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ON THE THRUST CAPABILITY OF ELECTRODYNAMIC TETHERS WORKING IN GENERATOR MODE

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The problem of estimating the necessary conditions under which a passive electrodynamic tether (EDT) increases the orbital energy of a satellite is studied in its full generality. We derive the thrust conditions of both spinning and non-spinning EDT and the maximum achievable thrust for a generic orbit and tether attitude. After showing that in general thrust arcs are possible even when the orbital velocity exceeds the plasma velocity we show an example of EDT orbit raising starting from a low-altitude equatorial elliptic orbit around Jupiter.

INTRODUCTION

An electrodynamic tether (EDT) without external power supplies can be used for extracting useful power from the interaction with a planetary magnetic field in the presence of plasma and is said to be working in "passive" or "generator mode". Depending on spacecraft design and environmental conditions this scheme can provide a power generation scheme with higher performance with respect to conventional hardware.

In most circumstances a passive EDT optimized for power generation experiences orbit decay as part of the energy produced comes at the expense of orbital energy. In other words the resulting Lorentz force produced by the current flowing along the tether has a component which opposes the instantaneous orbital velocity hence acting as drag. However, in the general scenario both power generation and thrust are possible. For example a passive EDT in circular equatorial orbit experiences thrust whenever the local plasma velocity exceeds the spacecraft velocity. In the Jupiter system, where the plasmasphere extends well beyond stationary orbit, this allows for efficient orbit control with continuous power generation [1].

In this article we show that when elliptical and/or inclined orbits are considered the picture becomes more complex and some novel results emerge. In particular thrust arcs become possible even for the case in which the spacecraft orbital velocity is higher than that of the local planet-corotating plasma allowing in principle orbit raising at arbitrarily small orbit radius and therefore enhancing orbit controllability.

The structure of the article is the following. First we derive the equations describing the Lorentz thrust profile of an EDT whose line is orthogonal to the magnetic field and inclined by

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and angle β with respect to the local motional electric field. From the thrust profile we obtain the tether attitude range which provides a positive Lorentz force component in the direction of the instantaneous velocity vector as well as the orientation angle for maximum force.

We will consider two types of The system considered here is a passive EDT spinning in the orbital plane and whose current can be switched on and off depending on both the tether rotation angle and the location along the orbit in order to maximize thrust capability. Two classes of orbits are considered: elliptic equatorial orbits of varying eccentricities and circular orbits of varying inclinations. The necessary conditions for orbital energy increase are derived and the normalized thrust magnitude is mapped along the parameters space of the relevant orbital elements. Numerical values are then computed for Earth, Jupiter and Saturn orbits. Lastly, based on the results obtained, a numerical example of orbit raising starting from a low altitude orbit around Jupiter is investigated.

<to be extended…>

TETHER ORIENTATION FOR MAXIMUM THRUST

Let us consider a passive bare electrodynamic tether of length L flying in a generic planetary orbit in the presence of a local magnetic field **B** and plasma of electron density N_e. Let $\mathbf{v}_{sc}$ and $\mathbf{v}_{pl}$ indicate the inertial velocity of the tether center of mass and the local plasma at a given time t.

The motional electric field along the orbit is defined as:

$$\mathbf{E} = \left[\left(\mathbf{v}_{sc} - \mathbf{v}_{pl}\right) \wedge \mathbf{B}\right], \qquad (1)$$

and can be assumed constant along the tether for reasonable tether size.

Eq.(1) can also be written as:

$$\mathbf{E} = B\mathbf{R}_{\pi/2}\left(\mathbf{v}_{sc}^{\perp} - \mathbf{v}_{pl}^{\perp}\right), \qquad (2)$$

where B is the magnetic field magnitude, $\mathbf{v}_{sc}^{\perp}, \mathbf{v}_{pl}^{\perp}$ are the component of the spacecraft and plasma velocity orthogonal to the magnetic field and $\mathbf{R}_{\pi/2}$ is a rotation matrix of angle $\pi/2$ around the z axis.

We will now pose the following basic questions: given the three vectors $\mathbf{v}_{sc}$, $\mathbf{v}_{pl}$ and **B** what is, if it exists, the attitude range of the tether line for which the resulting Lorentz force increases the orbital energy of the system? And for what orientation such energy increase is maximum?

After noticing that any component of the tether line parallel to **B** does not produce any force the analysis can be restricted to the case in which the tether line is orthogonal to **B**.

Let us then set a right-handed Cartesian reference system centered at the tether center of mass and with the z axis aligned with **B** and the y axis aligned with **E**. Let β be the angle between the tether line and the y axis which corresponds to the angle between the Lorentz force vector and the x axis.

