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A Review of Electrodynamic Tether Missions from a Dimensionless Analysis Perspective and to Promote the Opening and Support of Markets in the Space Sector

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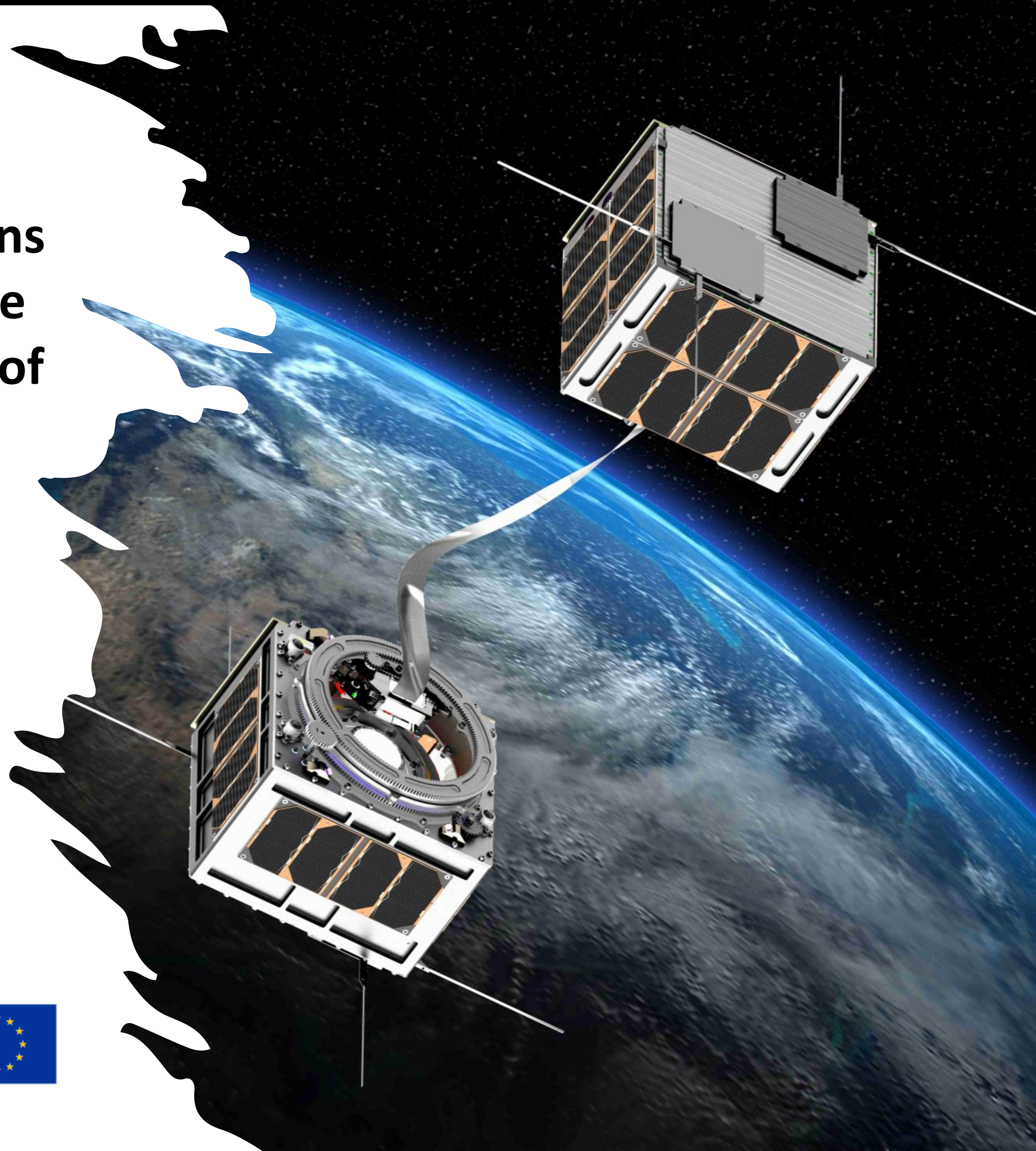

