International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:15, No:4, 2021

Deorbiting Performance of Electrodynamic Tethers to Mitigate Space Debris

Giulia Sarego, Lorenzo Olivieri, Andrea Valmorbida, Carlo Bettanini, Giacomo Colombatti, Marco Pertile, Enrico C. Lorenzini

Abstract—International guidelines recommend removing any artificial body in Low Earth Orbit (LEO) within 25 years from mission completion. Among disposal strategies, electrodynamic tethers appear to be a promising option for LEO, thanks to the limited storage mass and the minimum interface requirements to the host spacecraft. In particular, recent technological advances make it feasible to deorbit large objects with tether lengths of a few kilometers or less. To further investigate such an innovative passive system, the European Union is currently funding the project E.T.PACK – Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit in the framework of the H2020 Future Emerging Technologies (FET) Open program. The project focuses on the design of an end of life disposal kit for LEO satellites. This kit aims to deploy a taped tether that can be activated at the spacecraft end of life to perform autonomous deorbit within the international guidelines.
In this paper, the orbital performance of the E.T.PACK deorbiting kit is compared to other disposal methods. Besides, the orbital decay prediction is parametrized as a function of spacecraft mass and tether system performance. Different values of length, width, and thickness of the tether will be evaluated for various scenarios (i.e., different initial orbital parameters). The results will be compared to other end-of-life disposal methods with similar allocated resources. The analysis of the more innovative system's performance with the tape coated with a thermionic material, which has a low work-function (LWT), for which no active component for the cathode is required, will also be briefly discussed.

The results show that the electrodynamic tether option can be a competitive and performant solution for satellite disposal compared to other deorbit technologies.

Keywords—Deorbiting performance, H2020, spacecraft disposal, space electrodynamic tethers.

I. Introduction

THE increasing number of artificial objects in near-earth space is creating growing concerns among the scientific community due to the hazard they pose on the spacecraft population. In particular, it has been estimated that collisions between large pieces of space junk or with operative spacecraft might cause cascade effects up to the creation of artificial belts of debris in the most crowded orbits, as firstly hypothesized by Kessler [1].

The first aspect of the problem is related to the current debris population. To face this aspect, many space debris capturing and removal methods have been proposed and tested in recent years to stabilize the growth of space debris number [2]. These key technologies are necessary to reduce the current number of large and massive objects in space [3] and clean up space, only if both good coordination between all the space-related actors and an effective removal policy are provided [4].

However, to fully address the space debris problem, there is a second aspect of fundamental importance: newly launched objects are expected to comply with end-of-life disposal guidelines. This condition is even more relevant for the recent introduction of large constellations of thousands of small satellites (e.g., [5]–[7]), which will significantly a ffect the space environment. As a reference, the Starlink constellation provider has launched into orbit 540 satellites to June 15, 2020, with plans to deploy up to 1500 spacecraft on an orbit shell with an altitude of 500 km (orbits inclination of 53 deg) and about 2800 spacecraft on a range of altitudes between 1100 and 1350 km [8]. Current international guidelines recommend several actions to mitigate the instruction of new satellites on the environment (e.g., the 25-years instruction to deorbit all new satellites within 25 years since mission completion if their deployment orbit altitude is below 2000 km [9]). In the meantime, concerns are still arising on the effectiveness of these guidelines on controlling the growth of space debris population [10]–[12].

In this context, all major satellite providers are currently moving towards a self-regulating approach to respect at least the 25-years recommendation. In this context, in 2018, the European Commission awarded an H2020 Future Emerging Technologies (FET) Open project titled "Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit" (E.T.PACK), that aims at the development of a Deorbit Kit prototype based on electrodynamic tether technology [13]. In this paper, the orbital performance of the electrodynamic tether technology is evaluated and compared to other end-of-life disposal technologies, namely chemical propulsion and drag-sail devices, for four reference configurations concerning satellites that are about to be launched in the next few years (i.e. EarthCARE, a large satellite for earth observation in sun-synchronous orbit, and three different large constellation spacecraft orbiting at altitudes from 1000 km to 1500 km). Moreover, a series of numerical simulations for the electrodynamic tether technology has been completed to underline several parameters' influence on the technology performance.

The paper is organized as follows. Section II describes the considered disposal methods. Section III compares the deorbit

This work was supported by European Commission's H2020 Research and Innovation Programme under Grant Agreement No. 828902 (E.T.PACK Project).

G. Sarego is with the University of Padova, Padova, Italy (corresponding author, phone: +39 049 827 6779; e-mail: giulia.sarego@unipd.it).

L. Olivieri, A. Valmorbida, C. Bettanini, G. Colombatti, M. Pertile, and E. C. Lorenzini are with the University of Padova, Padova, Italy (e-mail: lorenzo.olivieri@unipd.it, andrea.valmorbida@unipd.it, carlo.bettanini@unipd.it, giacomo.colombatti@unipd.it, marco.pertile@unipd.it, enrico.lorenzini@unipd.it).

performances of electrodynamic tethers, chemical propulsion systems, and drag sails, showing that the first option is more attractive, particularly for satellites at high altitudes. Section IV lists all the different system parameters taken into account, explains their influence on the system behavior by showing the results of a large set of simulations, and describes a strategy to compute the relationship between parameters and system performance. Besides, the innovative concept of Low Work-function Tether (LWT) is briefly introduced and discussed. Relevant conclusions are drawn in Section V.

