Invited Article: Electric solar wind sail: Toward test missions

P. Janhunen,[1,a)] P. K. Toivanen,[1] J. Polkko,[1] S. Merikallio,[1] P. Salminen,[2] E. Haeggström,[3] H. Seppänen,[3] R. Kurppa,[1] J. Ukkonen,[3] S. Kiprich,[4] G. Thornell,[5] H. Kratz,[5] L. Richter,[6] O. Krömer,[7] R. Rosta,[7] M. Noorma,[8,9] J. Envall,[9] S. Lätt,[8,9] G. Mengali,[10] A. A. Quarta,[10] H. Koivisto,[11] O. Tarvainen,[11] T. Kalvas,[11] J. Kauppinen,[11] A. Nuottajärvi,[11] and A. Obraztsov[12,13]

[1]*Finnish Meteorological Institute, Helsinki FIN-00100, Finland*
[2]*SkyTron, Akaa FI-37800, Finland*
[3]*Department of Physics, University of Helsinki, Helsinki FI-00560, Finland*
[4]*National Science Center Kharkov Institute of Physics and Technology, Kharkov UA-61108, Ukraine*
[5]*Ångström Space Technology Center, Uppsala SE-75121, Sweden*
[6]*Utopia Consultancies, Alfter D-53347, Germany*
[7]*German Aerospace Center, Bremen D-28359, Germany*
[8]*University of Tartu, Tartu EE-50090, Estonia*
[9]*Tartu Observatory, Toravere EE-61602, Estonia*
[10]*University of Pisa, Pisa 56122, Italy*
[11]*University of Jyväskylä, FI-40014, Finland*
[12]*University of Eastern Finland at Joensuu, Joensuu FI-80101, Finland*
[13]*Moscow State University, Moscow 119991, Russia*

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The electric solar wind sail (E-sail) is a space propulsion concept that 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 concept gains its efficiency from the fact that the effective sail area, i.e., the potential structure 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 the rather near future, providing a revolutionary level of propulsive performance (specific acceleration) for travel in the solar system. Here we give a review 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. © *2010 American Institute of Physics.* [doi:10.1063/1.3514548]

I. INTRODUCTION

The electric solar wind sail[1–3] (electric sail or E-sail for short) is a novel propulsion method that uses the solar wind as a thrust source. The E-sail consists of a number (e.g., 50–100) of long, conducting tethers, which are kept positively biased and centrifugally stretched by the spacecraft spin (Fig. 1). The tethers must be micrometeoroid-tolerant, so they must have a redundant multiline construction such as the Hoytether.[4] The solar wind ions are repelled by the positive E-sail tethers so that momentum is extracted from the solar wind flow. The E-sail shares some similarities with other nonchemical propulsion systems: (1) it uses the solar wind momentum flux as a thrust source as does the magnetic sail,[5] (2) it uses electric power to generate thrust as does the ion engine, and (3) it makes use of long, conducting tethers as the electrodynamic tether propulsion.[6] The E-sail can produce thrust anywhere in the solar wind (and possibly also in the corotating plasmas of Jupiter and other giant planets although this has not been analyzed in detail yet).

The E-sail was proposed in 2004 (Ref. 1) as a theoretical alternative to Zubrin's magnetic solar wind propulsion,[5] which had faced considerable technical difficulties in a recent pilot study initiated by the European Space Agency.[7] The original E-sail publication[1] required the use of a large wire grid, a technically difficult concept to accomplish. In early 2006, however, a simpler and technically feasible idea of building the E-sail was invented[8] when it was realized that a connected grid is not needed since a set of independent and centrifugally stretched wires (tethers) is simpler to deploy and control and furthermore it retains nearly optimal thrust capability in widely varying solar wind plasma densities. The tether spinplane can be controlled by regulating the tether potentials individually in a synchronized way with the rotation because the thrust that each tether receives from the solar wind depends on its voltage.

According to our estimates,[3] the baseline E-sail, which is the target of our investigations, provides 1 N thrust, which scales in distance to the Sun as $\sim 1/r$, weighs ~ 100 kg, provides $\sim 30°$ of thrust vectoring capability, and needs no propellant or other consumables. Such a system is two to three orders of magnitude more efficient than currently used

[a)]Electronic mail: pekka.janhunen@fmi.fi. http://www.space.fmi.fi/~pjanhune; http://www.electric-sailing.fi

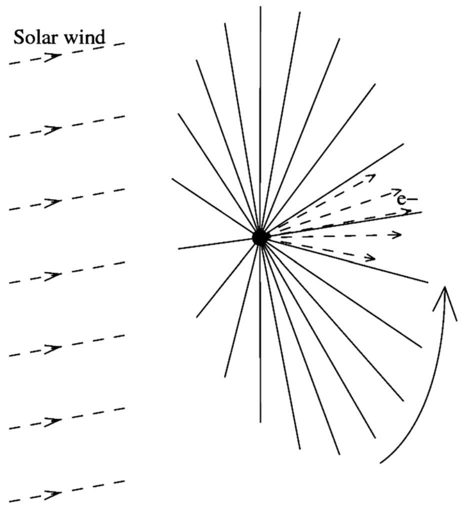

FIG. 1. Original E-sail concept.

