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UNIVERSITÀ DEGLI STUDI DI PADOVA

Green in-space transportation with tether technology

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Ph.D. in Science Technologies and Measurement for Space, Curriculum MMIS, XXXVI Cycle

in cotutela with

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Admission to the ***Final Exam***

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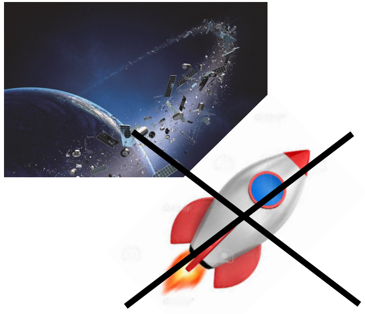
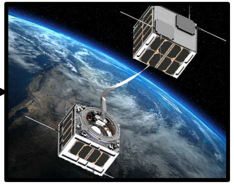
Contents

1. Introduction

Contemporary research efforts are experiencing a significant paradigm shift for moving in space, primarily motivated by *the SPACE DEBRIS PROBLEM and SPACE ENVIRONMENTAL POLLUTION*



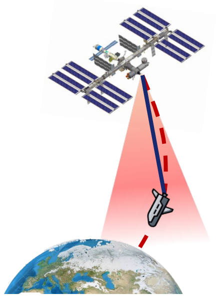
<u>Propellant-Free Technology</u>
offers a revolutionary departure from traditional propellant-based technologies for ***reducing traditional propellant consumption*** and ***increasing the long-term ecological footprint***



<u>Space Tethers</u>

Momentum Exchange Tether

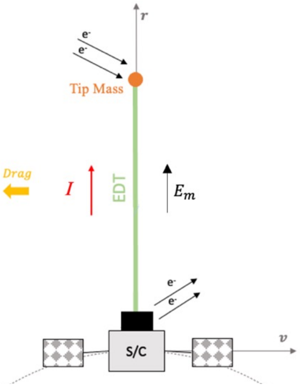
De-orbiting payload from space
Preserving cleanliness of space environment

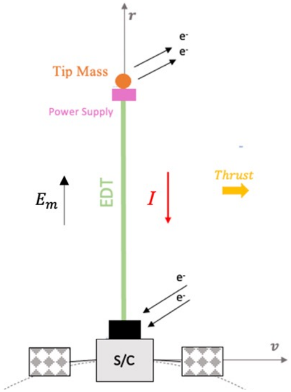


Electrodynamic Tethers

a) De-orbiting end-of-life satellites
Space debris mitigation

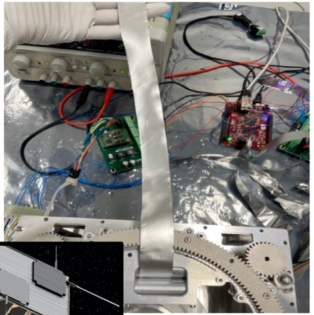
b) Reboost LEO satellites
i.e., station keeping





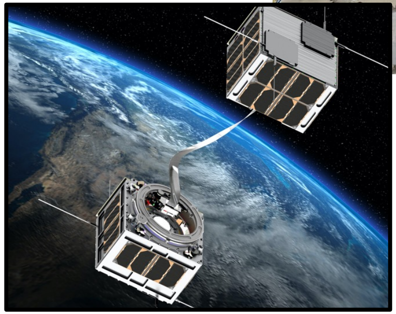
2. Reserach Objectives

Space tethers have the potential to revolutionize in-space trasportation by offering efficient versatile solutions for debris removal, reboost and station-keeping operations.



Challenge: transition from an experimental/scientific device to a reliable, robust and efficient space product, focusing on:

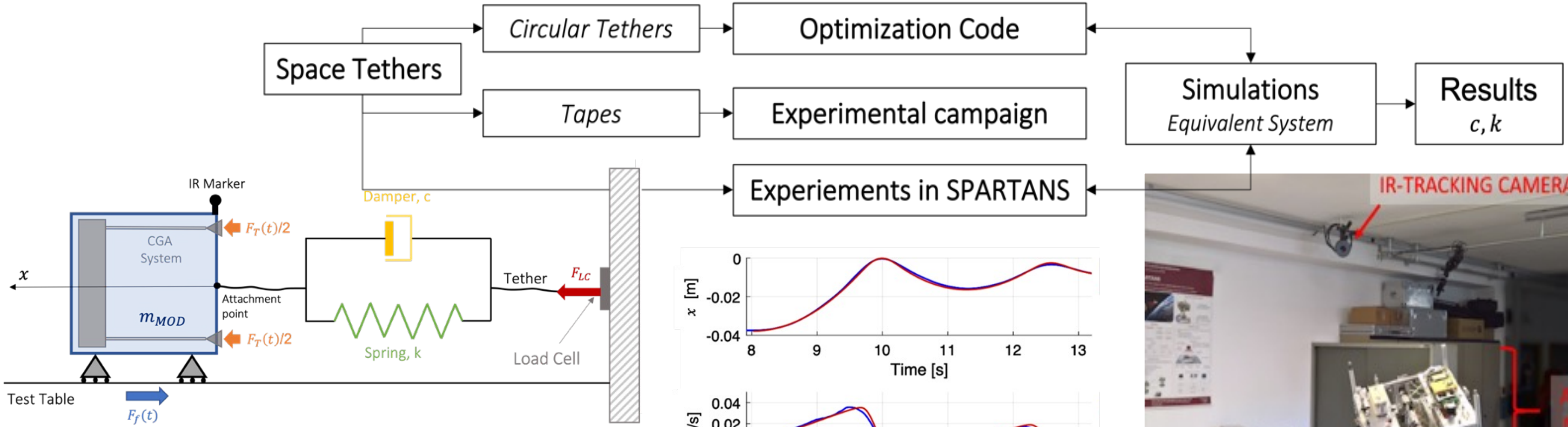
1. *Space tether materials,*
2. *Deployment mechanism intricacies,*
3. *Control laws development,*
4. *Current control strategies.*

