Using charged tether Coulomb drag: E-sail and plasma brake

P. Janhunen*, P. Toivanen† and J. Envall‡

Finnish Meteorological Institute, Erik Palménin aukio 1, FI-00560, Helsinki, Finland

A. Slavinskis§

Tartu Observatory, Observatooriumi 1, Tõravere, EE-61602 Tartu county, Estonia

A voltage-biased metallic tether creates an electrostatic potential structure around itself. If put into flowing plasma, the electrostatic field deflects the trajectories of plasma ions. The resulting momentum transfer from plasma to the tether can be used for propulsive purposes. The electric solar wind sail (E-sail) is one such application. The E-sail has a set of centrifugally stabilised positively biased tethers in the solar wind. It enables propellantless propulsion in the solar wind, much in the same way as the photonic solar sail, but typically with order of magnitude higher thrust per propulsion system mass. The E-sail’s high efficiency stems from the fact that the tether’s electrostatic field penetrates a significant distance (some 100-200 m distance at 1 au) into the solar wind plasma while the tether that creates the electric field can be made very thin. As a result, the E-sail’s virtual sail area can be millions of times larger than the physical area of the wires of which the tether is made. Thus, even though the solar wind’s dynamic pressure is 5000 times less than the photonic pressure, the E-sail can achieve high thrust per mass. If using 20 kV voltage, the achieved thrust is some 0.5 mN/km while a kilometre of tether weighs about 10 grams.

Even though E-sail’s thrust source - the solar wind - is highly variable, the E-sail’s thrust varies much less, due to some nontrivial plasma feedback mechanisms. Furthermore, because the thrust is independently controllable in direction (by inclining the sail) and magnitude (by changing the voltage), the E-sail is accurately navigable and also able to tack sunward.

The E-sail works everywhere in the solar system except inside Earth’s magnetosphere, because inside the magnetosphere there is no solar wind. However, in low Earth orbit (LEO), a closely related device called the plasma brake can be used for satellite orbit lowering and deorbiting. The plasma brake is a negatively biased Coulomb drag tether with moderate voltage. It uses the relative velocity between the orbiting satellite and nearly stationary ionospheric plasma to provide controllable orbit-lowering drag. As the E-sail, the plasma brake is also very efficient in terms of thrust per mass. Another important benefit of the plasma brake is that the tether is so thin that it is safe to other space assets in case of accidental collision.

In the presentation we review the development status of Coulomb drag tether propulsion and discuss some interesting application ideas.

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*Research Manager, PhD, Finnish Meteorological Institute, pekka.janhunen@fmi.fi.
†Researcher, PhD, Finnish Meteorological Institute, petri.toivanen@fmi.fi.
‡Researcher, D.Sc. (Tech.), Finnish Meteorological Institute, jouni.envall@fmi.fi.
§PhD Researcher, Space Technology, Tartu Observatory, andris@to.ee.

For more information on the E-sail and plasma brake, see http://www.electric-sailing.fi
I. Introduction

Coulomb drag propulsion means putting a long, thin and charged tether into a natural plasma flow and tapping momentum from the flow by Coulombic deflection of the flow ions by the electric field that surrounds the tether. Coulomb drag propulsion was first proposed\(^1\) for interplanetary propulsion by the electric solar wind sail (electric sail, E-sail), Fig. 1.

The E-sail has potentially revolutionary performance level in comparison to other propulsion systems.\(^4\) The tether weighs only 10 grams per kilometre and produces a thrust of $\sim 0.5$ 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 per 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 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.\(^2\)

$$\frac{dI}{dz} = e n_o \sqrt{\frac{2eV_0}{m_e}} \left(2r_{w_{\text{base}}}^2 + 4.5 \times r_{w_{\text{loop}}}^2\right). \quad (1)$$

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, $r_{w_{\text{base}}} = 25 \mu m$ is the base wire radius of the micrometeoroid-resistant tether, which is assumed to have four wires in Eq. (1) with parallel wire radius $r_{w_{\text{base}}}$ = 25 $\mu$m and loop wire radius $r_{w_{\text{loop}}}$ = 12.5 $\mu$m.