II. End-of-Life Self-Disposal Methods

End-of-life disposal systems can be classified into capturing methods (e.g., tentacles, arms, net, harpoon) and removal methods. The latter category includes self-disposal methods involving devices originally mounted on the spacecraft and methods requiring an additional satellite chasing and acting on the target debris [2], [14]. In this paper, three major classes of self-disposal methods have been considered: drag augmentation devices (e.g., sails), propulsion systems, and electrodynamic devices (e.g., ElectroDynamic Tethers, EDT).

Drag sails have been extensively studied for spacecraft re-entry [15], [16] and recently tested in space as disposal systems for low altitude orbits [17], [18]. Current studies aim at implementing strategies to enhance their capabilities even for higher altitudes, for example, through ionospheric drag [19], and at developing kits to be installed as independent modules on spacecraft (ADEO - [20]–[22]).

Propulsion-based disposal methods can use chemical thrusters and can be implemented through either a dedicated kit or on-board systems [23]. However, they need to adequately address technological issues, such as propellant leakage or degradation in prolonged storage time, and attitude control demands during disposal maneuvers [24].

Electrodynamic tethered systems appear to be a promising option as they could overcome the mass requirement limitations of traditional propulsion-based systems and are effective in a broader range of altitudes compared to drag augmentation devices. Electrodynamic tethers collect ionospheric electrons (Bare Electrodynamic Tethers - BET [25]) from the plasma environment and re-emit them through a cathode or a "Low-Work-Function" segment of the same tether by using thermionic and photoelectric effects (Low Work-function Tether – LWT [26], [27]). In both configurations, the resulting electric current flowing through the conductive tether generates a drag Lorentz force thanks to the interaction with the Earth's magnetic field that progressively decreases the satellite's orbit altitude, causing its re-entry into the atmosphere.

Those three technologies' deorbiting performance has been analyzed and compared for a set of Low Earth Orbit (LEO) satellites planned to be launched soon.

III. Performance Analysis of Different Self-Disposal Technologies

Following the Inter-Agency Space Debris Coordination Committee (IADC) guidelines, end-of-mission disposal devices are a fundamental priority for LEO satellite, especially for

1) satellites planned for highly desirable orbits, like Earth Observation (EO) satellites for which sun-synchronous orbits are preferred, and
2) satellites planned to operate in soon-to-be densely populated orbits, namely part of large commercial constellations.

TABLE I
Simulated Satellites for the Deorbiting Comparison with Different Technologies

Company/ Satellite Name	Type	S/C mass $[kg]$	Alt. $[km]$	Incl. $[deg]$	Ref.
SpaceX (Starlink)	Commun. Constel. (4425 S/C)	386	1150-1325	83 planes (53 - 81)	[30]
Telesat	Commun. Constel. (117 S/C)	800	1000-1248	11 planes (37.4, 99.5)	[31], [32]
Astrome	Commun. Constel. (200 S/C)	150	1515	30	[33]
EarthCARE (Earth Explorer 6)	*EO*	2270	400	97	[34]

The main parameters, such as mass, altitude, and orbit inclination of each study case are listed.

In this section, the performance of the different disposal methods mentioned above is compared for the EO satellite and the large communication constellation spacecraft listed in [28], [29]. Table I lists the four satellites taken into consideration for this comparison.

From accurate simulation results, electrodynamic devices effectively deorbit satellites in the 1-ton mass range with tape width as small as 2 cm and lengths as short as 3 km [35]. One of the E.T.PACK deorbiting kit configurations considered a tape tether 2.5-cm wide, 3-km long, and 40-μm thick, which has a tether mass of about 8 kg. Consequently, in the following set of simulations, the mass allocated for the compared technologies, i.e., exclusively for the drag sail itself or solely the chemical propellant, regardless of the rest of the device system, was set equal to 8 kg, and the deorbiting time has been evaluated. In the simulations, no attitude analyses have been carried out, so there are no stability problems or effects due to the spacecraft's tumbling during deorbit.

A. Drag Augmentation Devices

The analysis of a neutral drag sail's deorbiting performance has been performed through a numerical simulator developed in MATLAB® R2020b [36]. The numerical simulator consists of an orbit propagator where the specific drag force $\overrightarrow{F_a}$ is implemented as

$$\overrightarrow{F_a} = -\frac{1}{2} C_D \, \rho \, \frac{A_{DAD}}{m_{tot}} \, |\overrightarrow{v_{rel}}| \, \overrightarrow{v_{rel}} \quad (1)$$

where C_D is the drag coefficient (fixed at 2.2), ρ is the air density, $\overrightarrow{v_{rel}}$ is the relative velocity of the spacecraft with respect to the air, A_{DAD} the cross-sectional area of the drag augmentation device, and m_{tot} the total mass of the spacecraft and the device. In particular, the atmosphere is modeled as co-rotating with Earth and its density has been computed through the NRLMSISE-00 Atmosphere Model [37]. No additional wind models have been included. The code has been validated through the comparison with the results in [38]. A recent development in drag sails is related to the ADEO drag sail family, which is currently being developed under the European Space Agency's direct supervision by a large team of European stakeholders [20]. For these simulations, the adopted deorbiting system is ADEO-L [21], which has been designed with the following characteristics:

- for satellites between 100-1500 kg;
- 25 m^2 drag-sail subsystem;
- volume in stowed condition: 400 mm $\times$ 400 mm $\times$ 160 mm;
- total mass of about 7-10 kg.