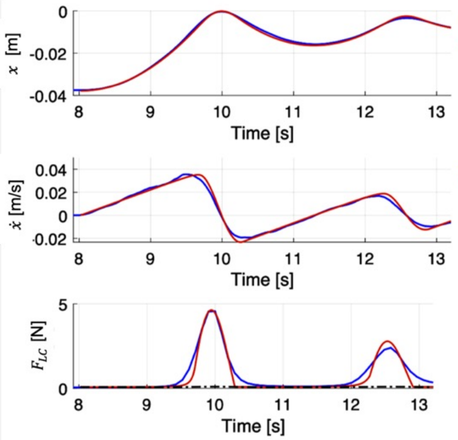


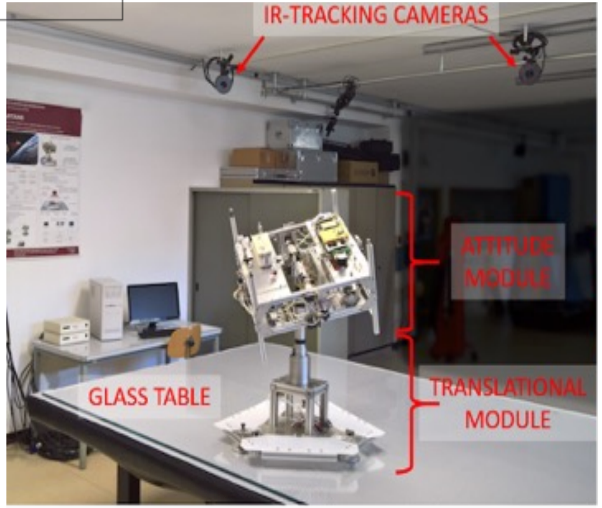
Demonstrate different configurations of tether systems to overcome the limitations of rocket propulsions, enable new classes of missions currently unaffordable or unfeasible, significantly advance the tether technology to an operational level.

3. Mechanical Properties Determination

The characterization of mechanical properties entails the elucidation of elastic constants and damping coefficients inherent to materials, particularly those deemed suitable for contemporary and prospective space tether application.





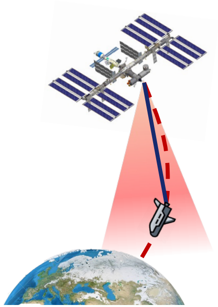


Result

Materials	Stiffness	Damping coefficient
Spectra™	753 N/m	35 Ns/m
Al-1100	24734.25 N/m	48.16 Ns/m
PEEK	1810.91 N/m	0.37 Ns/m

4. The Iperdrone.1 Program

Deorbiting strategy and baseline design

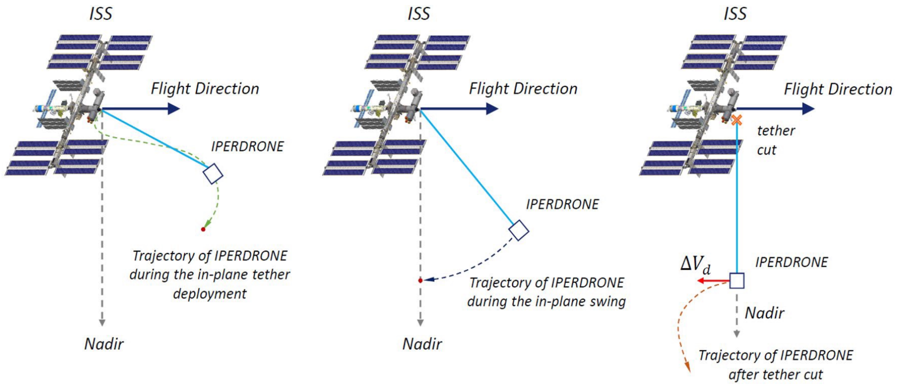


- **Iperdrone.1** aim at demonstrating the ability to deorbiting a payload from the ISS with the use of a Momentum Exchange Tether.
- Key technologies, and deorbit strategies were investigated with the goal of providing a safe and controlled deorbit of the space drone

Deorbiting strategy

- *Launching site*:
  Nanoracks Kaber System
- *The launch speed*:
  V_0 = 1.3 m/s