Later it was found\(^5,6\) that Coulomb drag propulsion can also be used for satellite deorbiting in low Earth orbit (LEO). Contrary to the solar wind, in LEO it seems more attractive to use negative tether polarity because it needs less power than a positive polarity one and because the balancing ion emitter can in LEO conditions often be implemented simply by the satellite’s conducting surface. The LEO application is called the plasma brake (Fig. 2). According to simulations, a 5 km long negatively charged plasma brake tether weighing 0.055 kg could produce 0.43 mN braking force which is enough to reduce the orbital altitude of a 260 kg object by 100 km per year.\(^7\)

![Figure 2. Negatively biased gravity-stabilised Coulomb drag plasma brake in LEO for satellite deorbiting.\(^8\)](image)

Part of the material in this paper is taken from the Space Propulsion 2014 proceedings paper.\(^9\)

II. 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).
II.A. 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. 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 E-sail geometry (Fig. 1), trapped electron orbits are chaotised whenever the electron visits the central “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. 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 many trapped electrons are present in the final state, although the question was recently analysed also using a novel, indirect approach.

The E-sail thrust per tether length \( \frac{dF}{dz} \) is given by

\[
\frac{dF}{dz} = K P_{\text{dyn}} r_s
\]

where \( K \) is a numerical coefficient of order unity, \( P_{\text{dyn}} = \rho v^2 \) 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. where Ar plasma (ion mass \( m_i = 40 \text{ u} \)) of density \( n_o = 2.4 \cdot 10^{11} \text{ m}^{-3} \) accelerated to 20 eV bulk flow energy (hence speed \( v = 9.8 \text{ km/s} \)) was used and let to interact with \( r_w = 2.5 \text{ mm} \) 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 \( r_s = 12 \text{ cm} \) and at 400 V it is \( r_s = 28 \text{ cm} \) (from their Figure 8). For estimating the corresponding \( \frac{dF}{dz} \), 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 less than 90°. In their experiment \( P_{\text{dyn}} = 1.54 \mu \text{Pa} \) so Eq. 2 gives \( \frac{dF}{dz} = 370 \text{ nN/m} \) and \( \frac{dF}{dz} = 860 \text{ nN/m} \) 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

\[
\lambda_{D,\text{eff}} = \sqrt{\frac{e_o (V_0 - V_1)}{e n_o}}
\]
where \( V_1 = (1/2)m_i v^2/e \) 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 \( \lambda_{\text{eff}}^D \) 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\(^4\) 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 Signier et al.,\(^{13}\) 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.**

<table>
<thead>
<tr>
<th>( V_0 = 100 \text{ V} )</th>
<th>( V_0 = 400 \text{ V} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigier et al.(^{13})</td>
<td>370 nN/m</td>
</tr>
<tr>
<td>( \lambda_{\text{eff}}^D ), Eq. 3</td>
<td>420 nN/m</td>
</tr>
<tr>
<td>Theory of(^4) with ( n_e = 0 )</td>
<td>220 nN/m</td>
</tr>
</tbody>
</table>

We conclude from Table 1 that experimental results of\(^{13}\) are consistent with the assumption of no trapped electrons, i.e. maximal E-sail thrust.

II.B. 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\(^7\) and it was found that the following formula gives a good fit to the PIC simulations:

\[
\frac{dF}{dz} = 3.864 \times P_{\text{dyn}} \sqrt{\frac{e_o V}{e n_o}} \exp \left( -\frac{V_1}{V} \right) .
\]

(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), \( P_{\text{dyn}} = m_i n_o v_o^2 \) 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),

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

$r_w^*$ is the tether’s effective electric radius (Appendix A of 2), $\lambda_D^{\text{eff}} = \sqrt{\epsilon_0 |V_0|/(en_o)}$ is the effective Debye length and $V_1 = (1/2)m_i v_o^2/e$ 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 $\mu$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. The reduction grows with increasing voltage: it is 17% at $-320$ V bias voltage and 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.

### III. ESTCube-1 experiment

ESTCube-1 was a 1-U Estonian cubesat which flew in 2013-2015. ESTCube-1 carried a preliminary 10 m version of our tether experiment. The experiment did not work because the tether reel failed to rotate. A reason was identified after the launch in ground testing: a gold-plated slipring was pressed by a steel spring contactor and during launch vibration, the contactor carved a small hole into the slipring which was enough to prevent the piezoelectric motor from turning the reel. Although the error was in our tether payload, it was a “shallow” problem whose reason was insufficient vibration testing before launch, which in turn was due to 5-month accelerated schedule of the satellite in a late phase, due to sudden emergence of a free launch opportunity and the satellite team’s decision to accept it. The error was thus not directly related to any deeper aspects of Coulomb drag tether technology.

