COULOMB DRAG DEVICES: ELECTRIC SOLAR WIND SAIL PROPULSION AND IONOSPHERIC DEORBITING

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Abstract

A charged tether or wire experiences Coulomb drag when inserted into flowing plasma. In the solar wind the Coulomb drag can be utilised as efficient propellantless interplanetary propulsion as the electric solar wind sail (electric sail, E-sail). In low Earth orbit (LEO) the same plasma physical effect can be utilised for efficient low-thrust deorbiting of space debris objects (the plasma brake). The E-sail is rotationally stabilised while the deorbiting Coulomb drag devices can be stabilised either by spinning or by Earth's gravity gradient.

According to numerical estimates, Coulomb drag devices have very promising performance figures, both for interplanetary propulsion and for deorbiting in LEO. Much of the technology is common to both applications. E-sail technology development was carried out in ESAIL FP7 project (2011-2013) which achieved TRL 4-5 for key hardware components that can enable 1 N class interplanetary Esail weighing less than 200 kg. The thrust of the E-sail scales as inverse solar distance and its power consumption (nominally 700 W/N at 1 au) scales as the inverse distance squared. As part of the ESAIL project, a continuous 1 km sample of E-sail tether was produced by an automatic and scalable "tether factory". The manufacturing method uses ultrasonic wire to wire bonding which was developed from ordinary wire to plate bonding for the E-sail purpose. Also a "Remote Unit" device which takes care of deployment and spin rate control was prototyped and successfully environmentally tested. Our Remote Unit prototype is operable in the solar distance range of 0.9-4 au.

The 1-U CubeSat ESTCube-1 was launched in May 2013 and it will try to measure the Coulomb drag acting on a 10 m long tether in LEO when charged to 500 V positive or negative. A more advanced version of the experiment with 100 m tether is under preparation and will be launched in 2015 with the Aalto-1 3-U CubeSat to polar LEO.

1 Introduction

The concept of solar wind electric sail (electric sail, E-sail, Fig. 1) was proposed as a device which harnesses the momentum flux of the natural solar wind [1, 2]. The first attempt to predict the thrust per unit tether length was based on electrostatic particle-in-cell (PIC) simulations [2]. The initial thrust estimate was later corrected upward [3].

It was realised that not only a positive, but also a negative tether would produce a Coulomb drag effect [4]. As a new application for the technology, it was proposed that a single gravity-stabilised negatively biased tether could be used for satellite and space debris deorbiting in low Earth orbit (LEO) [5] (Fig. 2).

The E-sail has potentially revolutionary performance level in comparison to other propulsion systems [6]. The tether weighs only 10 grams per kilometre and produces a thrust of ~ 0.5 mN/km at 1 au distance. The E-sail thrust scales as proportional to 1/r where r is the solar distance. The reason is that while the solar wind dynamic pressure decays as $\sim 1/r^2$, the plasma Debye length (by which the electric field penetration distance and hence the virtual sail size scales) varies as $\sim r$, thus giving an overall 1/r dependence for the thrust. For example, hundred 20 km long tethers would weigh 20 kg and they would produce 1 N thrust at 1 au which gives a 30 km/s velocity change pear year for a 1000 kg spacecraft.

E-sail thrust magnitude can be easily controlled between zero and a maximum value by changing the voltage of the tethers. The tether voltage is maintained by continuously operating an electron gun which pumps out negative charge from the system, hence tether voltage can be actuated easily by changing the current and voltage of the electron gun beam. The power consumption of the electron gun is moderate (700 W nominally at 1 au for large 1 N sail) and it scales as $1/r^2$, i.e. in the same way as the illumination power of solar panels. The

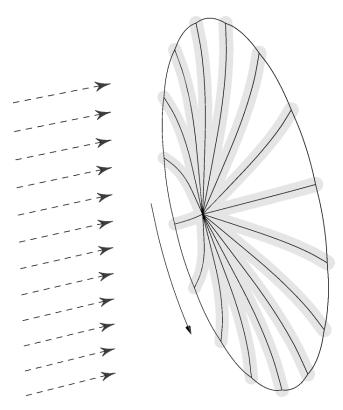


Figure 1: Centrifugally stabilised E-sail with auxiliary tethers [6]. The auxiliary tethers connect the tips of the main tether and prevent the main tethers from colliding with each other despite solar wind variations. A "Remote Unit" (Fig. 6) is located at the tip of each main tether (not visible in this scale). The Remote Unit hosts the auxiliary tether reels and a thruster (e.g. cold gas, ionic liquid FEEP or photonic blade) to initiate the spin during deployment and to manage the spinrate during flight if needed.