Swing and Release technique

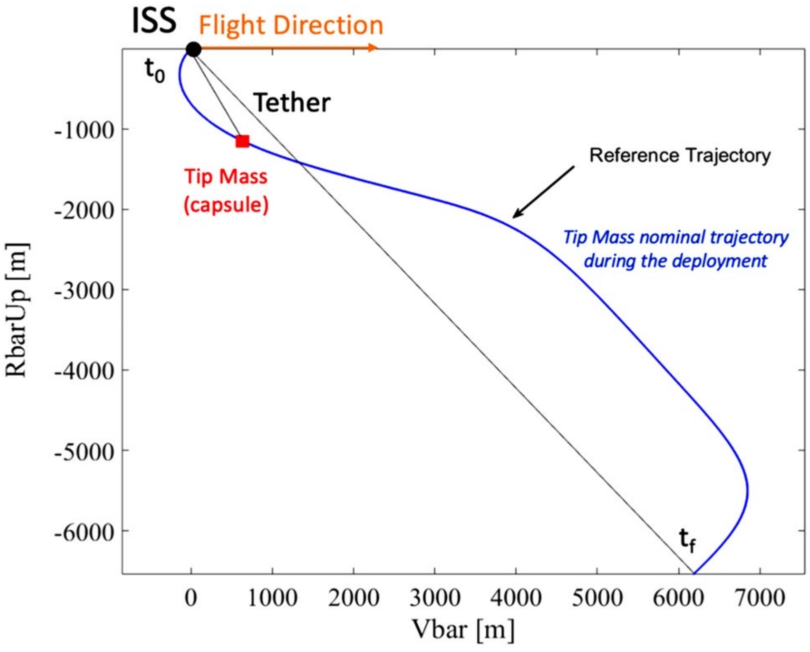


System Base-line Design

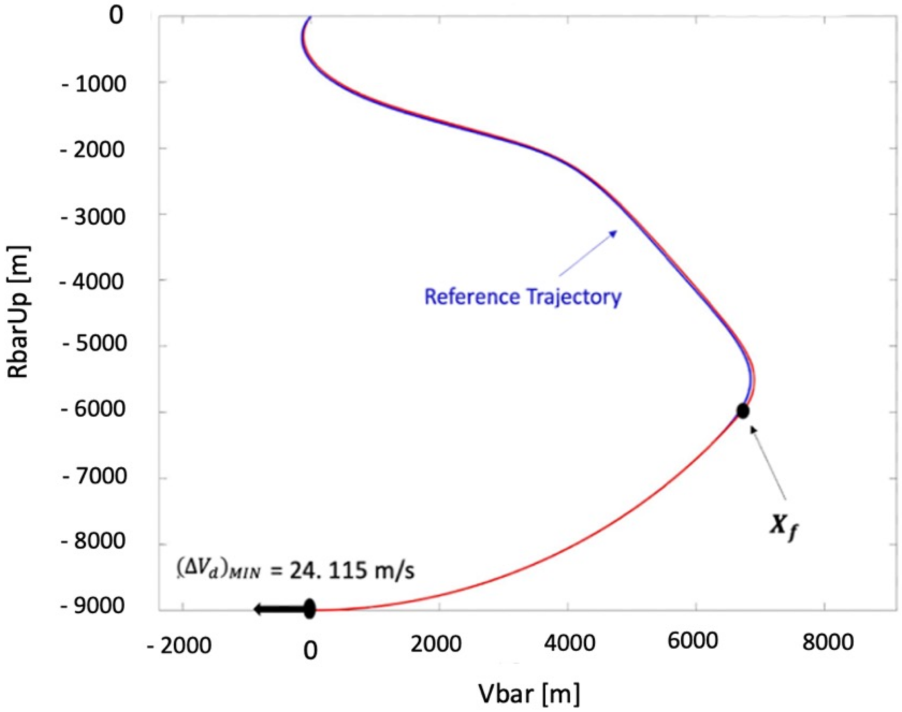
- *A braided Spectra™ 1000 round tether, length 9km and diameter of 1 mm.*

4.1 Reference trajectory and control law

- Reference Trajectory
  - *Optimization code based on the numerical integration of the equation of motion (CW formulation)*



- PD Control around the feed-forwarded reference trajectory
  - *Sensitivy analysis*