The Lorentz force is a vector orthogonal to the tether line with magnitude:

$$F = LI_{av}B \ , \tag{3}$$

where Iav is the average current in the bare electrodynamic tether. For the case of a tape tether the latter can be expressed as [2]:

$$I_{av} = \frac{4\eta}{15\pi}(5-2\zeta)\zeta^{3/2}wL^{3/2}N_e\sqrt{\frac{2q_e^{\ 3}}{m_e}}\sqrt{E|\cos\beta|} \ , \tag{4}$$

where w is the tether width, q_e and m_e are the electron mass and charge and ζ is the dimensionless zero-bias length for a tether with no ohmic effects. The parameter ζ can be optimized for maximum onboard power generation or can be set to one for maximum thrust and no power generation.

Finally η<1 is a parameter which takes into account the decrease in current due to ohmic effects and/or ion collection in the negatively biased portion of the tether, if present.

At this point we can write the x and y component of the force vector as a function of the tether attitude as follows:

$$\mathbf{F} = F_{\max} \times \left(\sqrt{\cos\beta}\cos\beta, \sqrt{\cos\beta}\sin\beta\right)^T, \ \ [-\pi/2 < \beta < \pi/2], \tag{5}$$

where F_{max} is the maximum force achievable, which is obtained from Eqs. (3,4) after setting β=0:

$$F_{\max} = \frac{4\eta}{15\pi}\sqrt{\frac{2q_e^{\ 3}}{m_e}}(5-2\zeta)\zeta^{3/2}wL^{5/2}B\sqrt{E}N_e, \tag{6}$$

The curve is plotted in Fig. 1 and related to the vectors $\mathbf{v}_{sc}^{\perp}$ and $\mathbf{v}_{pl}^{\perp}$. *Clearly, with the exception of the case in which the spacecraft velocity component* $\mathbf{v}_{sc}^{\perp}$ *is parallel and either smaller or opposite to the plasma velocity component* $\mathbf{v}_{pl}^{\perp}$*, there always exists a range of tether orientations (*$\Delta\beta$*) for which the Lorentz force acts as thrust (i.e. increases the energy of the orbit).*

This means that in general the EDT can not only supply “propellantless” thrust but also “power-free” thrust. In other words it is the kinetic energy of the rotating plasmasphere alone which directly supplies mechanical energy to the spacecraft motion. In such case external energy supplies will no longer be indispensable in order to obtain thrust.

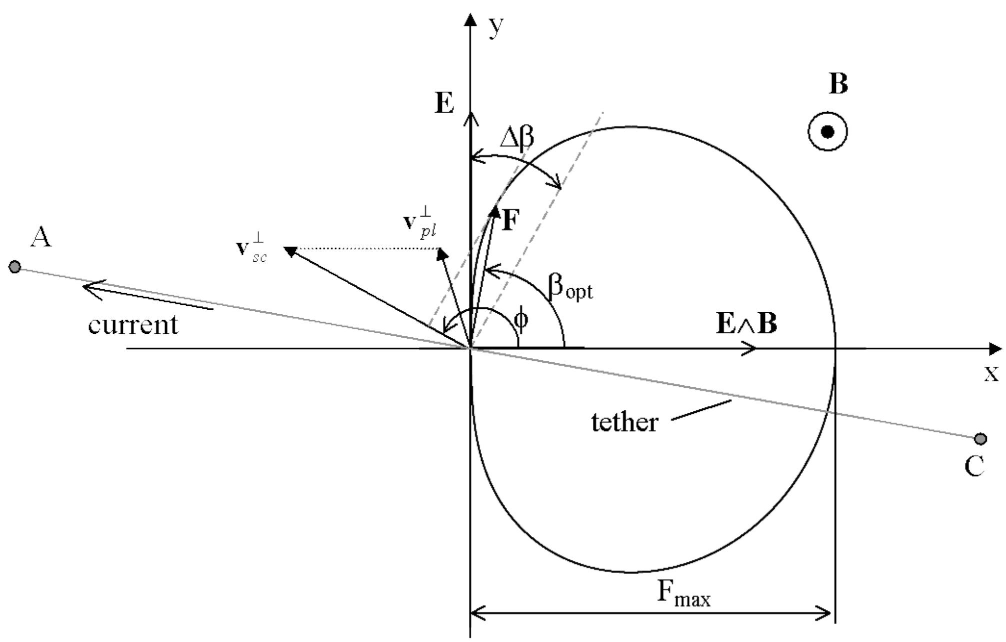

Fig.1. Force curve and optimum thrust orientation for an EDT. The magnetic field vector B is directed out of the page