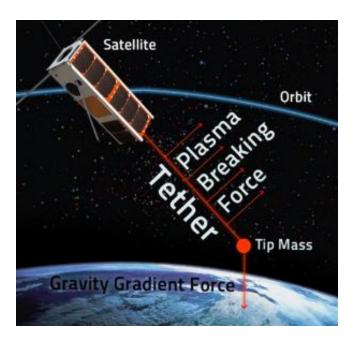


Figure 2: Negatively biased gravity-stabilised Coulomb drag plasma brake in LEO for satellite deorbiting [35].

power consumption stems from the electron current gathered from the surrounding solar wind plasma by the positively charged tethers which can be estimated by so-called orbital motion limited (OML) cylindrical Langmuir probe theory [2],

$$\frac{dI}{dz} = en_o \sqrt{\frac{2eV_0}{m_e}} \left(2r_w^{\text{base}} + 4.5 \times r_w^{\text{loop}} \right). \tag{1}$$

Here e is the electron charge, n_o is the solar wind plasma density, V_0 is the tether bias voltage, m_e is electron mass, $r_w^{\rm base} = 25 \, \mu \rm m$ is the base wire radius of the micrometeoroid-resistant 4-wire Heytether [7, 8], $r_w^{\rm loop} = 12.5 \, \mu \rm m$ is the loop wire radius [7, 8] and dI/dz is the gathered current per unit length of the tether. Clearly, to minimise power consumption, the tether outer surface area should be made as small as possible while keeping the tethers micrometeoroid-tolerant and their resistance low enough to avoid significant ohmic power losses. The ultrasonically bonded 4-wire aluminium Heytether satisfies these requirements [7, 8].

The thrust direction of the E-sail can be changed by inclining the sail with respect to the solar wind flow. Tilting of the spinplane of the tethers can be actuated by modulating the voltages of the tethers differentially so as to produce net torque which turns the sail. Such tilting manoeuvres typically take a few hours. Even without applying closed loop control for sail orientation during the journey, it was shown by Monte Carlo calculations with real measured solar wind data that a planet such as Mars can be reached by using a simple controller which increases (decreases) the tether voltage when the spacecraft is behind (ahead of) schedule on its planned trajectory towards the target [9]. Thus, although the E-sail's thrust source is the highly variable and basically unpredictable solar wind, its navigability can be made comparable to other propulsion systems. In addition, the E-sail's thrust magnitude and thrust direction can be varied independently of each other which is a benefit in comparison e.g. to the photon sail where they typically vary in unison.

In missions which spiral inward or outward in the solar system there is a secular tendency due to orbital Coriolis force for the spin rate to decrease or increase, respectively [10]. Because the E-sail effect itself in general cannot produce propulsion within the spin plane, the Coriolis effect must be counteracted by auxiliary propulsion system on the Remote Units installed on tips of the main tethers [6]. To this end, in the ESAIL FP7 project, a prototype Remote Unit was developed with two alterna-

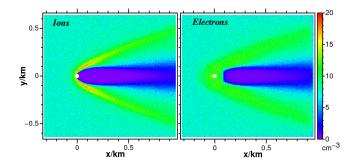


Figure 3: PIC simulation of positively charged E-sail tether interacting with streaming solar wind plasma [23]. Solar wind (density 7.3 cm^{-3} , speed 400 km/s) arrives from the left and interacts with +5.6 kV charged tether at (white dot).

tive propulsion systems (cold gas and ionic liquid FEEP) [11]. Photonic blade auxiliary propulsion devices have also been considered for this task [12].