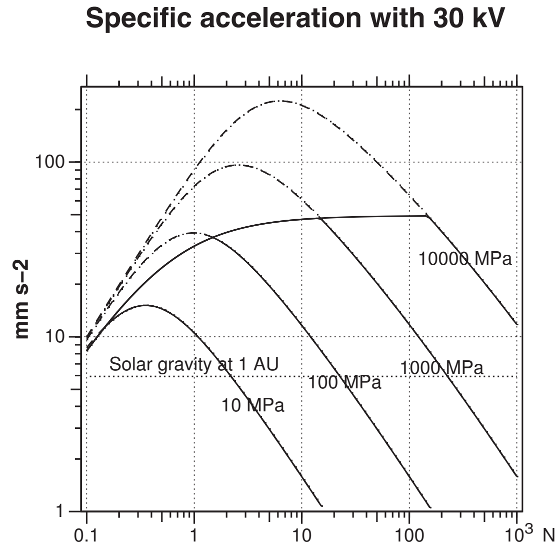

FIG. 2. E-sail specific acceleration as function of thrust for four tether usable tensile strength values. Dashed lines are cases where the tether wire is thinner than 18 μm. The 10 MPa curve corresponds to current ultrasonically bonded aluminum tether. A system base mass of 10 kg and a voltage of 30 kV are assumed. Dotted horizontal line gives the level of solar gravity at 1 AU for reference (propulsion systems reaching solar gravity acceleration are usually considered very good).

systems (chemical rockets and ion engines), and thus it has the potential to be quite a revolutionary step in future space technology. The E-sail would enable at moderate cost level a number of exciting solar system science missions such as a mission out of the heliosphere, rapid flyby missions of Kuiper belt or other objects,[9] sample return from many targets and non-Keplerian orbit missions.[10] It could also make asteroid resource utilization economically advantageous by providing a very efficient way of transporting the mined materials. With more advanced tether materials than aluminum, the performance of the E-sail could be larger than the baseline system since for fixed E-sail mass, the reached thrust level is roughly proportional to the usable tensile strength per mass density of the tethers. In Fig. 2, if one wants a specific acceleration of 10 $\mathrm{mm/s^2}$, with aluminum tethers (10 MPa usable tensile strength), the thrust is 1 N, while with a tensile strength of 100 MPa, the thrust is over 10 N. 100 MPa usable tether strength should not be unrealistic since, e.g., carbon fibers and silicon carbide fibers routinely reach several gigapascal strength. With hypothetical carbon nanotube tethers (strength $\geq$10 GPa), a 10^5 kg E-sail with 1000 km tethers might haul 10^6 kg payload at 1 $\mathrm{mm/s^2}$ acceleration, assuming that control and other issues would also be solved.

When will the E-sail be ready? No major unsolved problems are currently known, which would hinder its realization, but some key items are yet to be demonstrated. Most fundamentally, the E-sail effect must be experimentally measured to confirm its existence and magnitude. Experimental investigation of the E-sail effect is the goal of ESTCube-1 Estonian nanosatellite whose planned launch is 2012. Likewise, an experimental demonstration of reliable reeling (i.e., one-time reeling in at the factory and one-time reeling out in space) of the E-sail tether is needed. This topic will be attacked as soon as long enough tether samples exist. Thus far, a few meter tether samples have been produced by an ultrasonic wire bonding technique whose scaling to at least kilometer length tethers is expectedly straightforward. By the end of 2010, at least 10 m of tether is planned to be ready, which is enough for ESTCube-1 and for starting the experimental reeling tests.

The structure of the paper is as follows. We start from the plasma physical basis of the E-sail effect (thrust estimation) and go on to document the work done on tether dynamical simulation including deployment and propulsive flight dynamics. Then we describe the status of tether manufacturing, after which we review the large body of work already done on E-sail mission trajectory calculations, including the nontrivial result that solar wind variations, although large in magnitude, are not a problem for accurate navigability of the E-sail. Then we describe the project status of the ESTCube-1 nanosatellite E-sail LEO test mission including the tether and the electron gun. After that, we discuss the needed next step in E-sail experimental investigations, which would be a solar wind test mission. We discuss ways how to try and accomplish such a test mission with low cost. Finally, we give an overview of E-sail scientific and commercial applications. The paper ends with conclusions.

II. 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. The tether also collects electrons and the electron current is expected to be[3] well approximated by the orbital motion limited (OML) theory. Because the field is static, the energy of the proton remains unchanged in the frame 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 that 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 that arises from a piling up of protons and their associated positive charge density on the sunward side of the tether.

Photoelectrons emitted by the tether in response to solar UV radiation do not play a role since the positively charged tether (electric field ~ 100 V/μm) pulls them back very quickly. Likewise, secondary electrons produced by primary electrons hitting the tether do not contribute to the plasma density either.

The E-sail force is clearly proportional to the dynamic pressure of the solar wind ~ 2 nPa times the electron sheath cross section times the tether length ~ 20 km. Predicting the thrust thus boils down to predicting the electron sheath width (~ 100 m according to most recent results in average solar wind at 1 AU). In the region of parameters that is relevant here (tether voltage much higher than electron temperature), the electron sheath can be more than one order of magnitude larger than the electron Debye length of the ambient plasma.[11] The first plasma simulation based estimates of the electric sail thrust relied on the assumption that the trapped electron population, which necessarily forms when the potential is turned on, remains and contributes to the shielding of the tether charge, thus reducing the size of the potential structure and therefore also reducing the thrust.[2] Later, a natural electron scattering mechanism (electron orbit chaotization in the complex three-dimensional (3D) potential structure surrounding the spacecraft) was identified, which is able to remove trapped electrons typically in a few minute timescale.[3] Also it was found[3] 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 earlier.[2] The absence of trapped electrons is a standard assumption in most of the literature concerning electrodynamic tethers (see, e.g., Ref. 11), 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 them in a simpler way, which is, however, algebraically equivalent to the original form.[3] When V_0 is the tether voltage, m_i is the solar wind ion (proton) mass, and e is the electron charge, $V_1=(1/2)m_i v^2/e$ is the voltage corresponding to the bulk kinetic energy of a solar wind proton ($V_1 \approx 1$ kV for bulk speed $v=400$ km/s). Then if n_0 is the solar wind plasma density, one solves the electron sheath radius R iteratively from the nonlinear equation

$$R = \frac{\tilde{V}\sqrt{2\epsilon_0/P_{\mathrm{dyn}}}}{1+\sqrt{1+en_e\tilde{V}/P_{\mathrm{dyn}}}}, \tag{1}$$

where ϵ_0 is the vacuum permittivity and $\tilde{V}$ is an abbreviation for

$$\tilde{V} \equiv \frac{\max[0, V_0 - V_1 - (en_e/(4\epsilon_0))R^2]}{\log(R/r_w^*)}.$$

Here $P_{\mathrm{dyn}}=m_i n_0 v^2$ 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,[3] the thrust will be reduced only mildly.[3] A useful initial guess for the iteration is $R=\sqrt{\epsilon_0 V_0/(4n_0 e)}$. Once R is found, the thrust per unit length is given by[3]

$$\frac{dF}{dz} = K P_{\mathrm{dyn}} R, \quad K = 3.09. \tag{2}$$

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

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

Furthermore, since typically $V_0 \sim 20-40$ kV and $V_1 \approx 1$ kV, the V_1 term can often be neglected. Equation (3) has been derived under the assumption $n_e \ll n_0$.

