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Overall review on thin-tape bare tethers operation as just thermodynamic process

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This presentation is a mixture of the three types of contributions solicited by the 14th SCTC, all 3 revolving here about the thermodynamic character of tether operation:

***A*)** Retrospective review of “forgotten” old work,

***B*)** Review of recent advances,

***C*)** New research.

A). -- As regards *old work*, the Retrospective review deals with the basic physics underlying electrodynamic tether operation, how it all started, and the respective roles of R. D. *Moore* and H. *Alfven*. I will first recall that *rigid-body* motion is a definite property of the thermodynamic equilibrium of macroscopic systems, a consequence of maximum entropy requiring maximum internal energy and minimum macroscopic energy ε, this being a characteristic of rigid-body motion.

Surprisingly, thorough *introductory treaties*, such as the 3-volume *Feynman Lectures* or the 5-volume *Berkeley Course*, and *advanced treaties* such as the *Sommerfeld Lectures*, fully ignore the above property of thermodynamic equilibrium. This is not the case of the *Landau-Lifshitz Course*, which explicitly brings it forth in its 5th volume. Different dissipative physics can be involved in the approach to this equilibrium: dry friction, viscosity, tidal forces…

The case of tethers involves dissipation arising from *Relativity* physics. Consider two macroscopic systems S and S' approaching in free motion in certain space-time domain [1], S moving with velocity $\mathbf{V_{rel}}$, constant and uniform, relative to S'; both systems could stand for inertial reference frames. The velocity $\mathbf{V_{rel}}$ may now be looked at in two respects. First, $\mathbf{V_{rel}}$ by itself might give rise to reduction of mechanical energy by any dissipative mechanism available to make S and S' move as a single rigid-body. Secondly, a Lorentz transformation of fields may explicitly introduce $\mathbf{V_{rel}}$ in the analysis of S motion.

Let system S' be a magnetized, highly conductive plasma, and S a conductive wire travelling through S', and let V_{rel} be much smaller than the light speed c. The electric field in the plasma will then vanish in its own frame, $\boldsymbol{E}' = 0$, whereas in the S frame will read

$$\overline{E} = \overline{E}_m \equiv \overline{V}_{rel} \times \vec{B}_0 ,$$

where $\boldsymbol{E_m}$ is called *motional* field and $\boldsymbol{B_0}$ is the ambient magnetic field, which keeps about equal in both frames. This motional field, which may drive a current in the wire, underlies the physics involved in the applications of ED (*Electrodynamic*) space tethers. In the simplest case of that current coming out weak, the wire would be near equipotential in its own frame. Note that Lorentz force on the wire current makes the field $\boldsymbol{B_0}$ enter that drag twice, making its thermodynamic, unidirectional character manifest.

The story of tethers might start in 1960, when *Beard* and *Johnson* discussed the magnetic drag on a satellite as a conductor moving across the geomagnetic field lines, in XIX *century* physics language [2]. They estimated that a voltage of order 200 V/km would be induced, and the magnetic drag on the resulting current would exceed the air drag at altitudes above 1200 km for satellite sizes over 50 m; they concluded that magnetic drag effects could be ignored.

A new analysis of the problem of a conductor moving across a magnetic field was carried out by *Drell et al* in 1965 [3]. They straightforwardly considered current as arising from the electric field as seen by a co-moving observer. They suggested that the main impedance in the current circuit, closed through the ambient ionosphere, was radiation impedance of *Alfven* waves. They called drag from such emission Alfven propulsion; it was not propulsion introduced by Alfven. Note that impedance for steady emission by a tether depends on the way it exchanges current with the ambient plasma. Models of current flowing from $y = -\infty$ to $y = +\infty$ (if lying along some axis y, say) did underestimate impedance by a factor of order $1/n^2$, n being the very high refraction index.

Drell et al implied that current did easily flow in and out of wire and ambient plasma. In work presented in early 1966, *R. D. Moore* thought otherwise and discussed ambient plasma-wire contact impedances in the current circuit. He argued the need for using plasma-contactor devices such as used in electric propulsion to neutralize ion engines exhaust [4]. He also realized that a long wire would be needed to attain a large *motional* electromotive force and suggested that gravity-gradient force could keep the wire vertically stable in Low Earth Orbit. He was somehow setting the foundations of the new technology of ED tethers for use in LEO.