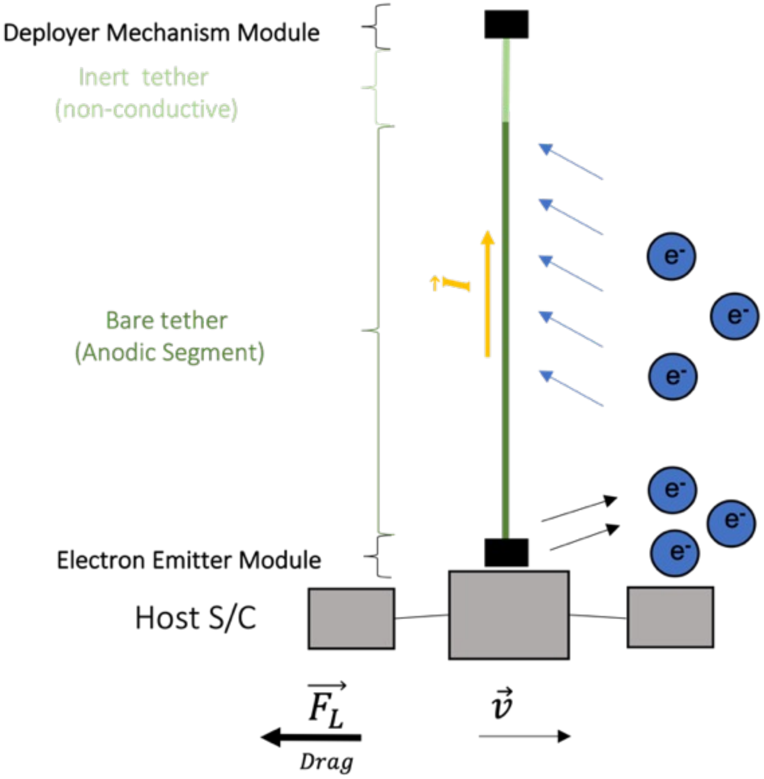


5. The E.T.PACK Program

- E.T.PACK Program

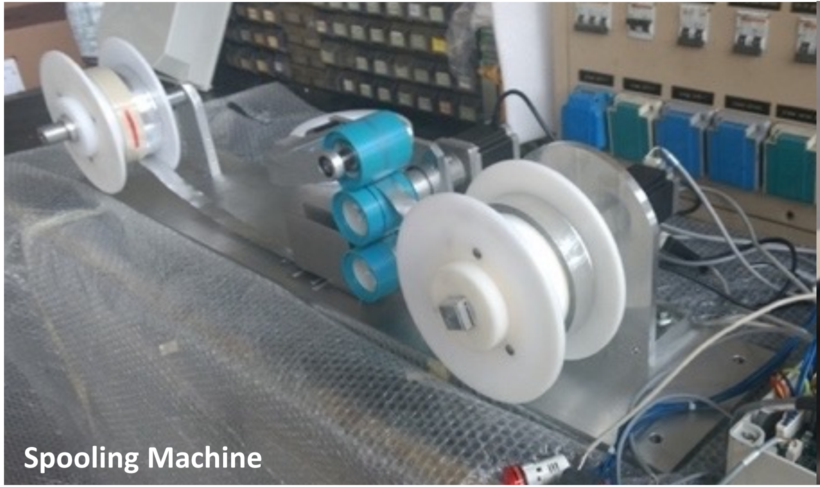
is expressly oriented towards the design, manufacturing, and testing of an autonomous Deorbit Kit Prototype, founded upon EDT technology, for satellite end of life deorbiting.

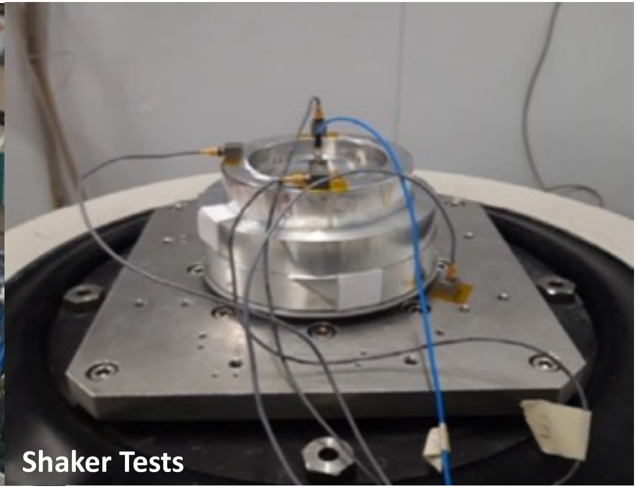
- The Bare Electrodynamic Tether
  - The Bare Electrodynamic Tether (BET) is a long conductor (e.g., a thin tape) that interact with the ambient plasma of Low Earth orbits. The motional electric field drives a current on the tether and a Lorenz force is produced, if a good contact with the ambient plasma is present.
  - The total length is ~500 m long. The bare portion of the E.T.PACK BET consist in a conductive aluminum tape of 2.5 cm of width and 40 μm of thickness. For the insulated portion of the tether, the material chosen is PEEK with 50 μm of thickness.



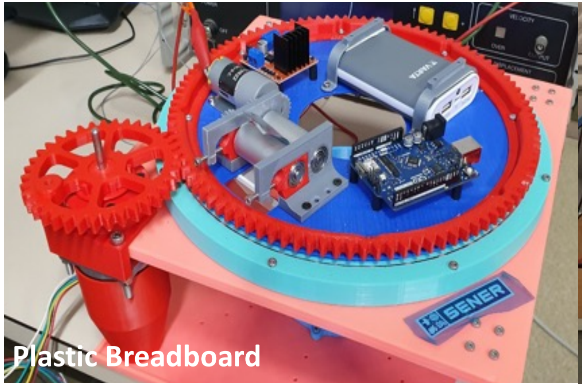
5.1 Deployer Hardware Design

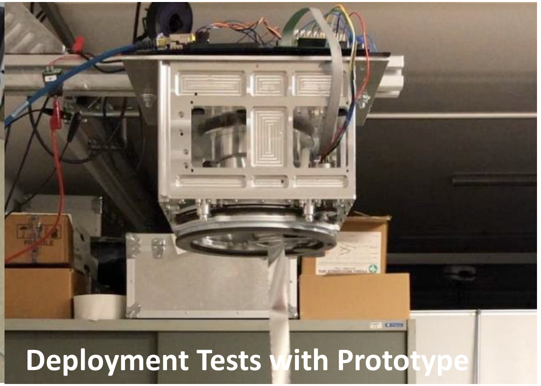
- Tape Spool
  - *Trade off analysis*
  - *Spooling Machine*
  - *Shaker Tests*





- Deployer Mechanism
  - *Design*
  - *Manufacturing*
  - *Functional Tests*





5.1.1 Deployer Functional Tests

Deployment tests are meant for checking the ability of the DM prototype and its pulleys system to deploy smoothly different sections of tape made of 40-µm-thick bare Aluminum and 50-µm PEEK.

