Comparison of Technologies for De-orbiting Spacecraft from Low-Earth-Orbit at End of Mission

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1. Introduction

- This work shows that Bare Electrodynamic Tethers (BET) are the most promising technology for deorbiting spacecraft at the end of mission.
- Is a tether conference the right place for this work?
  - New results from *FP7/BETs.*
  - Our group identified “misconceptions” and “prejudices” about tethers outside tether community.
- The following messages are important for space agencies/companies:
  - There is a clear commercial case: deorbiting scenarios
  - BETs can de-orbit multi-ton spacecraft in few months, passively, without propellant and power supply..
  - Typical tether length is just “few kilometers”.
  - State-of-the-art tethers are much simpler and robuster than old one.

1. Introduction: list of requirements

51th Session of COPUOS (Sanmartin, 2014)

1) Bring de-orbit time below some threshold (25 years maximum for initial orbit at critical altitudes and inclinations)

2) Be a small mass fraction of its spacecraft.

3) Allow scalable design for a wide range of spacecraft mass (reaching multi-ton)

4) Allow maneuvers in case of long de-orbiting to avoid large trackable debris.

5) Be simple and reliable.

6) Decrease the frontal area by de-orbit time product, $A \times t_D$, or demonstrate that, in case of collision, it will not damage other operative spacecraft.

Two additional requirements make technologies even more attractive

7) Allow controlled re-entry.

8) Be able to produce de-orbiting and reboost in multi-mission scenarios

1. Introduction: list of requirements

Device / **Requirement**	*Chemical rockets*	*Ion-thruster*	*Drag Augmentation*	*Tethers*
1. Deorbit Time				
2.- Scalable				
3.- Mass ratio				
4.- Manoeuver				
5.- Simple/Reliable				
6.- Active Attitude Control				
7- Multi-mission				
8.- Reduce AxT_D				
9 Controlled Re-entry				

2. Tether comparisons

1) Electrodynamic versus Electrostatic (e-sail[1]) tethers

$$\frac{Lorentz}{Coulomb} \sim \frac{perimeter}{r_{max}} \times \sqrt{\frac{m_i}{m_e}} \times \left(\frac{L\Omega_i}{v_{orb}}\right)^{3/2} \xrightarrow{\text{LEO}} \frac{Lorentz}{Coulomb} \sim \frac{perimeter}{r_{max}(W,\lambda_D)} \times \left(\frac{L}{3\,m}\right)^{3/2}$$

Conclusions:

- Lorentz drag dominates in LEO and it does not require power.
- Coulomb drag dominates in the solar wind.

[1] See invited talk: Pekka Janhunen and Andris Slavinskis, “Using charged tether Coulomb drag: E-sail and plasma brake”.

2. Tether comparisons

A fair comparison requires equal mass and length

2) Tape versus round tethers[1]

- Tapes have greater perimeters → more current is collected → Faster deorbiting
- Tapes are more robust against cuts by small debris[1,2].

1] Khan, S. B., and Sanmartín, J.,R., "Survival Probability of Round and Tape Tethers Against Debri Impact," *J. of Spacecraft and Rockets,* Vol 50, No 3, 2013.

2] Francesconi A., et al, "Survivability to Hypervelocity Impacts of Electrodynamic Tape Tethers for Deorbiting Spacecraft in LEO". ESA/ESOC, Germany, 2013.

2. Tether Comparisons

A fair comparison requires equal mass and length

3) Single tape versus multi-line1 tethers

- Equal cross section area requires $f \times N \pi R^2 = wh$, $f > 1$ (cross connections)
- A higher perimeter for a multi-line tether, $N \pi R > w$, requires

$$N > \frac{fw}{\pi h} \sim 500,$$ for typical tapes values w = 3cm and h =30 μm

- As N is increased, both the probability of collection interference among the tether lines and the size range of single debris producing cuts increases. .

1] Forward, R.L., Hoyt, R.P.,"Failsafe Multiline Hoytether Lifetimes", AIAA paper 95-289031st. AIAA/SAE/ASME/ASEE Joint Propulsion Conference, San Diego, CA, July 1995.