Referring to Fig.1 the vector tangent to the force curve is:

$$\mathbf{F}' = \frac{F_{\max}}{2} \times \left(-3\sqrt{\cos\beta}\sin\beta, -\frac{\sin^2\beta}{\sqrt{\cos\beta}} + 2(\cos\beta)^{3/2} \right)^T . \tag{7}$$

The maximum thrust condition is obtained when the latter is orthogonal to the velocity vector:

$$\mathbf{v}_{sc} = v_{sc} \times (\cos\phi, \sin\phi)^T \ , \tag{8}$$

so that the equation to be solved is:

$$\mathbf{v}_{sc}{}^T \mathbf{F}' = \frac{2\cos^2\beta\sin\phi - 3\cos\beta\sin\beta\cos\phi - \sin^2\beta\sin\phi}{2\sqrt{\cos\beta}} = 0 \ , \tag{9}$$

from which we derive the optimal tether orientation as:

$$\beta_{opt} = \begin{cases} f_1(\phi); & \phi \in \left[-\pi, -\frac{\pi}{2}\right] \cup \left[\frac{\pi}{2}, \pi\right] \\ f_2(\phi); & \phi \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \end{cases}, \tag{10}$$

with

$$f_1(\phi) = \tan^{-1}\left(\frac{-3 - \sqrt{9 + 8\tan^2\phi}}{\tan\phi}\right) \tag{11.1}$$

$$f_2(\phi) = \tan^{-1}\left(\frac{-3 + \sqrt{9 + 8\tan^2\phi}}{\tan\phi}\right) \tag{11.2}$$

To avoid the use of the piecewise function the following empirical expression can be used:

$$\beta_{opt} \cong 2\tan^{-1}\left(\frac{\phi}{\pi}\right) \ , \tag{12}$$

with an error of less than 5%.

The range of tether orientations for which thrust is achieved can be computed from Fig.1:

$$
[\beta_{\min};\beta_{\max}] = \begin{cases} \left[-\dfrac{\pi}{2};\phi+\dfrac{\pi}{2}\right], & -\pi < \phi < 0 \\ \left[\phi-\dfrac{\pi}{2};\dfrac{\pi}{2}\right], & 0 < \phi < \pi \end{cases} \tag{13}
$$

Once the optimal tether orientation is obtained one can define the force reduction coefficient which is defined as the ratio between the total force magnitude and the maximum force achievable for the same tether at that orbit location:

$$
\mu = \frac{F(\beta_{opt})}{F_{\max}}. \tag{14}
$$

The coefficient μ can be computed according to Eq (12). Alternatively the following empirical expression can be used within an error of 2%:

$$
\mu \cong \sqrt{\cos\left[2\tan^{-1}\left(\frac{\phi}{\pi}\right)\right]}. \tag{15}
$$

Perhaps more useful for quantifying the thrust capability of the EDT is the thrust reduction coefficient, defined as the ratio between the Lorentz force component along the velocity vector and the maximum force magnitude:

$$
\mu_T = \frac{F(\beta_{opt})\cos(\phi-\beta_{opt})\cos\nu}{F_{\max}},. \tag{16}
$$

where ν is the angle between the spacecraft velocity vector and the force plane.

From equation (12,15) one can obtain:

$$
\mu_T = \sqrt{\cos\left[2\tan^{-1}\left(\frac{\phi}{\pi}\right)\right]}\cos\left[\phi-2\tan^{-1}\left(\frac{\phi}{\pi}\right)\right]\cos\nu \tag{17}
$$

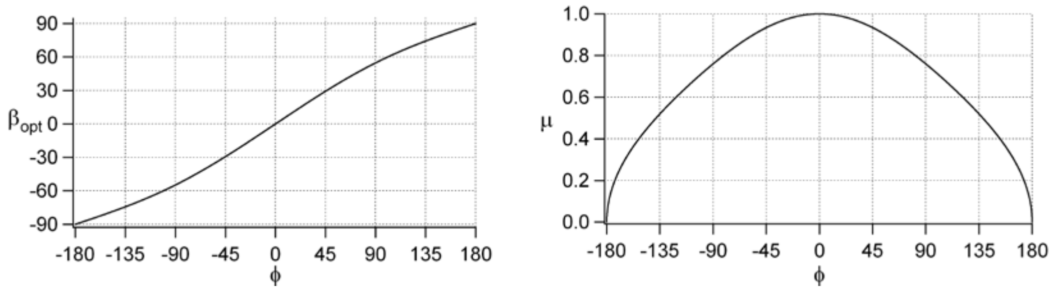

Fig.**2**. Optimal EDT orientation angle (left) and force reduction coefficient (right).