E.T.PACK-F

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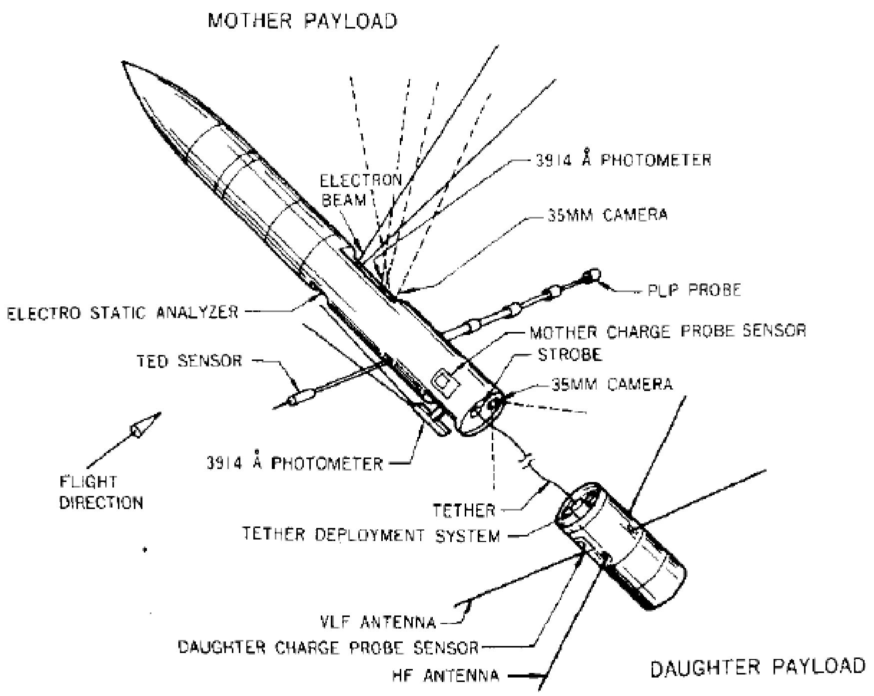
Review of missions with conductive tethers

About this work

- The information in this work was obtained from about 80 papers on tether missions
- The analysis was restricted to missions with conductive tethers
- Authors thank J. Carroll, Y. Ohkawa, M Nohmi, S. Kawamoto, and P. Janhunen for providing key information about some of the missions



Payload configuration of TPE-3 (Charge 1) from S. Sasaki et al., *J. of Spacecraft*, 24(5), 1987

Mission (Year)	Orbit (km)	Radius (mm)	Length (km)	Conductive Tether	Cathode
TPE-1 (1980)	Suborbital 328	0.33	0.4	Stainless steel	Electron gun
TPE-2 (1981)	Suborbital 322	0.33	0.5	Stainless steel	Electron gun
Charge-1 (1983)	Suborbital 218	0.33	0.5	Stainless steel	Electron gun
MAIMIK (1985)	Suborbital 381	0.25	0.4	Stainless steel	Electron gun
Charge 2 (1985)	Suborbital 262	0.33	0.5	Stainless steel	Electron gun
Echo-7 (1988)	Suborbital 292		0.06		Electron gun
OEDIPUS-A (1989)	Suborbital 512	1	1.2	Tin–Copper	None
Charge 2B (1992)	Suborbital 270		0.5		Electron gun
TSS-1 (1992)	$i = 28°$ 300×300	1.27	20	Cu	Electron gun
PMG (1993)	$i = 26°$ 874×193	0.79	0.5	Cu	Hollow cathode
Oedipus C (1995)	Suborbital 824	0.3	1.2	Tin–Copper	None
TSS-1R (1996)	$i = 28.5°$ 300×300	1.27	20	Copper	Electron gun

Missions in the 20th century

- All missions, except TSS-1, TSS-1R, and PMG, were suborbital flights
- Only TSS-1, TSS-1R, and PMG were designed to achieve good anodic and cathodic contacts
- All missions used insulated and round tethers
- Only PMG used a hollow cathode
- Key outcomes:
  - EDT operation in the *generator* and *thrust* modes
  - Dynamics of tethered satellites (vertical and spinning)
  - Spacecraft charging
  - Plasma wave excitation and propagation
  - Properties of the auroral ionospheric plasma
  - Determination of magenotosphere geometry
  - Measurement of electric fields

