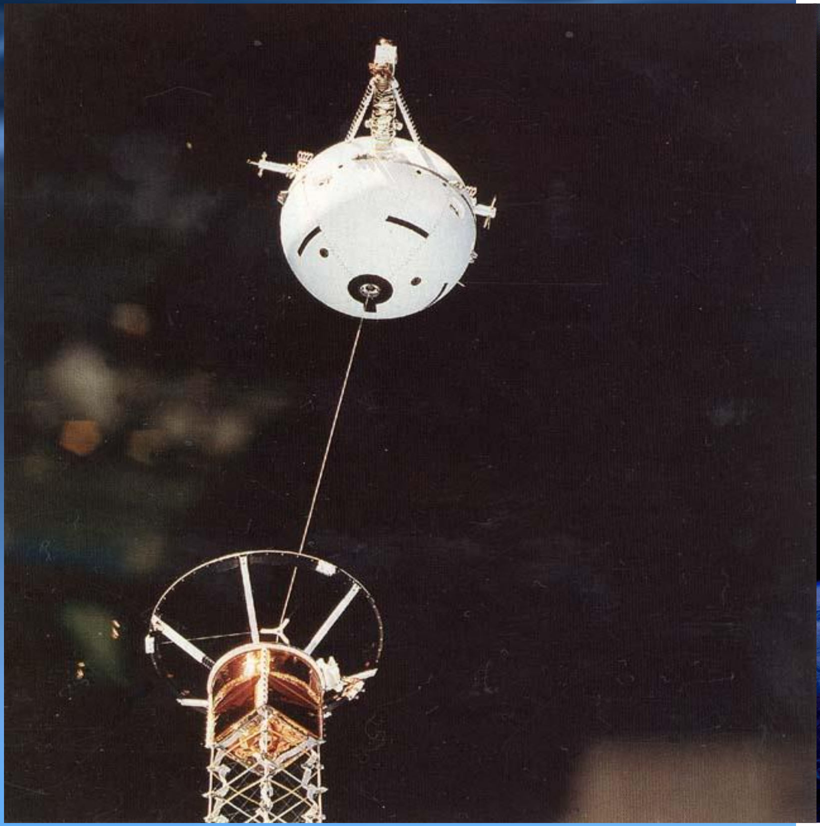
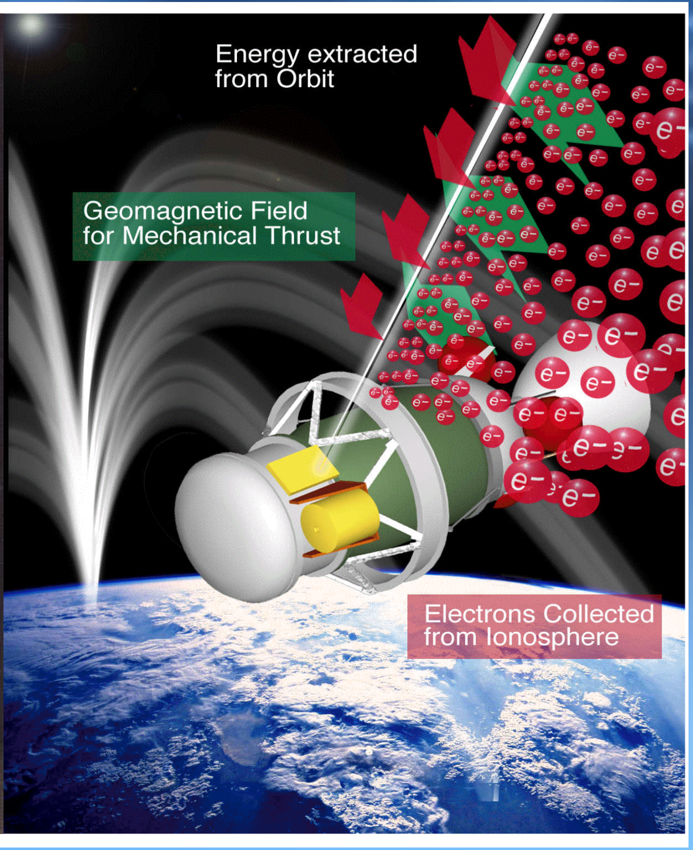




The evolution of space tethers technology

Enrico Lorenzini - University of Padova

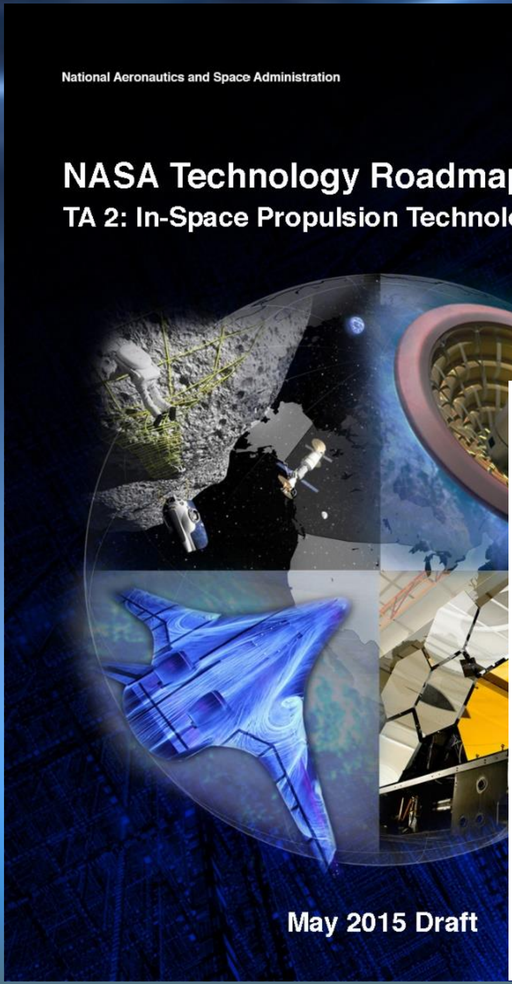
UNIVERSITÀ DEGLI STUDI DI PADOVA

CISAS G. COLOMBO

Presentation outline

- Benefits of tethers in space *according to NASA*
- Tether missions flown thus far
- Types and shapes of tethers
- Evolution of anode technology for EDTs
- Deployment control laws
- Applications of electrodynamic tethers
- Concluding Remarks

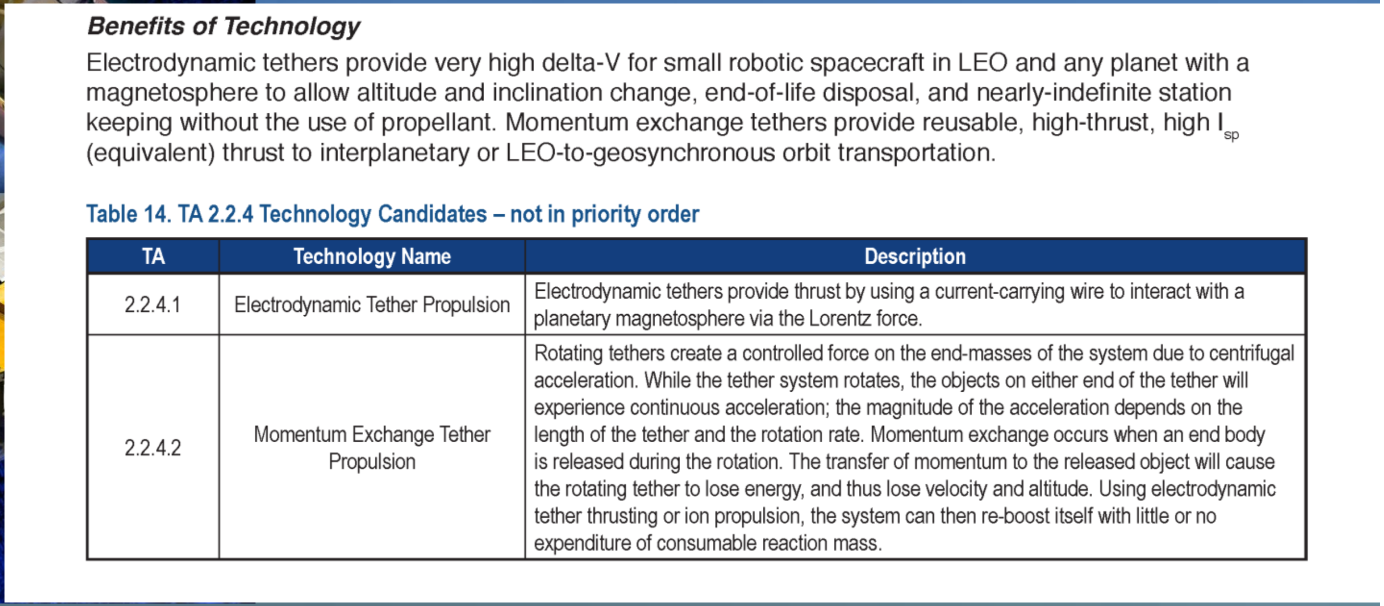
Benefits of tethers in space - NASA



National Aeronautics and Space Administration

NASA Technology Roadmaps
TA 2: In-Space Propulsion Technologies

May 2015 Draft



Benefits of Technology

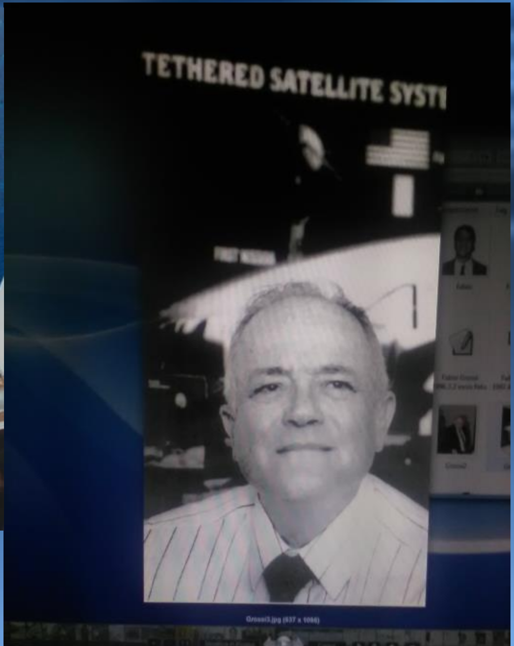
Electrodynamic tethers provide very high delta-V for small robotic spacecraft in LEO and any planet with a magnetosphere to allow altitude and inclination change, end-of-life disposal, and nearly-indefinite station keeping without the use of propellant. Momentum exchange tethers provide reusable, high-thrust, high I_{sp} (equivalent) thrust to interplanetary or LEO-to-geosynchronous orbit transportation.