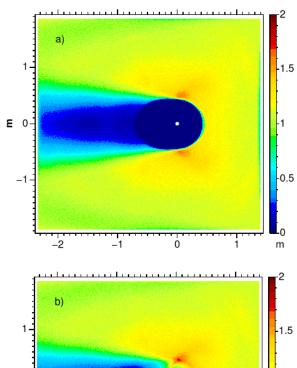
The E-sail has potentially revolutionary level of performance and hence it has a large number of applications in solar system missions [13, 14, 15, 16, 17, 18, 19, 20]. The various E-sail solar system applications are discussed and summarised by [21] and a readable yet rigorous presentation of the mission possibilities from the orbital calculations perspective is available [22].

2 Physics of Coulomb drag

When plasma streams past a charged thin tether, the tether's electric field penetrates some distance into the plasma and deflects the charged particles of the stream. Because electrons are lightweight, the momentum flux carried by them is negligible so it is enough to consider the deflection of ions. Both positively and negatively biased tethers cause ion deflection and hence Coulomb drag. A positive tether deflects positively charged ions by repelling them (Fig. 3). A negative tether deflects ions by attracting them so that their paths cross behind the tether (Fig. 4).

2.1 Positively biased tether

A positively biased tether repels stream ions and attracts electrons. When the potential is turned on, a population of trapped electrons gets formed [2]. In most of the literature concerning biased tethers, it is implicitly or explicitly assumed that trapped electrons are not present in the asymptotic state. In a multi-tether starfish-shaped Esail geometry (Fig. 1), trapped electron orbits are chaotised whenever the electron visits the central



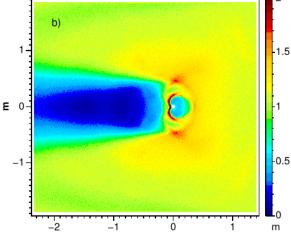


Figure 4: Electron density (a) and ion density (b) normalised to plasma stream density in the final state (t = 2.43 ms) in LEO conditions [25]. Flow arrives from the right.

"hub" which is the spacecraft, and chaotised electrons have a small nonzero probability of getting injected into an orbit which takes them to collision course with a tether wire so that trapped electrons are removed by this mechanism in few minute timescale in nominal 1 au solar wind [3]. It might be that other processes such as plasma waves occur in nature which speed up the process. By PIC simulations alone it is not easy to predict how much if any trapped electrons are present in the final state.

The E-sail thrust per tether length dF/dz is given by

$$\frac{dF}{dz} = KP_{\rm dyn}r_s \tag{2}$$

where K is a numerical coefficient of order unity, $P_{\rm dyn} = \rho v^2$ is the dynamic pressure of the plasma flow and r_s is the radius of the electron sheath (the penetration distance of the electric field into the plasma). The quantity r_s can be inferred from recent laboratory measurements of Siguier et al. [24] where Ar^+ plasma (ion mass $m_i = 40$ u) of density $n_0 = 2.4 \cdot 10^{11} \text{ m}^{-3}$ accelerated to 20 eV bulk flow energy (hence speed v = 9.8 km/s) was used and let to interact with $r_w = 2.5$ mm radius metal tether biased to $V_0 = 100 \text{ V}$ and 400 V in two experiments. At $V_0 = 100 \text{ V}$ the sheath radius as visually determined from their Figure 7 is $r_s = 12$ cm and at 400 V it is $r_s = 28$ cm (from their Figure 8). For estimating the corresponding dF/dz, let us assume K=2 in the above formula [Eq. (2)]. This corresponds to assuming that ions incident on the sheath are on average deflected by 90° (notice that the size of the virtual obstacle made by the sheath is twice its radius). We think that this is a reasonable first estimate since ions arriving head-on towards the tether are reflected backwards while ions arriving near the boundaries of the sheath are probably deflected by less than 90°. In their experiment $P_{\rm dyn}=1.54~\mu{\rm Pa}$ so Eq. 2 gives dF/dz=370nN/m and dF/dz = 860 nN/m for V_0 equal to 100 V and 400 V, respectively.

Let us compare these experimentally inferred values with theoretical estimates. A simple theoretical estimate for the sheath radius is the effective Debye length

$$\lambda_D^{\text{eff}} = \sqrt{\frac{\epsilon_0 \left(V_0 - V_1 \right)}{e n_0}} \tag{3}$$

where $V_1=(1/2)m_iv^2/e$ is the stream ion bulk flow energy. The expression (3) for the effective Debye length is obtained from the usual formula for ordinary electron Debye length by replacing the electron temperature by the tether voltage. We also subtract the bulk energy term V_1 to model the fact that if the tether voltage is lower than the bulk energy, it can no longer reflect back or stop ions but only weakly deflects them even if they arrive with zero boost parameter; the subtraction of V_1 however has only modest impact to our results. If one takes r_s to be equal to $\lambda_D^{\rm eff}$ in Eq. (2), one obtains dF/dz equal to 420 nN/m and 910 nN/m for V_0 equal to 100 V and 400 V, respectively.