○ CYLINDRICAL TETHER

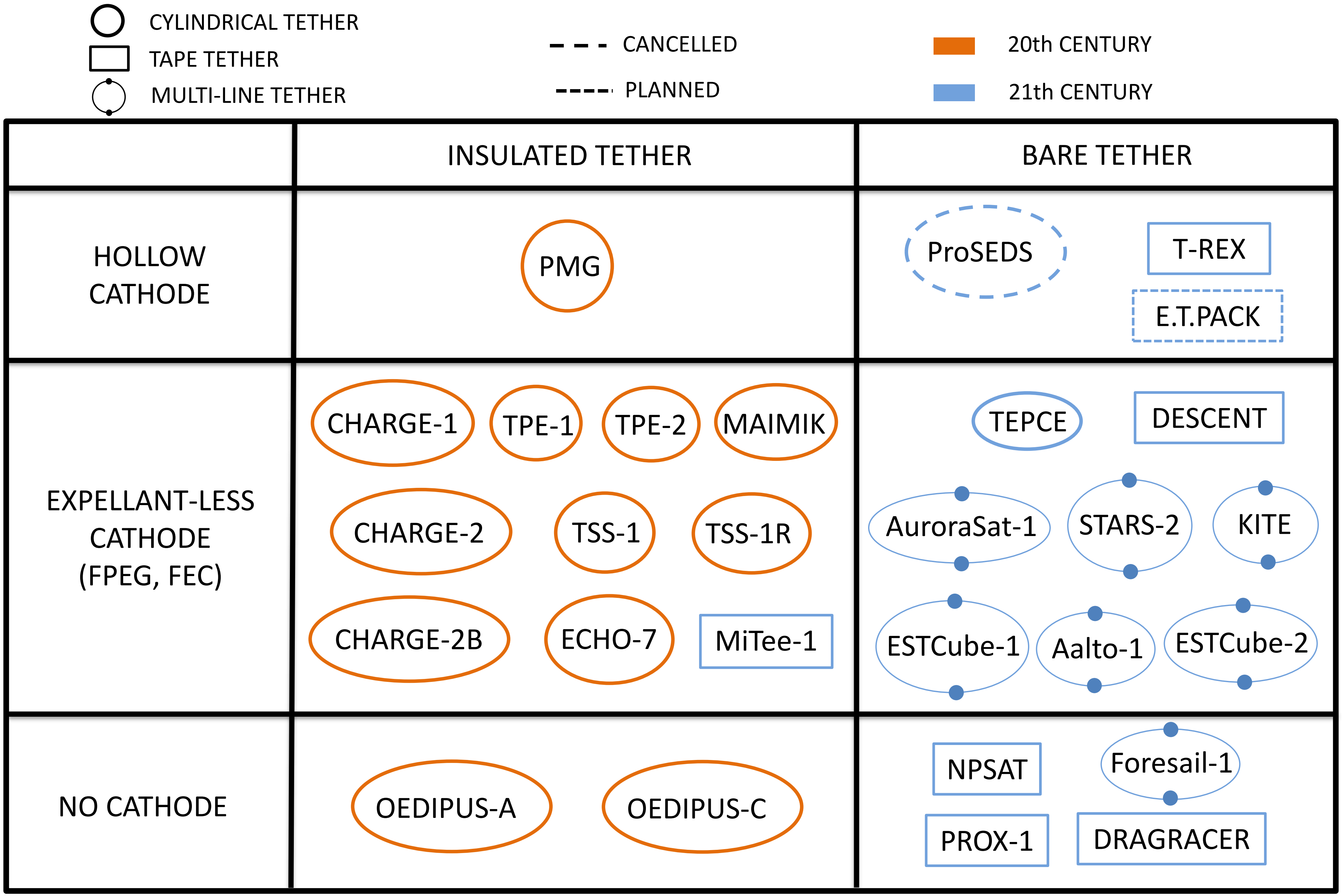
20th CENTURY

	INSULATED TETHER	BARE TETHER
HOLLOW CATHODE	PMG	
EXPELLANT-LESS CATHODE (FPEG, FEC)	CHARGE-1, TPE-1, TPE-2, MAIMIK, CHARGE-2, TSS-1, TSS-1R, CHARGE-2B, ECHO-7	
NO CATHODE	OEDIPUS-A, OEDIPUS-C	