Table 14. TA 2.2.4 Technology Candidates – not in priority order

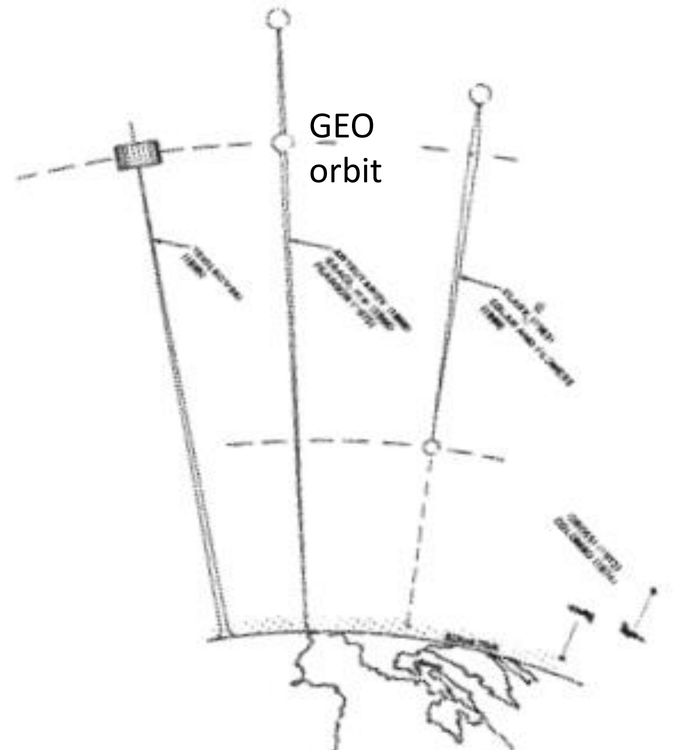
TA	Technology Name	Description
2.2.4.1	Electrodynamic Tether Propulsion	Electrodynamic tethers provide thrust by using a current-carrying wire to interact with a planetary magnetosphere via the Lorentz force.
2.2.4.2	Momentum Exchange Tether Propulsion	Rotating tethers create a controlled force on the end-masses of the system due to centrifugal acceleration. While the tether system rotates, the objects on either end of the tether will experience continuous acceleration; the magnitude of the acceleration depends on the length of the tether and the rotation rate. Momentum exchange occurs when an end body is released during the rotation. The transfer of momentum to the released object will cause the rotating tether to lose energy, and thus lose velocity and altitude. Using electrodynamic tether thrusting or ion propulsion, the system can then re-boost itself with little or no expenditure of consumable reaction mass.

Tethered satellite pioneers

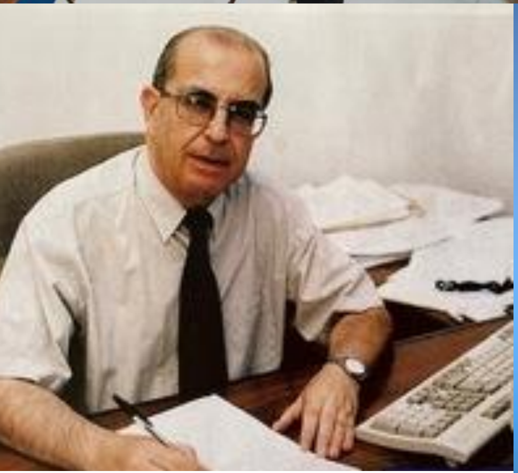
Giuseppe "Bepi" Colombo,
Universitá di Padova



Mario Grossi, Smithsonian Astrophysical Observatory



Tsiolkovsky, 1895; Arsutanov, 1960; Isaacs, 1966; Pearson 1975, Grossi 1983, Colombo 1984, Sanmartin, 1993, and many others

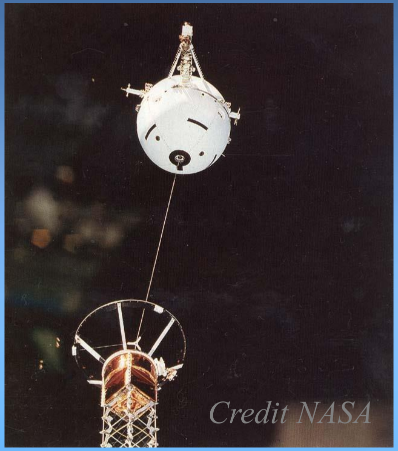


Juan Sanmartin, Universidad Politecnica de Madrid

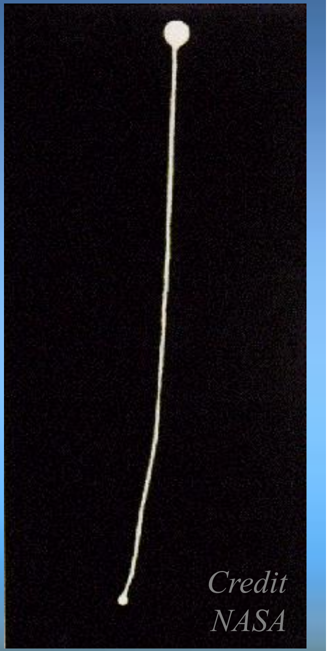
Tethered-satellite missions (not all)

NAME	Date	Orbit	Length	Agency	Comments
H-9M-69	1980	suborbital	500 m	NASA	partial deployment
S-520-2	1981	suborbital	500 m	NASA	partial deployment
Charge-1	1983	suborbital	500 m	NASA	full deployment
Charge-2	1984	suborbital	500 m	NASA	full deployment
Oedipus-A	1989	suborbital	958 m	Canadian NRC/NASA	spin stable 0.7 rpm, magentic field aligned
Charge-2B	1992	suborbital	500 m	NASA	full deployment
TSS-1	1992	LEO	<1 km	NASA/ASI	electrodynamic, partial deployment & retrieval
SEDS-I	1993	LEO	20 km	NASA	downward full deployment, swing & cut
PMG	1993	LEO	500 m	NASA	electrodynamic, upward deployed
SEDS-II	1994	LEO	20 km	NASA	full deployment, local vertical stable
Oedipus-C	1995	suborbital	1 km	Canadian NRC/NASA	spin stable 0.7 rpm, magnetic field aligned
TSS-1R	1996	LEO	19.6 km	NASA/ASI	electrodynamic, close to full deployment, severed
TiPS	1996	LEO	4 km	NRL	long life tether on-orbit (~10 years)
ATEx	1999	LEO	6 km	NRL	partial deployment
ProSEDS*	2003	LEO	15 km	NASA	H/W built but not flown
MAST	2004	LEO	1 km	NASA	Cubesat - did not deploy
YES2	2007	LEO	32 km	ESA	full deployment, swing & release of reentry capsule
T-REX	2010	suborbital	135 m	JAXA	flat bare-tether technology
KITE	2017	Orbital	700 m	JAXA	did not deploy
TEPCE	2019	Orbital	1 km	NRL	deorbited in 2 months
Dragracer	2020	Orbital	70 m	Private	Metallized tape, no cathode Deorbited in 8 months

KITE-Kounotori, JAXA (2017)



TSS-1R, NASA/ASI, deploys from Shuttle (1996)



SEDS-II in orbit, NASA (1994)

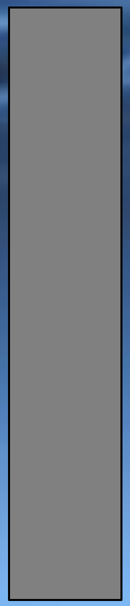
Types and shapes of tethers in space

Tether Configurations

Single line (multi-strand)

Caduceus

Hoyt tether



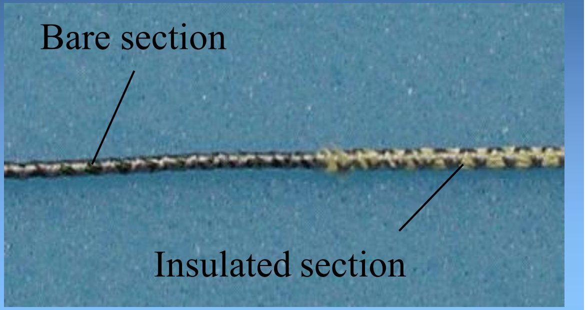
Al-alloy tape

- Improving survivability to M/OD impacts and e^- collecting area

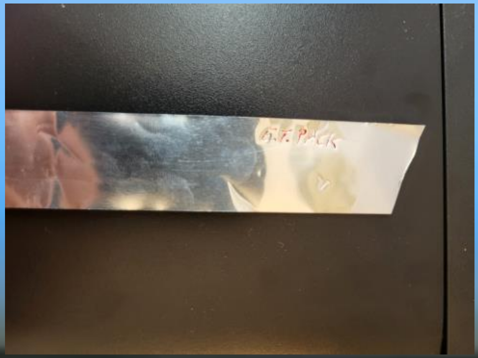
Electrodynamic Tether Examples

- **TSS tether**: 10 strands #34AWG Copper wires wrapped around a Nomex core and insulated with Teflon jacket + kevlar overbraid + nomex overbraid. length = 20 km; mass = 167 kg
- **ProSEDS bare tether**:
  7 strands #28AWG Aluminum wires conformally coated with conductive polymer and wrapped around Kevlar core. length = 5 km; mass ≈ 10 kg
- E.T.PACK bare tape: flat Aluminum tape 25 mm wide; length = 450 m; mass ≈ 1 kg

TSS ED tether



ProSEDS ED tether

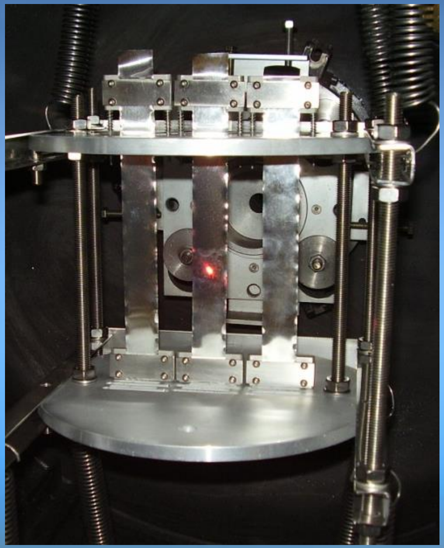


E.T.PACK tape

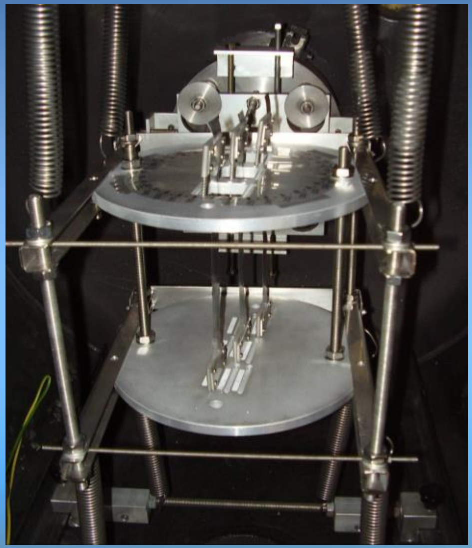
Testing Hypervelocity Impacts on tapes

Hypervelocity lab.: A. Francesconi, CISAS-UniPD

- ***Test equipment***
  - *CISAS-UniPD light-gas accelerator*
  - *Taylored tether support structure for multiple samples to maximize the test success rate even at high impact angles (up to 90°)*