Numerically, a 20 kV charged tether in average solar wind conditions produces ~ 500 nN/m thrust per length at 1 AU.[3] For example, an electric sail composed of 100 tethers 20 km long each would then provide ~ 1 N thrust. The current idea is to use 25 μm aluminum wire as tether raw material so that the total mass of the tethers is 11 kg when fourfold Hoytether construction[4] is employed for micrometeoroid tolerance. The electron gun requires ~ 400 W power[2], and we estimate that the whole E-sail propulsion system mass (tethers, tether reels, deployment and spinup mechanisms, power system, and tether direction sensor) would be about 100 kg in this case. Such a device would accelerate a 1000 kg payload at 1 mm/s^2. For more modest propulsive needs, the device can be easily scaled down.

Overall, the power consumed by the electron gun is modest and depends on the current gathered by the tethers. The latter should be accurately given by OML theory,[2,3] and the power consumption is then proportional to $n_0 V_0^{3/2}$. Luckily, the power consumption scales with solar distance r in the same way ($1/r^2$) as the power produced by solar panels because for fixed voltage, the power consumption is proportional to the solar wind density. Also luckily, if for a fixed r one adjusts V_0 so that the power consumption is constant, the resulting thrust varies remarkably little despite solar wind fluctuations.[17] We return to the latter point below.

Consider now a 10-year mission, which does not move very far from 1 AU (for example, an asteroid deflection mission[12] or an off-Lagrange point solar wind monitor). The baseline E-sail (1 N thrust, 100 kg mass) then generates 3×10^8 N s total lifetime-integrated impulse. This total impulse is equivalent to using 100 tons of chemical propellant (specific impulse 300 s) or 10 tons of ion engine propellant (specific impulse 3000 s). In this sense, the performance of the baseline aluminum tether E-sail is two to three orders of magnitude higher than chemical rockets or ion engines. If the mission is designed to move far away from the Sun faster than in 10 years, the performance gain will be smaller but still more than one order of magnitude better. The longer the E-sail stays in the region where the solar wind flows (i.e., until and if its mission takes it out of the solar system), the more total impulse it can generate and the larger is its relative performance benefit in comparison to propellant-consuming rockets.

The direction of the thrust can be controlled by changing the orientation of the spinplane. Taking into account that the thrust exerted on a tether by the solar wind is always perpendicular to it, one sees with a simple geometrical consideration that the total thrust vector of the spinning E-sail points to approximately halfway between the solar wind and the spinplane normal directions. One can expect to be able to direct the thrust by $\sim \pm 30° - 35°$ away from the solar wind, which is approximately radial from the sun. The turning of the spinplane can be obtained by changing the tether voltages slightly on different sides, in a synchronous way with the rotation. The applied flight algorithm resembles helicopter flight where instead of modifying the attack angles of the rotor blades one modifies the tether voltages through a potentiometer installed between each tether and the spacecraft.

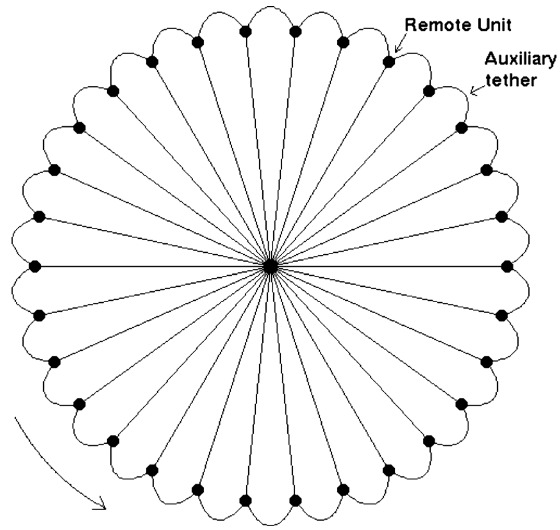

FIG. 3. Currently preferred E-sail concept with centrifugally stabilizing auxiliary tethers and remote units, which contain the auxiliary tether reels and small thrusters for spinup and spin control.

III. TETHER DYNAMICAL SIMULATION

A detailed mechanical flight simulation that models the dynamics of the rotating tethers by Newton's laws and E-sail thrust modeling has been written. Besides the solar wind force, the program includes other effects, e.g., due to tether elasticity, tether temperature due to the varying orientation of the Sun, and the associated thermal expansion.

An accurate and efficient calculation of the mutual Coulomb repulsion is a challenge that is yet to be met. The Coulomb repulsion has an effect only over regions where the electron sheaths of adjacent tethers partly overlap. The overlap region is near the root of the tethers where the tether tension is the largest. A rough estimation of the Coulomb repulsion between the tether roots has been programmed, however, and comparative runs indicate 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 end, the charges redistribute themselves so as to minimize the Coulomb repulsion at that point.

The E-sail tethers must be conducting and provide enough mechanical strength so that they can withstand the centrifugal force. The spin rate of the system must be selected such that the centrifugal force overcomes the expected solar wind force by a factor that 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 is 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 aluminum 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 aluminum tethers, a 1 N E-sail weighs about 100 kg. If one uses a 20 kV nominal voltage, such an E-sail needs about 2000 km of total tether length (e.g., 100 tethers each one 20 km long). If a stronger material than aluminum 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 aluminum tethers it is possible to make E-sails with higher thrust than 1 N at 1 AU, but at the expense of a reduced thrust versus mass ratio. For example, a 2 N E-sail would weigh about 400 kg.