### IV. Aalto-1 satellite

Aalto-1 is a Finnish 3-U, 4 kg cubesat which will be launched in polar LEO in July 2016 onboard SpaceX Falcon-9 rocket. Like ESTCube-1, the Aalto-1 cubesat is built by university students while the payloads are made by research groups. Aalto-1 carries three payloads, AASI imaging Fabry-Perot spectrometer (hyperspectral camera) by VTT, a compact radiation monitor (RADMON) by the University of Turku and our Coulomb drag tether experiment.

### V. Aalto-1 tether experiment

The tether experiment of Aalto-1 is a debugged version of the ESTCube-1 experiment: known problems have been fixed, testing was more complete than in case of ESTCube-1, and more diagnostics were added so that if something goes wrong, we will be able to know more precisely what it was.

The length of the tether in Aalto-1 is 100 m i.e. ten times longer than in ESTCube-1. The tether is made of four 25 and 50 micrometre diameter aluminium wires that are ultrasonically bonded together every few centimetre intervals. The tether can be charged by an onboard voltage source up to one kilovolt positive or negative with respect to surrounding plasma. The negative polarity Coulomb drag experiment of Aalto-1, in particular, is expected to yield a practical demonstration of plasma braking by significantly lowering the orbit of the satellite or even deorbiting it entirely.

Figure 6 shows the high-voltage (HV) and motor cards of the Aalto-1 tether payload. The motor card also hosts the tether reel. The lateral size of both cards is about $10 \times 10$ cm (a standard cubesat circuit board) and together they take 50.5 mm of vertical space so that both cards together take 0.5U of volume. The motor card weighs 148 g and the HV card weighs 114 g so that together they weigh 262 g.
When the tether experiment is started, the satellite is spun up using magnetic coils, the 1.2 g endmass and reel locks are released and the motor is commanded to turn the reel. The tether then starts to deploy and the centrifugal pull of the endmass keeps it under proper tension. When deployment proceeds, the tether tension first increases almost linearly with tether length. When the moment of inertia of the deployed part of the tether has become comparable to the satellite’s moment of inertia, the tension reaches a maximum at $\sim 1.5$ m tether length and then starts to decrease again because the satellite’s rotation slows down due to angular momentum conservation.

We deploy first about 10 m of the tether and then start positive tether polarity experiments by operating the satellite’s cold cathode electron gun. The reason for starting positive mode experiments with relatively short tether is to ensure that the current produced by the gun is sufficient to balance the electron current gathered by the positively biased tether from the plasma. Otherwise there would be a risk that the tether voltage would drop an unknown amount below the electron gun beam voltage so that the tether voltage would become unknown.

The tether spins in equatorial plane and we perform the Coulomb drag experiment primarily over high latitudes so that the plasma ram flow is in the plane of the tether. We measure the Coulomb drag thrust in the following indirect way. We keep the tether voltage on whenever the tether is moving downstream with respect to plasma ram flow and keep it off when it moves upstream. In this way the Coulomb drag that is exerted on the tether accelerates the tether’s and the satellite’s spin during each spin period. Because the effect accumulates over successive spins, it relatively quickly should yield a change in the satellite’s spin rate which is large enough to be easily measurable by the attitude control system and also by simple and robust methods such as looking at the periodicity of the sun sensor signals or power produced by a particular solar panel. The purpose of positive mode experiments is to determine the positive mode thrust as a function of plasma density, which can be estimated based on orbital location and geophysical conditions from ionospheric models such as International Reference Ionosphere (IRI).

After successful positive mode tests at $\sim 10$ m length, a similar series of negative mode experiments is also carried out. The negative mode does not need the electron gun, but only a HV source which forces the tether negative with respect the satellite frame. Conducting parts of the satellite surface then go weakly
positive until they gather enough thermal electron flux from the plasma to balance the negative tether’s
gathered plasma ion current. As a result, the tether’s negative voltage will be very nearly the same as the
voltage given by the source so that the tether will be in a known negative voltage.