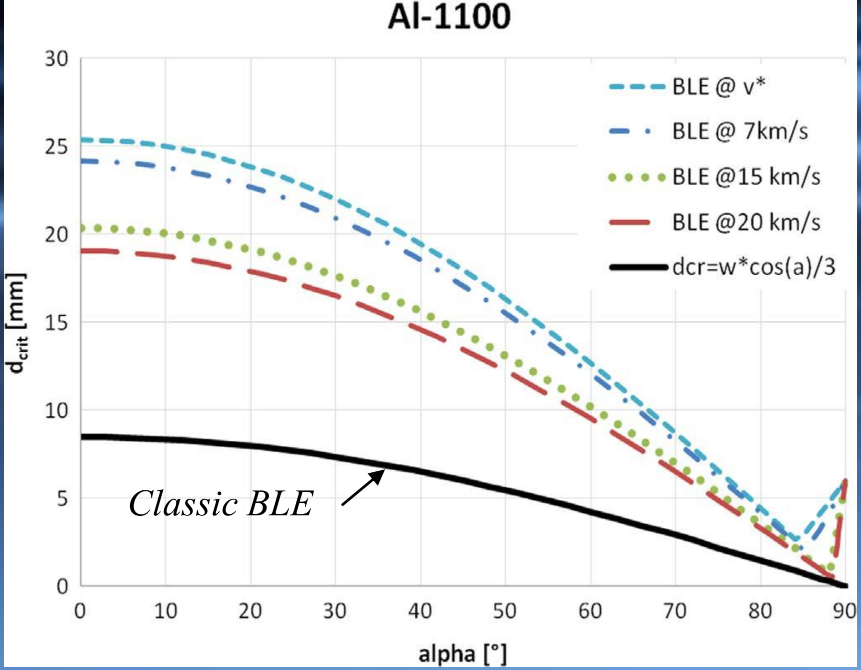


$\alpha_{loc} = 0°$ *(flat on)*

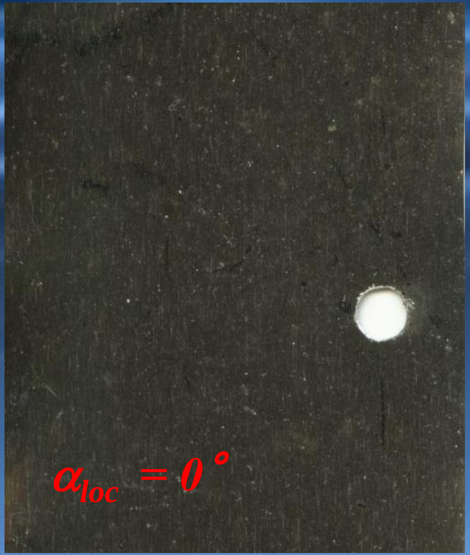


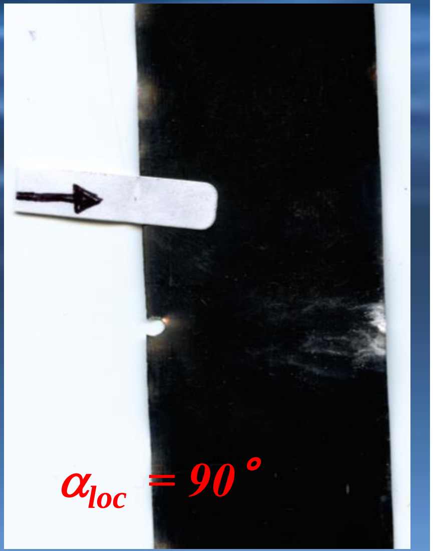
$\alpha_{loc} \approx 90°$ *(edge on)*

Survivability of tapes to M/OD impacts



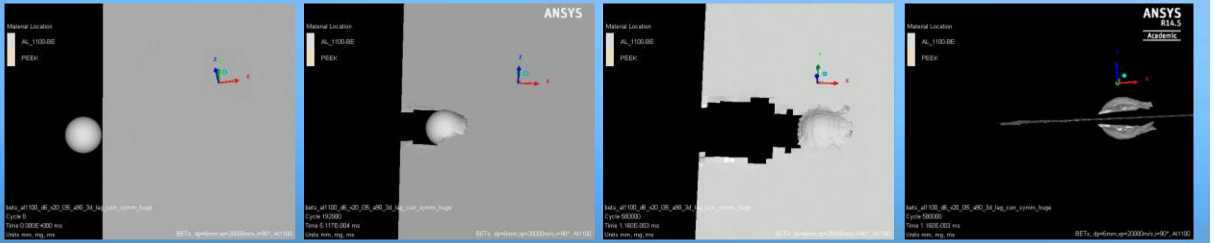
New Ballistic Limit Eqn (BLE) for *Al* tape, *[Francesconi et al, Acta Astronautica, 2016]*





From impact tests at V_{impact} = 4.5 km/s

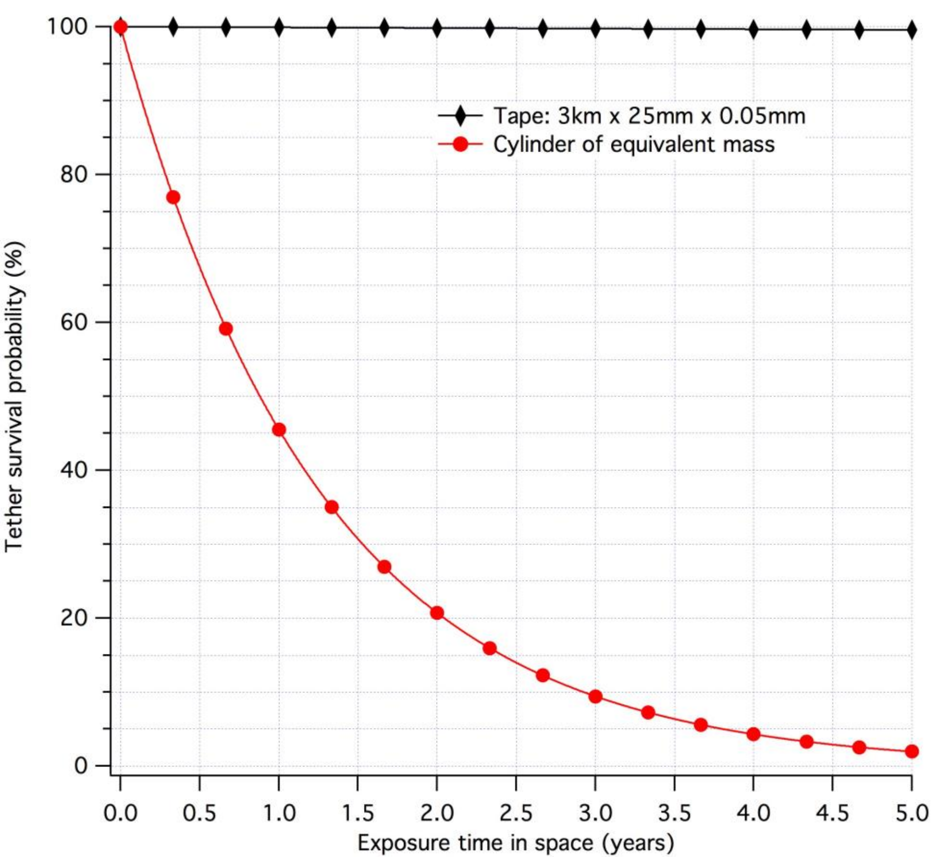
[From project BETs, EC-FP7 Program, 2014]



The screenshot on the right shows that the debris fractured into two pieces.

Survivability to small impacts (M/ODs)

- Tapes are more than 2 orders of magnitude more survivable to M/OD impacts than single-line cylindrical tethers of equal mass
- Caduceus and Hoyt tethers are also highly more survival than single-line tethers depending on number of lines and interconnections



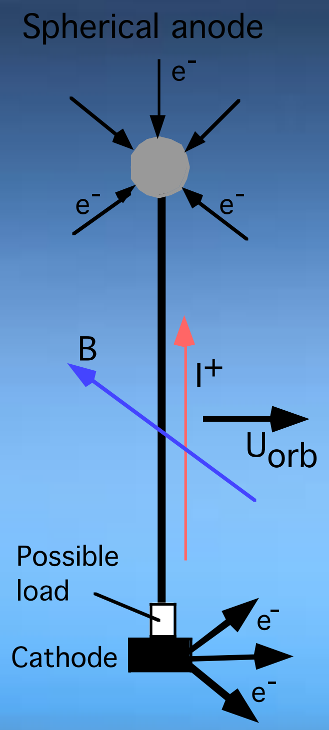
Evolution of space tethers anodes

Spherical Anodes (electron collectors)

- Tether current is driven by e.m.f. and limited by tether anode collection efficiency, tether and load impedances (if load is present)
- Spherical anodes collect ionospheric electrons according to the Parker-Murphy (PM) law