Whenever the E-sail is inclined with respect to the solar wind, different tethers of the E-sail experience a different thrust history because of their exposure to the varying solar wind in orientations, which are unique to each tether. Because of the inclination, this thrust also has a component in the spinplane, 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, eventually resulting in tether collisions. Tether collisions must be avoided since they may cause tangling and mechanical wear of the tethers. In addition, they may cause sparking because adjacent tethers have somewhat different potentials due to spinplane control maneuvering.

Thus, all E-sail designs must prevent tether collisions. The original plan (Fig. 1) included continuous tether length fine-tuning during flight so that the conservation of the angular momentum is able to keep the tethers apart. This has the drawback, however, of requiring moving parts. Also, we do not trust that the multiline tether, which is partly damaged by micrometeoroid impacts, could be reliably and repeatedly reeled in and out for several years. Therefore, the part that is repeatedly reeled should be made of thicker monofilament or tape tether instead of the lightweight multiline tether. 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, and even a temporary failure of the onboard algorithm or its sensor inputs would be mission-critical.

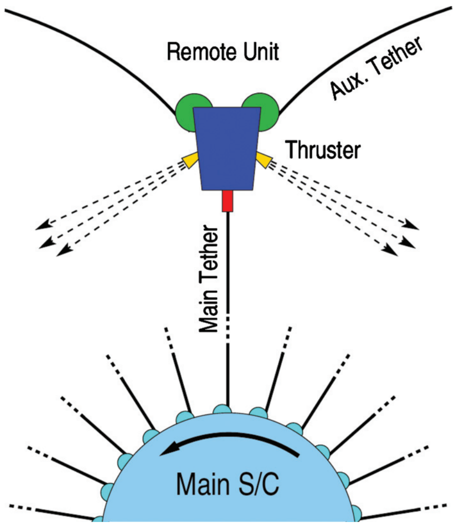

FIG. 4. (Color) Schematic top view of one remote unit.

To overcome these issues, an alternative tether collision prevention concept was developed in the summer of 2009 (Fig. 3). In the alternative concept, the tips of the tethers are connected with each other by nonconducting auxiliary tethers. For safe deployment, the reels of the auxiliary tethers must reside at the tips of the main tethers, in small autonomous devices that are referred to as the "remote units" (Fig. 4). Having the remote units available, it is also straightforward to install small gas or ion thrusters there to create the initial spin of the system. The Δv that the remote unit thrusters must generate to initiate the spin is generally less than 100 m/s. The remote units make the tethers heavier, and therefore the tether spin period, which is otherwise a free parameter, must be increased to keep the tether tension the same. The remote units are typically powered by CubeSat type fixed solar panels on the surface.

The auxiliary tethers are ~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 that 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. According to dynamical simulations, the system remains stable if the auxiliary tether mass is at least the same as the remote unit mass.

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 that are operated only during the deployment), that it does not rely on any 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.

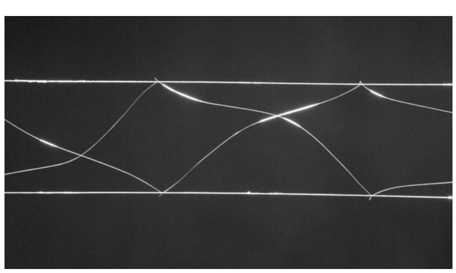

FIG. 5. Four-wire Hoytether made of 25 and 50 μm aluminum wires by ultrasonic bonding.

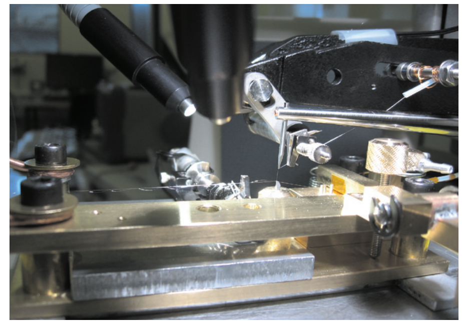

FIG. 6. (Color) The semiautomatic tether factory (March 10, 2010).

A separate simulation has been written for modeling deployment where the tethers are considered massless (a good approximation in the early deployment phase at least), but the spacecraft and the remote units are modeled with full finite-size rigid body dynamics. For reasonably chosen parameters (tethers lengths, remote unit masses, etc.), the simulated deployment works without instabilities. One way to improve stability is to insert small mechanical dampers at the remote units. Finite tether stiffness could make real-world stability better than in the simulation.

IV. TETHER MANUFACTURE

The E-sail main tethers must provide mechanical strength and 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 aluminum wires that are made into a multiline tether structure by ultrasonic bonding.

Regarding tether material selection, aluminum tolerates space environment well, it is a good conductor, and it has a reasonable strength versus density ratio. Aluminum wires can also be bonded together using the ultrasonic welding technique. Ultrasonic welding produces minimal destruction of the bonded wires, and it is possible in ambient room temperature conditions.

The first geometry considered was a four-wire Hoytether[4] (Fig. 5), but our current baseline is a somewhat different "Heytether" geometry that has one parallel wire and three interleaved loop wires; see Fig. 7 for a simpler two-wire version of Heytether. The Heytether is technically simpler to produce and also has the benefit that only one parallel

FIG. 7. (Color) Two-line Heytether.