Theoretical E-sail thrust formulas of [6] contain the average electron density n_e inside the sheath as a free parameter, the choice $n_e = 0$ giving the largest E-sail thrust. Assuming $n_e = 0$ and applying the formulas for the experimental parameters of Siguier et al. [24], one obtains 220 nN/m and 740 nN/m thrust per length for V_0 equal to 100 V and 400 V, respectively.

We summarise the experimental and theoretical results in Table 1.

Table 1: Comparison of experimental and theoretical E-sail thrust per length in LEO-like conditions.

	$V_0 = 100 \text{ V}$	$V_0 = 400 \text{ V}$
Siguier et al. [24]	370 nN/m	860 nN/m
$\lambda_D^{\mathrm{eff}},\mathrm{Eq.}3$	$420~\mathrm{nN/m}$	$910~\mathrm{nN/m}$
Theory of [6] /w n_e =0	$220~\mathrm{nN/m}$	$740~\mathrm{nN/m}$

We conclude from Table 1 that experimental results of [24] are consistent with the assumption of no trapped electrons, i.e. maximal E-sail thrust.

2.2 Negatively biased tether

In the negative polarity case, electrons are simply repelled by the tether (Fig. 4) and hence the physics of electrons is simple. We believe that PIC simulations therefore have a good chance of predicting the thrust correctly in the negative polarity case. Using a new supercomputer, a comprehensive set of negative polarity PIC simulations for LEO-like parameters was recently conducted [25] and it was found that the following formula gives a good fit to the PIC simulations:

$$\frac{dF}{dz} = 3.864 \times P_{\rm dyn} \sqrt{\frac{\epsilon_0 \tilde{V}}{e n_0}} \exp\left(-V_i/\tilde{V}\right). \tag{4}$$

Here v_o is the ionospheric plasma ram flow speed relative to spacecraft (assumed to be perpendicular to the tether or else v_o denotes only the perpendicular component), $P_{\rm dyn} = m_i n_o v_o^2$ is the flow dynamic pressure, m_i is the ion mass (typically the plasma is singly ionised atomic oxygen so that $m_i \approx 16$ u),

$$\tilde{V} = \frac{|V_0|}{\ln(\lambda_D^{\text{eff}}/r_w^*)},\tag{5}$$

 r_w^* is the tether's effective electric radius (Appendix A of [2]), $\lambda_D^{\rm eff} = \sqrt{\epsilon_0 |V_0|/(en_0)}$ is the effective Debye length and $V_i = (1/2) m_i v_o^2/e$ is the bulk ion flow energy in voltage units. The effective electric radius is approximately given by $r_w^* = \sqrt{br_w} \approx 1$ mm, where r_w is the tether wire radius, typically 12.5-25 μ m, and b is the tether width, typically 2 cm (a rough value of b is sufficient to know because r_w^* enters into Eq. (4) only logarithmically).

Thus, although experimental confirmation is needed, there is good reason to believe that Eq. 4 describes LEO plasma brake thrust well. The only exception is that if the geomagnetic field is predominantly oriented along the tether, the interaction becomes turbulent and the thrust is moderately reduced [25]. The reduction grows with increasing voltage: it is 17% at -320 V bias voltage and



Figure 5: 1 km tether (mass 11 grams) on its $\emptyset = 5$ cm reel [8].



Figure 6: ESAIL project Remote Unit prototype [11].

27% at -760 V. For a vertical gravity-stabilised plasma brake tether in polar orbit, efficiency reduction with respect to Eq. (4) is thus expected at high latitudes.

We emphasise that Eq. (4) has thus far only been verified with simulations in LEO plasma environment conditions. If negative polarity Coulomb drag devices would become relevant in the future also in other plasma conditions, the applicability of Eq. (4) should be considered carefully on a case by case basis.