3. Deorbiting technologies comparisons

Device	High/Low Thrust		Mass ratio
Rockets	$\Delta v = \frac{1}{2}\sqrt{\frac{\mu_E}{R_E + H_0}}\frac{H_0 - H_F}{R_E + H_0}$	Tsiolkovsky Equation $\Delta v = c_{ex} ln\left[1 + \frac{m_p}{m_s + k_r m_p}\right]$	$\frac{m_r}{m_s} = (1 + k_r)\left(\frac{1}{e^{\Delta v / c_{ex}} - 1} - k_r\right)^{-1}$

3. Deorbiting technologies comparisons

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Plasma Thruster	$\frac{dH}{dt} = \frac{2(R_E+H)^2}{\mu}\frac{\boldsymbol{F}_p\cdot\boldsymbol{v}}{m_s}$	$\boldsymbol{F}_p\cdot\boldsymbol{v} = -\dot{m}c_{ex}v$	$\frac{m_e}{m_s} = \sqrt{\frac{2\alpha(1+k_e)}{\eta t_D}}\sqrt{\frac{\mu_E}{R_E+H_0}}\left(\sqrt{\frac{R_E+H_0}{R_E+H_F}}-1\right)$

3. Deorbiting technologies comparisons

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DAD		$\boldsymbol{F}_p\cdot\boldsymbol{v} = -C_D\rho_0 A_{DAD} v^3/2$	$\frac{m_{DAD}}{m_s} = \frac{b}{C_D t_D\sqrt{\mu_E}}\int_{H_F}^{H_0}\frac{dH}{\rho_0\sqrt{R_E+H}}$

3. Deorbiting technologies comparisons

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Rockets	$\Delta v = \frac{1}{2}\sqrt{\frac{\mu_E}{R_E + H_0}}\frac{H_0 - H_F}{R_E + H_0}$	Tsiolkovsky Equation $\Delta v = c_{ex} ln\left[1 + \frac{m_p}{m_s + k_r m_p}\right]$	$\frac{m_r}{m_s} = (1 + k_r)\left(\frac{1}{e^{\Delta v/c_{ex}} - 1} - k_r\right)^{-1}$
Plasma Thruster	$\frac{dH}{dt} = \frac{2(R_E + H)^2}{\mu}\frac{\boldsymbol{F}_p \cdot \boldsymbol{v}}{m_s}$	$\boldsymbol{F}_p \cdot \boldsymbol{v} = -\dot{m} c_{ex} v$	$\frac{m_e}{m_s} = \sqrt{\frac{2\alpha(1 + k_e)}{\eta t_D}}$ $\sqrt{\frac{\mu_E}{R_E + H_0}}\left(\sqrt{\frac{R_E + H_0}{R_E + H_F}} - 1\right)$
DAD		$\boldsymbol{F}_p \cdot \boldsymbol{v} = -C_D \rho_0 A_{DAD} v^3/2$	$\frac{m_{DAD}}{m_s} = \frac{b}{C_D t_D \sqrt{\mu_E}}\int_{H_F}^{H_0}\frac{dH}{\rho_0\sqrt{R_E + H}}$
BET		$\boldsymbol{F}_p \cdot \boldsymbol{v} = \boldsymbol{v} \cdot \int_0^L I(s)\boldsymbol{u}_t \times \boldsymbol{B} ds$ $= -m_c \frac{\sigma}{\rho_t} {E_m}^2 i_{av}$	$\frac{m_{BET}}{m_s} = \frac{\mu_E \rho_t k_{BET}}{2\sigma_t t_D}\int_{H_F}^{H_0}\frac{dH}{(R_E + H)^2 i_{av} E_m^2}$

3. Deorbiting technologies comparisons

Chemical Propulsion:

$k_r = 0.25$
$c_{ex} = 2.6$km/s

Electrical Propulsion:

$k_r = 0.12$
$\alpha = 20$kg/kW
$\eta = 0.65$

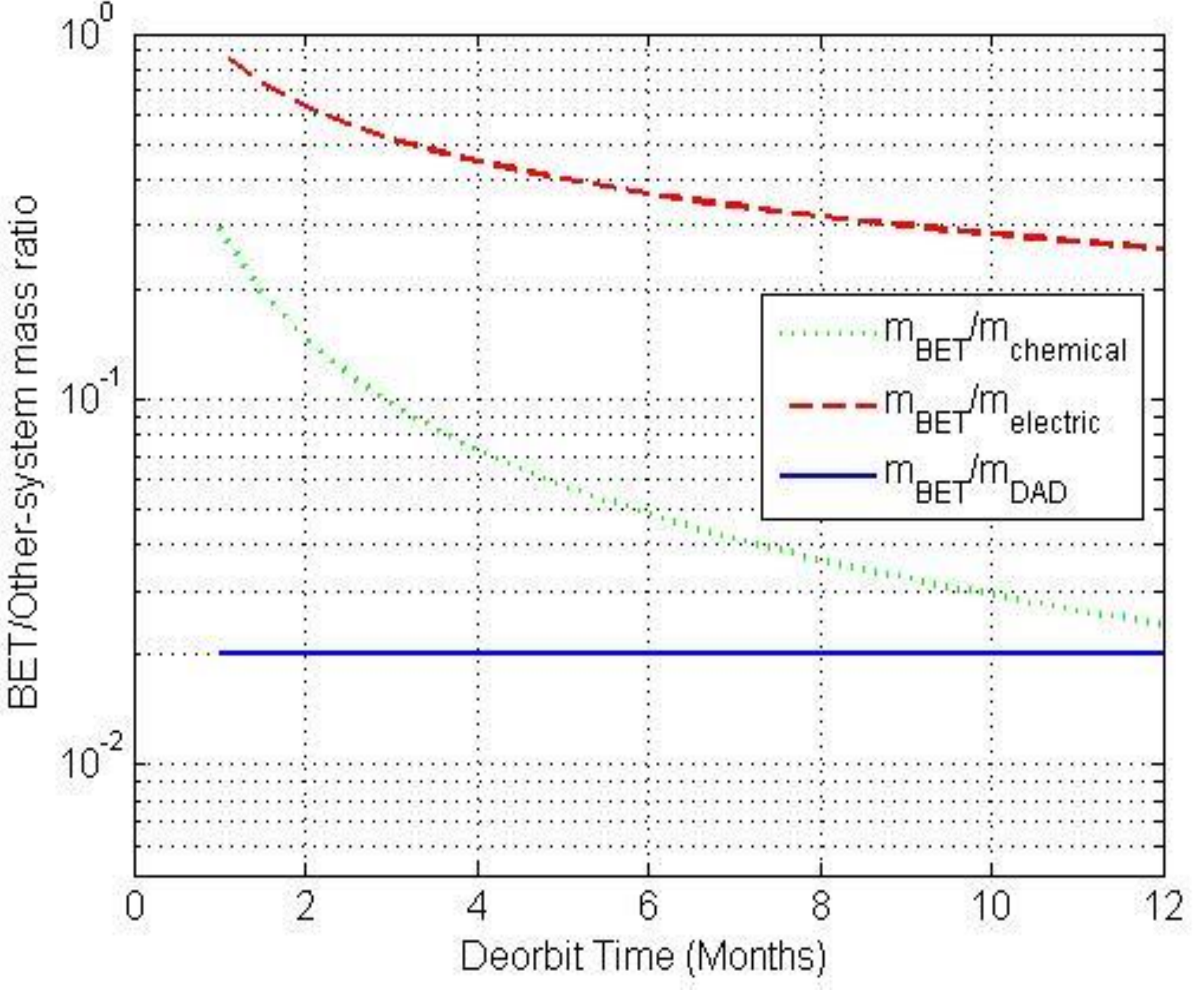
Drag Augmentation:

$b = 75$ gr/m^2
$C_D = 2$

Electrodynamic tether:

Aluminium tether
$k_{BET} = 3$
$i_{av} = 0.25$
$E_m = 160$ V/km

H0 = 850 km, Medium Solar Activity



4. Tether mission design and performance: The π-algorithm[1]

- A fair comparison also needs a rational selection of tether geometry.
- Given a deorbit mission (spaecraft mass and initial orbit), the π-algorithm helps to determine the optimal tether geometry (length L, width w and thickness h).
- The π-algorithm combines two equations (orbital mechanics + tether cut probability model) to construct two figures of merit:

$$\Pi_1 \equiv \frac{m_c}{m_s} \times N_f = function(w, h, L/h^{2/3}, H_0, i)$$

$$\Pi_2 \equiv \frac{m_c}{m_s} \times t_D = function(L/h^{2/3}, H_0, i)$$

- Function Π_1 versus $L/h^{2/3}$ has a minimum and Π_1 does not involve tether width.
- The friendly software BETsMA[2,3] implements the algorithm

[1] Sanmartín et al, "Optimum Sizing of Bare-Tethers for De-orbiting Satellite at End of Mission," *Adv. in Space Res.*, Vol 56, No 7, October, 2015, 1485-1492.

[2] Sánchez-Arriaga, et al, "The Impact of Nonideal Effects on Bare Electrodynamic Tether Performance," *J. of Prop. and Power, 31,3* 2015, 951-955.

[3] See also a poster about BETsMA in this conference.

4. Tether mission design and performance

Table 1 H_0=850 km, H_F=300 km, epoch 2010, IGRF11, IRI2012, MASTER

i(º)	m_s(kg)	L(km)	w(cm)	h(μm)	m_c/m_s (%)	N_f (<1m)	N_f (>1m)	t_D (days)
25	50	1	1.25	10	0.7	0.006	0.0007	56
	500	2	1.75	15	0.28	0.008	0.0023	87
	5000	3.75	3.25	40	0.26	0.0038	0.0047	96
63	50	1.25	2.0	10	1.35	0.008	0.0017	101
	500	3	2.75	20	0.9	0.0075	0.0041	103
	5000	5.5	5	60	0.9	0.005	0.0084	116
98	50	1.5	3	12	2.9	0.0094	0.0032	164
	500	3.25	5	20	1.7	0.0085	0.0079	185
	5000	7.0	6.75	80	2.0	0.001	0.0167	181

4. Tether mission design and performance

For <u>tape</u> tether with <u>well-chosen</u> geometry, one finds:

- Deorbit times is wihin few months.
- The BET system is scalable
- Tether system mass is within few percent the spacecraft mass, reaching the multi-ton range.
- Switching on/off the HC the BET can manoeuver (to avoid large trackable objects).
- The BET system is passive (no propellant, no power supply).
- Precise attitude control is not needed. Howver, measures have to be taken to kill the dynamic instability of BET → see Padova University works in *BETs* final report.
- The AxT_D is reduced between 1 and 2 orders of magnitude.
- In case of collision, it is highly improbable that the tether would disrupt the S/C operation.
- Muti-mission (deorbit and reboost) is possible but BETs do not allow controlled re-entry.
- The bare tether concept still has room for improvement → thermionic bare tether[1.]

1] Williams, J. D., et al, "Low work-function coating for an entirely propellantless bare electrodynamic tether", IEEE Trans. On Plasma Science, 40, 5, 1441-1445, 2012

4. Tether mission design and performance

Device Requirement	Chemical rockets	Ion-thruster	Drag Augmentation	Electrodynamic Tethers
1. Deorbit Time	🟩 days	🟨 a year	🟨 decades	🟩 months
2.- Scalable	🟩	🟩	🟥	🟩 From tens of kg to tons
3.- Mass ratio	🟥 High	🟨 Moderately High	🟩 Low	🟩 Low (below 10%)
4.- Manoeuver	🟥	🟩	🟥	🟩 HC on/off
5.- Simple/Reliable	🟩	🟨	🟨	🟨 In-orbit demonstration is required
6.- Active Attitude Control	🟨	🟨	🟨	🟩 Not needed
7- Multi-mission	🟥	🟨	🟥	🟩 Active/Passive mode
8.- Reduce AxT_D	🟩	🟩	🟥	🟩 Reduced 1-2 orders of magnitude
9 Controlled Re-entry	🟩	🟥	🟥	🟥