The EarthCARE case has been simulated, even though it does not strictly comply with such characteristics, recognizing its low altitude as a particularly favorable parameter for the successful deorbiting. Table II reports the deorbiting time for each study case. Some research works [15] state that purely atmospheric disposal systems are effective below 1300 km, whereas additional intervention is needed above that altitude. However, a more realistic altitude for drag sails is 800 km, since at 1300 km the atmosphere density is ten times smaller than at 800 km, and a ten-time bigger sail would be required for the re-entry. In this study, all the reference systems have an altitude lower than 1300 km; however, the large constellation satellites did not deorbit within 25 years. It is evidently due to the limited allocated resources, whereas a very large drag augmentation device would have possibly deorbited the satellites. However, it is imperative to point out that while a neutral drag sail can help satisfy the 25-year re-entry guideline for a satellite in mid-LEO altitudes, neutral drag sails are practically incapable of reducing the impact risk with other spacecraft during deorbiting. An object's impact risk with other objects in space is given by its "Area $\times$ Deorbit Time" product. For a neutral drag sail, the deorbit time is inversely proportional to the area, and consequently, by deploying a large sail, the "Area $\times$ Deorbit Time" product is practically unchanged with respect to that of the satellite without the sail. In brief, drag augmentation devices do not reduce the impact risk with other space objects during deorbit.

B. *Chemical Propulsion*

Among the propulsion-based disposal technologies, solid propellants have proven to be attractively simple, reliable, and low cost, despite their limited specific impulse and limited flexibility [39]. Disposal maneuvers with chemical propulsion have the advantage of a shorter operational time (in the range of one orbital period) when compared to tether and drag-sail deorbiting strategies. Besides, tethers and drag sails require dedicated modules, whereas propulsive maneuvers are usually performed with hardware already on board the S/C. On the other hand, a specific amount of propellant has to be stored for the entire operational life and saved for disposal at the end of the mission. A single-impulse maneuver to lower the perigee has been considered, considering a typical value for the specific impulse of 240 s. Two separate sets of computations have been implemented:

1) the first set corresponds to the perigee achieved by an 8-kg propellant impulse,
2) the second set corresponds to the propellant necessary for achieving a 350-km perigee, recognizing that at that altitude, the drag would help in naturally deorbiting the spacecraft within one year [40].

Table III summarizes the results, showing that with the Δv obtained by the same allocated mass of the tether system (8 kg), the perigee of the transfer orbit is higher than 950 km for all the large constellation cases; therefore, they are not expected to deorbit naturally, unless other interventions are adequately implemented. As for the EO satellite, the altitude decrease is still limited; however, the perigee is low enough to let it naturally deorbit within some months.

TABLE II
DEORBITING CAPABILITIES FOR DRAG SAIL TECHNOLOGY FOR THE CASES REPORTED IN TABLE I

Company/ Satellite Name	Type	Deorbiting Time
SpaceX (Starlink)	Commun. Constel. (4425 S/C)	$>$ 25 years
Telesat	Commun. Constel. (117 S/C)	$>$ 25 years
Astrome	Commun. Constel. (200 S/C)	$>$ 25 years
EarthCARE (Earth Explorer 6)	*EO*	60 days

TABLE III
DEORBITING PERFORMANCE FOR CHEMICAL PROPULSION FOR THE CASES REPORTED IN TABLE I

Company/ Satellite Name	Type	Alt. $[km]$	Mass-fixed achieved Perigee $[km]$	Perigee-fixed propellant mass $[kg]$
SpaceX (Starlink)	Commun. Constel. (4425 S/C)	1150	950	32.5
Telesat	Commun. Constel. (117 S/C)	1248	1150	74.5
Astrome	Commun. Constel. (200 S/C)	1515	950	17.3
EarthCARE (Earth Explorer 6)	*EO*	400	370	13.7

The fourth column lists the perigee achieved with a single-impulse given by the same mass allocated for the other two systems, while the fifth column shows the mass required to lower the perigee to 350 km.

C. *Electrodynamic Tethers*

For all the simulations regarding the EDT results, FLEXSIM, a software tool developed in FORTRAN has been employed.

FLEXSIM is a simulator for tethered satellite systems developed at the University of Padova, where the tether is constantly aligned with the local vertical direction while deorbiting. The electrical properties of the tether are related to its geometry and to a lesser extent its temperature, that affects the electrical conductivity. The electrical current distribution along the tether is modeled based on the Orbital-Motion-Limited (OML) electron collection regime [25]. Perturbations such as lunisolar (third body) attraction and higher-order gravitational harmonics (4x4 gravity model) are also included. As for the environmental models, the International Reference Ionosphere IRI-2007 [41], the International Geomagnetic Reference Field - IGRF [42], and the NRLMSISE-00 Atmosphere Model [37] are implemented. Stability problems are not addressed in this paper. However, a common practice for guaranteeing stability is to limit the current flowing through the tether, decreasing somewhat the rate of decay in the latter (and shorter) part of deorbiting. In the simulations shown herewith, no current limits are activated. Besides, the nonzero potential drop at the cathode reduces the system's overall performance [35]. In these simulations, the voltage drop at the cathode is set equal to 40 V, a typical value for a hollow-cathode plasma contactor. Smaller potential drops would lead to faster deorbits, especially for high-inclination orbits.