3 E-SAIL DEVELOPMENT

The goal of ESAIL FP7 project (2011-2013) was to develop prototypes of key components of a 1 N E-sail at technical readiness level (TRL) 4-5 [26]. The main achievements were the following:

• Demonstrated manufacturing of 1 km continuous 4-wire E-sail tether (Fig. 5, [8]).

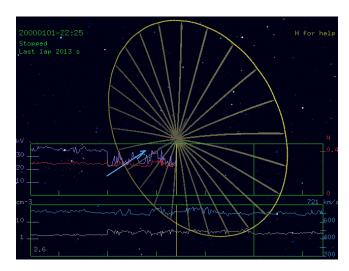


Figure 7: Screenshot from E-sail dynamical simulator [30].

- Demonstrated successful reel-out of 100 m tether at low (0.25 gram) tension, also after reel was shaken in launch vibration test facility [27].
- Built and tested low-mass prototype Remote Unit with 0.9-4 au operational range (Fig. 6, [11, 28]).
- Proposed and prototyped solution for auxiliary tether (perforated kapton tape, [29]).
- E-sail "flight simulator" software (Fig. 7, [30, 31]), E-sail failure mode and recovery strategy analysis [32], E-sail mass budget estimation [33], applications [22].

These achievements suggest that a large-scale (up to 1 N) E-sail is feasible to build. While a lot of work certainly remains to be done before a large-scale E-sail becomes a reality, no unsolved technical problems are currently known.

4 Plasma brake development

Recall from section 2.2 that for LEO parameters, Eq. 4 is a good fit to PIC simulations (except for modest thrust reduction due to turbulence when the dominant component of the geomagnetic field is along the tether) which in turn are expectedly good models of reality in case of negative tether voltage.

One noteworthy fact is that LEO plasma brake thrust according to Eq. 4 is proportional (through linear dependence on P_{dyn}) to the ion mass m_i . Thus, plasma brake thrust is 16 times larger in pure oxygen O° plasma than in pure proton plasma.

Table 2: Predicted plasma brake thrust (nN/m) for solar min/solar max conditions.

Altitude	MLT 12-00	MLT 06-18	Average
700 km	47/157	42/140	44/149
$800~\mathrm{km}$	33/117	30/108	32/112
$900~\mathrm{km}$	25/88	22/84	23/86

For example, at $V_0 = -1$ kV, $n_0 = 3 \cdot 10^{10}$ m⁻³, v = 7.5 km/s and $m_i = 16$ u, Eq. 4 gives 85 nN/m thrust. In the negative bias case, usable tether voltage is limited by onset of electron field emission. We think that above 1-2 kV, field emission might start to become an issue.

Table 2 gives plasma brake thrust based on Eq. 4, assuming $V_0 = -1$ kV, v = 7.5 km/s and using plasma density and chemical composition taken from the IRI-2012 ionospheric model, for noonmidnight (mean local time MLT 12-00) and dawndusk (MLT 06-18) polar orbits and for solar minimum and maximum ionospheric conditions. We see from Table 2 that the dependence on solar cycle is relatively significant, about factor 3.5. The solar cycle dependence is due to increased plasma density and increased oxygen abundance during solar maximum conditions. There is obviously also an altitude dependence. Below 700 km the thrust would continue to increase until $\sim 400-500$ km, provided that the hardware is designed to take advantage of it. The dependence on MLT is weak.

As a numeric example, consider a 10 km long plasma brake tether which starts bringing down a debris object of 200 kg mass from 800 km circular orbit in an MLT which is average between dawndusk and noon-midnight. The required Δv from 800 km to 700 km is 53.5 m/s and from 700 kmto 400 km 165 m/s. During solar minimum, deorbiting from 800 km to 700 km takes 0.88 years and the rest from 700 km to 400 km (assuming the same thrust as at 700 km) takes 2.4 years, thus altogether 3.25 years. During solar maximum the $800\rightarrow700$ km deorbiting takes 0.25 years and $700\rightarrow400$ km 0.7 years, thus altogether 0.96 years. These estimates are conservative since in reality plasma density and oxygen concentration and hence plasma brake thrust continue to grow below 700 km.