In Fig.3 we visualize the maximum-thrust orientation of an EDT dumbbell for an elliptical equatorial orbit where the magnetic field is modeled as dipole aligned with the planet rotation axis and the plasma is rigidly co-rotating with the planet.

Evidently, the tether orientation is in general far from the equilibrium configuration of a gravity gradient stabilized system so that achieving maximum thrust along the whole orbit would possibly require a continuos and complex attitude control scheme. A more reasonable control strategy would possibly employ a spinning system phased in such a way to achieve sub-optimum thrust conditions but requiring a much simpler control algorithm to achieve proper phasing. Finally, fast-spinning tethers can also be considered in which case the attitude control burden can be reduced to a minimum while still providing thrust capability. The latter scheme will be dealt with in the next section.

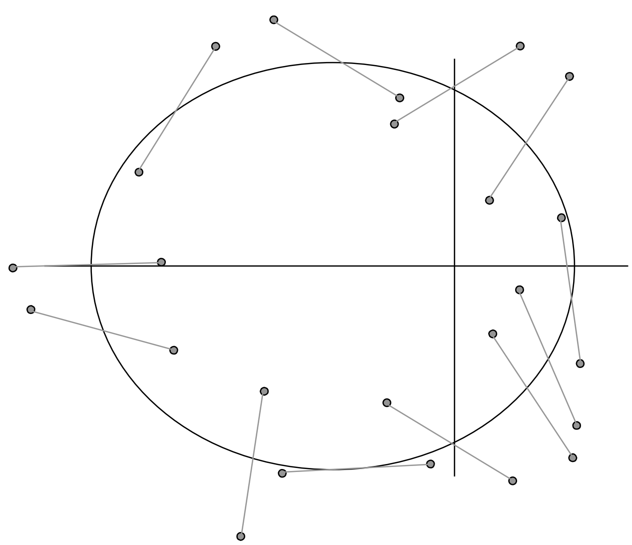

Fig.**3**. Optimal EDT orientation along an equatorial elliptic orbit with eccentricity 0.5. An aligned magnetic field dipole is assumed and a planet co-rotating plasmasphere.

AVERAGE THRUST FOR FAST-SPINNING EDT

For the case of a spinning EDT with period much smaller than the orbital period the Lorentz force can be averaged along a full tether rotation while still retaining good orbit propagation accuracy.

We will start by deriving the average Lorentz force for the simplified case in which the tether spins around an axis always parallel to the direction of the magnetic field. This is the case of having the EDT flying in equatorial orbits while spinning in the orbital plane and neglecting the magnetic dipole tilt.

From Eq. (5) and after denoting with n_C the number of cathods (n_C =2 for dual-cathod EDT, n_C =1 for single-cathod EDT) the average Lorentz force components along the thrust arc $\Delta\beta$ yield:

$$\overline{F}_{x0} = \frac{n_C F_{\max}}{2\pi}\left[S_{x0}(\beta_{\max}) - S_{x0}(\beta_{\min})\right], \tag{18.1}$$

$$\overline{F}_{y0} = \frac{n_C F_{\max}}{2\pi}\left[S_{y0}(\beta_{\max}) - S_{y0}(\beta_{\min})\right], \tag{18.2}$$

with

$$S_{x0}(\beta) = \int_0^{\beta} \sqrt{\cos\tau}\,\cos\tau\, d\tau = \frac{2}{3}\left[\sin\beta\sqrt{\cos\beta} + \widehat{F}\left(\sin\frac{\beta}{2}, \sqrt{2}\right)\right], \tag{19.1}$$

$$S_{y0}(\beta) = \int_0^{\beta} \sqrt{\cos\tau}\,\sin\tau\, d\tau = -\frac{2}{3}(\cos\beta)^{3/2}, \tag{19.2}$$

and where

$$\widehat{F}(z,k) = \int_o^z \frac{dx}{\sqrt{(1-x^2)(1-k^2x^2)}}, \tag{20}$$

indicates an incomplete elliptic integral of the first kind.

After plugging Eqs.(19) into Eqs.(18) we obtain the final expression of the average force components:

$$\overline{F}_{x0} = \frac{n_C F_{\max}}{3\pi}\left[\cos\phi\sqrt{|\sin\phi|} + \widehat{F}\left(\sin\frac{2|\phi|+\pi}{4}, \sqrt{2}\right) + \widehat{F}\left(\frac{\sqrt{2}}{2}, \sqrt{2}\right)\right] \tag{21.1}$$

$$\overline{F}_{y0} = \frac{n_C F_{\max}}{3\pi}\frac{\phi}{|\phi|}|\sin\phi|^{3/2} \tag{21.2}$$

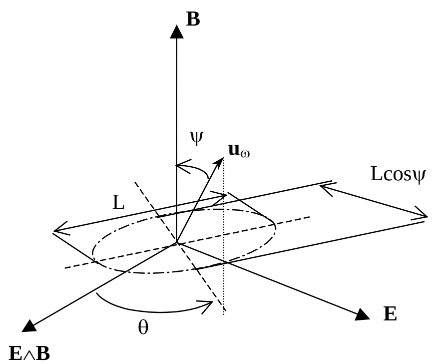

Fig.4. Orientation of tether spin axis with respect to the magnetic field vector and force plane.