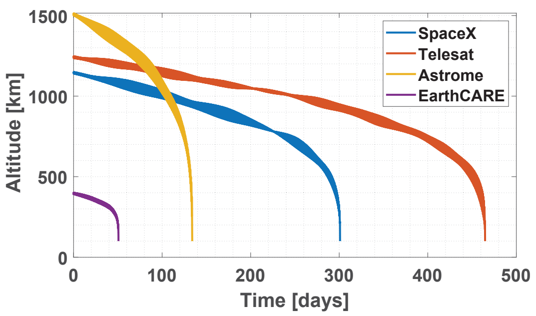

Fig. 1 Deorbiting performance of the electrodynamic technology for the cases reported in Table I

Fig. 1 shows that EDT systems can deorbit successfully and efficiently all the satellites considered within 1.5 years, far below the 25-year guideline and with a limited allocated mass. It should also be noted that unlike what happens for drag augmentation devices, the "Area × Deorbit-Time" product is drastically reduced because the deployed tape, besides being subject to the atmospheric drag, produces an electrodynamic drag force that is typically two to three orders of magnitude stronger than neutral drag for altitudes above 700 km.

An additional attractive feature of the EDT systems is that they can provide, during the deorbiting phase, a maneuver capability through tether current modulation, which is highly desirable for avoiding collision with large trackable objects.

IV. Performance of Electrodynamic Tether Technology

The promising EDT deorbiting system has been recently recognized by the European Commission that granted the FET Open project E.T.PACK, within which a deorbit kit prototype has to be developed [43], [44]. The team is currently working on developing a 12U CubeSat as a Deorbit Kit Demonstrator prototype to increase the technology readiness level (TRL)[45]. E.T.PACK deorbit kit is taken as reference configuration, and its geometry, as well as its target orbit, are slightly varied to point out the effects on the deorbiting performance. All the orbits are initially 600-km circular orbits, and no current limiter is activated. The parameters considered are set as following:

- thickness varying between 40 μm, 60 μm, 80 μm;
- width varying between 2 cm, 2.5 cm, 3 cm;
- tether length varying between 500 m, 1500 m, 3000 m;
- satellite mass varying between 12 kg, 24 kg, 36 kg;
- orbit inclination varying between 0 deg, 25 deg, 55 deg, 75 deg, 98 deg.

The complete set consists of 405 simulations with all the combinations of the parameters mentioned above. Therefore, the orbital decay prediction is computed as a function of spacecraft mass, tether length, width, thickness, and orbital inclinations.

The selected parameters affect the system's deorbiting capabilities since they influence in different ways the current flowing through the tether. For example, the thickness and width of the tape increase the tether's cross-sectional area; therefore, its electrical resistance decreases, allowing for a higher current, provided that all the other conditions remain constant. Changing the area exposed (to space) of the tether, the received and emitted thermal fluxes change in the same manner, and the equilibrium temperature stays about the same. Even though the general trends of the relation between these parameters and the system performance may be predictable (see Figs. 2, 3, and 4), assessing analytically their effects is not always immediate, since most of them interact concurrently to define the overall performance and their influence is in general nonlinear, except for the influence of the overall system mass.

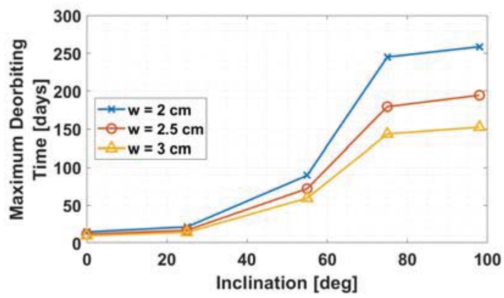

Fig. 2 Influence of different values of width of the tether on the deorbiting performance of the EDT. Each point in the plot identifies the maximum deorbiting time among all the results of the subset of simulations with a specific tether width and a specific inclination. The effect of different values of width is more evident for high inclination orbits

In this study, given the large amount of data and the nonlinear nature of the relationship between the parameters and the deorbiting performance, a neural network generated by the MATLAB® Deep Learning Toolbox has been employed to establish such relation. A single hidden-layer feed-forward neural network was used with

- a 5 × 405 Input Matrix, where the five rows contain the varying parameters and the 405 columns correspond to the total number of simulations or samples;

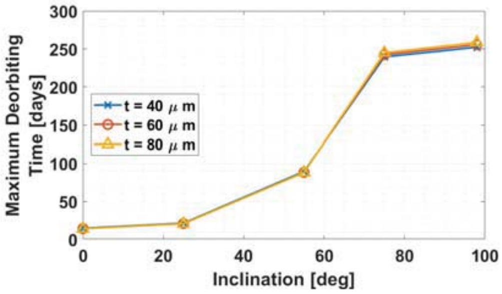

Fig. 3 Influence of different values of thickness of the tether on the deorbiting performance of the EDT. Each point in the plot identifies the maximum deorbiting time among all the results of the subset of simulations with a specific tether thickness and a specific inclination