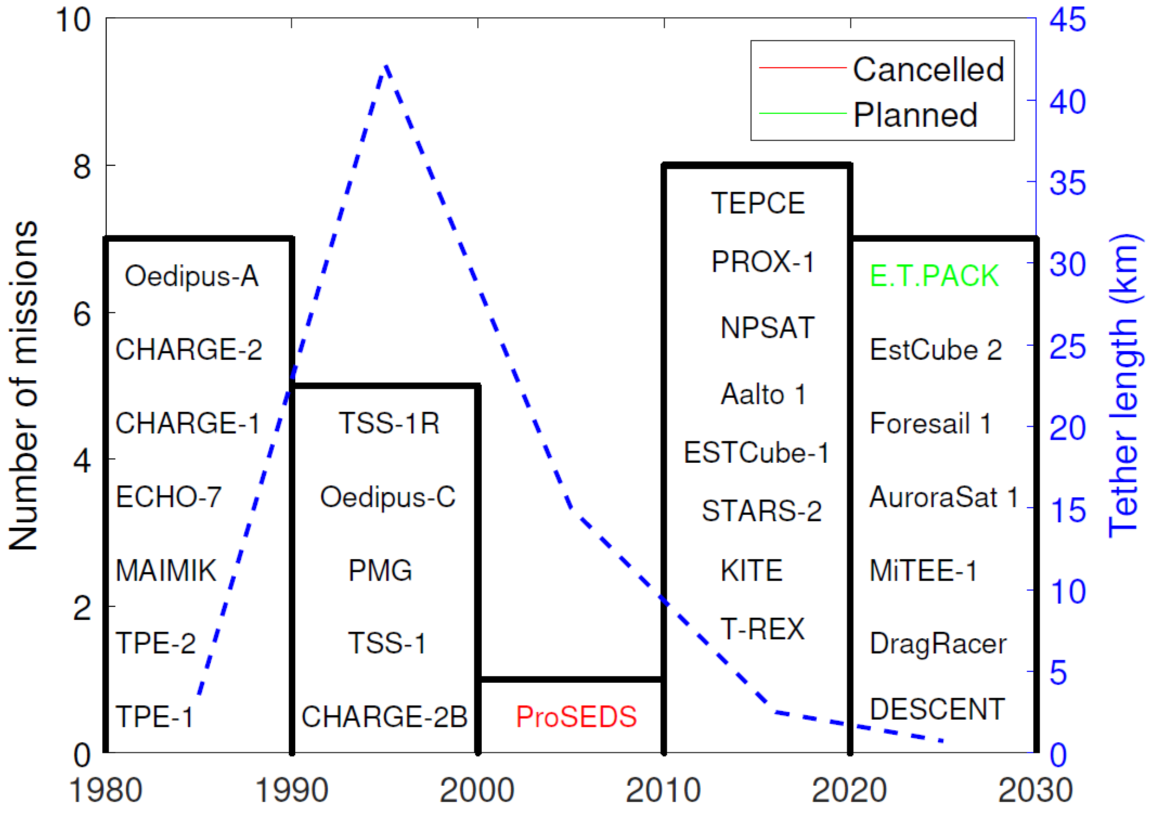
Missions in the 21th century

Name (Year)	Orbit (km)	Cross-Section (mm)	Length (km)	Tether Material	Cathode
ProSEDS (Canceled)	$i = 36°$ 275×275	Circular 0.6	15	Al + C-COR	Hollow cathode
T-REX (2010)	Suborbital 307	Tape 25×0.05	0.3	Al	Hollow cathode
ESTCube-1 (2013)	Orbital 665	Multiline $0.0125 - 0.025$	0.015	Al	Electron gun
STARS-2 (2014)	$i = 65°$ 380×380	Multiline	0.3	Stainless steel + Al	Electron gun
KITE (2016)	$i = 52°$ 370×370	Multiline	0.72	Stainless steel + Al	FEC
Aalto-1 (2017)	$i = 97°$ 497×517	Multiline $0.0125 - 0.025$	0.1	Al	Electron gun
NPSAT (2019)	$i = 24°$ 720×720	Tape $150 \times ?$	0.07	Metalized films + aramid fibers	None
PROX-1 (2019)	$i = 24°$ 705×725	Tape $150 \times ?$	0.07	Metalized films + aramid fibers	None
TEPCE (2019)	$i = 28{,}5°$ 297×848	Braided 1.6×0.25	1.03	Ni-Cu	Electron gun
DESCENT (2020)	$i = 52°$ 411×420	Tape 5×0.035	0.1	Polymer + Al coating	FEC
Dragracer (2020)	$i = 52°$ 400×400	Tape $150 \times ?$	0.07	Metalized films + aramid fibers	None
MiTEE-1 (2021)	$i = 51.5°$ 500×500	Circular Boom	0.001		Electron gun
AuroraSat-1 (2022)	Orbital 500×550	Multiline 0.025	0.5	Al	Electron gun
Foresail-1 (2022)	$i = 97.5°$ 530×530	Multiline 0.05	0.06	Al	None
ESTCube-2 (2023)	Orbital 564	Multiline 0.025	0.05	Al	Electron gun
E.T.PACK (Planned)	$i = 50°$ 600×600	Tape 25×0.04	0.5	Al	Hollow cathode