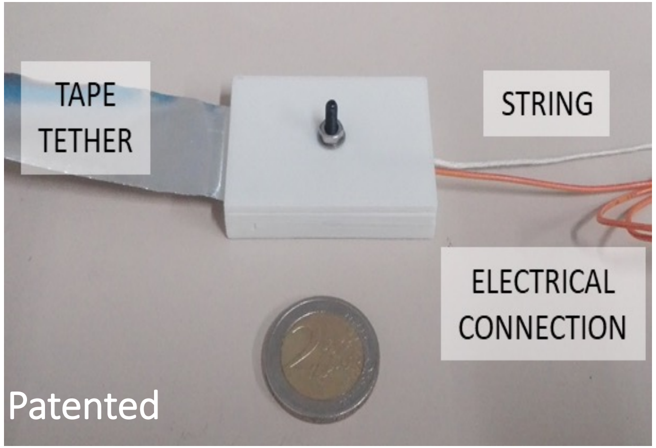
A number of deployment tests on representative tape lengths to valuate the system functionality and in particular to check the performance with regards to the following points:

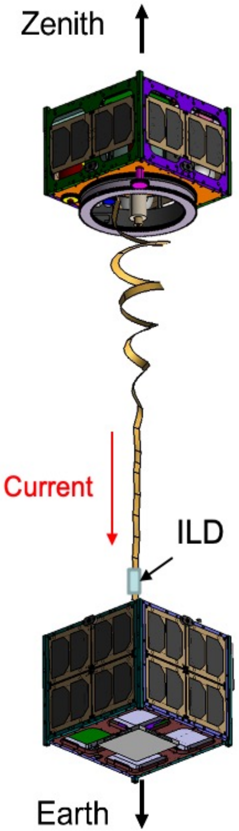
1. *Specific Deployment Velocities*
2. *Transition between the Aluminium and Peek sections of tape*
3. *Velocity ramp up from zero to 500 RPM of orbitator motor*
4. *Deployment profile*

Result: TRL 4-5

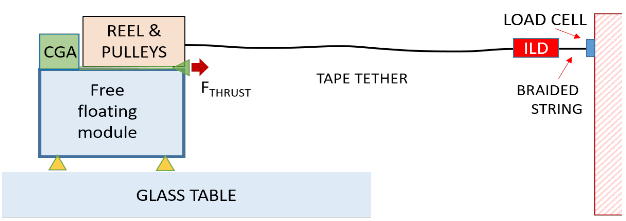
- ILD, design and manufacturing

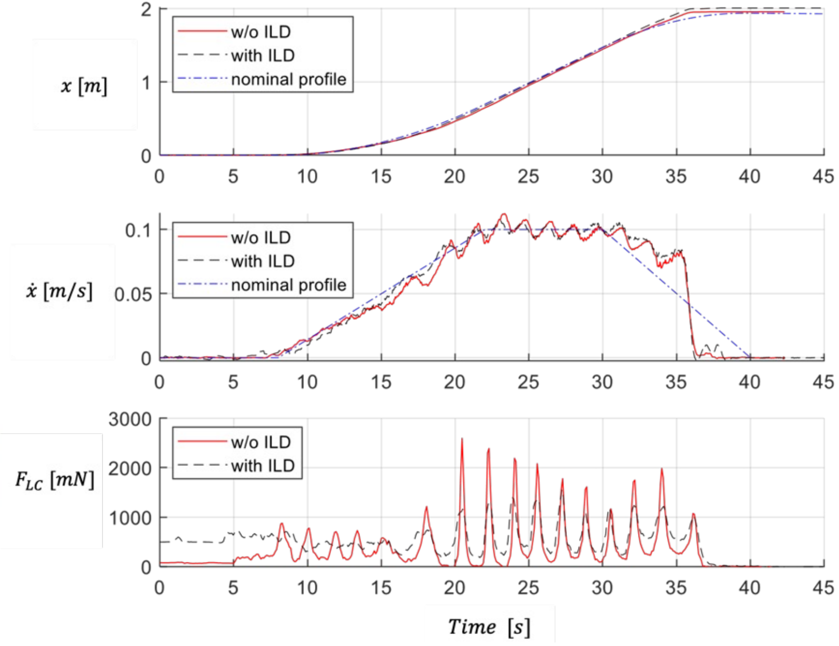
will be used to damp tether oscillations that can affect the deployer maneuver and the deployment trajectory and optimize performance of the system during deorbiting





- Tests





6. EDT for station-keeping

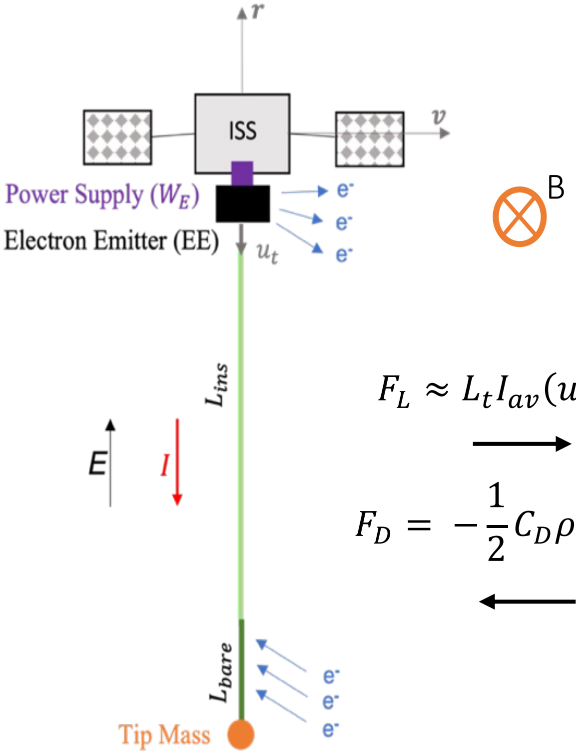
the case of the ISS

The ISS orbit at around 400 km and uses ~ 8 tons of fuel every year for station-keeping

- EDTs are a promising option for station-keeping operations:

Thrust generation (Active Mode). Thanks to a power source, that provides a power W_E , the electric current I flows in the opposite direction to the motional electric field ($E = v \times B$), satisfying $I \cdot E < 0$.