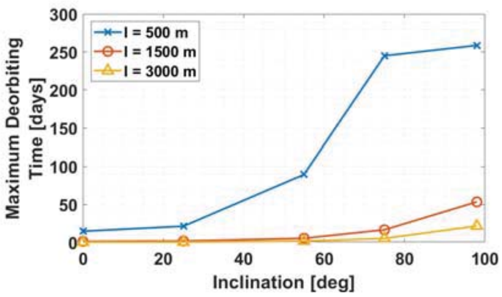

Fig. 4 Influence of different values of length of the tether on the deorbiting performance of the EDT. Each point in the plot identifies the maximum deorbiting time among all the results of the subset of simulations with a specific tether length and a specific inclination

- a 1 × 405 Output Matrix, where each element corresponds to a deorbiting time.

The hidden layer contains 15 neurons with a sigmoid activation function, the backpropagation for the training is solved by the Levenberg-Marquardt algorithm. The training set has been reduced to a 70% of the original set (283 samples); the remaining 30% of the samples of the set is equally divided into a validation set (61 samples) and a testing set (61 samples). The training set is used to train the network, which analyzes the set over different epochs (i.e., one epoch is when an entire training set is passed forward and backward through the neural network once) and learns the data features to predict the output of future new data accurately. The validation set is employed during training to avoid over-fitting and to measure network generalization. Lastly, the network uses the test set after the training to establish the network capabilities independently. An accurate network has to show good performance for all the sets. Fig. 5 shows the network behavior for the three separate subsets (top right, top left, and bottom left) and the entire data set (bottom right). In each plot, the network targets (i.e., the deorbiting time in days) are represented on the x axis: these are the results of FLEXSIM simulations. The network outputs (i.e., the prediction of the deorbiting time) are represented on the y axis. A black circle represents each simulation. The solid line identifies the linear regression curve, whose equation is expressed on the y axis for each set. A dotted black line is representing the prediction of the "perfect" network, for which the outputs of the network (Y) are equal to the targets (T). These results show that all the fitting curves are in good agreement with the Y=T curve, meaning that the neural network can easily capture the nonlinearities of the tethered system behavior and predict its performance accurately.

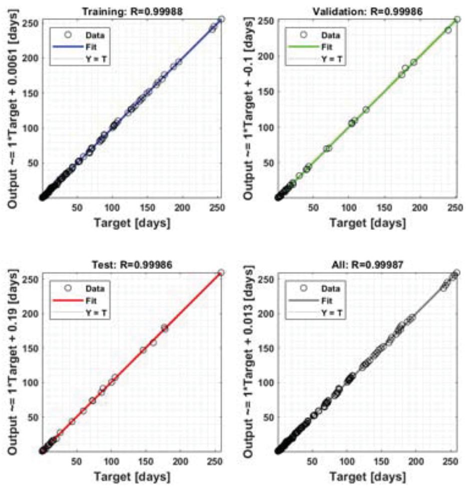

Fig. 5 Output of the performance of the neural network created for estimating the deorbiting performance of a tether satellite. Three plots correspond to the performance of the neural network in the three subsets (training set, validation set, and testing set), while the bottom left plot contains the entire set performance

In more than a decade, Padova university has developed a FORTRAN simulator called FLEX, including the effect of the flexibility of the tether discretized as lumped masses. The more accurate model enables the system to describe a moderately higher Lorentz force that slightly shortens the deorbiting phase. However, FLEX requires additional computational and time resources that are not straightforwardly compatible with a parametric study such as the one just described.

Future developments of the EDT technology include enhancing the tether system with the coating of a Low Work-function material able to emit electrons efficiently without using a dedicated component such as the active electron emitter. The most promising coating material so far is the electride C12A7:e- [27]. This improvement leads the system to require fewer resources (mass, power) than before and reduce the device complexity. This new system performance has been preliminarily analyzed in [27].

V. Conclusion

In this paper, the electrodynamic tether (EDT) technology has been described and compared to traditional chemical propulsive systems and drag augmentation devices. An additional set of 405 simulations with different geometrical and orbital parameters has been evaluated to analyze their effect on the system's overall performance.

The electrodynamic tether technology is promising compared to the other options thanks to: (1) the reduced mass budget, (2) the limited control requirement from the host at the end of the mission, which makes it more attractive than propulsion systems, (3) the range of operational orbits (up to the highest large constellation orbital shells, that are unsuitable for drag sails), and (4) the possibility to perform collision avoidance maneuvers during disposal. Electrodynamic tethers, particularly the E.T.PACK kit, will be also suitable for high-altitude large constellation spacecraft that otherwise would require large amounts of propellant and cannot be deorbited with drag sails.