Moore went further in mid-1966 and took the *motional* field concept to the Solar Wind plasma, although, with no gravity-gradient force available there, he tried to escape the need for a long wire [5]. Alfven first considered a propulsion problem in 1972 [6], and again later that year, with U. *Fahleson* at the Royal Institute of Technology in Stockholm [7]; in Note added in proof in this last paper, Alfven apologized for their ignorance of Moore's work 6 years earlier:

We have just learned that some of the ideas proposed in (1) *and* (2) *have already been discussed by Moore* (6). *Our results are in general agreement with those of Moore, and we regret very much our ignorance of his work.* [(1), (2), and (6) are references by Fahleson and Alfven, Alfven, and Moore respectively.]

Alfven, who was then at the *University of California-San Diego*, suggested using the field $\mathbf{E_m}$ to power an electric thruster, ultimately making the wire and its S/C to approach the Solar Wind velocity.

There is a basic difference between tethers orbiting planets and in solar-wind use. For systems large enough that gravitational energy need be accounted for macroscopic energy ε, *rigid-body* motion may occur away from thermodynamic equilibrium. The consequence is one of the paradoxes of gravitation, less known than the *Jeans* instability: *Rigid-body* motion may then correspond to two opposite types of *extrema*. It may indeed correspond to ε minimum (entropy maximum, at thermodynamic equilibrium), case of *Charon* orbiting *Pluto*, but also to ε maximum (entropy minimum, far away from thermodynamic equilibrium), at the *geostationary* orbit. This is 'why' satellites re-enter, escaping from *rigid-body* co-rotation with Earth, at geostationary.

There is, anyway, a basic difficulty in using the *motional* Lorentz drag in the Solar Wind, that being its extremely low values of both ambient plasma density and magnetic field. This has given rise to the alternative electric solar-sail concept, using an array of wires biased by solar power to deflect Solar Wind ions, hence generating drag/thrust through Coulomb, rather than Lorentz, forces [8]. Note that this scheme does require use of an independent power source, and lacks the thermodynamic, ready-to-use character of Lorentz drag.

Actually, the use of space tethers and, in general, long structures in space for just mechanical or structural purposes goes far back in time to concepts such as *Orbital-Tower* and *Skyhook*, the first one having been introduced as early as the late XIXth century. An important history of such developments was recalled in a NASA Report by *von Tiesenhausen* in 1984 [9], who referred to both Alfven and Moore but did not acknowledge merits of Moore as preceding Alfven by 6 years.

Paul *Penzo*, in a Report of the Jet Propulsion Laboratory a little later, referred to the Alfven papers but completely ignored Moore`s work [10]. Penzo, who discussed use of tethers at Jupiter in his Report, also considered its use for detection of gravitational waves. Anyway, a new NASA impulse to the ED-tether field came through work by *G. Colombo* and *M. Grossi* in the 70’s and 80’s, at SAO.

B) -- As regards *recent research advances*, de-orbiting satellites at end of life, so as to prevent generation of new space debris, is a paradigmatic mission exhibiting the thermodynamic character of electrodynamic tethers. Space debris remain a constant menace to operative satellites in Low Earth Orbit. I will here sketch results from a basic analysis on the *tape* geometry of tethers as de-orbit systems to be used just at end of mission. It follows work on overall development of tether systems, under a Project, *BETs*, supported by the *European Commission* from November 2010 to February 2014 [11].

Any de-orbiting system faces two basic requirements: it must *i*) be light when compared to its satellite, and *ii*) operate fast to avoid its accidental, catastrophic collision with another large orbiting object, resulting in a myriad of debris pieces. A tether system also faces three particular issues: *a*) it might be somewhat ineffective at high inclination orbits for which $\boldsymbol{E_m}$ could prove too low; *b*) its geometry (long and thin) makes it prone to being cut by abundant tiny debris, leading to a failed operation; and *c*) its geometry (long) might make it also prone to cut by a big debris.