- ProSEDS had a high performance EDT (bare tether + HC) but was cancelled
- After ProSEDs, later missions were based on miniaturized hardware
- There is a variety of cross-sections: round, tape, multi-line
- All tethers were bare except the one of MiTEE-1
- A variety of cathodic contactors (HC, thermionic emitter and FEC) was used
- Missions can be organized into three categories:
  - **EDT missions**: ProSEDS, T-REX, STARS-2, KITE, TEPCE, DESCENT, MiTEE, E.T.PACK
  - **Electrostatic tether missions**: ESTCube-1, Aalto-1, AuroraSat-1, Foresail-1, ESTCube-2
  - **Terminator Tape™**: NPSAT, PROX-1, Dragracer


CYLINDRICAL TETHER
TAPE TETHER
MULTI-LINE TETHER
CANCELLED
PLANNED
20th CENTURY
21th CENTURY
INSULATED TETHER
BARE TETHER
HOLLOW CATHODE
PMG
ProSEDS
T-REX
E.T.PACK
EXPELLANT-LESS CATHODE (FPEG, FEC)
CHARGE-1
TPE-1
TPE-2
MAIMIK
CHARGE-2
TSS-1
TSS-1R
CHARGE-2B
ECHO-7
MiTee-1
TEPCE
DESCENT
AuroraSat-1
STARS-2
KITE
ESTCube-1
Aalto-1
ESTCube-2
NO CATHODE
OEDIPUS-A
OEDIPUS-C
NPSAT
Foresail-1
PROX-1
DRAGRACER

Number of missions and tether length



- The twelve missions in the 20th century flew more than 45 km of tether
- However, less than 4 km were flown in the 14 missions flown in the 21th century
- The cancellation of ProSEDS severely impacted tethers development
- The lack of funding and big projects delayed the in-orbit demonstration of the high-performance EDT (bare tether+HC)

Dimensionless number of missions using conductive tethers

Parameter	ProSEDS	PROX-1	TEPCE	E.T.PACK
L_b (m)	5000	70	1030	450
L_i (m)	10000	0	0	50
A_c (mm^2)	0.53	3	0.02	1
p_b (mm)	3.8	300	1.4	50
σ_t ($\times 10^7/\Omega$m)	3.54	3.54	3	3.54
R_{eq} (mm)	0.6	37.5	0.4	6.3
L_* (m)	2100	360	425	570
I_{av} (mA)	1400	2.4	10	500
A (m^2)	23.7	6.7	0.45	8
$\|W_L\|$ (W)	1060	0.025	1.54	33.7
$\|W_A\|$ (W)	32.11	9.06	0.61	10.8
m_P	20.4	63	1.64	13
m_C	994	1.0	1.64	9.7
m_t	12	0.5	0.42	1.3
f_e	0.6	0.36	0.6	0.6

- Four representative missions were selected: ProSEDS, PROX-1, TEPCE, and E.T.PACK
- To compare them, we used the parameters in the table and $E_m = 150$ V/km, $N_0 = 5 \cdot 10^{11}$ 1/m^3, $\rho_a = 3 \cdot 10^{-12}$ kg/m^3.
- Since some key characteristics were not available for some of these missions, we estimated them
- Such estimation does not affect the main conclusions of this work