Further investigations on the effect of other parameters on the overall electrodynamic tether performance will be carried out, including comparisons with other deorbiting systems. Additionally, further studies will be considering the application of Deep Neural Networks on the estimation of the deorbiting performance of a tethered system, including parameters such as a different initial date for the deorbiting phase (this will involve different solar activities), a different initial altitude (so to span the entire LEO range), the activation of a current limiter (for stability reasons) and an extensive study of interesting orbital conditions, such as polar orbits.

References

[1] D. J. Kessler and B. G. Cour-Palais, "Collision frequency of artificial satellites: The creation of a debris belt," *Journal of Geophysical Research: Space Physics*, vol. 83, no. A6, pp. 2637–2646, 1978.
[2] M. Shan, J. Guo, and E. Gill, "Review and comparison of active space debris capturing and removal methods," *Progress in Aerospace Sciences*, vol. 80, pp. 18–32, 2016.
[3] *Active debris removal*, https://www.esa.int/Safety_Security/Space_Debris/Active_debris_removal, Last accessed on 2020-12-31.
[4] N. Adilov, P. J. Alexander, and B. M. Cunningham, "The economics of orbital debris generation, accumulation, mitigation, and remediation," *Journal of Space Safety Engineering*, vol. 7, no. 3, pp. 447–450, 2020.
[5] W. A. Hanson, "In their own words: Oneweb's internet constellation as described in their FCC Form 312 Application," *New Space*, vol. 4, no. 3, pp. 153–167, 2016.
[6] J. Alvarez and B. Walls, "Constellations, clusters, and communication technology: Expanding small satellite access to space," in *2016 IEEE Aerospace Conference*, IEEE, 2016, pp. 1–11.
[7] S. Kawamoto, T. Hirai, S. Kitajima, S. Abe, and T. Hanada, "Evaluation of space debris mitigation measures using a debris evolutionary model," *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, vol. 16, no. 7, pp. 599–603, 2018.
[8] SpaceFlightNow, https://spaceflightnow.com/2020/04/21/spacex-modifies-starlink-network-design-as-another-60-satellites-gear-up-for-launch/, Last accessed on 2020-12-01.
[9] H. Stokes, Y. Akahoshi, C. Bonnal, *et al.*, "Evolution of ISO's space debris mitigation standards," *Journal of Space Safety Engineering*, vol. 7, no. 3, pp. 325–331, 2020.
[10] A. G. Karacalioglu and J. Stupl, " The Impact of New Trends in Satellite Launches on the Orbital Debris Environment," NASA, Tech. Rep., 2016, online, at https://ntrs.nasa.gov/search.jsp?R=20160011184, Last accessed on 2020-12-01.
[11] V. L. Foreman, A. Siddiqi, and O. De Weck, "Large satellite constellation orbital debris impacts: Case studies of oneweb and spacex proposals," in *AIAA SPACE and Astronautics Forum and Exposition*, 2017, p. 5200.
[12] L. Olivieri and A. Francesconi, "Large constellations assessment and optimization in LEO space debris environment," *Advances in Space Research*, vol. 65, no. 1, pp. 351–363, 2020.
[13] *FET OPEN project, Electrodynamic Tether Technology for Passive Consumable-less Deorbit Kit (E.T.PACK)*, Project no. 828902, 1/3/2019-31/5/2022, https://etpack.eu/, Last accessed on 2020-12-31.
[14] C. P. Mark and S. Kamath, "Review of active space debris removal methods," *Space Policy*, vol. 47, pp. 194–206, 2019.
[15] J. L. Rhatigan and W. Lan, "Drag-enhancing deorbit devices for spacecraft self-disposal: A review of progress and opportunities," *Journal of Space Safety Engineering*, vol. 7, no. 3, pp. 340–344, 2020.
[16] A. Black and D. A. Spencer, "Dragsail systems for satellite deorbit and targeted reentry," *Journal of Space Safety Engineering*, vol. 7, no. 3, pp. 397–403, 2020.
[17] B. Cotton, I. Bennett, and R. Zee, "On-Orbit Results from the CanX-7 Drag Sail Deorbit Mission," 2017.
[18] B. Taylor, C. Underwood, A. Viquerat, *et al.*, "Flight Results of the InflateSail Spacecraft and Future Applications of DragSails," in *32nd Annual AIAA/USU Conference on Small Satellites, Logan, Utah*, 2018.
[19] B. Smith, C. Capon, M. Brown, and R. Boyce, "Ionospheric drag for accelerated deorbit from upper low earth orbit," *Acta Astronautica*, vol. 176, pp. 520–530, 2020.
[20] T. Sinn, L. Tiedemann, A. Riemer, *et al.*, "ADEO passive de-orbit subsystem activity leading to a dragsail demonstrator: conclusions and next steps," in *Proceeding of 68th International Astronautical Congress (IAC), Adelaide, Australia*, 2017, pp. 25–29.
[21] E. K. Pfeiffer, T. Sinn, H. G. Hemme, *et al.*, "ADEO - The European Commercial Passive De-Orbit Subsystem Family Enabling Space Debris Mitigation," in *1st Aerospace Europe Conference (AEC) 2020, Bordeaux, France*, 2020.
[22] R. Ernst, T. Sinn, H. G. Hemme, *et al.*, "For a cleaner space, the de-orbiting approach of the PROBA P200 platform with the dragsail subsystem ADEO 2," in *1st Aerospace Europe Conference (AEC) 2020, Bordeaux, France*, 2020.
[23] H. Hakima and M. R. Emami, "Assessment of active methods for removal of LEO debris," *Acta Astronautica*, vol. 144, pp. 225–243, 2018.
[24] M. Leomanni, G. Bianchini, A. Garulli, A. Giannitrapani, and R. Quartullo, "Orbit Control Techniques for Space Debris Removal Missions Using Electric Propulsion," *Journal of Guidance, Control, and Dynamics*, pp. 1–10, 2020.
[25] J. Sanmartin, M. Martinez-Sanchez, and E. Ahedo, "Bare wire anodes for electrodynamic tethers," *Journal of Propulsion and Power*, vol. 9, no. 3, pp. 353–360, 1993.
[26] J. D. Williams, J. R. Sanmartin, and L. P. Rand, "Low work-function coating for an entirely propellantless bare electrodynamic tether," *IEEE Transactions on plasma science*, vol. 40, no. 5, pp. 1441–1445, 2012.
[27] G. Sanchez-Arriaga and X. Chen, "Modeling and performance of electrodynamic low-work-function tethers with photoemission effects," *Journal of Propulsion and Power*, vol. 34, no. 1, pp. 213–220, 2018.
[28] G. Curzi, D. Modenini, and P. Tortora, "Large constellations of small satellites: A survey of near future challenges and missions," *Aerospace*, vol. 7, no. 9, p. 133, 2020.
[29] *A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband*, http://www.mit.edu/~portillo/files/Comparison-LEO-IAC-2018-slides.pdf, Last accessed on 2020-12-31.
[30] *SpaceX seeks permission for 4,425-satellite internet constellation*, https://www.spaceflightinsider.com/organizations/space-exploration-technologies/spacex-seeks-permission-4425-satellite-internet-constellation/, Last accessed on 2020-12-31.
[31] *The Next Wave: Low Earth Orbit Constellations*, http://satellitemarkets.com/news-analysis/next-wave-low-earth-orbit-constellations, Last accessed on 2020-12-31.
[32] *News Analysis — Telesat's deliberate pace to LEO broadband*, https://spacenews.com/news-analysis-telesats-deliberate-pace-to-leo-broadband/, Last accessed on 2020-12-31.
[33] N. Satak, P. H. Laxminarayana, and P. D. Keskar, *System and method for integrated optimization of design and performance of satellite constellations*, International Publication Number: WO 2018/037424 Al, Aug. 2017. [Online]. Available: https://patentimages.storage.googleapis.com/67/22/92/2d0b0d4eceb1aa/WO2018037424A1.pdf.
[34] *EarthCARE (Earth Explorer 6)*, https://space.skyrocket.de/doc_sdat/earthcare.htm, Last accessed on 2020-12-31.
[35] G. Sánchez-Arriaga, C. Bombardelli, and X. Chen, "Impact of nonideal effects on bare electrodynamic tether performance," *Journal of Propulsion and Power*, vol. 31, no. 3, pp. 951–955, 2015.
[36] *MATLAB – MathWorks – MATLAB & Simulink*, https://www.mathworks.com/products/matlab.html, Last accessed on 2020-12-31.
[37] J. Picone, A. Hedin, D. P. Drob, and A. Aikin, "NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and