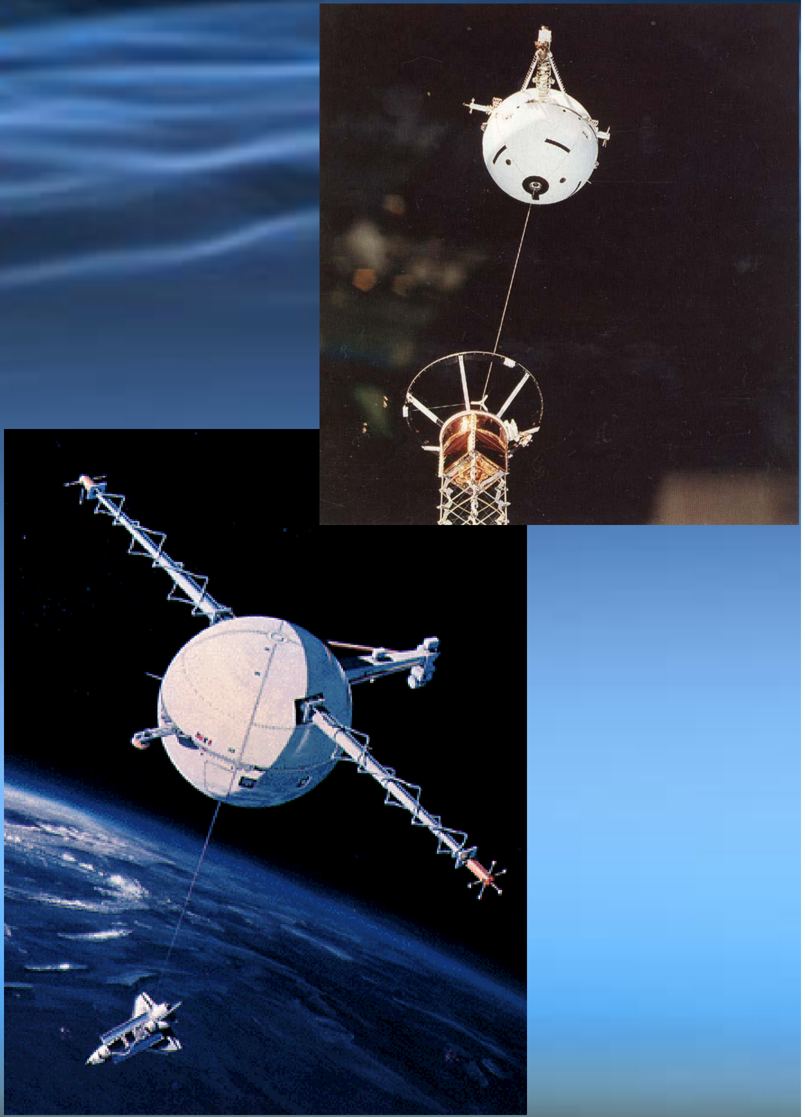
$$I_{PM} = J_{th} \cdot 4\pi R_S^2 \cdot \left[1/2 + \left(l_e / R_S \right) \cdot \sqrt{2eV_a / \left(kT_e \right)} \right]$$

J_{th} = thermal current density; l_e = electron gyro radius
R_S = sphere radius; V_a = anode bias voltage
kT_e = electron energy (eV)



TSS-1R flight (1996)

- TSS-1R used a 20-km ED tether (all insulated)
- Satellite/anode: 1.6-m-diameter *spherical anode*
- Deployed in 1996 from Shuttle Columbia at 300 km of altitude
- Satellite lost to electrical spark that severed tether at a length of 19.6 km
- Had 12 on-board/ground experiments
- Produced good data on electron collection during the mission life span



TSS-1R Flight Results

- TSS-1R electrodynamic data showed a current ~3 time higher than predicted by PM law
- Current vs. voltage follows general trend of PM law
- The max. current registered *(not shown here)* of 1 A was limited by electron gun (cathode) performance

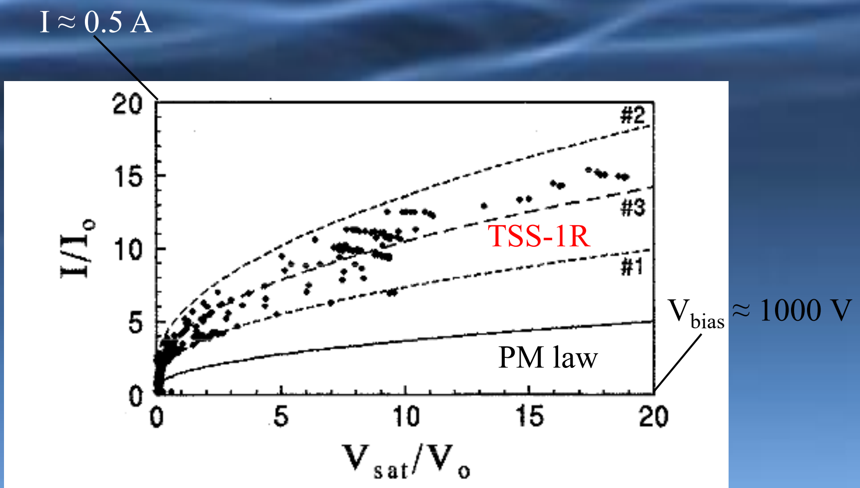
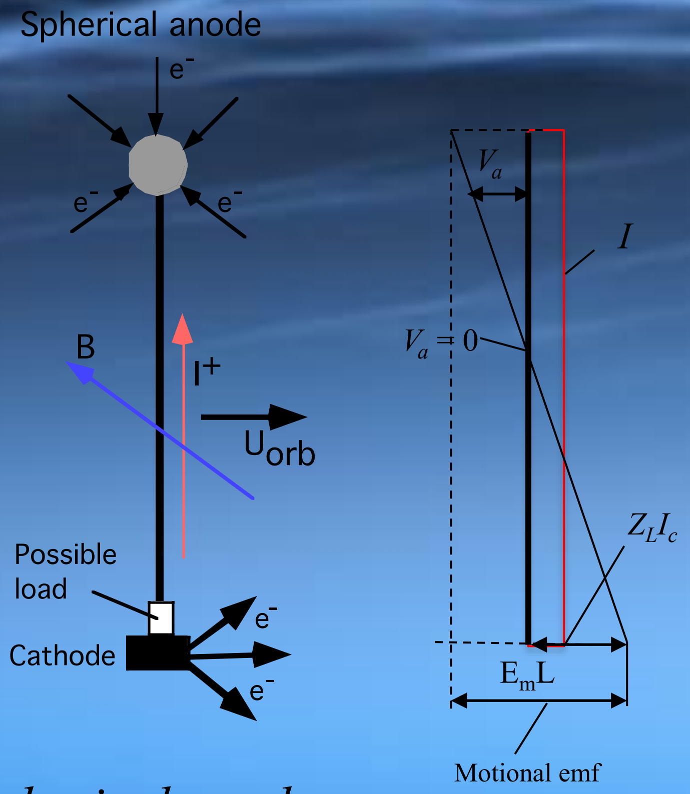


Figure 2. Cumulative representation of all the experimental I-V characteristics obtained during the IV-24 cycles plotted vs. V_{sat}/V_0. The solid line is the curve of the PM model. The dashed line #3 represents the best fit of data with the typical 1/2 power law of the PM model. This corresponds to the PM curve enhanced of a factor 2.85. The two dashed lines #1 and #2 are the curves obtained by considering the uncertainties on n_e and T_e of +20% (line #1) and -20% (line #2).

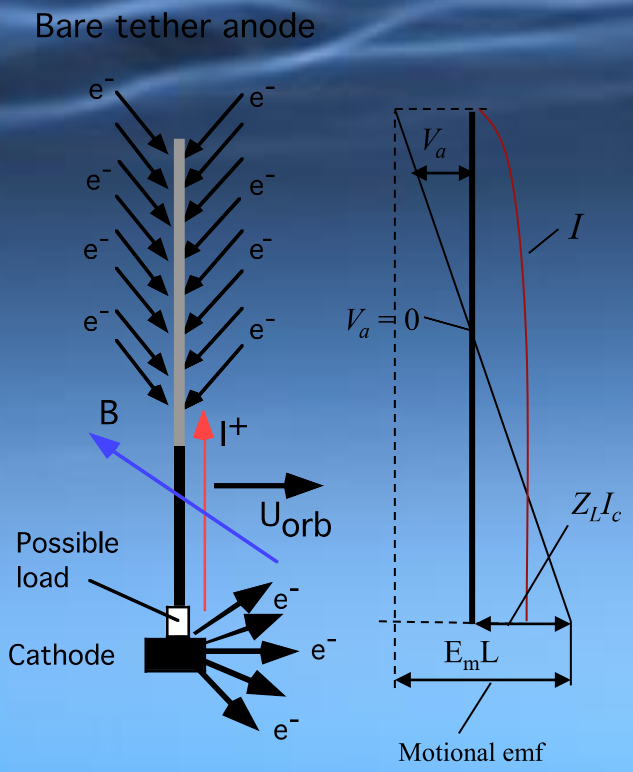
[Vannaroni et al. GRL, 1998]

Anode technology evolution

[Sanmartin et al, JPP 1993]



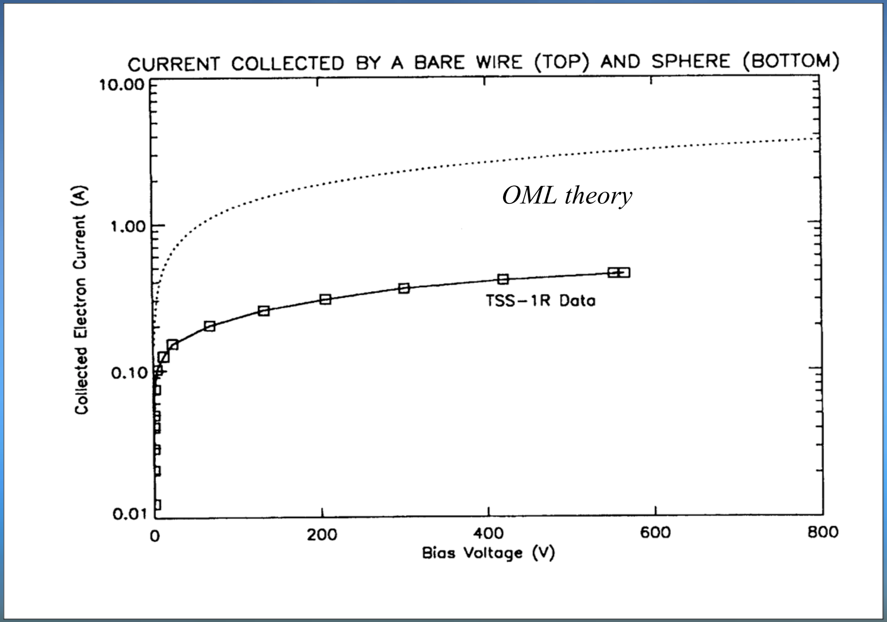
Spherical anode:
used in TSS missions



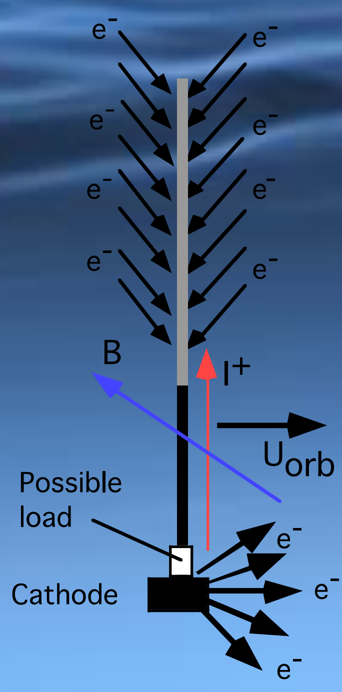
Bare tether anode: simplicity,
large area and high efficiency