The objective is to identify control strategies, the amount of power that must feed the EDT to perform the ISS station keeping, and the optimum tether lenght.



$$F_L \approx L_t I_{av} (u_t \times B)$$

$$F_D = -\frac{1}{2} C_D \rho_{air} A v v$$

6.1 Control Strategies and optimization code

- **Altitude Variation** Considering the ISS subjected to the gravitational force, the air drag F_D, and the electrodynamic thrust F_L:

$$\frac{dH}{dt} = \frac{2r^2}{\mu} \frac{(\boldsymbol{F}_L + \boldsymbol{F}_D) \cdot \boldsymbol{v}}{m_{ISS}}$$

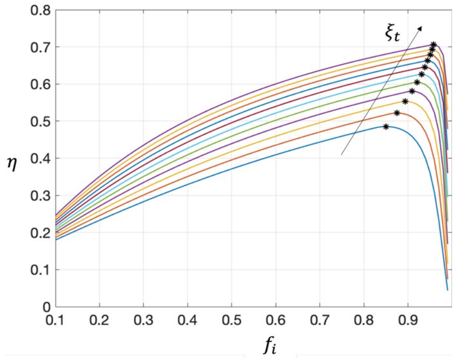
1. $\boldsymbol{dH/dt = 0}$: Air Drag Compensation Strategy

to adjust, instantaneously, the input power W_E to cancel out the power of the aerodynamic drag ($W_D = F_D \cdot v$) with the power of the Lorentz thrust ($W_L = F_L \cdot v$)

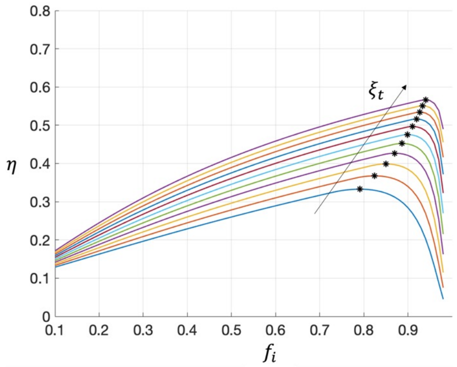
2. $\boldsymbol{dH/dt \neq 0}$: Zig-Zag Strategy

to reboost the ISS up to an altitude H_{max} whenever the satellite falls below a certain altitude H_{min}.

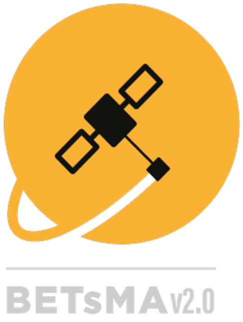
- **Optimal Design** A parametric analysis, based on a set of simplyfied hypotesis, varying ξ_t and f_i was used to compute the electrical power W_e



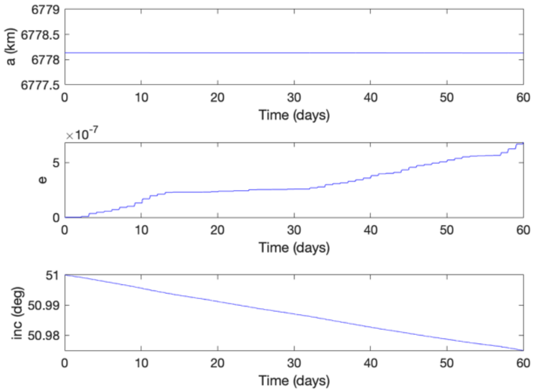
Result: the EDT mass is reduced with the respect to past works (i.e., Estes et Al. (2000)) by almost four times and the tether length by 40%, while the system efficiency is kept constant and around 0.60

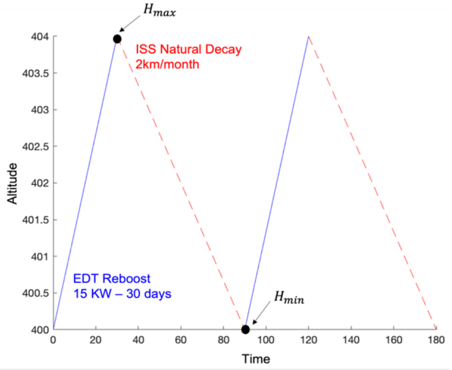


6.2 BETsMA simulations



BETsMA v2.0 is a software for EDT mission analyses that integrates the orbits numerically. Given a full set of input parameters, the software uses numerical models to obtain the environmental variables (e.g., IRI, IGRF, NLRMSISE) and computes the evolution of the orbit by solving the equations of motion of the satellite and the tether. BETsMA v2.0 uses, at every time step, the instantaneous values of the ambient values and it propagates the orbit of the satellite under the action of the gravitational force, the aerodynamic drag and the Lorentz's perturbation force.





Air drag compensation strategy

- High Tether Cut Probability.