scientific issues," *Journal of Geophysical Research: Space Physics*, vol. 107, no. A12, SIA–15, 2002.

[38] D. Romagnoli and S. Theil, "De-orbiting satellites in leo using solar sails," *Journal of Aerospace Engineering*, vol. 4, no. 2, p. 49, 2012.

[39] L. DeLuca, F. Bernelli, F. Maggi, *et al.*, "Active space debris removal by a hybrid propulsion module," *Acta Astronautica*, vol. 91, pp. 20–33, 2013.

[40] M. Leomanni, A. Garulli, A. Giannitrapani, and F. Scortecci, "Propulsion options for very low earth orbit microsatellites," *Acta Astronautica*, vol. 133, pp. 444–454, 2017.

[41] D. Bilitza and B. W. Reinisch, "International reference ionosphere 2007: Improvements and new parameters," *Advances in space research*, vol. 42, no. 4, pp. 599–609, 2008.

[42] M. Mandea, S. Macmillan, T. Bondar, *et al.*, "International geomagnetic reference field—2000," *Physics of the Earth and planetary interiors*, vol. 120, no. 1, pp. 39–42, 2000.

[43] G. Sánchez-Arriaga, S. Naghdi, K. Wätzig, *et al.*, "The ET PACK project: Towards a fully passive and consumable-less deorbit kit based on low-work-function tether technology," *Acta Astronautica*, vol. 177, pp. 821–827, 2020.

[44] L. Tarabini-Castellani, A. Ortega, A. Gimenez, *et al.*, "Low work-function tether Deorbit Kit," *Journal of Space Safety Engineering*, vol. 7, no. 3, pp. 332–339, 2020.

[45] L. Tarabini-Castellani, A. Ortega, S. Garcia, *et al.*, "Development Roadmap of a Deorbit Kit Based on Electrodynamic Tether," in *Proceeding of 71th International Astronautical Congress (IAC), The CyberSpace Edition, 12-14 October 2020*, 2020, p. 56 858.

