Electric Solar Wind Sail In-Space Propulsion Status Report

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The electric solar wind sail (E-sail) is a space propulsion concept which uses the natural solar wind dynamic pressure for producing spacecraft thrust. In its baseline form the E-sail consists of a number of long, thin, conducting and centrifugally stretched tethers which are kept in a high positive potential by an onboard electron gun. The methods gains its efficiency from the fact that the effective sail area of the tethers can be millions of times larger than the physical area of the thin tethers wires which offsets the fact that the dynamic pressure of the solar wind is very weak. Indeed, according to the most recent published estimates, an E-sail of 1 N thrust and 100 kg mass could be built in rather near future, providing a revolutionary level of propulsive performance (specific acceleration) for travel in the solar system. Here we give an overview and status report of the ongoing technical development work of the E-sail, covering tether construction, overall mechanical design alternatives, guidance and navigation strategies and dynamical and orbital simulations.

Introduction

The electric solar wind sail [1, 2, 6] (electric sail or E-sail for short) is an innovative propulsion concept that, similar to a more conventional solar sail, allows a spacecraft to deliver a payload to some high-energy orbit without the need for some reaction mass. The spacecraft is spun around the symmetry axis and the rotational motion is used to deploy a number (e.g., 50-100) of long, conducting tethers which are held at a high positive potential by an onboard electron gun, whose electron beam is shot roughly along the spin axis (Fig. 1). The E-sail is similar to the magnetic sail [5] in its use of the solar wind momentum flux as a thrust source. The E-sail is similar to an ion engine in its use of electric power to generate thrust. Finally, the E-sail is similar to electrodynamic tether propulsion in its use of long, conducting tethers. Despite these similarities, however, the E-sail is a unique propulsion concept whose underlying physical principle (Coulomb drag interaction between charged tethers and the solar wind) differs fundamentally from other propulsion methods.

The E-sail was proposed in 2004 [1] as a theoretical alternative to Zubrin's magnetic solar wind propulsion [5] which had faced considerable technical difficulties in a recent ESA pilot study [3]. The original E-sail publication[1] called for building a large wire grid which was technically difficult. In early 2006, however, a simpler and technically feasible idea of building the E-sail was invented [4] when it was realised that a connected grid is not needed since a set of independent and centrifugally stretched wires (tethers) can do the same trick and furthermore retain nearly optimal thrust capability in widely varying solar wind plasma densities. Interest towards the E-sail has grown steadily since then and has evolved into the present-day multinational European collaboration.

Part of the material presented below has been published earlier in the Aosta 2009 workshop proceedings [7].

Thrust estimation

When a highly charged tether is placed in the solar wind, its electrostatic field scatters solar wind protons from their originally straight trajectories. Because the field is static, the energy of the proton remains unchanged in the frame

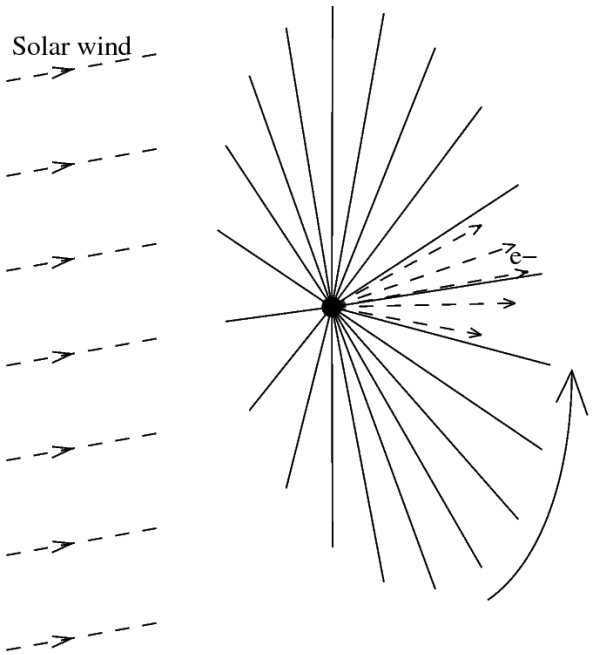

Figure 1: Original E-sail concept

of reference of the tether. However, although the magnitude of the proton's velocity remains the same, its direction changes by the interaction. Thus any electric field induced scattering process which permanently deflects the proton from its original straight trajectory extracts some momentum from it. This momentum gets transmitted into pushing the charged tether by a secondary electric field which forms due to piling up of protons and their associated positive charge density on the sunward side of the tether.