In the most general scenario the tether spin axis is not parallel to the magnetic field which reduces the average force achievable. Referring to Fig. 4 the tether spin axis $\mathbf{u}_\omega$ is inclined with respect to the magnetic field and force plane by the angles θ and ψ. To simplify the notation we assume, without loss of generality $0<\psi<\pi/2$.

After calling λ the tether rotation angle around $\mathbf{u}_\omega$ we derive, from basic trigonometry, the projected tether length $\rho(t)$ on the force plane and the sine and cosine of the angle between the latter and the x axis:

$$\rho(\lambda) = \sqrt{\sin^2\lambda + \cos^2\psi\cos^2\lambda} \tag{22}$$

$$\sin(\beta) = \frac{\cos\psi\sin\theta\cos\lambda + \cos\theta\sin\lambda}{\rho(\lambda)} \tag{23.1}$$

$$\cos(\beta) = \frac{\cos\psi\cos\theta\cos\lambda - \sin\theta\sin\lambda}{\rho(\lambda)} \tag{23.2}$$

In addition, we have :

$$\tan(\lambda) = \frac{\cos\theta \tan\beta - \sin\theta \cos\psi}{\sin\theta \tan\beta + \cos\theta} \tag{24}$$

So that the general expression of the force vector becomes:

$$Fx = F_{\max}\left\lfloor \sqrt{S^2\lambda + C^2\psi C^2\lambda} \times \left(C\psi C\theta C\lambda - S\theta S\lambda\right)^{3/2} \right\rfloor \tag{25.1}$$

$$Fy = F_{\max}\left\lfloor \sqrt{(S^2\lambda + C^2\psi C^2\lambda)\left(C\psi C\theta C\lambda - S\theta S\lambda\right)} \times \left(C\psi S\theta C\lambda + C\theta S\lambda\right) \right\rfloor \tag{25.2}$$

defined in the interval:

$$\begin{cases} \lambda^* < \lambda < \pi + \lambda^*, & -\pi/2 < \theta < 0 \\ \lambda^* - \pi < \lambda < \lambda^*, & 0 < \theta < \pi/2 \end{cases} \tag{26}$$

with:

$$\lambda^* = \tan^{-1}\left(\frac{C\theta C\psi}{S\theta}\right) \tag{27}$$

The interval [$\lambda_{\min}$ $\lambda_{\max}$] that provides thrust can be derived starting from $\beta_{\min}$ and $\beta_{\max}$ and with some trigonometry considerations. Finally one obtains:

$$\left[\lambda_{\min} \quad \lambda_{\max}\right] =$$

$$\begin{array}{ll} \left[\lambda^* \quad \tilde{\lambda}\right] & \theta > 0 \quad and \quad -\pi < \phi < \theta \\ \left[\lambda^* \quad \tilde{\lambda} + \pi\right], & \theta < 0 \quad and \quad \theta < \phi < 0 \\ \left[\lambda^* - \pi \quad \tilde{\lambda} - \pi\right] & \theta > 0 \quad and \quad -\pi < \phi < -2\theta \\ \left[\lambda^* - \pi \quad \tilde{\lambda}\right] & \theta > 0 \quad and \quad -2\theta < \phi < 0 \end{array}$$

$$\begin{array}{ll} \left[\tilde{\lambda} - \pi \quad \lambda^*\right] & \theta > 0 \quad and \quad 0 < \phi < \theta \\ \left[\tilde{\lambda} \quad \lambda^*\right] & \theta > 0 \quad and \quad \theta < \phi < \pi \\ \left[\tilde{\lambda} \quad \lambda^* + \pi\right] & \theta < 0 \quad and \quad \theta < \phi < -2\theta \\ \left[\tilde{\lambda} + \pi \quad \lambda^* + \pi\right] & \theta < 0 \quad and \quad -2\theta < \phi < \pi \end{array}$$

with

$$\tilde{\lambda} = \tan^{-1}\left(\frac{\cos\theta \tan\beta - \sin\theta \cos\psi}{\sin\theta \tan\beta + \cos\theta}\right) \tag{28.1}$$

$$\lambda^* = \tan^{-1}\left(\frac{C\theta C\psi}{S\theta}\right) \tag{28.2}$$

It is now possible to compute the average value of the force components as:

$$\overline{F}_x = \frac{n_C}{2\pi} \times \int_{\lambda_{\min}}^{\lambda_{\min}} F_x(\lambda)\, d\lambda\,, \tag{29.1}$$

$$\overline{F}_y = \frac{n_C}{2\pi} \times \int_{\lambda_{\min}}^{\lambda_{\min}} F_y(\lambda)\, d\lambda\,, \tag{29.2}$$

Unfortunately, in the most general case the integrals cannot be solved in close analytical form. The preferred solution is to compute the integral numerically at every integration step.