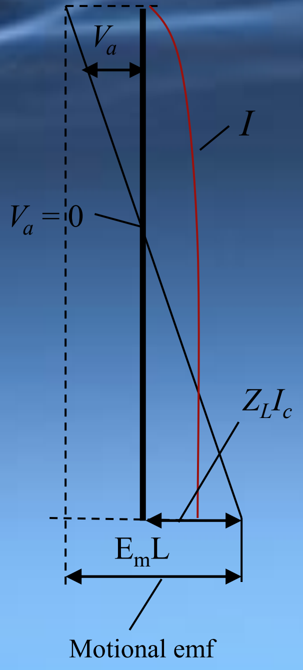
Bare-tether Anodes

- Bare-tether anodes collect electrons directly on a portion of tether left uninsulated
- If tether radius $R_t < \lambda_D$ (Debye length) then bare tethers collect in the Orbital Motion Limited (OML) regime that is an order of magnitude more efficient than spheres of equal surface



Bare tether anode



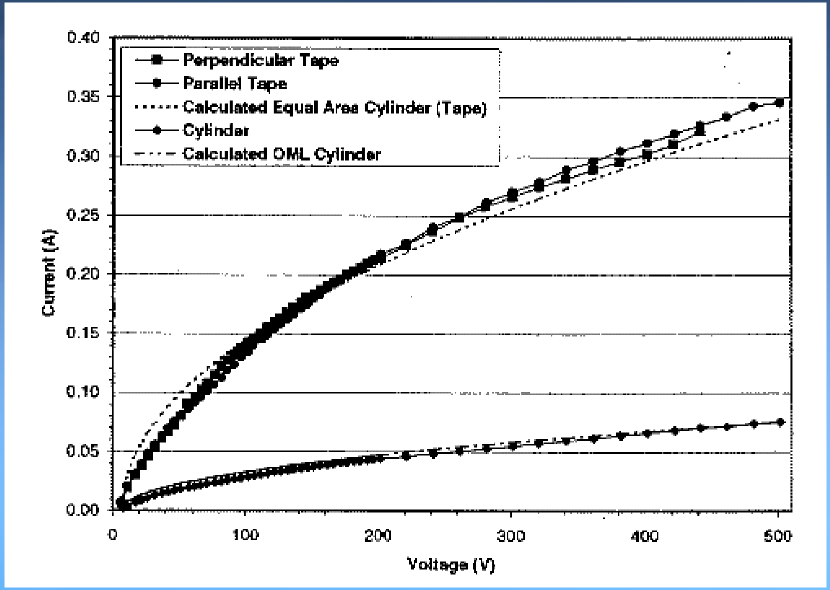


$$\delta I_{OML} = J_{th} \cdot 2\pi R_t \delta l \cdot \sqrt{4eV_a/(\pi k T_e)}$$

Bare-tether Anodes (cont'd)

- OML collection to thin cylindrical tethers and tapes tethers verified in plasma chamber tests at U. of Michigan
- Current collection follows the expected dependence with bias voltage
- Current proportional to perimeter of sample cross section as expected

Current vs. bias voltage compared to OML theory



[Gilchrist et al., IEEE Plasma Science, 2002]

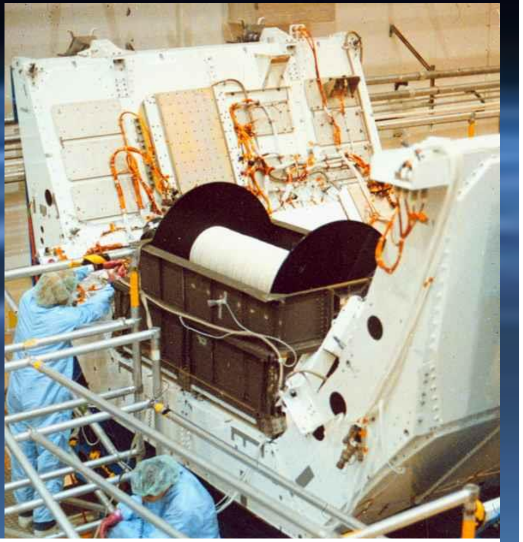
E. C. Lorenzini, University of Padova,
Department of Industrial Engineering

Deployment control laws

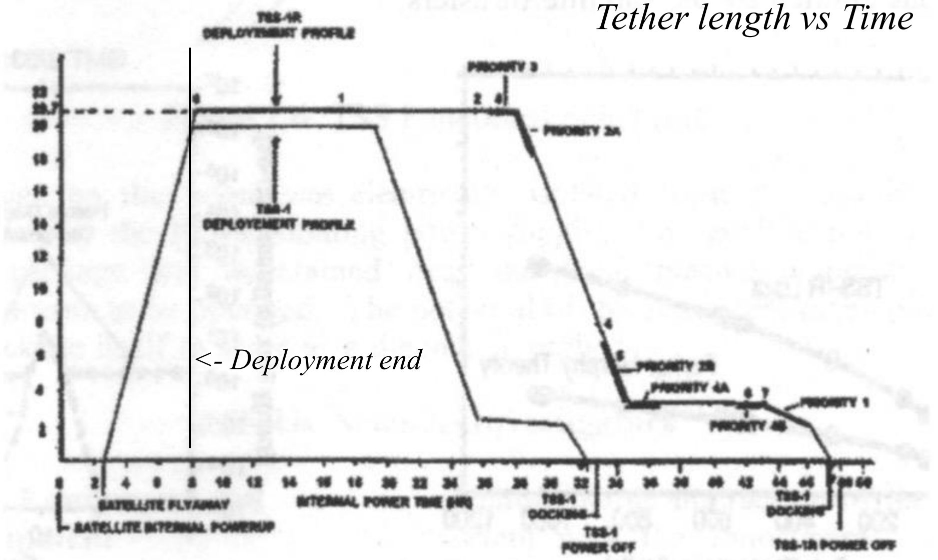
TSS deployment control

- TSS-1 (1992); TSS-1R (1996)
- Massive, reeling deployer (can deploy and retrieve)
- Deployment characteristics
  - Velocity control law of reel; Yo-yo phase for amplitude libration reduction
  - Deployment duration: ~6 hours to deploy 20 km

Deployer reel on Space Shuttle pallet
Credit: NASA



Tether length vs Time

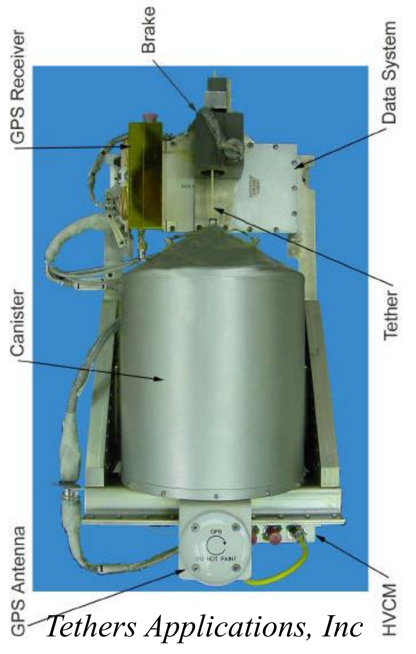


<- Deployment end

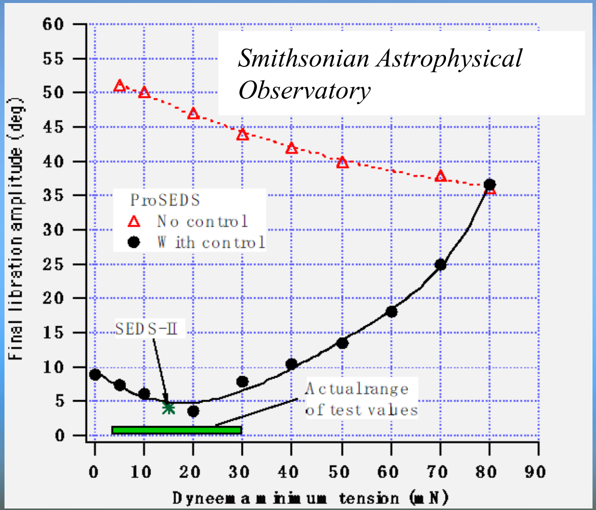
Figure 1.3 TSS1 and TSS1R Timelines

SEDS-II Deployment

- SEDS-II (1994)
- Compact and light stationary deployer (deploys only)
- Control law characteristics
  - Tension control with Input-Output linearization and feed-forward reference length and velocity profiles
  - Deployment duration for 20 km = 1 hr 15 min *(less than 1 orbit)*
  - Residual libration amplitude < 4 deg at end of deployment