The E-sail force is proportional to the dynamic pressure of the solar wind ∼2 nPa times the sheath width ∼100 m times the tether length ∼20 km is created. The first plasma simulation based estimates of the electric sail thrust were based on the assumption that trapped electrons that necessarily form when the potential is turned on remain and contribute to the shielding of the tether charge [2]. Later, a natural electron scattering mechanism was identified which is able to remove trapped electrons in a few minute timescale typically [6], and it was found [6] that if trapped electrons are absent, then the electric sail thrust per unit length of tether is roughly five times higher than what was reported in [2]. The absence of trapped electrons is a standard assumption in most of the literature concerning electrodynamic tethers (e.g., [8]) and thus it seems to be justified at least most of the time in the case of electric solar wind sailing.

The formulas needed to predict E-sail thrust per unit length are as follows. Below we shall write in them in a simpler way which is however algebraically equivalent to the original form [6]. When V_0 is the tether voltage $V_1 = (1/2)m_p v^2/e$ is the voltage corresponding to the bulk kinetic energy of a solar wind proton ($V_1 \approx 1$ kV for $v =$ 400 km/s) and n_0 is the solar wind plasma density, one solves iteratively the following nonlinear pair of equations:

$$\begin{aligned} \tilde{V} &= \frac{\max(0, V_0 - V_1 - (en_e/(4\epsilon_0))R^2)}{\log(R/r_w^*)} \\ R &= \sqrt{\frac{2\epsilon_0 \tilde{V}^2}{P_{\rm dyn}}} \frac{1}{1+\sqrt{1+en_e\tilde{V}/P_{\rm dyn}}}. \end{aligned} \tag{1}$$

Here $P_{\rm dyn} = m_i n v^2$ is the solar wind dynamic pressure, $r_w^* \approx 1$ mm is the effective electric radius of the multiline tether [2] and n_e is the total electron density inside the electron sheath, assumed to be spatially constant in this simplified model. In the absence of trapped electrons, $n_e \ll n_0$ holds and $n_e = 0$ is a good approximation. Even if n_e is larger, e.g. if $n_e = n_0$ which corresponds to a large number of trapped electrons for which there is no evidence [6], the thrust will be reduced only mildly [6]. The parameter R is the radius of the electron sheath and comes out from the iterative solution. A useful initial guess for the iterative process of Eqs. (1) is $R = \sqrt{\epsilon_0 V_0/(4n_0 e)}$, or one can use $R = 100$ m in the vicinity of 1 AU. Once R has been found, the thrust per unit length is given by [6]

$$\frac{dF}{dz} = KP_{\rm dyn}R, \qquad K = 3.09. \tag{2}$$

A simplified form of Eqs. (1)-(2) which is approximately valid in the solar wind for typical E-sail parameters and not too far from 1 AU is

$$\frac{dF}{dz} \approx 0.18 \max(0, V_0 - V_1)\sqrt{\epsilon_0 P_{\rm dyn}} \tag{3}$$

where V_0 is the tether voltage, $eV_1 = (1/2)m_i v^2$ is the bulk kinetic energy of the solar wind ions and $P_{\rm dyn} = m_i n v^2$ is the solar wind dynamic pressure. Furthermore, since typically $V_0 \sim 20-40$ kV and $V_1 \approx 1$ kV, the V_1 term can often be neglected. The formula has been derived under the assumption that the average density of trapped electrons within the electron sheath, if nonzero, is anyway smaller than the ambient plasma density n.

Without trapped electrons, a 20 kV charged tether at 1 AU distance in average solar wind achieves ∼500 nN/m thrust per length [6]. For example, an electric sail composed of 100 tethers 20 km long each would then achieve ∼1 N thrust. Such tethers weigh 11 kg if made from 25 μm aluminium using the 4-fold Hoytether construction [9] and the electron gun requires ∼400 W power [2]. We estimate that the whole E-sail propulsion system mass could be less than 100 kg in this case. Such a device would give 1 mm/s^2 acceleration to a 1000 kg spacecraft, of which 90% is payload. Alternatively, for a small probe of 50 kg total mass, the same acceleration would be provided by a small electric sail composed of only 10 tethers 10 km long each, with 50 mN total thrust at 1 AU.

Consider a ten year long mission which doesn't move very far from 1 AU (for example, an asteroid deflection mission or an off-Lagrange point solar wind monitor). The baseline E-sail (1 N thrust, 100 kg mass) then generates

$3 \cdot 10^8$ Ns total lifetime-integrated impulse. This total impulse is equivalent to using 100 tonnes of chemical propellant (specific impulse 300 s) or 10 tonnes of ion engine propellant (specific impulse 3000 s). In this sense the performance of the baseline aluminium tether E-sail is 2-3 orders of magnitude higher than chemical rockets or ion engines. If the mission moves far away from the Sun faster than 10 years, the performance gain will be smaller, but still more than one order of magnitude. The performance gain of the E-sail in comparison to propellant-consuming rockets grows linearly with the mission time and has no theoretical upper limit.

Tether dynamical simulation

A detailed mechanical simulation has been written which models the dynamics of the rotating tethers by Newton's laws and E-sail thrust modelling. The programme includes effects e.g. due to tether elasticity, tether temperature due to the varying orientation of the sun and the associated thermal expansion, solar wind force.