OPTIMUM VELOCITY CONDITIONS WITH RESPECT TO THE PLASMA

Let us suppose that our EDT crosses the plasmasphere with velocity of given magnitude v_{sc} while the local plasma velocity has magnitude v_{pl}. Let α be the angle between the two velocity vectors. It is interesting to evaluate the achievable thrust for varying α and to search for optimum conditions.

The direction of the maximum Lorentz force vector can be computed as:

$$\mathbf{E} \wedge \mathbf{B} = B^2(\mathbf{v}_{pl}^{\perp} - \mathbf{v}_{sc}^{\perp})\,. \tag{30}$$

As seen in the previous section the maximum thrust is achieved when the absolute value of angle between the latter and the spacecraft velocity $\mathbf{v}_{sc}^{\perp}$ is minimum.

Referring to Fig. 5 two cases need to be distinguished. When the spacecraft velocity is greater than that of the plasma (Fig. 3, left side) the optimum condition obeys:

$$\begin{cases} v_{sc}^{\perp} > v_{pl}^{\perp} \\ (\mathbf{v}_{pl}^{\perp} - \mathbf{v}_{sc}^{\perp}) \cdot \mathbf{v}_{pl}^{\perp} = 0 \end{cases} \tag{31}$$

in other words *when the EDT is faster than the plasma the optimum thrust conditions occur when the spacecraft velocity component in the direction of the plasma velocity vector is equal to the plasma velocity magnitude*.

On the other hand when the spacecraft velocity is smaller than that of the plasma (Fig. 3, right side) the optimum condition obeys:

$$\begin{cases} v_{sc}^{\perp} < v_{pl}^{\perp} \\ \mathbf{v}_{sc}^{\perp} \,//\, \mathbf{v}_{pl}^{\perp} \end{cases}$$

which means that *when the EDT is slower than the plasma the optimum thrust conditions occur when the spacecraft velocity is parallel to the plasma velocity*.

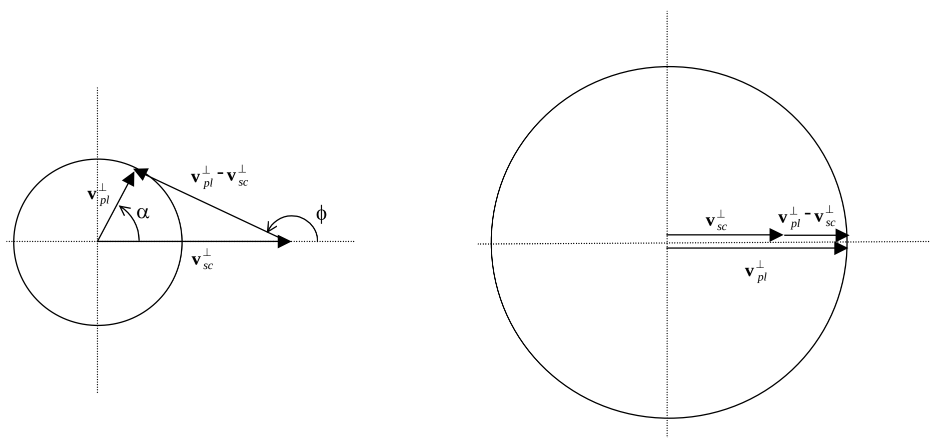

Fig.5. Optimal spacecraft velocity orientation with respect to local plasma velocity for the two cases of spacecraft faster(a) and slower(b) than the plasma.

PERFORMANCE ALONG ELLIPTIC EQUATORIAL ORBITS AROUND JUPITER

We will now apply the results obtained in the previous section to real mission cases considering two control schemes:

a) The tether line is constantly oriented along the thrust-optimum direction and the current is always switched on.

b) The tether spins around an axis of fixed inertial orientation and the current is switched on whenever the Lorentz force corresponds to an increase in orbital energy.

The scenario a) is useful from the theoretical point of view as it represents an upper limit for the thrust achievable and, in turns, a quasi-optimum solution to the orbit raising problem. While the *real optimum* solution could still require the current to be switched off at convenient times the full optimization problem will not be addressed in this article.