The tether cut probability depends, in addition to the the tether geometry, on the mission duration. With BETsMA, that uses the MASTER 2009 debris flux model, a tether cut probability of ≅ 0.1% was computed, and this value is not enough to satisfy the stringent safety requirements of the ISS

↓

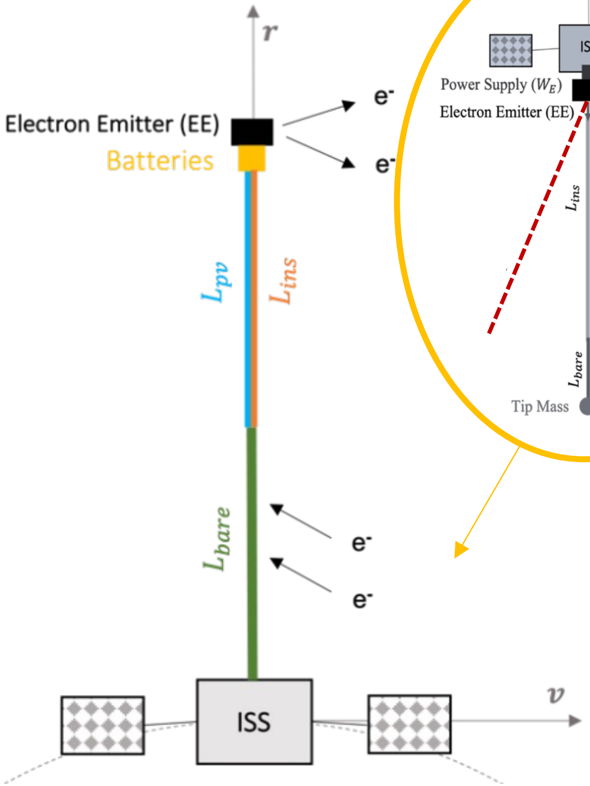
Zig-Zag strategy

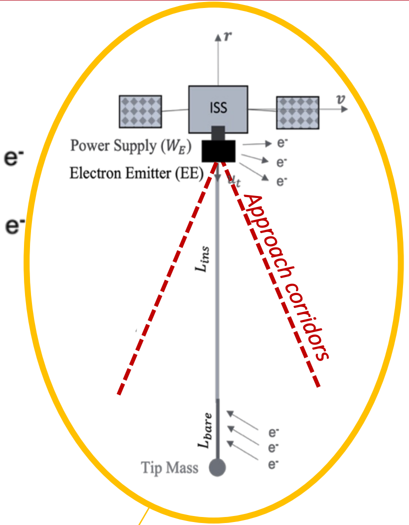
- *Since a cyclic tether deployment/retrieval is supposed for the Zig-zag strategy, the tether cut probability with the respect to the air drag compensation strategy is reduced of one order on magnitude (0.03%)*
- *A reboost simulation in constant power W_E = 15 KW, from H_{min} = 400 km to H_{max} = 404 km in 30 days.*

6.3 Bare Photovoltaic Tether

Since the power to feed the EE (at the top) needs to be sourced from the available electric power of the ISS, the EDT configuration must be downward (i.e., toward Earth). The downward-facing part of the ISS is highly regulated, with designated corridors for approaching vehicles. These corridors extend downward, forward (in the flight direction), and backward.

To meet the requirements of both the needed power and an upward tether deployment, a proposed solution is the implementation of a bare-photovoltaic tether (BPT) that combines a bare segment and a photovoltaic segment composed of thin film solar cells (Sunplugged GmbH)

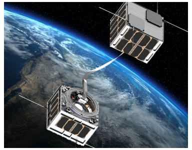


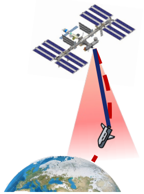


Stored power

Result: to perform the zig-zag strategy, that requires 15 KW to push the ISS up to 4 km in 30 days, the BPT must be longer. A 8 km-long tether with 90% of photovoltaic segment can be used.

7. Results and Gantt-Chart





	TASK TITLE	I Year (Oct 2020)												II Year (Oct 2021)	III Year (Oct 2022)	Proroga
	Space Tethers: Mechanical Properties Characterization															
1	**State of art**				31	31										
2	**Experiments on Tapes**					31	42	31								
2.1	*Young modulus*															
2.2	*Damping coefficient*															
2.3	*Uncertainty analysis*															
3	**SPARTANS Facility**							31	25	31						
3.1	*Tests on Space Tethers*															
4	**MATLAB © Simulations**								25	31	42	42	42			
4.1	*The equivalent system*															
5	**Optimization Code**								25	31	42	42	42			
5.1	*Optimization code for tethers*															
	A Momentum Exchange Tether for Space Return from The ISS in the context of Iperdrone.1 Program															
1	**State of art**	*	62													
1.2	*Feasibility study and analysis*															
1.3	*Requirement and goals*															
2	**Deorbiting strategy**		62	42	31											
2.1	*Strategy of deorbiting*															
3	**System Design**			42	31	31	42	31	25							
3.1	*Baseline design of the DM*															
4	**Software design**				31	31	42	31	25	31						
4.1	*Reference trajectory*															
4.2	*PD Control law*															
4.3	*Stability and sensors*															

*125 h = 1 month

Space Tethers, mechanical properties characterization
Mechanical properties for materials that exibit a higher degree of receptiveness were experimentally determined and validated.

Iperdrone.1, a MET for deorbiting
The use of a 9 km-long Momentum Exchange Tether can provide a real opportunity for releasing capsules from the ISS, eventually leading to their controlled deorbiting.