A rough estimation of the Coulomb repulsion between the tethers is available as an option, whereas the default is to neglect the Coulomb repulsion. An accurate and efficient calculation of the mutual Coulomb repulsion is a challenge that has not yet been resolved. On the other hand, including the Coulomb repulsion should only help stability since it tends to prevent tether collisions. Therefore by leaving out Coulomb repulsion gives a conservative estimate of tether stability. Runs made with the approximate Coulomb repulsion calculation have indicated that the effect of the Coulomb repulsion is not likely to be important. A physical reason for this is that when two similarly charged tethers are brought close to each other at one point, the charges redistribute themselves so as to minimise the Coulomb repulsion at that point.

The E-sail tethers must be conducting and provide enough mechanical strength so that they are not broken by the centrifugal force. The spin rate of the system must be selected such that the centrifugal force overcomes by expected solar wind force by a factor which is typically about five. For example, if the tether length is 20 km, at 500 nN/m thrust per unit length (see previous section) the expected solar wind force is 10 mN and the centrifugal force 50 mN if it is required to exceed the solar wind force fivefold. Thus in this case the required tether pull strength is 5 g. The pull strength of typical 25 μm aluminium bonding wire is 15 g which leaves us a safety factor of three. This safety factor also includes the loss of strength due to the fact that the wire bonds are somewhat weaker than the plain wire.

With a tether material with increased tensile strength, the efficiency of the E-sail (produced thrust versus propulsion system mass) can be increased. With aluminium tethers, a 1 N E-sail weighs about 100 kg. If using 20 kV nominal voltage, such an E-sail needs about 2000 km total tether length (e.g., 100 tethers 20 km long each). If a stronger material than aluminium were available, it would be possible to increase the thrust by increasing the number or length of the tethers, without much increasing the mass of the system. Already with aluminium tethers it is possible to make E-sails with higher thrust than 1 N at 1 AU, but at the expense of reduced thrust versus mass ratio. For example, a 2 N E-sail would weigh about 400 kg.

Whenever the E-sail is inclined to the solar wind, different tethers of the E-sail experience a different time history of the solar wind thrust. Because of the inclination, this thrust also has a component in the spin plane, which tends to accelerate or decelerate the spin of the tether, depending on the rotational phase of the tether at the time when the solar wind change occurred. The net result of this is that unless some preventive measures are taken, differences in the rotation rates of the tethers will develop and slowly accumulate, resulting in tether collisions. These collisions must be avoided because they would cause mechanical wearing down of the tethers and also sparking due to the fact that adjacent tethers have somewhat different potentials due to us exercising spinplane control manoeuvring.

As a rule, then, all E-sail designs must prevent tether collisions in some way. The original idea (Fig. 1) was to do continuous tether length fine-tuning during flight so that the conservation of the angular momentum then keeps the tethers apart. This has the drawback, however, of requiring moving parts. Also, we do not assume that the Hoytether which is partly damaged by micrometeoroid impacts could be reliably and repeatedly reeled in and out for several years. Therefore the part which is repeatedly reeled should be made of thicker monofilament or tape tether instead of the lightweight Hoytether. This would limit the amount of length fine-tuning possible and necessitate a rather intelligent algorithm. Proving that the algorithm works under all conceivable solar wind conditions would not be an easy task.

To overcome these issues, an alternative tether collision prevention concept was developed in summer 2009 (Fig. 2). In the alternative concept, the tips of the tethers are connected with each other by non-conducting auxiliary tethers. For safe deployment, the reels of the auxiliary tethers must reside at the tips of the main tethers, in small autonomous devices which we call the "Remote Units" (Fig. 3). Once having the Remote Units there, it is also straightforward to install small gas or ion thrusters there, to create the initial spin of the system.

The auxiliary tethers are $\sim$1.5 times longer than the average linear distance between the main tether tips and are stretched outward by the centrifugal force. The centrifugal force acting on the auxiliary tethers is the mechanism which keeps the main tethers apart: if two main tethers approach each other, the auxiliary tethers provide a restoring force which tends to keep the main tethers equidistant.