From the practical point of view the scenario a) is not very realistic for different reasons. Most importantly it may not be possible to control a very-large-angular-momentum system to track a quickly changing attitude as required to satisfy the maximum thrust conditions. In addition the tether itself would likely encounter zero-tension conditions as the optimum attitude generally lies away from the maximum gravity gradient condition.

Scenario b) is undoubtedly more close to a real life situation. In fact a fast spinning EDT would undergo a small pointing drift from an inertially fixed axis as long as the angular velocity is sufficiently high [3]. On the other hand it is reasonable to think that some improvements on the EDT performance could be gained when compared to scenario b). For example a clever phasing of the spin rate with the orbit could allow the tether to be close to the ideal orientation at convenient points along the orbit.

In the example below we start from a low Jupiter orbit with eccentricity 0.35 and periapsis radius at 1.06 Jupiter radii (altitude of 4300 km). A 40-km-long aluminum tape tether with 0.05 mm thickness and 5 cm width was employed for a total tether mass of 270 kg. A payload of 200 kg mass was added, for a total 470 kg mass. A full Divine-Garrett ionospheric model was employed while ohmic effects were neglected.
Result based on scenario a) and b) are plotted in Figs. 6-11.

It is interesting to notice how the plasma/spacecraft electrodynamic interaction results in a circularization of the initial orbit with an overall gain in orbital energy. The difference between the ideally-controlled with the uncontrolled EDT is overwhelming.
Finally we can see that the Lorentz force component normal to the orbit is more than one order of magnitude bigger than the tangential one suggesting that its role on the orbit evolution may be substantial if not dominant.

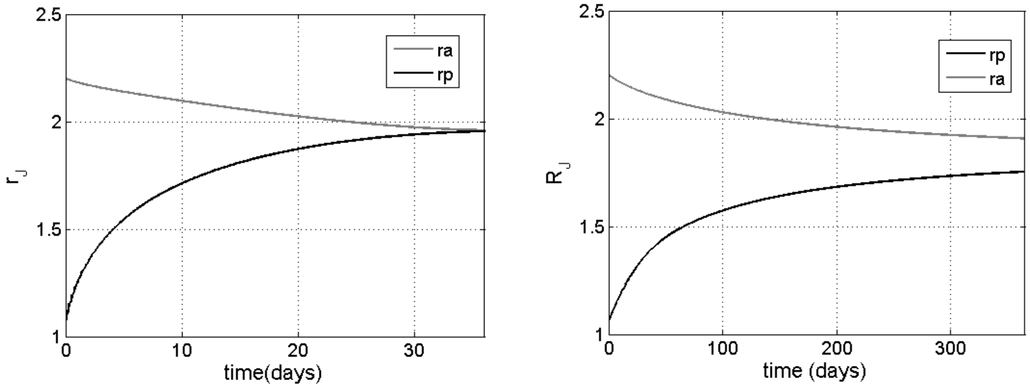

Fig.6. Evolution of periapsis and apoapsis for scenario a (left) and b (right)

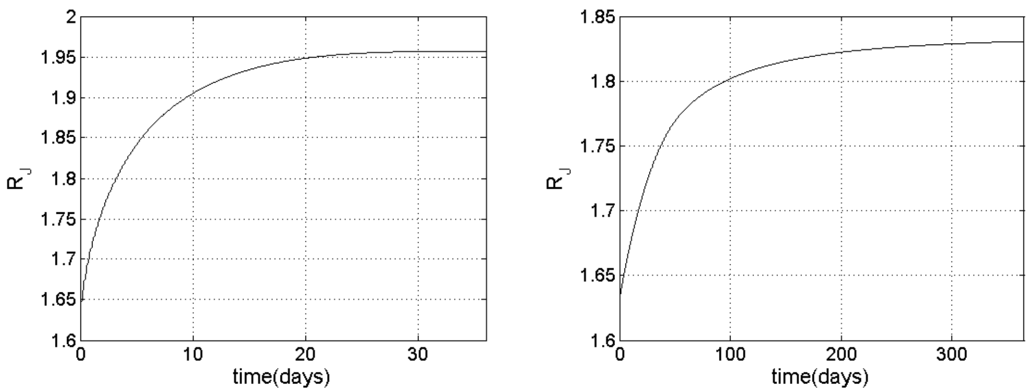

Fig.7. Evolution of semimajor axis for scenario a (left) and b (right)