Giulia Sarego Giulia Sarego received a Ph.D. degree in *Sciences, Technologies and Measurements for Space* at the Center of Studies and Activities for Space "Giuseppe Colombo" (CISAS), University of Padova, in 2016 and currently is a postdoctoral fellow at the the very same centre of the University of Padova. In her academic career, she worked in several international project, among the others, the ReDSHIFT and FET Open E.T.PACK projects in the framework of the European H2020 program. Her fields of work have included fracture mechanics, structural health monitoring, satellite fragmentation and electrodynamic tethered systems.

Lorenzo Olivieri Lorenzo Olivieri is a postdoctoral fellow at the Center for Space Studies CISAS G. Colombo of the University of Padova. He graduated in Aerospace Engineering in 2011 and he received a Ph.D. in Measures for Space from the University of Padova in 2015. His research interests include small satellites technologies, docking systems and capturing strategies, and debris protection and removal. During his career he worked in the international teams of the ReDSHIFT and E.T.PACK projects in the framework of the European H2020 program.

Andrea Valmorbida Andrea Valmorbida received his master's degree cum laude in Aerospace Engineering in 2009 at the University of Padova (Italy). From 2010 to 2014 he attended the Ph.D. school in Sciences, Technologies and Measurements for Space at the Center of Studies and Activities for Space "Giuseppe Colombo" (CISAS), University of Padova, working on the development and testing of Model Predictive Control (MPC) strategies for Spacecraft Formation Flying, and he obtained his Ph.D. degree in 2014. From 2014 to 2020 he was a post-doctoral research fellow at the University of Padova and now he is a researcher at the Department of Industrial Engineering of the same institution. His major fields of study include: (a) the development and experimental testing of relative measurements systems and guidance navigation and control algorithms for satellite proximity operations, and (b) measurement systems, dynamics and control for electrodynamic and inert tethered satellite systems. He was member of the research group of 6 international and national projects, of which one H2020 (E.T.PACK) and one FP7 (BETs). He is author of 8 peer-reviewed journal articles and 26 peer-reviewed papers for international conference and national congress.

Carlo Bettanini Carlo Bettanini is Assistant Professor at the University of Padova teaching courses in Aerospace Flight Dynamics. His research activity has been carried on continuously for more than 20 years and is mainly related to the analysis of sensors performance and the identification of optimal techniques to monitor and reconstruct dynamic behavior of flying systems for low and high atmosphere and for space application. He has collaborated in the design, construction, testing and qualification of components for numerous scientific missions for both the US Space Agency and the European Space Agency and was program manager of DREAMS (Dust characterization Risk assessment and Environmental Analyzer on the Martian Surface) instrument of ExoMars 2016 mission.

Giacomo Colombatti Giacomo Colombatti received his Master degree thesis in 1997 in Physics at the University of Padova and Ph.D. in "Mechanical measurements for Engineering" with a thesis titled: "Temperature sensors for Planetary Atmospheres". His research interest include planetary atmosphere sensors development, from design to data analysis; dynamics of tethers, both bare and electrodynamics; entry planetary probes dynamics and data analysis. He is now working at the CISAS "Giuseppe Colombo", Center for space studies of the University of Padova.

Marco Pertile PhD in Space Science and Technology at the University of Padova. Associate Professor in Mechanical and Thermal Measurements in the Industrial Engineering Dept. – University of Padova. Main research interests: mechanical and thermal measurements, design of experimental tests and set-up for space systems, design of measurement systems based on vision systems and laser scanners, robotics, autonomous vehicles, uncertainty evaluation. Involved in several international projects, such as: H2020 Project E.T.PACK Electrodynamic Tether PACKaged in a reel on board the spacecraft; SIMBIO-SYS Experiment on board of the ESA mission BEPI Colombo; DREAMS EDM Payload for the EXOMARS2016 mission; OSIRIS (Optical Spectroscopic Infrared Imaging System) of the ESA Rosetta mission. Recipient of the following awards: "Paolo Cappa" Award for the best paper in the Italian National Forum on Measurements 2018; Best Paper in Mechanical and Thermal Measurement for Aerospace in the IEEE Int. W. in Metrology for Aerospace 2014; "one of Transactions Outstanding Reviewers of 2014" from the IEEE Instrumentation and Measurement Society; Santini Award for best paper space section from the Italian Association of Aeronautics and Astronautics 2007.

Enrico Lorenzini Enrico Lorenzini is a Professor at the Department of Industrial Engineering of the University of Padova (Italy) since 2006, teaching courses in Aerospace Engineering for Master's and Ph.D. degree programs. His research interests include Astrodynamics, Spacecraft Dynamics and Control; Conceptual design of space systems including Tethered Satellites; Design and analysis of systems for measuring small accelerations and displacements. He is an AIAA Associate Fellow, an IEEE Member, an AIDAA (Italian Association of Aeronautics and Astronautics) Member, an Academic Editor of the International Journal of Aerospace Engineering. He has 158 publications listed in SCOPUS (search for Enrico C. Lorenzini) of which 79 papers in peer-reviewed journals, 76 in conference proceedings, 1 monograph, 1 book chapter and 1 front-cover article in *Scientific American* (August 2004 issue).