The benefits of this concept are that it is free of moving parts during flight (the only moving parts are the main tether reels and auxiliary tether reels which are operated only during the deployment), that it does not rely on any

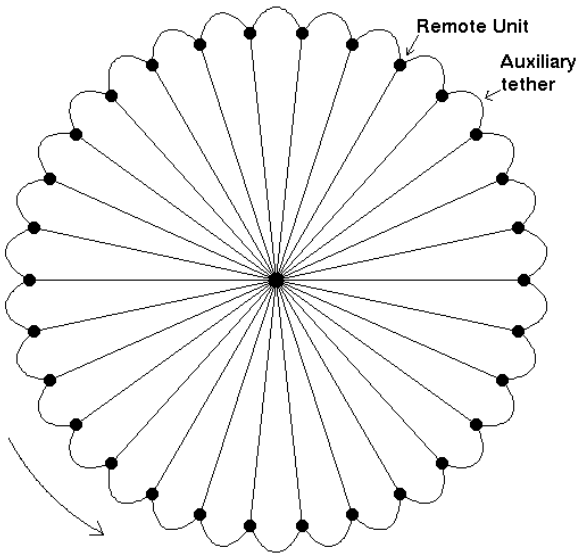

Figure 2: Currently preferred E-sail concept with centrifugally stabilising auxiliary tethers and Remote Units which contain the auxiliary tether reels and small thrusters for spinup and spin control.

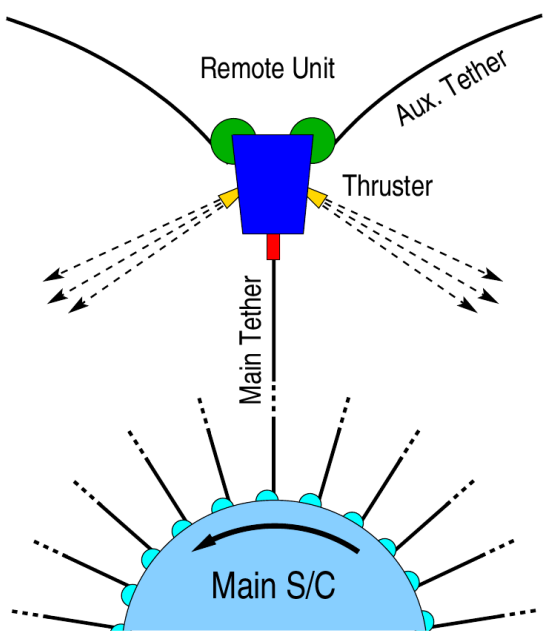

Figure 3: Schematic top view of one Remote Unit

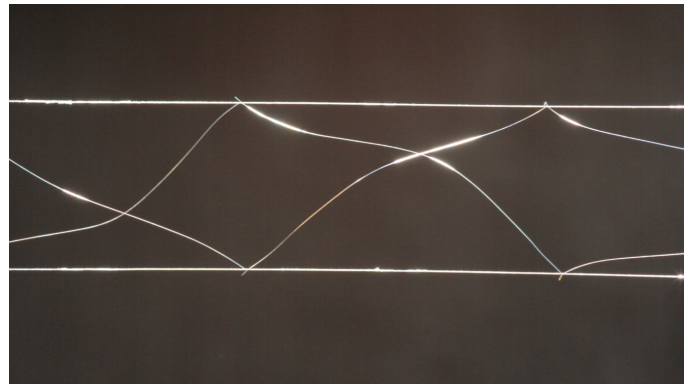

Figure 4: 4-wire Hoytether made of 25 and 50 μm aluminium wire by ultrasonic bonding.

sophisticated control algorithms , that it provides a way of spinning up the system during deployment without any additional arrangements and that it also provides a way to control the spin rate later during flight, if needed. The auxiliary tether concept is currently our baseline way of constructing a full-scale E-sail.

Tether manufacture

The E-sail main tethers must provide mechanical strength, conductivity and they must survive the micrometeoroid flux and other aspects of the space environment (mainly vacuum, radiation and temperature changes due to varying solar angle of the tether and solar distance of the spacecraft). The baseline is to use aluminium wires which are made into a multiline Hoytether structure [9] by ultrasonic bonding (Fig. 4). Aluminium tolerates space environment well, is a good conductor and is reasonably although not phenomenally strong. Aluminium wires are also possible to bond together using the ultrasonic welding technique. Ultrasonic welding produces minimal destruction of the bonded wires and is possible to do in ambient room temperature conditions.

A semiautomatic "tether factory" was built at University of Helsinki and thus far operated to produce about 4 m of close to final-type tether (Fig. 5). The tether factory is a small tabletop device which is operated in connection with a commercial wire bonder machine in cleanroom environment. New versions of the tether factory will be built The goal for 2010 is to produce 10 m of tether for the ESTCube-1 test mission which will be launched in 2012.