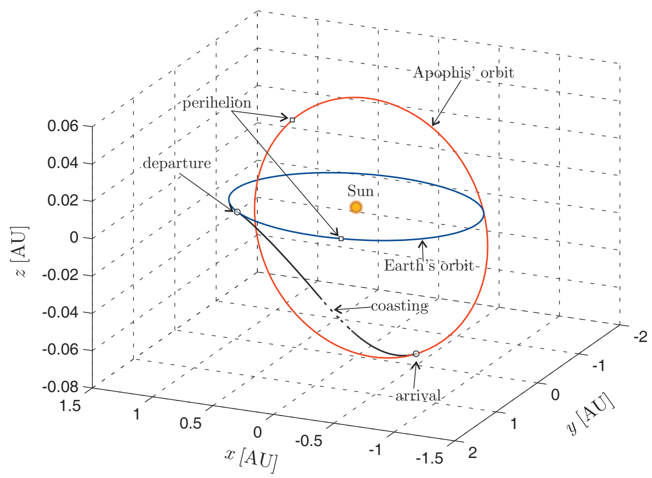

FIG. 8. (Color) Optimal Earth-Apophis transfer trajectory with 1 $\mathrm{mm/s^2}$ E-sail.

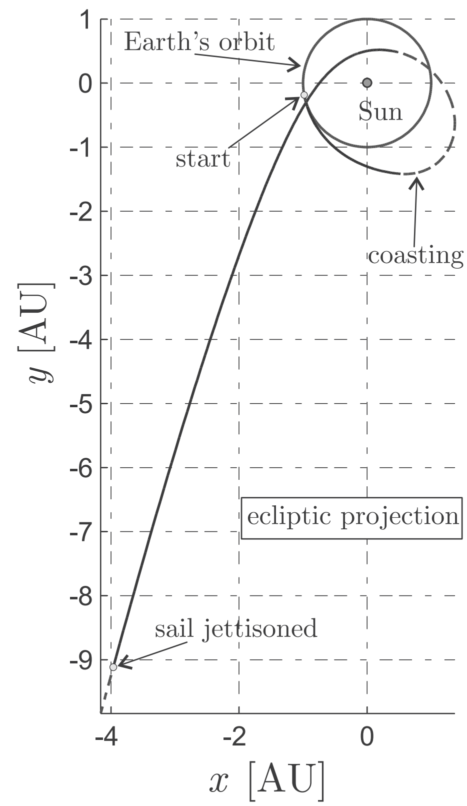

FIG. 9. Beginning part of transfer trajectory toward heliopause nose.

wire is needed. The latter reduces the mass overhead arising from the fact that the bonded wires have different thicknesses. According to our practical experience, ultrasonic bonding is reliable only when the bonded wires have somewhat differing thicknesses.

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. 6). The tether factory is a small tabletop device that is operated in connection with a commercial wire bonder machine in cleanroom environment. New versions of the tether factory will be built soon. The goal for 2010 is to produce 10 m of tether for the ESTCube-1 test mission that will be launched in 2012.

V. MISSION TRAJECTORY CALCULATIONS

The E-sail performance has been investigated by considering a number of different mission types. In most cases the problem was addressed in terms of finding the steering law that minimizes a given scalar performance index. The mathematical details for a two-dimensional (2D) analysis can be found in Ref. 13, where a classical minimum time, circle-to-circle, 2D transfer is discussed.

More refined trajectory studies have been performed using a 3D mathematical model in which the optimal steering law is found using the modified equinoctial orbital elements. For example, missions toward potentially hazardous asteroids (PHAs) represent an interesting option for an E-sail whose peculiar characteristics allow the spacecraft to fulfill transfers that otherwise will need either a considerable propellant mass or tailoring of the launch date to utilize planetary flyby maneuvers. Moreover, unlike conventional chemical propulsion systems, an E-sail offers more flexibility in the selection of the launch window. A thorough analysis of E-sail potential to perform rendezvous missions toward any of the current cataloged PHAs is discussed in Ref. 14. For example, Fig. 8 shows the minimum time transfer trajectory toward asteroid 99942 Apophis, for an E-sail spacecraft with a characteristic acceleration (acceleration at 1 AU) of 1 $\mathrm{mm/s^2}$.

It is known that an interplanetary mission transfer usually requires large changes in orbital energy. For conventional (chemical) propulsion systems the high necessary Δv corresponds to a considerable propellant mass required to accomplish the mission. A possible alternative to reduce the total propellant mass is obtained by combining a chemical thruster or aerocapture with an E-sail. Typically, the chemical thruster or aerocapture is used at the target planet for orbit insertion, while the E-sail is used during the long heliocentric transfer. Such a hybrid propulsion concept has been applied for a 2D interplanetary transfer.[15]

Recently, missions toward the boundaries of the Solar System with an E-sail spacecraft have been studied.[9,16] In particular, the performance of an E-sail for obtaining escape conditions from the Sun and planning a mission to reach the heliosphere boundaries has been studied in an optimal framework by minimizing the time to reach a given solar distance or a given hyperbolic excess speed. A medium-performance E-sail was shown to have the potential to reach the heliosheath, at a distance of 100 AU from the Sun, in about 15 years. Also, the Interstellar Heliopause Probe mission was used as a reference mission to further quantify the E-sail capabilities for an optimal transfer toward the heliopause nose (200 AU). For example, Fig. 9 shows the first part of the transfer trajectory toward the heliopause nose for an E-sail with a characteristic acceleration of 2 $\mathrm{mm/s^2}$.

Less conventional mission scenarios have also been investigated. An interesting example is a mission whose aim is to observe the Sun's polar regions. These mission types, when achieved with chemical propulsion, require the use of highly elliptic trajectories of considerable inclination, whose

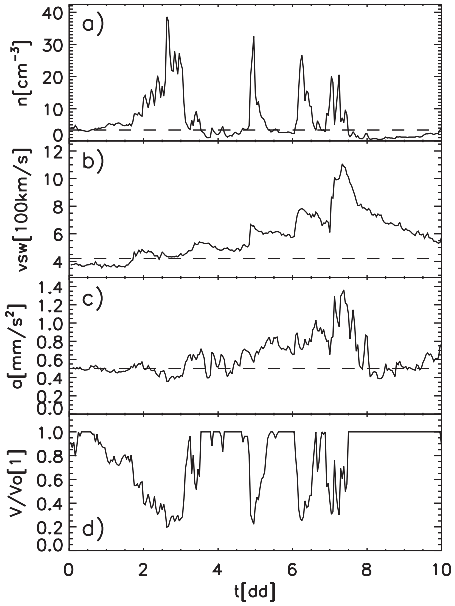

FIG. 10. Solar wind density (a) and speed (b), resulting E-sail acceleration (c) and V_0 variation relative to its hardware limit (d), over a 10-day period with large solar wind variations (Ref. 17). Density below which V_0 is at the hardware limit was 3.4 cm^{-3}. With this choice, at 1 AU the E-sail is driven at maximum power 75% of the time on average.