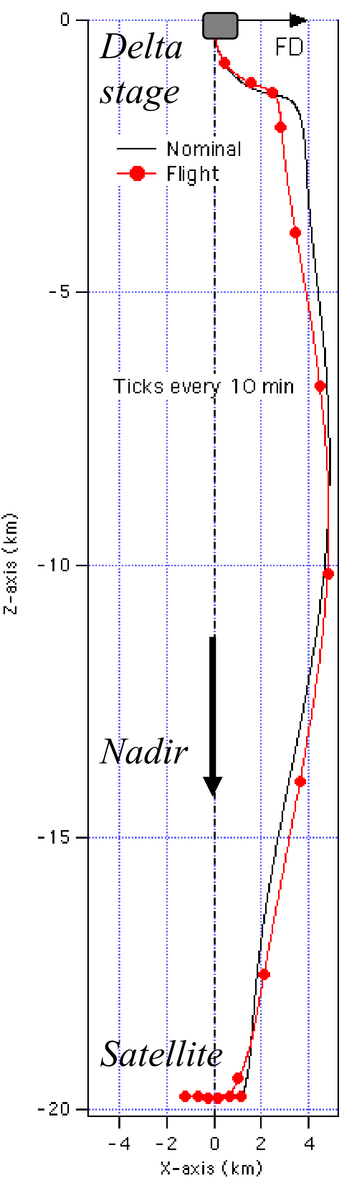


Tethers Applications, Inc



Smithsonian Astrophysical Observatory

Trajectory of satellite

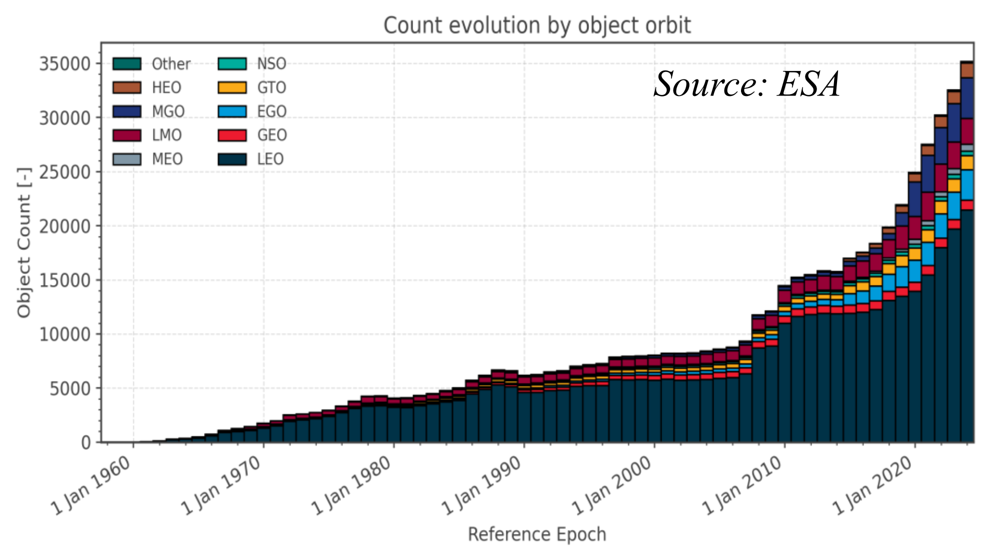


Applications of EDTs

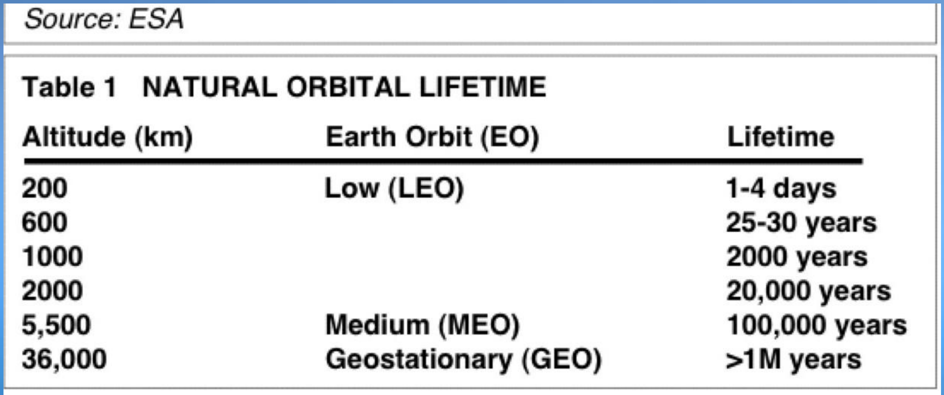
- Features
  - Propellantless system
  - Green propulsion
  - Convert energy
  - Reversable: drag and thrust
  - Scalable
  - Performance depends on environmental parameters

- Applications
  - Deorbiting spent satellites from LEO
  - Drag makeup/station-keeping
  - Planetary applications at Jupiter and Saturn
  - *Orbital parameters changes*
  - *Power generation at the expense of orbital energy*

Deorbiting of spent satellites



Source: ESA

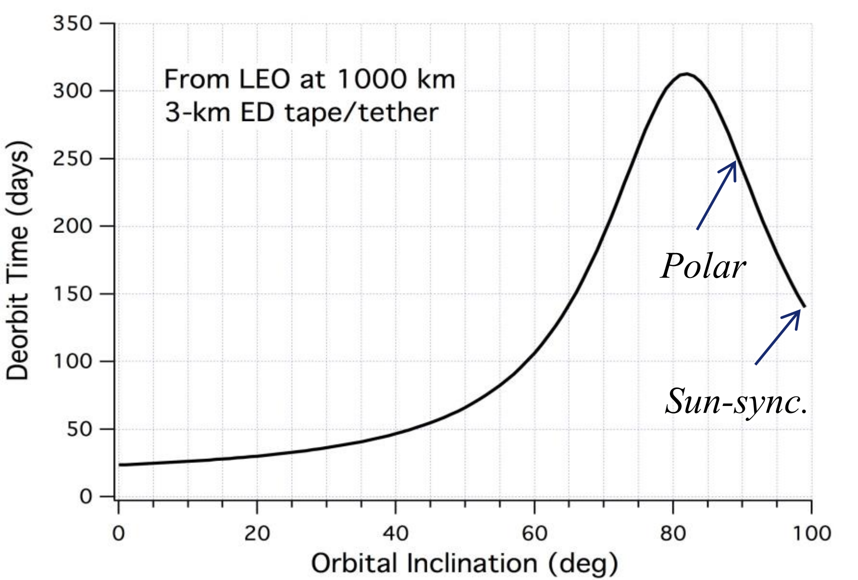


Source: ESA

Table 1 NATURAL ORBITAL LIFETIME

Altitude (km)	Earth Orbit (EO)	Lifetime
200	Low (LEO)	1-4 days
600		25-30 years
1000		2000 years
2000		20,000 years
5,500	Medium (MEO)	100,000 years
36,000	Geostationary (GEO)	>1M years

- Reentry time vs orbital inclination with EDT attached to 1000-kg satellite starting at 1000 km altitude:
    - ~1 month at low inclinations
    - ~5 months in Sun-Sync
    - ~9 months in polar orbit

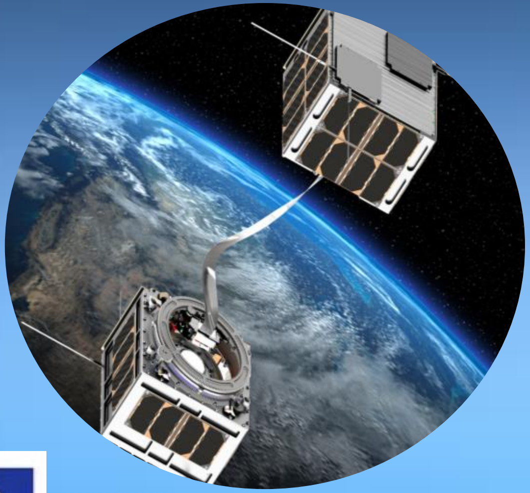


From project BETs, EC-FP7 Program, 2014

E.T.PACK Project Initiative

- E.T.PACK-F funded by the EIC Transition Program
- Partners: UC3M (coordinator), UniPD, TUD, SENER and RFA
- Objective: develop a tape-tether system for a demonstration flight of deorbiting by means of an EDT from LEO

- Two modules with a total volume of 12U Cubesat, ~24kg of mass
- Bare tape-tether with a length of ~450m
- Reentry time from low LEO in less than 100 days



E.T.PACK-F

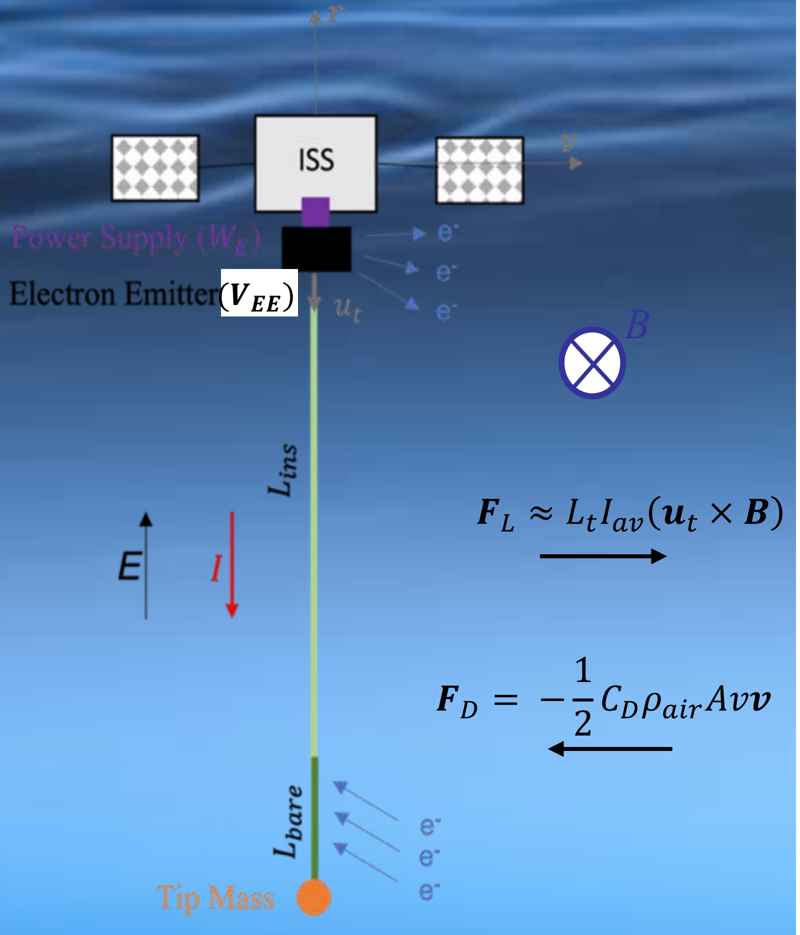
European Innovation Council

[Sanchez-Arriaga et al., Acta Astronautica 2020]

ISS Atmospheric Drag Makeup with EDT

- **EDT Configuration:**
  1. Bare tether segment (L_{bare})
  2. Insulated tether segment segment (L_{ins})
  3. EDT has fixed cross-sectional area $A_t = w_t \times h_t$ and Aluminum tether conductivity $\sigma_t = 3.5 \times 10^7\ 1/\Omega m$
  4. The Electron Emitter emits electrons at a cost of a potential drop $V_{EE} < 0$.

- **Thrust generation (Active Mode):** Thanks to a power source, to supply W_E *(kW),* the electric current $\boldsymbol{I}$ flows in the opposite direction to the motional electric field ($\boldsymbol{E} = \boldsymbol{v} \times \boldsymbol{B}$)
- **Deployment direction.** A downward deployment of the tether is dictated by the physics of the eastward-moving platform.