Mission trajectory calculations

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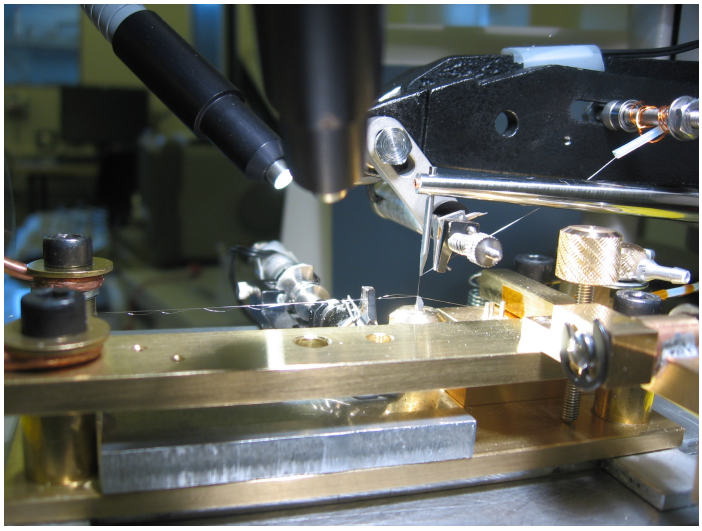

Figure 5: The semiautomatic tether factory (March 10, 2010)

Benignity of solar wind variations

The solar wind which is the thrust source of the electric sail is naturally highly variable, unlike for example the solar photon radiation field which is the thrust source of ordinary solar sails. Thus it is not clear *a priori* that the electric sail can be navigated accurately enough to be feasible to use it as the main or sole propulsion system for planetary missions. However, there are two mechanisms which efficiently damp the variations of the electric sail thrust even when the solar wind parameters (density and speed) vary strongly [10]. The first mechanism is due to the fact that the electron sheath width has an inverse square root dependence on the solar wind electron density. Thus when the solar wind density drops, the thrust becomes lower because the dynamic pressure decreases, but the simultaneous widening of the sheath partly compensates for it. The second mechanism arises from the natural desire to run the electric sail electron gun with the maximum power available from the solar panels. When the solar wind electron density drops, so does the electron current gathered by the tethers, so that one may then increase the electron beam and tether voltage without increasing power consumption. When both mechanisms are taken into account and the simple maximum power strategy is used, the obtained thrust is proportional to $n_0^{1/6}$ where n_0 is the solar wind density, i.e. the dependence of the thrust on the solar wind density is weak.

Fig. 6 shows an example 10-day period of measured solar wind data when the density and speed variations were large. Under high maximum voltage (40 kV), the resulting variations in the thrust (panel c) are much weaker than in the solar wind itself. The situation is further improved by the fact that in reaching a planetary target such as Mars, it is the average thrust over at least a one month timescale

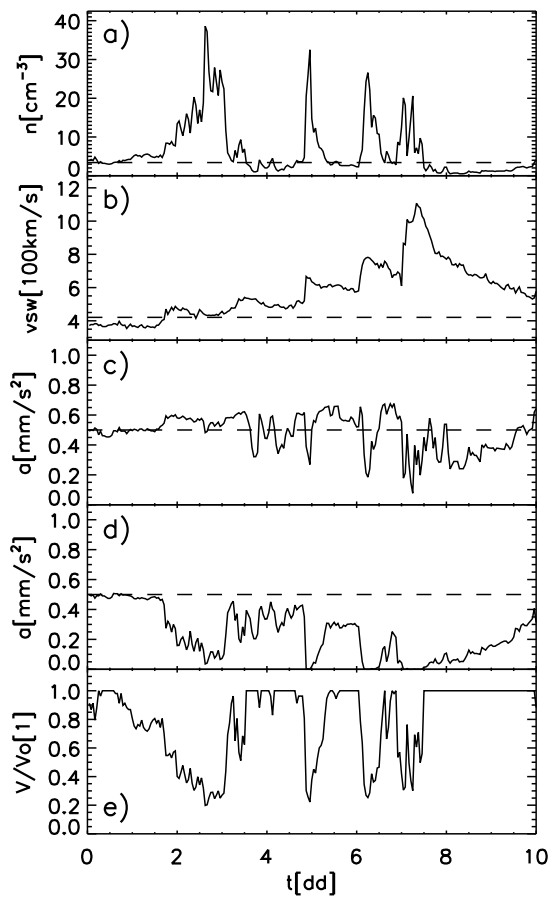

Figure 6: Solar wind density (a) and speed (b), resulting electric sail acceleration with 40 kV (c) and 10 kV (d) maximum voltage, as well as voltage variation compared to maximum (e), over a 10-day period when solar wind showed large variations [10].

that matters, not daily thrust values. Furthermore, if one modifies the maximum power strategy so that some electric power capability is kept in reserve, then the likelihood becomes high that the planned thrust level goal can be reached. One can also design the trajectory so that nearly maximum power is used in the beginning phase of the mission, but when approaching the target, more power is left in the reserve. In this way, if a prolonged period of weak solar wind should occur in the initial phase of the mission, this can be corrected for later by using the power margin provided by the designed power envelope. When all these considerations are put together, the conclusion is that the navigability of the electric sail is essentially as good as that of any other propulsion system such as an ion engine [10].