Dimensionless number of missions using conductive tethers

Parameter	ProSEDS	PROX-1	TEPCE	E.T.PACK
$eE_\mathrm{m}L_\mathrm{b}/k_\mathrm{B}T_\mathrm{e}$	6250	87.5	1287	563
$R_\mathrm{eq}/R_\mathrm{max}$	0.2	13	0.14	2.14
L_b/L_*	2.4	0.2	2.4	0.8
$W_\mathrm{L}/W_\mathrm{A}$	33	0.0028	2.54	3.12
h_CoM/L	0.97	0.98	0.5	0.4
L_i/L_b	2	0	0	0.11
ϵ_D	0.041	0.025	0.02	0.32

- R_{eq}/R_{max}: equivalent-to-maximum OML radius ratio
- L_b/L_*: bare-to-tether characteristic length ratio
- W_L/W_A: Lorentz-to-aerodynamic power ratio
- h_{COM}/L: center of mass distance-to tether length ratio
- L_i/L_b: inert-to-bare tether length ratio
- ϵ_D: Lorentz-to-gravity gradient torque ratio

- All missions satisfy the high bias condition
- ProSEDS and TEPCE satisfy OML condition
- E.T.PACK does not collect electrons under OML conditions (but almost)
- PROX-1 current collection is expected to be about 50% of that predicted by OML
- Ohmic effects are small in PROX-1 and E.T.PACK
- PROX-1 mainly acts as a drag augmentation devices, with the aerodynamic drag clearly dominating the electrodynamic drag
- To mitigate the dynamic instability, the E.T.PACK mission: (i) has an inert segment, (ii) limits the current, (iii) has an in-line damper

Opening new markets and opportunities

- DEORBITING
  - The post-mission disposal time of 5 years (FCC and ESA) already opened a market for deorbit devices because objects above around 500 km need propulsion to satisfy the regulation
  - Besides helping to satisfy the law, tethers can add value:
    - Collecting scientific data while deorbiting
    - Reducing the insurance cost (taking advantage of its capability to produce drag & thrust)
    - Harvest power while deorbiting

- DRAG COMPENSATION
  - EDTs can be an enabler for missions at very low LEO; however, power is needed to produce thrust
  - The bare-photovoltaic tether* (BPT) combines power + propellant-less force in a single device
  - The E.T.COMPACT project (EIC Pathfinder) will carry out R+D activities on the BPT

* Tajmar and Sanchez-Arriaga, A bare-photovoltaic tether for consumable-less and autonomous space propulsion and power generation, *Acta Astronautica*, 2021.

Opening new markets and opportunities

- IN-ORBIT SERVICING
  - According to Euroconsult, IoS will generate a market of about $4.4 billion by 2031 on life extension, active debris removal, etc.
  - As explained in previous works (see for instance EDDE, Levin's book, etc.), EDTs can be a key technology for
    - Reaching high-efficient orbital mobility to IoS vehicles, which could use an EDT for deorbiting and reboosting without propellant
    - Preparing compact deorbit devices that could be installed in the customer for active debris removal scenarios

- EMBODIED ENERGY REPURPOSING (see McTernan, S. G. Bilén, *J. Spacecraft and Rockets*, 2017)
  - Three simultaneous benefits: power generation + deorbiting + life extension

- SCIENTIFIC MISSIONS
  - In LEO (see past tether missions) and also to explore planets with magnetosphere

Conclusions

About the missions

- Past tether missions demonstrated a great variety of applications and singular features.
- However, the high performance EDT (bare tether + HC) has never been demonstrated on-orbit

Dimension-less parameter analysis

- Each tether mission involves many dimension-less parameters (in E.T.PACK we computed about 20)
- Sharing data of next EDT missions can maximize the lessons-learned and boost EDT development.

About market and opportunities

- Except power harvesting, past EDT missions already demonstrated the key capabilities of future products.
- Four simultaneous events and happening in Europe and can trigger a turning point for EDTs:
    - The European Innovation Council provided funds and stability to a team through 3 projects: E.T.PACK, E.T.PACK-F and E.T.COMPACT
    - The deorbit device of E.T.PACK, which involves a bare tether with a HC, will be flown in 2025
    - The new company PERSEI SPACE has been founded (see presentation on Wednesday)
    - The European Space Agency is promoting the Zero Debris Approach

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Thank you for your attention !