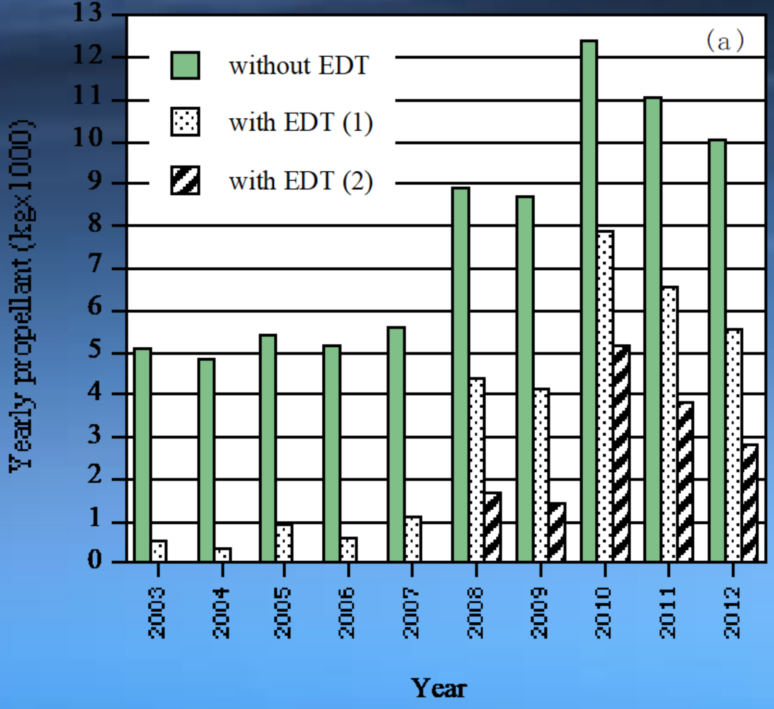
$$\boldsymbol{F}_L \approx L_t I_{av} (\boldsymbol{u}_t \times \boldsymbol{B})$$

$$\boldsymbol{F}_D = -\frac{1}{2} C_D \rho_{air} A v \boldsymbol{v}$$

[Brunello et al., IAC-2023]

ISS drag makeup – potential savings

[Estes et al, JSR 2000]



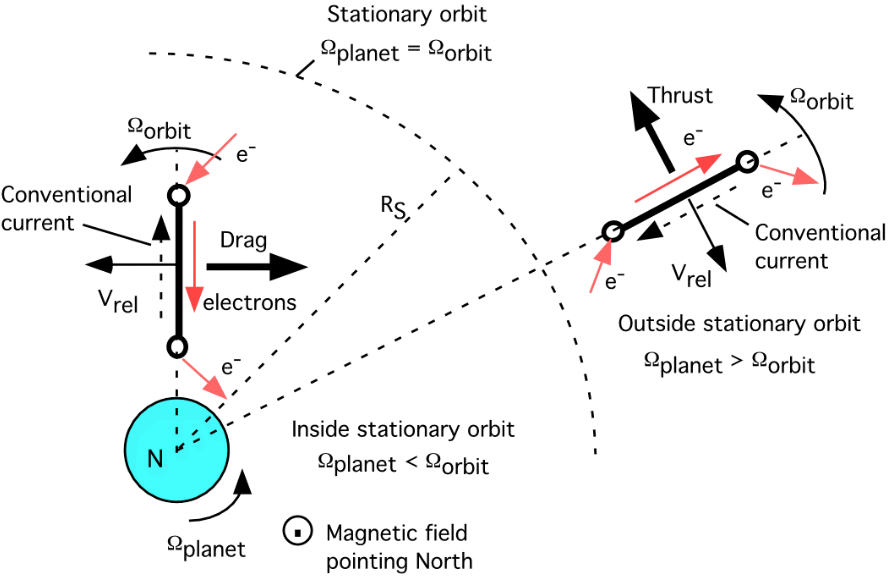
	Estes et al., JSR 2000	Brunello et al., IAC-2023
$w_t \times h_t$	10 mm x 0.6 mm	50 mm x 0.05 mm
L_t	10 km	6 km
W_{ESK}	10 kW	11.76 kW
Tether mass	162 kg	40.5 Kg
η	$\cong 0.60$	0.52
f_i	0.5	0.92

- EDT-1 = 50% fixed duty cycle; EDT-2 variable between 50% and 80%
Save up to 66 ton of propellant (out of 78 ton) over 10-year ISS lifetime

EDT Planetary Applications

- *Jupiter* has strong magnetic fields, adequate ionospheric density, and spins relatively fast
- Unlike Earth, ionosphere on Jupiter extends beyond stationary orbit ($R_S = 2.24\ R_J$)
- Above R_S EDT produce *thrust and power* simultaneously
- Below R_S EDT produce *drag and power* simultaneously

EDT above and below stationary orbit



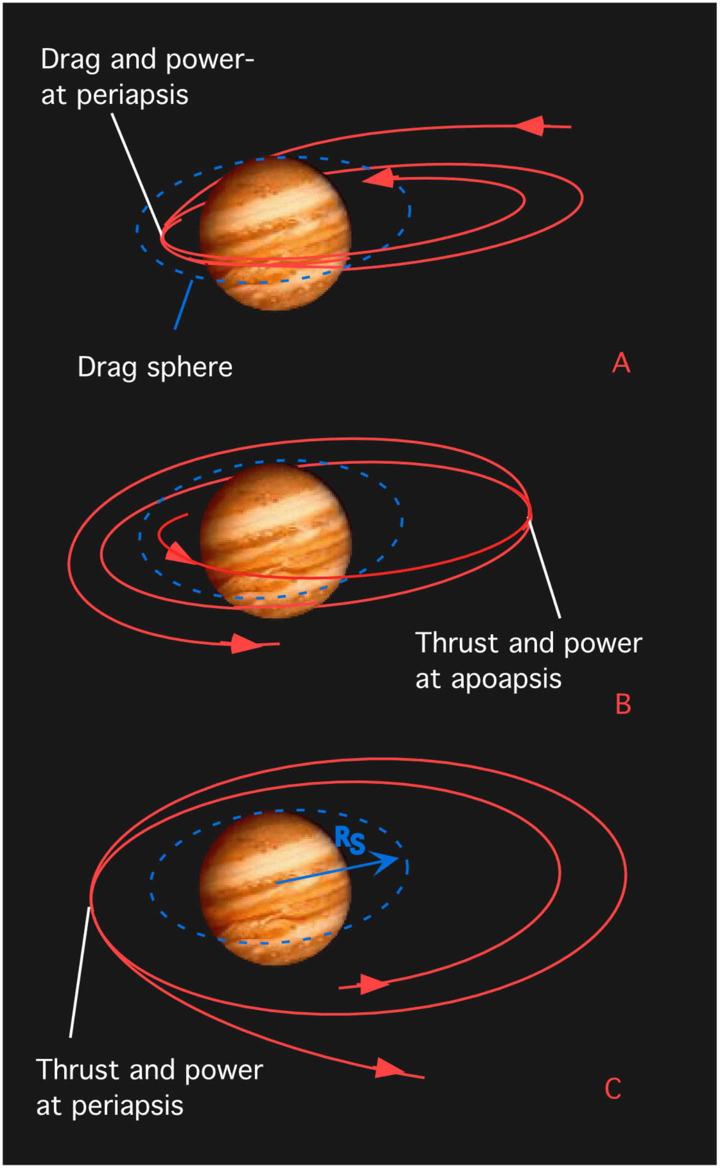
[Sanmartin and Lorenzini, JPP 2005]

EDT at Jupiter

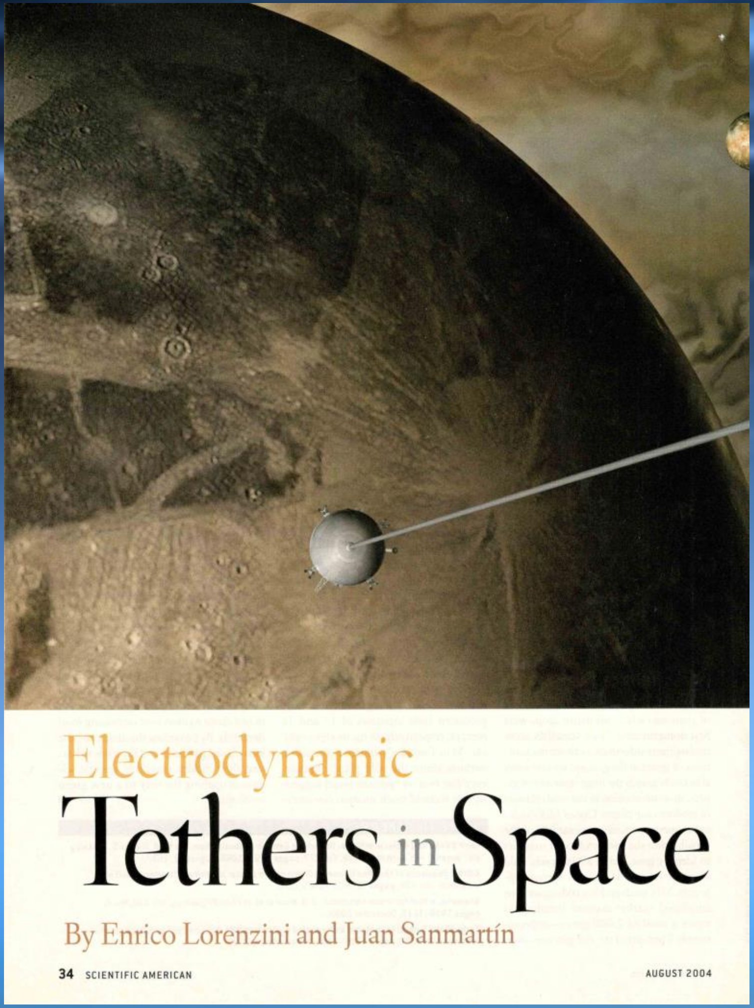
- Conceivable tour of Jupiter moon system with (almost) no propellant and on-board power generator with EDT:

- Phase A (periapsis below Jupiter stationary orbit R_S and ED drag at periapsis)
  - 1) slow-down and capture into highly elliptical orbit
  - 2) lowering apoapsis over multiple orbits while encountering moons
- Phase B (periapsis still below R_S); ED thrust at apoapsis to raise periapsis above R_S
- Phase C (entire orbit outside R_S); ED thrust at periapsis to raise apoapsis till orbit is made open

[Lorenzini and Sanmartin, SciAm 2004]