ESTCube-1 test mission

The ESTCube-1 will be a 1 kg, 10 cm across cubesat which is built mainly by students in Tartu and Tallinn and supervised by senior staff. The planned launch of ESTCube-1 is

in 2012 and its main purpose is to observe and measure the E-sail effect for the first time. ESTCube-1 will fly in polar low earth orbit (LEO) and deploy a single 10 m long conducting Hoytether which can be charged to ±500 V by an onboard voltage source and electron gun. The satellite will face a plasma stream which is up to 10^5 times denser than in the solar wind and composed mostly of singly charged atomic oxygen. The topside ionosphere plasma moves only at 7 km/s velocity relative to the satellite which is 50-100 times slower than the solar wind speed. The expected E-sail thrust per unit length in ESTCube-1 is slightly smaller than in the solar wind and the total E-sail force produced is $\sim 1\mu$N which is $\sim$10 times larger than the magnetic Lorentz force acting on the tether. The main source of uncertainty regarding the magnitude of the force (besides the accuracy of our theory) is the ionospheric plasma density which varies spatially, seasonally and has a strong dependence on the solar activity. Once ESTCube-1 flies, however, the plasma density can be inferred from the tether current measurement and from other LEO spacecraft so that the theory behind Eqs. (1)-(2) can be quantitatively tested.

The $\sim$1 μN E-sail force can be measured by ESTCube-1 by turning the electron gun on and off in sync with the tether's rotation. For example, if the voltage and therefore the E-sail force is turned on always when the tether is moving towards the incoming plasma flow, the rotation of the tether and the satellite slows down a bit at every rotation period so that the cumulative effect becomes easily measurable from the changes satellite spin period. If the experiment is continued to run for a longer time, the lowering of the satellite's orbit by the E-sail action should also become observable.

An E-sail effect also exists for a negatively charged tether [16]. In the solar wind the negative E-sail may not be more beneficial than the original positive polarity E-sail because then one needs an ion gun instead of an electron gun to maintain the voltage and because field emission of electrons limits the attainable value of the surface electric field for a negatively charged surface to a lower value than for a positively charge surface. However, in the ionosphere the situation is different because the plasma is so dense that an ion gun is usually not needed to maintain the tether voltage in the negative mode: the ability of the satellite's conducting surface to gather electrons is usually enough to compensate the ion current gathered by the tether (this is also helped by the fact that the ions are heavier than in the solar wind so that their thermal current is smaller). Consequently, a single negatively charged tether could be used as a braking device while needing no other hardware on the spacecraft than a voltage source. This Plasma Brake concept [17] would seem to be a promising device for satellite deorbiting for space debris prevention.

The ESTCube-1 tether can be run in both positive and negative tether mode, to study the E-sail effect and the plasma brake concept.

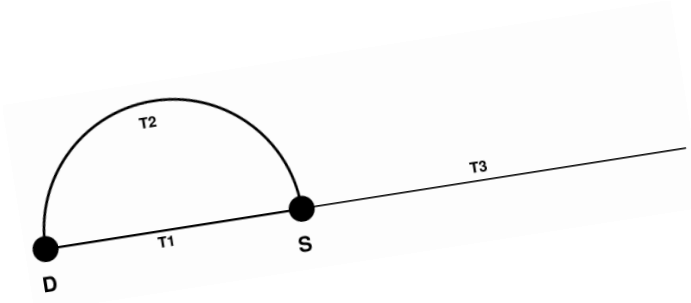

Figure 7: Configuration of simple two-mass solar wind test mission, comprising of spacecraft S, dummy mass D, their connecting load-bearing tape tether T_1, another centrifugally stretched tape tether T_2 and provision for testing also a Hoytether T_3.

Electron gun and voltage source

Since ESTCube-1 is a nanosatellite, its solar panels which cover all free surfaces of the cube produce only $\sim$1 W of power. This power level is not quite sufficient to run even a small heated electron gun cathode. Consequently, an advanced cold cathode electron gun solution is being developed for ESTCube-1 which is based on electron field emission from a nanographite surface. The nanographite coated cathode contains many sharp protruding graphene edges of only one or few atomic layers thin. At these sharp surface features, the applied electric field experiences strong geometric magnification which is enough to cause electron field emission from the graphite. The pull electrode (anode) is made of 1 μm silicon nitride membrane which is perforated with holes and thinly metallized to form a conducting accelerator grid.

The voltage source feeding the electron gun and connecting to the tether in the negative polarity mode is made of standard electronic components and contains no special challenges, besides the strive to minimise mass.

Solar wind test mission

Although a LEO satellite such as ESTCube-1 is expectedly able to measure the E-sail effect, demonstrating E-sail flight manoeuvres calls for a test mission in the solar wind.