fulfillment is typically obtained with the aid of complex multiple flyby maneuvers. An alternative consists of inserting a spacecraft equipped with a propellantless propulsion system (such as an E-sail or a solar sail) in a non-Keplerian orbit (NKO), whose plane does not pass through the Sun's center of mass. Such a displaced NKO can be maintained by suitably orienting the thrust direction so as to balance the centrifugal and gravitational components of spacecraft acceleration. Besides the study of optimal transfer trajectories toward the NKO, a performance comparison between an E-sail and an ideal solar sail has been studied in detail.[10]

VI. ROBUSTNESS AGAINST SOLAR WIND VARIATIONS

The solar wind experiences large natural variations over many timescales. Thus an accurate navigability of the E-sail is not clear *a priori*. However, there are two mechanisms that reduce the thrust variations with respect to solar wind density and speed variations.[17] 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 [Eq. (1)]. When the solar wind density drops, the thrust becomes lower because the dynamic pressure decreases [Eq. (3)], but the simultaneous widening of the sheath provides partial compensation. The second mechanism arises if one applies the natural strategy to use all the available power from the solar panels to run the E-sail. The OML electron current gathered by the tethers is proportional to the solar wind density so that to keep the power consumption constant one increases the voltage when the solar wind density drops. 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.

Figure 10 shows an example 10-day period of measured solar wind data when the density and speed variations are large. The thrust variations (panel c) are much weaker than those of the solar wind itself. The calculation method used to produce Fig. 10 is the same as that reported earlier[17] but was updated to use the new thrust formula [Eq. (2)] instead of the earlier results.[2]

When reaching a planetary target such as Mars, it is the average thrust over at least a 1 month timescale that matters, not daily thrust values. Furthermore, if one modifies the maximum power strategy so that some electric power is by default kept in reserve, then it is likely 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.[17]

VII. ESTCUBE-1 TEST MISSION

To validate the plasma physics side of the E-sail concept, the electrostatic force acting on a charged tether in moving plasma stream should be measured. To validate the technical concept, tether deployment and controllable E-sail flight should be demonstrated as well. The purpose of the ESTCube-1 test mission is to address the plasma physics question in LEO conditions and to demonstrate deployment of a short tether. A later solar wind test mission should measure the plasma physics force in the authentic environment (solar wind) and to demonstrate the capability of controlled E-sail flight.

The ESTCube-1 will be a 1 kg, 10 cm across CubeSat that is built mainly by students in Estonian universities of 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 and 9 mm wide conducting Heytether made of 50 μm base wire and three 25 μm loop wires. The tether can be charged to $\pm$450 V by an onboard voltage source and electron gun. The deployment is achieved by spinning the satellite and reeling out the tether with the help of centrifugal force.

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 ~1 μN, which is ~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

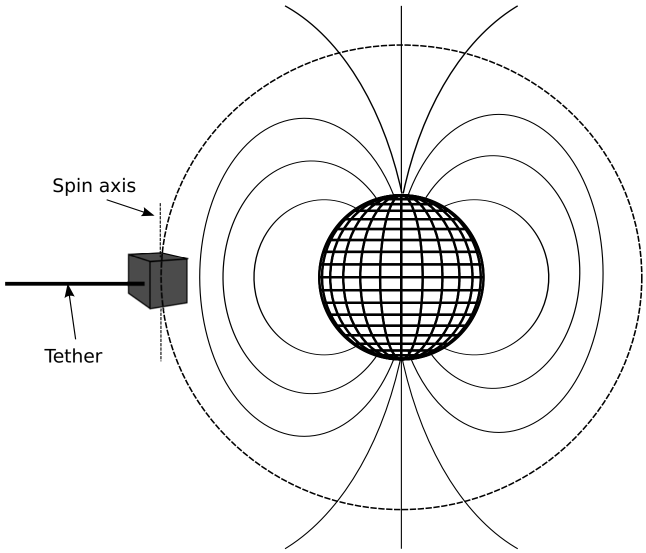

FIG. 11. Orbit and spinplane orientation of ESTCube-1 relative to Earth's dipole magnetic field.

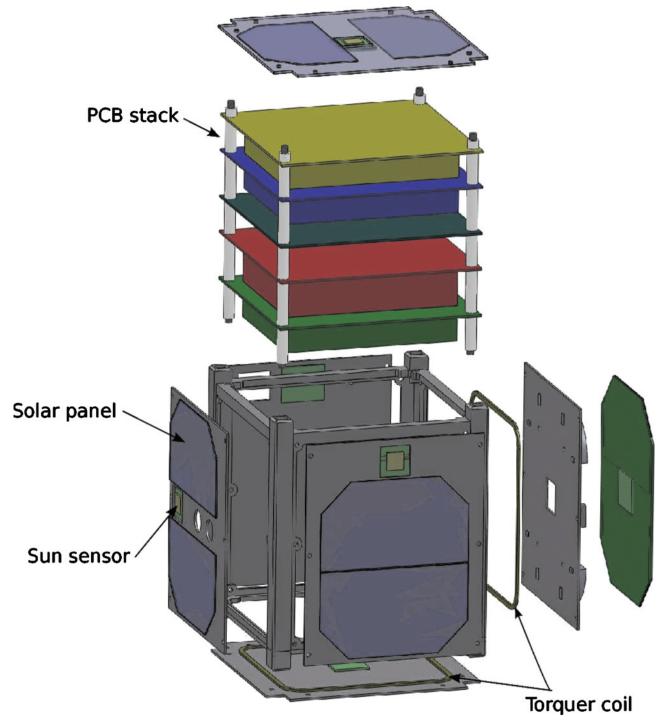

FIG. 12. (Color) Preliminary structural design of ESTCube-1. The PCB stack from top to bottom: ADCS, CHDS, PL, EPS, and COM.

plasma density that 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) and (2) can be quantitatively tested. The required duration of ESTCube-1 is a few weeks, and it can extend to about 1 year.