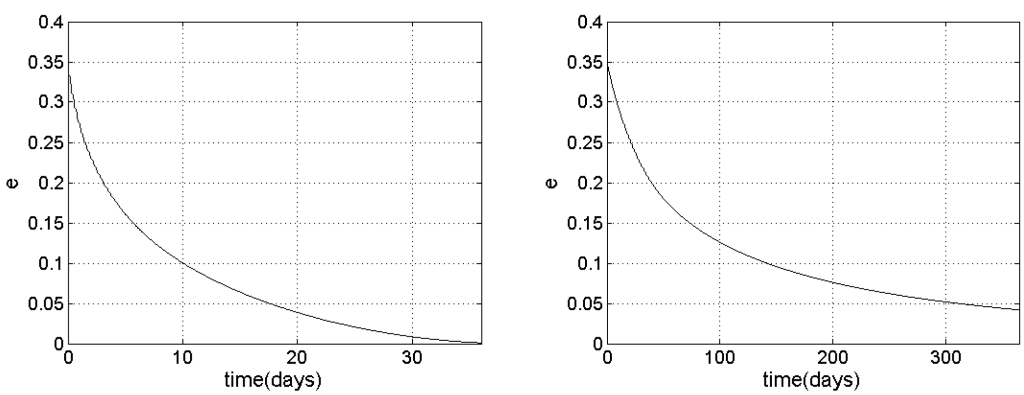

Fig.8. Evolution of eccentricity for scenario a (left) and b (right)

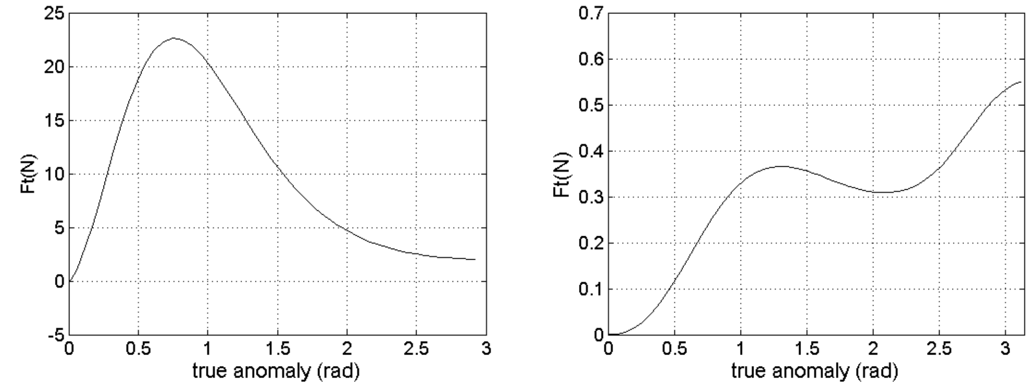

Fig.9.First orbit tangential thrust component for scenario a (left) and b (right)

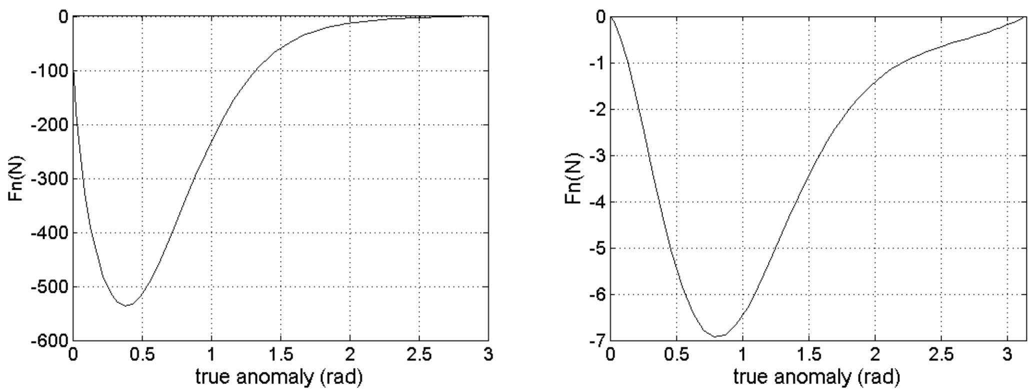

Fig.10.First orbit normal thrust component for scenario a (left) and b (right)

CONCLUSIONS

We have shown that in the most general scenario of orbits which are non-equatorial and/or non-circular electrodynamic tethers (EDT) working in passive mode can always produce thrust in such a way that the energy of the orbit increases. From an energetic point of view it is the planet-corotating plasmasphere which supplies mechanical energy to the spacecraft in the presence of the EDT. Optimum EDT orientations with respect to the local motional electric field were derived and can be used to optimize EDT orbital maneuvering around Earth and Jupiter. A numerical example starting from a low altitude elliptic orbit around Jupiter have been studied showing that the global effect of the Lorentz force is a circularization of the orbit superimposed to an increase of energy.

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