A concept for a simple solar wind test mission (Fig. 7) could consist of the spacecraft S and a dummy mass D which is connected to S by a metallic tape tether T_1. The system is rotated so that S and D orbit the system's centre of mass which resides somewhere around halfway along T_1 which has length of 1 km. The simple system of two masses connected by a straight tether is not quite enough for properly demonstrating the E-sail in the solar wind, however, because electron orbit chaotisation [6] does not occur in a cylindrically symmetric potential geometry. Therefore, a more or less sharp kink is needed somewhere along the conducting, biased path. A simple way to arrange this is to add tether T_2 which is longer than T_1 so that T_2 gets

pushed outward by the centrifugal force. If the length of T_2 is $\pi/2$ times the length of T_1, the system looks like a semicircle as in Fig. 7. Other choices for the length of T_2 are possible as well. The deployment of the system is simple and needs a thruster in S only.

By switching on and off voltages in T_1 and T_2, one can study experimentally the effect of electron chaotisation on the obtained E-sail thrust. We expect the thrust to be clearly smaller when only one of the tethers is turned on, compared to the case where both are biased.

The tethers T_1 and T_2 could be of any design, but in this concept they are selected to be simple metallic tape tethers which are easy to obtain and straightforward to reel. Therefore this solar wind test mission concept does not presuppose an ability to manufacture long Hoytethers. This is done so that the decision to build the mission could be done now, without waiting for a demonstrated ability to manufacture Hoytethers. However, once the mission is underway, it would be nice anyway to test the Hoytether which is probably available at the time the mission is flying. In the mission there is room for tether T_3 (Fig. 7) which can be a Hoytether. The length of T_3 can be shorter or longer, depending on what exists when the mission flies.

The orbit of this kind of test mission could be either a highly elliptic Earth orbit which periodically visits the solar wind or a high circular orbit. In both cases the apogee distance would be $\sim 30R_E$ i.e. about halfway towards the moon orbit. A moon orbit would not be very suitable because the gravity gradient would disturb the tether dynamics and periodic eclipsing would cause the tethers to thermally expand and contract and therefore to oscillate to some extent.

This kind of simple test mission would be able to demonstrate controlled propulsive E-sail flight and the obtained E-sail force could be measured accurately with an accelerometer. Because of the rather short tether length, however, it would probably not be able to fly to any more distant target.

Many other types of test missions could be envisioned as well. We presented here one of the simplest and therefore cheapest possibilities which is able to demonstrate propulsive E-sail flight and which is not required to fly to a concrete target.

E-sail applications

Ways to calculate pure electric sail trajectories to planetary and asteroid targets have been analysed [12, 13]. The "standard" ~1 N electric sail could be useful at least in four different tasks:

1. Fast one-way ride for a small payload (~200 kg) at > 50 km/s out of the solar system [14].

2. Relatively fast trip to a giant planet orbit for ~500 kg payload, using a chemical orbit insertion burn near the planet [11] and possibly also E-sailing and/or ED tethering in the giant planet's magnetosphere.

3. Back and forth sample return trip for a ~1000 kg payload in the inner solar system (at most the main asteroid belt distance) [12].

4. Non-Keplerian orbit for special purposes such a off-Lagrange point space weather monitoring or off-ecliptic solar orbit for helioseismological measurements [15]. Solar wind plasma measurements are not possible at the spacecraft when the E-sail is on, but since the neutralisation time of the tethers is only ~30 s at 1 AU, interleaved propulsive and measurement phases can be used in solar wind monitoring.

The E-sail's main limitations for travelling in the solar system are that it does not produce much thrust within Earth's magnetosphere (for giant planet magnetospheres the question is more complicated) and that because its thrust vector is always more or less pointing radially outward from the sun (the thrust direction can be altered by $\sim 30^{\circ}$), a return from the outer solar system in reasonable time is not possible by using the E-sail alone. Return from a giant planet orbit is possible, however, by performing an impulsive chemical rocket burn near the giant planet so as to eject the spacecraft towards the inner solar system [11]. If the opened E-sail tether rig could be engineered to survive the impulsive burn on both ways, this would open up the way to potentially very lightweight sample return missions from the giant planet moons, because besides E-sail propulsion, only two small chemical burns would be needed from Earth escape orbit to a given giant planet moon orbit and back. Another option would of course be to use a separate electric sail during the return trip which is deployed after the impulsive burn which initiates the return trip from the giant planet system.

Commercially, utilisation of asteroid resources such as water could become economical by using electric sails as a "logistic chain" for returning material from asteroids to Earth orbit. The extremely high ability of the E-sail to produce thrust for a long time without consuming propellant is particularly valuable in such an application.

Conclusions

We are not aware of any scientific, technical or other reason why the E-sail wouldn't eventually work at least roughly at the projected performance level. Because the projected performance level (deliverable impulse versus mass) is 2-3 orders of magnitude higher than for chemical rockets and ion engines, the margin for success is large. The most important next step will be a solar wind test mission which will demonstrate controlled propulsive flight in the authentic environment. The solar wind test mission can be designed so that it accomplishes it goals with simple tape tethers while also providing a flight testing opportunity for a Hoytether. Therefore the decision to build the solar wind test mission could be done now because all the technology is at sufficient maturity level.