5 ESTCUBE AND AALTO TEST MISSIONS

The ESTCube-1 nanosatellite (1 kg, 1-U Cube-Sat) was launched in May 7, 2013 onboard Vega from Kourou, French Guiana. The primary payload of ESTCube-1 is a Coulomb drag experiment

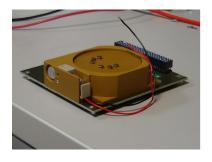




Figure 8: Left: ESTCube-1 Coulomb drag experiment payload (10x10 cm circuit board), Right: ESTCube-1 1-U CubeSat. Photographs by Jouni Envall and Tartu Observatory.

[34] and the goal of the mission is to measure the Coulomb drag force acting on its 10 m long tether in LEO conditions (670 km altitude polar orbit). The satellite can polarise the tether to ± 500 V, hence both E-sail (positive polarity) and plasma brake (negative polarity) experiments can be carried out. The positive mode uses nanographite electron guns while the negative mode in this case needs only a voltage source which creates a potential difference between the tether and the satellite body: electron collection by the satellite's conducting parts can balance the ion current gathered by the tether.

The ESTCube-1 tether experiment has not yet been started. The satellite is otherwise working fine, but there are some technical issues with its attitude control system. Work is ongoing to resolve those issues by software and we hope to be able to carry out the tether experiment soon. All aspects of ESTCube-1 are documented in an ESTCube-1 special issue of the *Proceedings of the Estonian Academy of Sciences* which is expected to appear in late May 2014.

Aalto-1 is a Finnish 3-U CubeSat which will be launched in 2015 [35]. Aalto-1 carries (among other things) a 100 m long Coulomb drag tether experiment. The work of building the satellite and the payload is proceeding at an advanced stage.

6 TECHNOLOGY ROADMAP

The E-sail and the plasma brake have a lot of technical synergy. The baseline concept is that the interplanetary E-sail uses positive voltages, electron gun and multiple centrifugally stabilised tethers while the plasma brake uses vertical gravity-stabilised tether(s), negative voltage and no electron or ion gun (a relatively small conducting object being enough to gather the balancing electron current in that case). However, it is not impossible to combine the elements of the technology also in

other ways.

One LEO CubeSat experiment (ESTCube-1) is already in orbit and another one (Aalto-1) is being built. If these experiments are technically successful, they will demonstrate deployment of 10 m and 100 m tether, respectively, and will measure the strength of negative and positive polarity Coulomb drag effects in LEO plasma conditions.

Our current plan for the next step is to fly a 3-U CubeSat experiment (ESTCube-3) in solar wind intersecting orbit which measures the E-sail effect with a 1 km long tether using 5-10 kV voltage. Because launch opportunities to solar wind intersecting orbit (for example a lunar orbit) are less frequent than ordinary LEO CubeSat launches, to ensure mission success we plan to prove the satellite's technologies by first flying an identical satellite (ESTCube-2) in LEO. ESTCube-2 also naturally demonstrates a 1 km long plasma brake. After ESTCube-3, we will have a measurement of the strength of the E-sail effect in the actual environment (solar wind), a demonstration of deploying a 1 km long tether and a demonstration of using the E-sail effect for spacecraft propulsion.

After ESTCube-3, we need an E-sail "pathfinder" mission (comparable to SMART-1 in its philosophy) which tests the use of E-sail propulsion for going to some target and carries some payload. For example, it could be a NEO mission equipped with imaging instruments.

7 Discussion and conclusions

Scaling up the manufacturing capacity of tethers and demonstrating their robust deployment in laboratory and in space is important and serves all applications of Coulomb drag devices. For the Esail, a specific challenge for raising the TRL is to get affordable launch opportunities into the relevant environment i.e. the solar wind. Demonstration of multi-tether centrifugal deployment is important as well, but it can be rather well simulated numerically and can also be demonstrated in LEO.

In conclusion, the development of Coulomb drag devices (E-sail and plasma brake) has gone well and their performance and other characteristics look very promising. While the possibility of negative surprises can never be excluded, presently we are not aware of any unsolved issues that could make it difficult to construct efficient plasma brake deorbiting devices and production scale interplanetary E-sails.

Acknowledgements. This research was financed

within the European Community's Seventh Framework Programme ([FP7/2007-2013]) under grant agreement number 262733 and the Academy of Finland grant decision 250591.

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