7. Results and Gantt- Chart

	TASK TITLE	I Year (Oct 2020)												II Year (Oct 2021)												III Year (Oct 2022)												Proroga		
	An Electrodynamic Tether for deorbiting in the context of the E.T.PACK Initiative																																							
1	**Study of the state of art**										42	42	42																											
1.1	*Requirement and goals*																																							
2	**DMM Design**													62	62	62	*	*	*	62	62	62																		
2.1	*Spool Design*																																							
2.2	*DM design*																																							
2.3	*In-line-damper design*																																							
3	**Test campaign**													62	62	62				62	62	62	*	*	*															
3.1	*Spool tests*																																							
3.2	*DM functional tests*																																							
3.3	*In-line damper tests*																																							
	Electrodynamic Tethers for Satellite Reboost: the example of the ISS																																							
1	**State of art**																									62	62	62												
2	**The EDT Model**																									62	62	62	*	*										
2.1	*Bare tether for reboost*																																							
2.2	*Control strategies*																																							
2.3	*Evolution of the or. elements*																																							
2.4	*BETsMA v2.0 simulations*																																							
3	**EDTs for station-keeping**																														*	*	*	*	*	*				
3.2	*Control strategies*																																							
3.3	*Tether optimal design*																																							
3.4	*BETsMA v2.0 simulations*																																							
3.5	*Bare Photovoltaic tether*																																							
	Other Activities																																							
	Educational Activities	30	30	30	30	30	30	30	30	30	30	30	20	30	30	30	30	30	30	30	30	30	30	30	20	4	4	4	4	4	4	4	4	4	4	4	6			
	Didactical support						10	10	10										10	10	10	10									10	10	10	10						
	Report /Admissions																																							
	Thesis																																							

**125 h = 1 month*

E.T.PACK Program, a BET for deorbiting

The advancements contributed significantly to the definition of the DM performances and TRL 4-5 was achieved.

Station-Keeping with EDTs, the case of the ISS

The potential of EDTs as an exhaust-less and environmentally friendly propulsion technology for satellite reboost and station-keeping operations was validated.

Publications

- <u>List of the publications included in the Ph.D. Thesis</u>
  - Journal and Books

[1] Brunello A., Valmorbida A., Lorenzini E., Cantoni S., De Stefano Fumo M., Fedele A., Gardi R., Votta R., (2020), Deorbiting small satellites from the ISS using a tether system, (2021), CEAS Space Journal, 13, 10.1007/s12567-020-00337-1.

[2] Brunello A., Valmorbida A., Lorenzini E., Cantoni S., De Stefano Fumo M., Fedele A., Gardi R., Votta R., Tethered Satellite-Controlled Re-Entry Dynamics From the International Space Station, (2021), IEEE Journal on Miniaturization for Air and Space Systems. PP. 1-1. 10.1109/JMASS.2020.3046182.

  - Conferences

[1] Brunello A., Olivieri L., Sarego G., Valmorbida A., Lungavia E., Lorenzini E., (2021), Space Tethers: Parameters Reconstruction and Tests, (2021, IEEE International Workshop on Metrology for Aerospace, Proceedings of the virtual conference MetroAerospace2021.

[2] A. Brunello, S. Garcia -Gonzalez, A. Valmorbida, G. Sarego, L. Olivieri, S. Fortuna, E. C. Lorenzini, Deployment Functional Tests Of An Electrodynamic Tape For Space Debris Mitigation, (2022), Proceedings the International Astronautical Congress IAC2022 – Paris.
(Finalist, Luigi Napolitano Award, Paris, 2022)

[3] A. Brunello, G. Anese, G. Borderes-Motta, A. Valmorbida, G. Sanchez-Arriaga, E. C. Lorenzini, Optimal design and current control strategies of an electrodynamic tape for ISS station-keeping. Proceedings of the International Astronautical Congress, IAC2023.
(Finalist, Young Pioneer Award, Baku, 2023)

Other research merits

- ## Journal and Books

[1] Sarego G., Olivieri L., Valmorbida A., **Brunello A**., Lorenzini E., Castellani L., Urgoiti E., Ortega A., Motta G., SanchezArriaga, G., (2021), Deployment requirements for deorbiting electrodynamic tether technology, (2021), CEAS Space Journal. 10.1007/s12567-021-00349-5. *(Best Paper Award – CEAS AerospaceEurope2020, Bordeaux)*

[2] Olivieri L., **Brunello A**., Sarego G., Valmorbida A., Lorenzini E.C, An in-line damper for tethers-in-space oscillations dissipation, (2021) Acta Astronautica, 189, pp. 559 – 566, DOI: 10.1016/j.actaastro.2021.09.012

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Other research merits

- International Patent

  In line Damper, damper device for Electrodynamic Tether Systems (“Smorzatore in linea per fili elettrodinamici”) 102021000027338 (10/11/2023), PCT International Extension WO2023/073533 (04/05/2023)

- Awards

  1. Best Paper Award at CEAS AerospaceEurope2020, Bordeaux (2020)
  2. Finalist, Luigi Napolitano Award 2022, IAC22, Paris (2022)
  3. Finalist, Young Pioneer Award 2023, IAC23, Baku (2023)

- Period spent abroad

  a) Research visit at *Sener Aerospacial* (Bilbao, Spain) in October 2021 (2 weeks)

  b) Research stay: 6 months at the *University Carlos III de Madrid* (Cotutela Program)

  - from 17th of October 2022 to 28th of February 2023 (4 months)
  - from 24th August 2023 to 30th October 2023 (2 months)

Thank you for the attention!

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