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Summary of present E-Sail Experimental Demonstrations
(Stauts: January 2022)

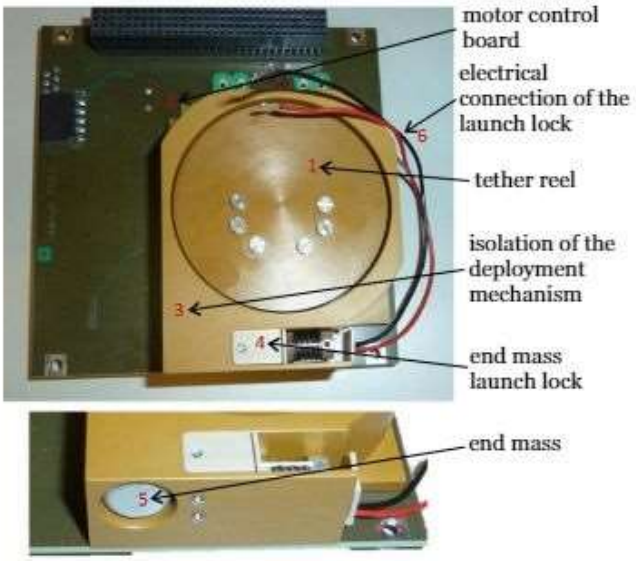
ESTCube-1 (May 2013-Feb 2017)
ESTCube-1 was the first Estonian satellite and first satellite in the world to attempt to use an electric solar wind sail (E-sail). It was launched on 7 May 2013 aboard Vega VV02 carrier rocket and successfully deployed into orbit. The CubeSat standard for nanosatellites was followed during the engineering of ESTCube-1, resulting in a 10×10×11.35 cm cube, with a volume of 1 liter and a mass of 1.048 kg.

Results: The mission ended officially in 17 February 2015 and it was said that during this time it resulted in 29 bachelor's and 19 master's dissertations, 5 doctoral theses and 4 start-ups. The deployment of the E-sail tether was unsuccessful, and thus no measurements were taken of the E-sail or of the plasma braking deployment system. The last signal from ESTCube-1 was received in 19 May 2015. [1]

Aalto-1 (June 2017 – ongoing)
Aalto-1 is a Finnish research nanosatellite, created by students of Aalto University in Espoo, Finland. Based on the CubeSat architecture, it was originally scheduled to be launched in 2013, it was launched on 23 June 2017. It is Finland's first student satellite project and indigenously-produced satellite. As of 2021, the satellite is operational.[
The Aalto-1 launch was shifted from the original planned Falcon 9 rocket to a launch vehicle provided by India, and was launched on 23 June 2017 by PSLV-C38. [2]

Results: Electrostatic Plasma Brake (EPB).
The electrostatic plasma brake experiment is a variant of the E-Sail concept developed by Finland (http://www.fmi.fi). The EPB consists of a single gravity-stabilized tether intended to deorbit a satellite after completing its mission to avoid additional space debris in a particular orbit. The Electric Sail Experiment onboard Aalto-1 is intended (1) to demonstrate the deployment of a conducting thin multiline tether, (2) to measure the electrostatic force exerted on the tether by the ram flow of the ionospheric plasma in different positive and negative tether voltages and finally, if all goes well, (3) to bring down the satellite and so to demonstrate the usefulness of the plasma brake as a satellite deorbiting device.
To measure the expected micro-newton scale electrostatic force, the voltage is turned on always in the same phase of the tether's rotation (e.g. always when the tether is moving towards the ram flow). After several spins, the effect accumulates enough to cause a detectable change in the tether's and satellite's spin rate, from which the force can be calculated. Over longer timescale, the effect of the force can be deduced from a lowering of the satellite orbit.
Although the mission was a partial success in terms of executing the experiments, the important lessons learned during this mission have been applied in the design of next variants of payloads and platforms. The RADMON instrument for radiation monitoring was successful in commissioning and measurement phases. Its compact, light-weight heritage has been used to design a more complex Particle Telescope (PATE) payload for the upcoming FORESAIL-1 mission. However, the EPB tether could not be deployed due to a failure in tether deployment hardware.
The lessons learned have been taken into consideration in development of the plasma brake experiments for upcoming FORESAIL-1 and ESTCube-2 missions. The AaSI (Aalto Spactral Imager) was the first nanosatellite-compatible hyper-spectral imager to be flown in space. The Aalto-1 project successfully demonstrated the expertise of Finalnd's Technical Research Center (VTT) in both visible and hyper-spectral miniature imager designs. The technology has many potential future applications to serve CubeSat and/or scientific industry/community. The subsystem is manufactured by consortium led by Finish Meteorological Institute (FMI). [3]

Aalto-1 Brake – Experiment Hardware Configuration [4]



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