ESTCube-1 will have a 600–800 km polar orbit, and the spinplane of the tether and the satellite coincides with the equatorial plane (Fig. 11). The E-sail experiment will be run primarily near the poles where the magnetic field is along the spin axis, while the plasma stream due to orbital motion is in the spinplane. Then the magnetic Lorentz force and the expected E-sail force that affect the tether are both in the spinplane so that they do not tend to turn the spin axis. An equatorial orbit would be best for the E-sail experiment because then the experiment could be run at any time. The polar orbit for ESTCube-1 was selected because of more frequent launch opportunities, more ground station options for telemetry and the possibility to create the satellite's spin by magnetic torquer coils. The last argument was especially compelling because other than magnetic spinup options are difficult to devise for a nanosatellite.

The $\sim 1\ \mu$N E-sail force can be measured by ESTCube-1 by turning the electron gun on and off in sync with the tether's rotation period of ~ 20 s. For example, if the voltage and therefore the E-sail force are turned on always when the tether is moving toward 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 of the 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.[18] 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 charged 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 sufficient 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[19] 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 modes to study the E-sail effect and the plasma brake concept.

A. Mechanical structure

ESTCube-1 is a single-unit CubeSat under the CubeSat standard of California Polytechnic State University and Stanford University. The shape of the satellite is a $10 \times 10 \times 10\ \mathrm{cm}^3$ cube and the maximum mass is 1.33 kg.

Figure 12 shows the preliminary structural design. The main frame and the side panels are made of aluminum (AW 6061-T6). Two solar panels for power generation and one sun sensor for attitude control are mounted on each side panel. Two antennas for uplink and downlink communication are rolled around a structure on one of the side panels and are deployed in orbit.

The inside of the satellite consists of five printed circuit boards (PCBs), stacked on top of each other as shown in Fig.

12. Each PCB is mainly devoted to one satellite subsystem. The subsystems are the attitude determination and control system (ADCS), command and data handling system (CDHS), payload (PL), electrical power system (EPS), and communications system (COM). The PCBs are attached to the satellite body by long vertical screws (Fig. 12).

The temperature of the satellite interior is kept between +5 and +30 °C. This is achieved by passive thermal control methods, e.g., with the choice of coating materials.

B. Power

As shown in Fig. 12, all six sides of the satellite are mainly covered by solar panels, giving a total solar panel area of 360 cm^2 and producing 2 W of power in sunlight. Two pieces of two-cell LiPo batteries are used to store energy for eclipse phases and to enable maximum instantaneous power up to 6 W for power-hungry operations such as reeling out the tether, deploying the antennas, and operating the electron guns.

C. Attitude control

The ESTCube-1 mission sets high demands for the ADCS and correct orientation of the satellite is mission-critical. The ADCS must orient the satellite correctly with respect to Earth's magnetic field and keep doing so while spinning the satellite.

The position information of the satellite is based on the two-line elements maintained by Norad. The ADCS calculates the satellite attitude from on-board magnetometer and sun sensor data using a model of Earth's magnetic field. The ADCS contains six sun sensors, one on each side of the satellite. Three three-axis magnetometers are used, one required and two redundant. The angular velocity information is obtained from on-board gyrosensors. The current design includes three three-axis MEMS systems gyroscopes, two of which are redundant.

The attitude control of the satellite is actuated by three magnetic torquer coils. The wirewound coils are placed on the inside walls of three side panels in order to achieve three-axis control of the satellite attitude. The coils are utilized to counter any unwanted torques experienced by the satellite. In order to do this, the direction of the local Earth magnetic field vector must be obtained from the magnetometer readings. The coils are then driven with current pulses provided by dedicated microcontroller unit (MCU) controlled drivers. During the E-sail experiment, the spinning motion of the satellite is achieved with the help of the coils. The magnetometers and the coils are operated sequentially to avoid the coils disturbing the magnetometer readings.

D. Communication and data handling

The communications with the satellite are carried out with radio amateur frequencies. The downlink is operated at uhf and S bands. The downlink is divided into low power and high power transmission modes, LPTM and HPTM, respectively. The approximate transmission powers are 0.1 W for LPTM and 0.5 W for HPTM.

The LPTM is a Morse coded beacon tone signal that can be received and interpreted with standard radio amateur equipment. It contains the identification of the satellite along with the most critical data about the instrument health and mission status. The exact content of the beacon signal is yet to be decided. It will include at least the battery voltage and temperature, the solar panel currents and information about the satellite attitude (e.g., gyrosensor readings). The beacon signal is autonomous and is transmitted periodically.

The HPTM is used for transmitting large amounts of mission data. These consist of housekeeping data from each subsystem and the experiment data, for example, a picture taken by the camera. The HPTM is turned on only by ground telecommanding.

The uplink for telecommanding operates at VHF band. The mission control can, for example, order the satellite to commence or to abort certain mission phases such as the E-sail experiment. The uplink is doubled for redundancy. The primary and secondary uplink receivers are connected to different MCUs in the satellite's data handling architecture.

The uplink and downlink antennas are made of beryllium copper. In stowed position the antennas are rolled around a structure on one of the side panels. Once in orbit, the antennas are released and they are deployed by their own structural tension.

The data handling architecture of ESTCube-1 includes five MCUs. The relatively large number of MCUs is justified by the large number of digital and analog signals between the subsystems, requiring a large number of input and output connections. In addition, the overall redundancy of the system is improved. For example, the EPS is able to operate independently of the CDHS, and in the case of CDHS failure, EPS is able to take over the handling of some critical operations. The CDHS MCU is duplicated for further error tolerance. The camera used to image the tether has its own MCU because of its need for fast image acquisition.