After successful experiments at \( \sim 10 \text{ m} \) length, one of the Coulomb drag effects is used to increase the
spinrate so that tether deployment can continue beyond 10 m while keeping a tether tension which is large
enough to keep it straight and to overcome any Coulomb drag effect by a large margin. The process is
continued until all 100 m have been deployed, likely interleaving deployment phases and spin acceleration
phases 2-3 times. At the end, the voltage is left on the tether all the time in negative mode so that the
spinrate is no longer modified, but the satellite’s centre of mass experiences the drag and the orbit is lowered.
If the experiment can run for months in this mode, clear lowering in satellite’s orbital altitude should be
observable, of order 5-10 km per month. In the very best case, if the satellite stays alive for a long enough
time, it’s possible that full deorbiting will eventually result due to the plasma brake effect followed by
engaging the atmospheric drag at lower altitudes.

VI. ESTCube-2

ESTCube-2 is a 3-U LEO cubesat, developed mostly by the students of University of Tartu and students
that join the ESTCube program from all over the world. The aim of ESTCube-2 is to further test Coulomb
drag propulsion. The satellite is also designed to be able to fly an experimental Earth observation payload as
well as a laser communication payload. The payloads are supported by high speed communications module
and a cold gas thruster module. The satellite is designed with the approach to integrate as many of the
satellite subsystems as possible to reduce the size of the satellite bus. The length of the Coulomb drag tether
in ESTCube-2 is planned to be 300 m.

Figure 7 shows a CAD drawing of the ESTCube-2. The development of the payload, the subsystems and
the integrated bus is ongoing and launch readiness testing of the system is to be finished in 2018.

VII. Expected plasma brake thrust

Recall from section II.B 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 \( \rho_{\text{ion}} \)) to the ion mass \( m_i \). Thus, plasma brake thrust is 16 times larger in pure oxygen \( \text{O}^\circ \)
plasma than in pure proton plasma.
For example, at $V_0 = -1 \text{ kV}$, $n_o = 3 \times 10^{10} \text{ m}^{-3}$, $v = 7.5 \text{ km/s}$ and $m_i = 16 \text{ u}$, 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. Predicted plasma brake thrust (nN/m) for solar min/solar max conditions.

<table>
<thead>
<tr>
<th>Altitude</th>
<th>MLT*12-00</th>
<th>MLT 06-18</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>700 km</td>
<td>47/157</td>
<td>42/140</td>
<td>44/149</td>
</tr>
<tr>
<td>800 km</td>
<td>33/117</td>
<td>30/108</td>
<td>32/112</td>
</tr>
<tr>
<td>900 km</td>
<td>25/88</td>
<td>22/84</td>
<td>23/86</td>
</tr>
</tbody>
</table>

*Mean local time

Table 2 gives plasma brake thrust based on Eq. 4, assuming $V_0 = -1 \text{ kV}$, $v = 7.5 \text{ km/s}$ and using plasma density and chemical composition taken from the IRI-2012 ionospheric model, for noon-midnight (mean local time MLT 12-00) and dawn-dusk (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 numerical 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 dawn-dusk and noon-midnight. The required $\Delta v$ from 800 km to 700 km is 53.5 m/s and from 700 km to 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$\rightarrow$700 km deorbiting takes 0.25 years and 700$\rightarrow$400 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.
VIII. Discussion and conclusions

Based on plasma simulations and an indirect laboratory result, there is good reason to think that the magnitude of tether Coulomb drag is in very useful range at least for (1) positive tether in solar wind (E-sail) and (2) negative tether in LEO (plasma brake).

Coulomb drag propulsion in both positive and negative mode will soon be attempted to be measured by Aalto-1 satellite. Aalto-1 is a 3-U cubesat to be launched in July 2016 in polar LEO. Ideally we will get a measurement of positive and negative mode Coulomb drag as function of plasma density, tether length and voltage. The results can then be compared with earlier simulation predictions. We should also be able to observe measurable lowering of the satellite orbit using the negative mode at 100 m tether length. In the very best case, if the satellite and the experiment stay alive long enough, we could even observe reentry into atmosphere. After Aalto-1, the more advanced ESTCube-2 cubesat which is currently in development will fly with a 300 m tether.

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