EDTs in popular science



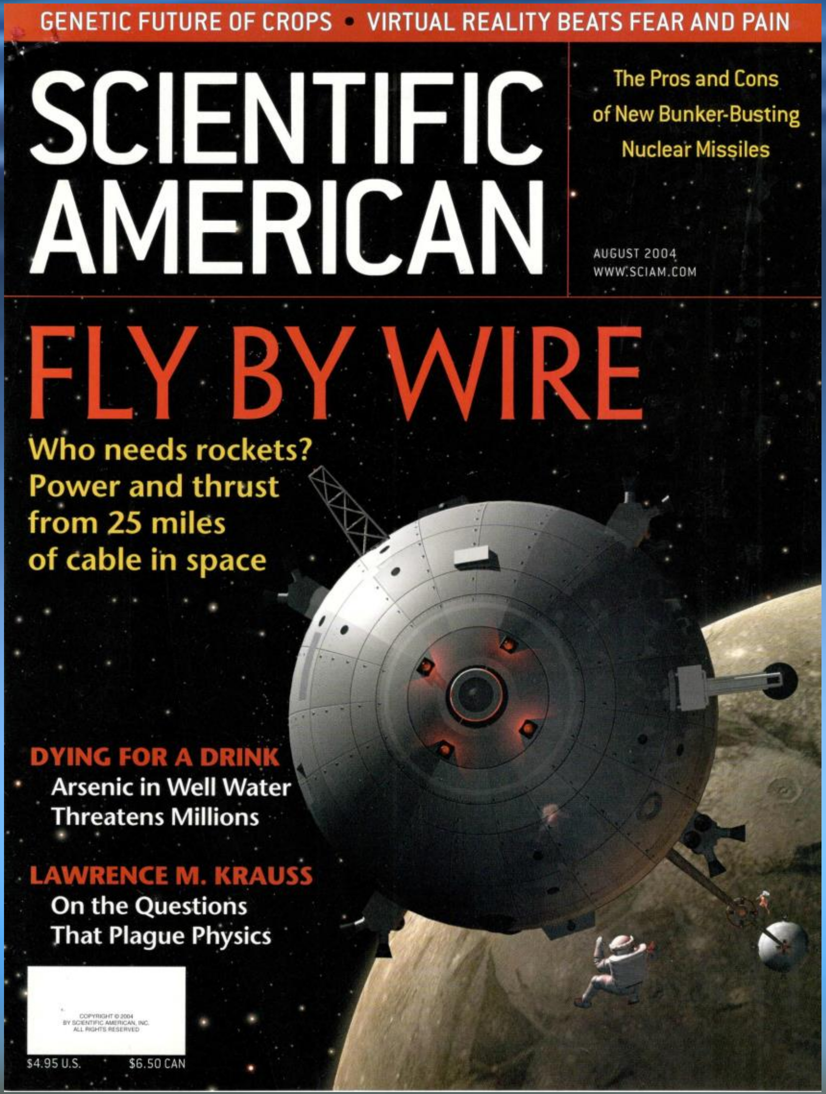
Electrodynamic

Tethers in Space

By Enrico Lorenzini and Juan Sanmartín

34 SCIENTIFIC AMERICAN AUGUST 2004

[Scientific American - August 2004]



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Concluding Remarks

- EDTs can enable propellantless propulsion in LEO and at suitable planets with magnetic field and ionosphere
- Flight tests thus far have demonstrated tether currents ~3 times higher than predicted (TSS-1R, 1996)
- Bare tether anodes can provide an order of magnitude improvement in current intensity per collecting area than spherical anodes
- New deployment control laws can deploy long tethers in less than one orbit and stabilize the system along the local vertical
- Multi-line tethers (e.g., Hoyt) and *tape-shaped tethers* have more than 1-2 orders of magnitude better survivability to M/OD impacts than single-line tether of same mass
- Systems to deorbit satellites at end of life are very promising especially in view of the new rules of permanence in LEO of spent satellites that reduce time in orbit from < 25 to < 5 years

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References (only a few)

Carroll J. A., “Guidebook for Analysis of Tether Applications, 1985.

Misra A. K. and Modi V. J., “**A survey on the dynamics and control of tethered satellite systems.”** NASA, AIAA, and PSN, International Conference on Tethers in Space, Arlington, VA, Sept. 17-19, 1986, Paper. 54, September 1986

Sanmartin, J. R., M. Martinez-Sanchez and E. Ahedo, “Bare Wire Anodes for Electrodynamic Tethers.” *J. of Propulsion and Power*, Vol. 9, No. 3, 353-360, 1993.

Lorenzini, E. C., S. Bortolami, C. Rupp, F. Angrilli, “Control and flight performance of tethered satellite small expendable deployment system-II”, *J. of Guidance, Control and Dynamics*, Vol. 19, No. 5, 1148-1156, 1996.

Cosmo M. L. and Lorenzini E. C., “Tethers in Space Handbook.” 3rd Edition, NASA Publication, 1997.

Vannaroni et al., “Current-voltage characteristics of the TSS-1R satellite: comparison with isotropic and unisotropic models.” *Geophysical Research Letters*, Vol. 25, No. 5, 749-752, 1998.

Estes, R.D., E.C. Lorenzini, J. Sanmartin, J. Pelaez, M. Martinez-Sanchez and C.L. Johnson, “Bare Tethers for Electrodynamic Spacecraft Propulsion.*” J. of Spacecraft and Rockets*, Vol. 37, No. 2, 205-211, 2000.

Forward R. I., Hoyt R. Uphoff C W., “ Terminator Tether: A Spacecraft Deorbit Device.” J.of Spacecrafty and Rockets, Vol. 37, No. 2, March-April 2000.

Gilchrist, B.E., S. Bilen, E. Choiniere, A.D. Gallimore and T.B. Smith, “Analysis of Chamber Simulations of Long Collecting Probes in High-Speed Dense Plasmas, *IEEE Transactions on Plasma Sciences*, Vol. 30, No. 5, 2023-2034, 2002.

Lorenzini E. and Sanmartin J., “Electrodynamic Tethers in Space.” *Scientific American,* Vol. 291, No. 2, 50-57, August 2004 (front-cover article)

Sanmartin, J.R. and E.C. Lorenzini, “Exploration of outer planets using tethers for power and propulsion.” *J. of Propulsion and Pow*er, Vol. 21, No. 3, 573-576, 2005.

Zanutto D., Lorenzini E. C., Mantellato R., Colombatti G., Sanchez-Torres A., “Orbital Debris Mitigation Through Deorbiting with Passive Electrodynamic Drag.” Procs. of the 6th International Astronautical Congress (IAC-2012), Paper IAC-12-D9.2.8, Naples, October 2-6, 2012.

Francesconi A., Giacomuzzo C., Bettiol L., Lorenzini E., "A new Ballistic Limit Equation for thin tape tethers", Acta Astronautica, Vol. 129, Dec. 2016, 325-334, 2016

Sanchez-Arriaga G., S. Naghdi, K. Watzig, J. Schilm, E. C. Lorenzini, M. Tajmar, E. Urgoiti, L. Tarabini, J. F. Plaza and A. Post “The E.T.PACK Project: towards a fully passive and consumable-less deorbit kit based on low work-function tether technology” *Acta Astronautica*, Vol. 177, 821-827, 2020.

Tajmar M and Sanchez-Arriaga G., “A bare-photovoltaic tether for consumable-less and autonomous space propulsion and power generation.” Acta Astronautica, Vol. 180, 350-360, 2021.

Brunello A., et al., “Optimal design and current control strategies of an electrodynamic tape for ISS station-keeping” 74th International Astronautical Congress (IAC2023), Baku, Azerbaijan, 2-6 October 2023.

Sun G. and Z. H. Zhu, “Fractional-Order Tension Control Law for Deployment of Space Tether System.” *J. of Guidance, Control and Dynamics,* Vol. 37, No. 6, 2024.

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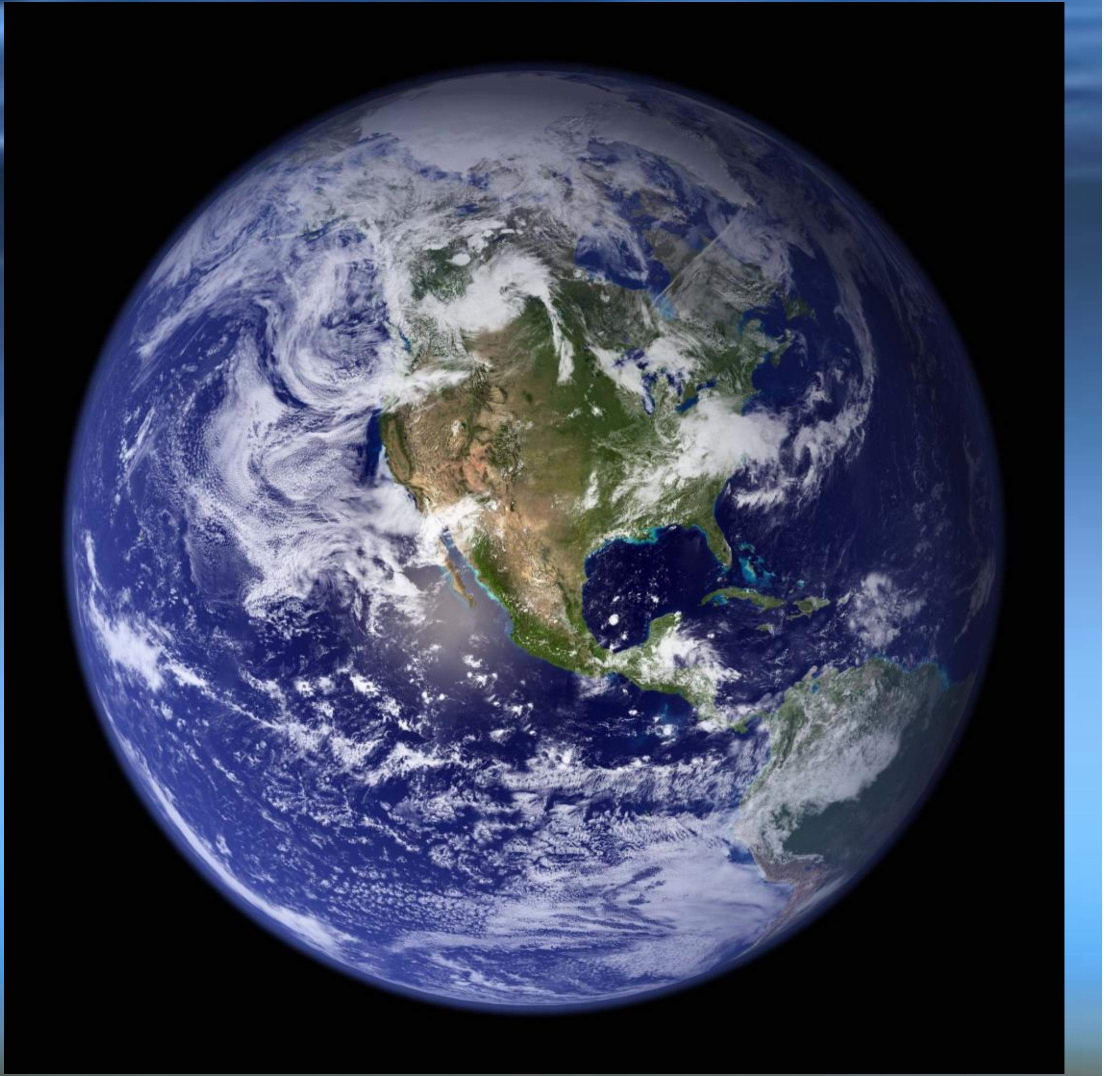

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