As regards point *b*) above, recent results showed that tape tethers have much greater survival probability than round tethers of equal length and mass [12]. Tether geometry has thus a relevant impact on system performance, and tape tethers are advantageous in this respect. Given a mission, i.e. initial orbital parameters and mass of the satellite, one might choose tether length L, width w, and thickness h to optimize figures of merit. Opposite requirements of both a light tether and survivability against debris lead to a design scheme based on the product $\mathbf{\Pi}$ of probability N_f of a cut by debris and tether-to-satellite mass ratio m_t/M_S. A complementary figure of merit is a product $\boldsymbol{\tau}$ involving de-orbit time t_f and mass ratio m_t/M_S.

The present work explicitly shows $\mathbf{\Pi}$ as a functional of orbital parameters and satellite mass, and tether geometry ($L/h^{2/3}$, w, h), which is derived by combining a fatal-impact rate model introduced in [13] and a simple satellite dynamical equation, which assumes a slow de-orbit evolution due to Lorentz drag, as sequence of near-circular orbits. Product $\boldsymbol{\tau}$ follows directly from the dynamical equation and depends on geometry through just $L/h^{2/3}$. The fatal-impact rate model reads

$$dN_c/dt \equiv L\dot{n}_c \approx L\delta^* F^* \times G(n_0, n_1, \delta^*/w, w/h), \tag{1}$$

$$G \equiv \frac{3n_0+2}{\pi(n_0-2)}\left(\frac{3\delta^*}{w}\right)^{n_0-1}\left(\frac{\pi w}{4h}\right)^{\frac{n_0}{2}-1} + \frac{n_0-n_1}{(n_1-1)(n_0-1)},$$

with n_0 and n_1 slopes in a log-log plot of space-debris flux F versus debris size δ for power laws in two ranges $\delta < \delta^*$ and $\delta > \delta^*$, respectively. The two straight lines in the log-log plot meet at the special point δ^*, F^*. All four parameters in the model depend on orbit altitude H and inclination. For ORDEM, debris flux might roughly be larger by one order of magnitude than the MASTER flux used here.

For tape-tether design analysis, we consider a satellite of mass M_S with a rigid tether along the vertical, in a circular orbit weakly perturbed by Lorentz drag, making the orbit slowly evolve through a long, spiraling sequence of quasi-circular orbits. The evolution equation, $M_s\, v dv/dt = E_m L I_{av}$, where E_m is $\boldsymbol{E_m}$ component along the tether and I_{av} length-averaged current, can be rewritten as equation for orbit-altitude H by using $v^2 = \mu_E / (R_E + H)$,

$$\frac{M_S}{m_t}\frac{dH}{dt} = -2(R_E + H)\frac{\sigma_c E_m^2}{\rho v^2} \times i_{av}(L/h^{2/3} l^{1/3}) , \qquad [\, i_{av}(L\ /h^{2/3} l^{1/3}) \equiv I_{av} / \sigma_c E_m w h \,], \qquad (2)$$

with ρ and σ_c (aluminum) tether density and conductivity, and N_e plasma density, in tether mass $m_t = \rho L w h$, and ambient dependent, characteristic length $l \propto \sigma_c^2 E_m / N_e^2$. Equation (2) holds over the fraction of orbital period with the motional field pointing upwards, about unity for not too high inclination.

Equation (2) and a combination of (1) and (2),

$$\frac{m_t}{M_s}\frac{dN_c}{dH} = -\frac{L/2}{R_E + H}\frac{\rho v^2}{\sigma_c E_m^2}\frac{\delta^* F^*}{i_{av}} \times G\left(n_0, n_1, \frac{\delta^*}{w}, \frac{w}{h}\right), \tag{3}$$

determine $t(H)$ and $N_c(H)$. Integrating from initial altitude H_0 at given inclination, down to H_f = 300 km (where air-drag on area ~ Lw would typically result in rapid re-entry), determines final values

$$\frac{m_t}{M_s} \times N_f = \Pi(w, h, L/h^{2/3}; H_0, inclination), \tag{4}$$

$$\frac{m_t}{M_S} \times t_f = \frac{\rho v_f^2}{\sigma_c \tilde{E}_m^2} \times \tau\left(\frac{L}{h^{2/3}}; H_0, inclination\right), \qquad \frac{\rho v_f^2}{\sigma_c \tilde{E}_m^2} \approx 1.45\times10^{-2} years, \; \tilde{E}_m \equiv 100 \text{ V / km} \tag{5}$$

Both integrals involve daily-averaged profiles in altitude H. An averaged solar flux of several 11-year cycles is considered for the ambient models [14].