E. Electron gun and voltage source

The power available in ESTCube-1 would be sufficient to run a small thermionic electron gun cathode, but it would unnecessarily stress the power budget and constrain experiment scheduling. 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.[20] 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 that is sufficient to cause electron field emission from the graphite. The puller electrode (anode) is made of 1 μm silicon nitride membrane that is perforated with holes and thinly metallized to form a conducting accelerator grid. The electron gun produces $\sim$2 mA current and consumes 1.5 W total power, of which 1 W goes into the output beam and 0.5 W is consumed by electrons hitting the anode instead of passing through the holes. The voltage source feeding the electron gun and connecting to the tether in the negative polarity mode is made of standard electronic components

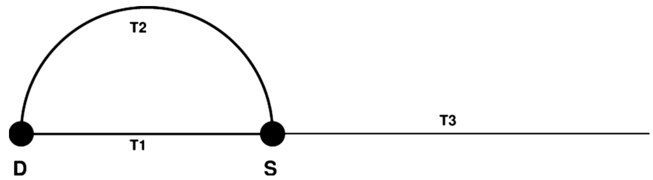

FIG. 13. Configuration of simple two-mass solar wind test mission, comprising of spacecraft S, dummy mass D, their connecting load-bearing tape tether T_1, another centrifugally stretched tape tether T_2, and provision for testing also a multiline tether T_3.

and contains no special challenges, besides the strive to minimize mass.

F. Tether deployment

Deploying the tether begins with initiating the satellite spin. The satellite is to be spun around an axis that coincides with Earth's axis. Magnetic torquer coils interacting with the Earth magnetic field are used to achieve the desired rotation rate of 1 Hz. The ADCS detects the direction of the local magnetic field lines and operates the torquer coils as explained above. Once the final rotation rate is reached, the satellite has become spin stabilized, maintaining the orientation of its spin axis.

The successful deployment of the tether is verified by observing the angular velocity of the satellite by the gyrosensors. Once the entire tether has been deployed, the rotation rate is expected to be 3 rpm. The onboard camera is used to take photographs of the tether and its ~ 0.3 g end mass during and after deployment. The tether deployment can be stopped and continued later if needed.

VIII. SOLAR WIND TEST MISSION

Although a LEO satellite such as ESTCube-1 is expectedly able to measure the E-sail effect, validating the concept in real conditions and demonstrating E-sail flight maneuvers calls for a test mission in the solar wind. A concept for a simple solar wind test mission (Fig. 13) 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 center of mass that resides somewhere around halfway along T_1, which has a 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[3] 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 a 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. 13. 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 chaotization 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 multiline tethers. This approach is proposed so that the decision to build the mission could be done now without waiting for a demonstrated ability to manufacture multiline tethers. However, once the mission is underway, it would be nice anyway to test the multiline tether that will be probably available at the time the mission is flying. In the mission there is room for tether T_3 (Fig. 13), which can be a lightweight multiline tether (i.e., Hoytether, Heytether, or similar). Because it is lightweight, T_3 can be also longer than T_1 and T_2 without destroying the dynamical properties. The T_3 can be deployed at the end of the mission, after T_1 and T_2 operations have been demonstrated. The optional T_3 provides a flight testing opportunity for an advanced tether while not requiring it for mission success.

The orbit of this kind of test mission could be either a highly elliptic Earth orbit that 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 toward 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 (e.g., three masses connected by three tethers or configurations with one spacecraft and several remote units, i.e., the same that is planned for production-scale missions or missions that not only demonstrate controlled flight but also accomplish a small mission to some target). We presented here one of the simplest and therefore cheapest possibilities that is able to demonstrate propulsive E-sail flight.

IX. E-SAIL APPLICATIONS

Mission trajectory calculations with pure E-sail to planetary and asteroid targets have been performed.[13,16] The baseline ~ 1 N E-sail could be useful, e.g., in the following tasks:

(1) fast one-way trip for a small payload (~ 200 kg) at > 50 km/s out of the solar system;[9]
(2) reasonably fast trip to a giant planet orbit for ~ 500 kg payload using a chemical orbit insertion burn near the planet[15] and possibly also E-sailing and/or electrodynamic tethering[6] in the giant planet's magnetosphere;[21]
(3) two-way trip for a ~ 1000 kg payload in the inner solar system;[13]
(4) non-Keplerian orbit for off-Lagrange point solar wind monitoring, off-ecliptic solar orbit for helioseismology,[10] or permanent viewing of Earth's polar region for polar meteorology or communications; and

(5) direct propulsive deflection of Earth-threatening asteroids (for example, with a single baseline 1 N E-sail, a 150 m asteroid can be deflected away from Earth's path in 6 years[12]).

The main limitations of the E-sail are that it does not produce much thrust inside Earth's magnetosphere (because the plasma there is usually slow-moving) and that the thrust direction control is limited. The thrust direction limitation (the thrust angle can be altered by $\sim 30°$) implies that a speedy return from the outer solar system is not possible by pure E-sail because the solar gravity at that distance is so weak that it takes time before it pulls the spacecraft inward. 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 toward the inner solar system.[15] If the opened E-sail tether rig can be engineered to survive the impulsive burns, this could open up the possibility of sample return missions from the giant planet moons. Because of its high total impulse capability in a mission that stays for a long time in the 1–3 AU distance range, the E-sail would suit particularly well to asteroid resource utilization applications.

X. CONCLUSIONS

We are not aware of any scientific, technical, or other reason why the E-sail would not eventually work at least roughly at the projected performance level. Because the projected performance level (deliverable impulse versus mass) is two to three orders of magnitude higher than for chemical rockets and ion engines, the margin for success is large. If better tether materials than aluminum could be employed (e.g., metallized carbon or silicon carbide fiber), the performance level could even increase significantly beyond this estimate. 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 its goals with simple tape tethers while also providing a flight testing opportunity for a multiline tether. 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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