More information about E.T.PACK at

www.etpack.eu

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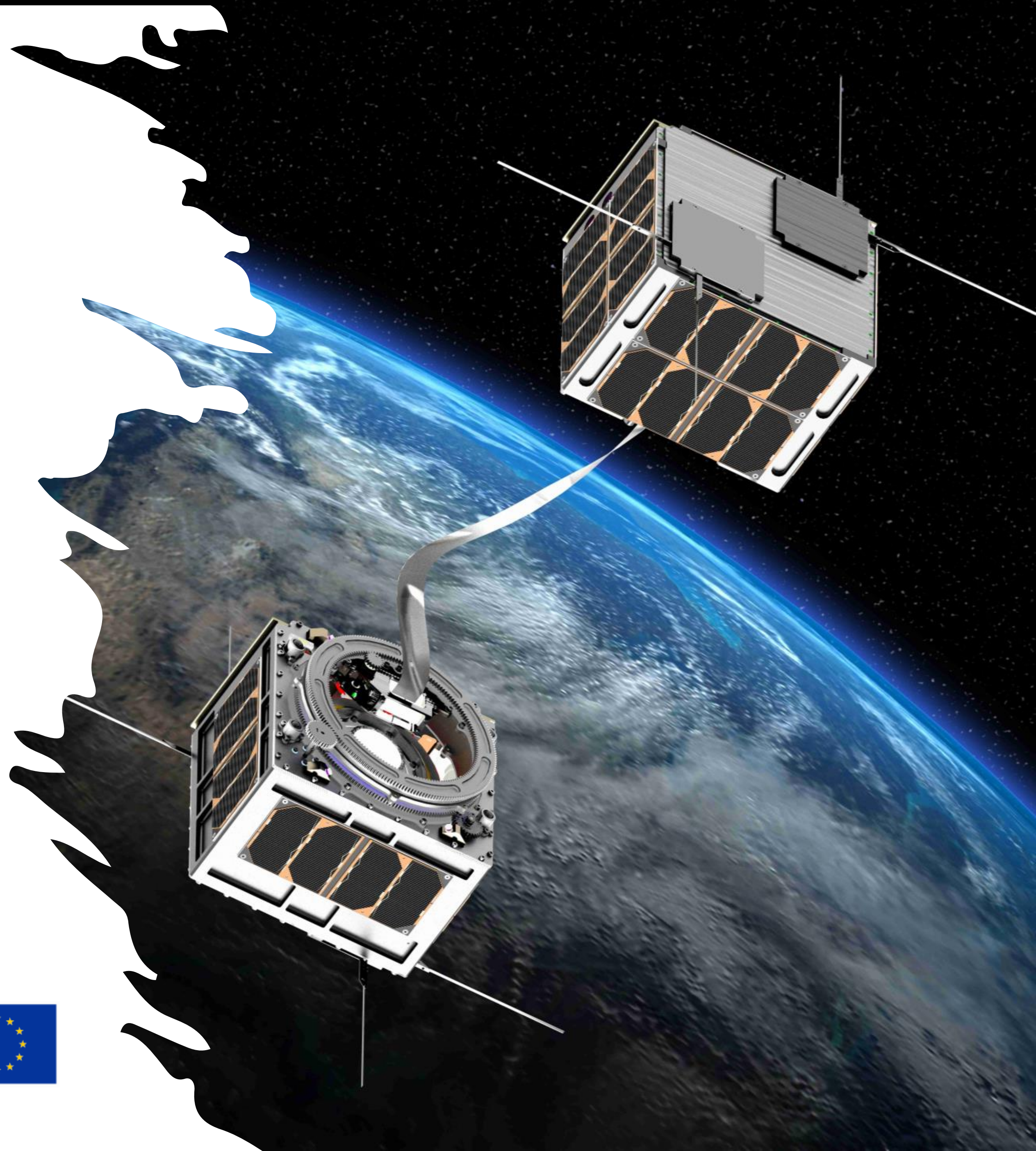

E.T.PACK-F

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Conclusions

About market and opportunities

- Past EDT missions already demonstrated most of the key performance/capabilities that are needed to be implmented in future products: propellant-less thrust and drag and capability to provide scientific data
- To the best of our knowledge, power was dissipated in past tether missions but none of them harvested power to be use onboard
- Four simultaneous events, which can trigger a turning point for EDTs, are happening in Europe:
    - The European Innovation Council provided funds and stability to a team through 3 projects: E.T.PACK, E.T.PACK-F and E.T.COMPACT
    - The deorbit device of E.T.PACK, which involves a bare tether with a HC, will be tested in 2025
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