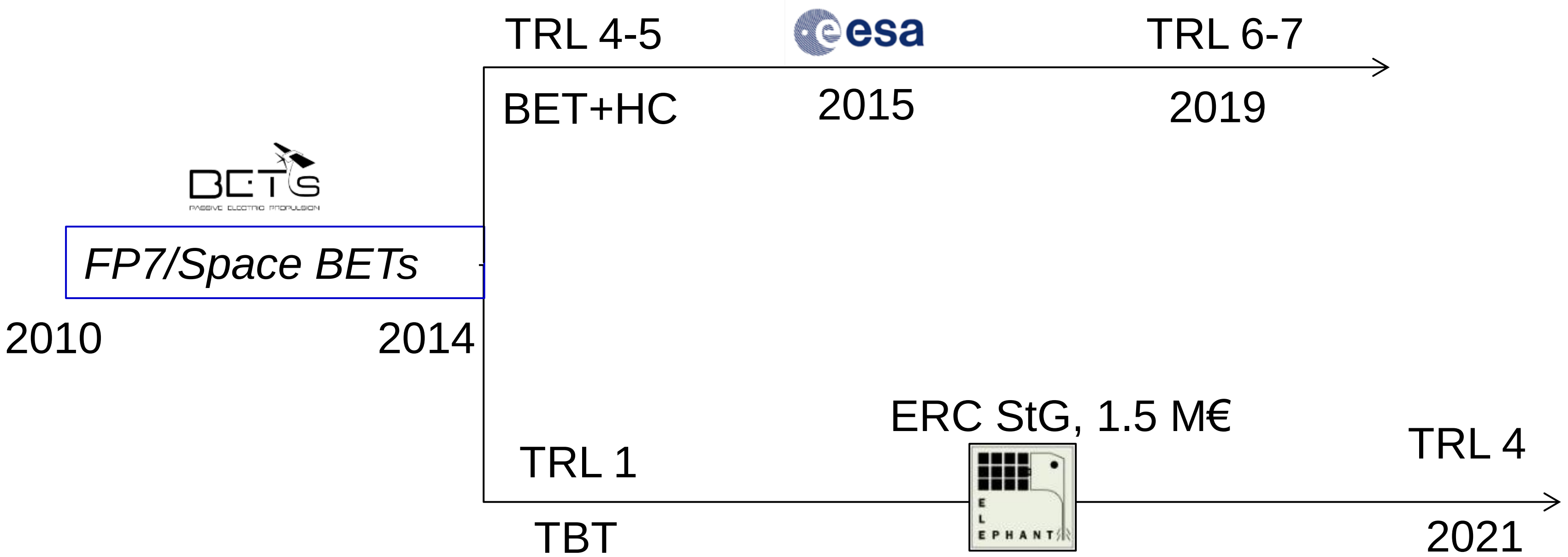
See also talks in this conference

1] J. Carroll “Collision Risks to and from Space Tethers”

2] R. Hoyt “Analysis of Electrodynamic Tethers for Orbit Maneuvering, Deorbit, and Power Generation”.

Conclusions and Roadmap

1. Bare Electrodynamic Tethers (BET) are the most promising technology for deorbiting spacecraft at the end of mission.
2. Electrodynamic tape tethers are the best choice for deorbiting from LEO.
3. A BET: (i) can deorbit tons in few months, (ii) reduce the AxT_D, *(iii)* is light and scalable and (iv) can manoeuver and allows multi-mission.
4. Possible roadmap:



TRL 4-5

TRL 6-7

BET+HC

2015

2019

FP7/Space BETs

2010

2014

ERC StG, 1.5 M€

TRL 1

TRL 4

TBT

2021