Results from the algorithm highlight important features of bare-tether technology. It is scalable, allowing it to be competitive for a satellite mass range from tens of kilograms to multiple tons, while high inclination effects are moderate. This is illustrated by applying the design algorithm to hypothetical missions for de-orbiting satellites from the Cryosat orbit. Cryosat, an operative Earth-observing satellite following a non-synchronous orbit at 720 km altitude and 92° inclination, was launched in April 2010 to measure polar ice thickness. The algorithm is applied to 75, 750, and 7500 kilogram satellites, and it is also similarly applied for 63° inclination.

For given H_0 and inclination, results show $\boldsymbol{\tau}$ continuously decreasing with increasing $s^{1/3} \equiv L/h^{2/3}$, whereas $\boldsymbol{\Pi}$ versus $s^{1/3}$ exhibits a minimum, lying at $s^{1/3} \approx 2 \times 10^6$ $\mathrm{m}^{1/3}$ for 63°. Independently, $\boldsymbol{\Pi}$ decreases by a factor of about 10 for w increasing from 1 to 6 cm, still roughly keeping within the OML collection regime [15]; hence tethers will be more efficient in de-orbiting heavier satellites, requiring wider tapes, as seen below. The dependence on h is, on the contrary, weak.

Tape design scalability

For simple scalable design, tether mass is written as $m_t = \rho w h^{5/3} s^{1/3}$, allowing some single, *optimum* s value to apply for a broad range of satellite masses, just playing with w and h values. A range $w =$ 1 – 6 cm would then require h ranging within a 5.4 factor to allow M_S reach scaling by two orders of magnitude. A value $s^{1/3} \sim 2 \times 10^6$ m$^{1/3}$ yields a minimum $\mathbf{\Pi}$**,** but $\boldsymbol{\tau}$ can be reduced by a 2/3 factor if moving to $s^{1/3} \sim 6 \times 10^6$ m$^{1/3}$; this might be critical for the higher inclinations.

Here we shall take $s^{1/3} \approx 6 \times 10^6$ m$^{1/3}$, values w = 1, 2.45, 6 cm, and h = 10, 23.2, 54 µm, then leading to tether mass m_t = 0.75, 7.5, 75 kg (and tether length L = 2.8, 4.9, 8.6 km) respectively, making for a ratio m_t/M_S = 0.01 for all three satellite masses M_s = 75, 750, and 7500 kg.

For 63° inclination and the $s^{1/3}$ and m_t/M_S values above, and the particular w, h values considered, we roughly find $10^4 \times \Pi \approx 0.8$, 0.2, 0.1 respectively, leading to probabilities of a tape cut by small debris $10^2 \times N_f \approx 0.8$, 0.2, 0.1. These very low probabilities resulting from use of the ESA debris-flux model, suggest use of the NASA's ORDEM flux, more conservative, would still yield low cut probabilities.

We also find $\tau = 5.06 \times 10^{-2}$, leading to t_f = 26.8 *days* independently of M_s. This short de-orbit time characterizes the probability of a catastrophic satellite collision with other big S/C, its *Area-time* product, of interest in design considerations, being $t_f \times d^2$ for a representative S/C *size* $d \sim 2$ - 3 m, say.

A related index, $t_f \times L$, characterizes the collision of a big S/C with the tether, a comparatively minor accident resulting in just tape being cut and de-orbit operation aborted, as if from cuts by small debris. Its *Area-time* product, $t_f L \times d$, characterizes the probability of such accident; for $d = 2.5$ m and again 63°, we find 508, 892, and 1552 m^{2}year for the three M_s masses above, below values found in the literature [16].

