detailed models of the DKD mission have been generated and simulated with 3 different simulators to verify requirements and assess design correctness. The DKD performances are in lines with the expected and the team is now starting the manufacturing of a breadboard. E.T.PACK will terminate in 2022 reaching TRL4, the demonstration mission is foreseen in 2024 and start the production of the DK in 2025.

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