High inclination effects

Considering now 92° inclination, results clearly show how moving from moderate to high inclination orbits makes tethers less efficient; tethers with given mass ratio will take longer in de-orbiting from higher inclination orbits, and, at higher inclinations, will not reach as low values of product Π. Let us first keep $s^{1/3}$ and m_t / M_S previous values. We would then have $\tau \approx 43.8 \times 10^{-2}$, which is about 8.6 times greater than the corresponding 63º value, leading to the same increase in time t_f. Also, Π would increase by about one order of magnitude.

A reasonable design choice would make mass-ratio and de-orbit time share the loss in performance by allowing m_t / M_S to increase by a factor about 2.1, and then t_f by a factor 4.1, yielding $m_t / M_S \approx 2.1 \times$

10^{-2} and $t_f \approx 109.9$ *days*, which still is about two orders of magnitude shorter than the 25 year bound on de-orbit time first established by NASA.

For the $M_S = 75$ and 750 kg cases above, we may get twice tether mass, about 1.5 and 15 kg, by just moving w to 2 and 4.9 cm respectively, and keeping h and thus L; this results in an increase of $t_f L$ by the 4.1 factor above. As regards the N_f probabilities, the Π increase resulting from moving to 92° inclination is partly compensated by the use of wider tapes, which reduce Π, and by the larger mass-ratio factor in Π; we find $10^2 \times N_f \approx 1.4$ and 0.5, as compared with respective values 0.8 and 0.2 for 63º.

The case for $M_S = 7500$ kg, and in general the multi-ton tether case, is different because any sensible w increase over 6 cm, say, would make collected current drop below OML current values as assumed from start. Doubling tether mass at w (and s) *constant* requires doubling $h^{5/3}$, i.e., increasing h by about 1.5 to 81 μm, and thus L by a 1.32 factor, and $t_f L$ increased accordingly. We again find $10^2 \times N_f$ about 0.5, as compared with 0.1 for 63º.

C). – As regards *new research* using the thermodynamic character of tethers, preliminary work presented at the recent EPSC-2015 at Nantes [17], and an extension submitted for publication, re-considers *capture* / *apojove lowering* studies on tether missions to Jupiter. Tens-of-kilometre long tapes, which Lorentz drag might need because of low ambient density N_e, result in electrons (intended to be collected) actually reaching the tape with energy so high that *range* (penetration length) δ_e exceed thickness *h*.

Design sets $h = \delta_e(\varepsilon_{max})$, with ε_{max} maximum energy of electrons reaching the anodic tether-end throughout perijove passes during operation, just hundreds of kilometres above the planet. The result is thin and short tethers, that capture S/C 3 times as heavy, just 200-300 kg, say, allowing for <u>cheap</u> missions. A similar analysis might possibly be applied for other *Giant* planets.

Need for reducing costs of space missions has been long a pressing one. The *motto* of *IAF*/*IAC* 2016, in Mexico, is *Making space accessible and affordable to all countries*. The Direction of NASA's Planetary Science Division has recently proposed designing and flying robotic space probes to so called *Ice giants*, Uranus and Neptune, with common space platforms (two copies). It insisted on looking at scaled back concepts to be developed at less cost, and identifying potential concepts across a spectrum of price points. One impediment to make missions happen is the huge price tag it takes getting out to the outer solar system.

Missions to all 4 Giant planets, Jupiter, Saturn, Uranus, and Neptune, face common issues. They are far from the Sun, and present deep gravitational wells, far from the Earth, setting both *power* and *propulsion* issues. Solar power might be hardly effective, and *poor* available power, making electric propulsion unfeasible, makes for a pressing propulsion issue, requiring huge wet mass for rockets, if not just a flyby mission but to operate through the planet gravitational well.

This leads to high cost and a mission-trip issue, the more so for the Ice giants, typically requiring very heavy S/C and very long times. It has been mentioned that the long times for designing, building, and flying such missions make them lie beyond the lifespan horizon of people involved in the missions from start. Fortunately, there are also useful points common to *Ice* and *Gas* Giants. They all have magnetic field and ambient-plasma electrons, allowing for common mission concepts (as well as *Rings* and *Radiation Belts*, as common secondary issues...). Electrodynamic tethers can provide propulsion using no propellant for both planetary capture and operation down the gravitational well. They could also generate power along, for use in those operations, or in storing to invert the tether current in operating up the well.

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