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Electric Sail Propulsion for Deep Space Missions

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Abstract

Electrostatic Sail (E-sail) propulsion extracts momentum from the solar wind, which has minimal speeds of 400 km/sec, through electrostatic repulsion of the positively charged solar wind ions. This momentum exchange is accomplished by an array of multi-kilometer-length charged tethers biased to a high positive voltage, producing an electric field around the tethers that deflect the positively charged solar wind particles. This electric field grows in diameter as the spacecraft moves away from the sun, increasing the E-sail effective area. The growth of the E-sail effective area allows the created propulsive force to decrease at a rate closer to 1/r out to distances from the sun of up to 20 Astronomical Units (AU). This is unlike solar sail propulsion, where the thrust decreases at a rate of $1/r^2$ and is only effective out to distances of ~5 AU. The propulsive force is applied without expending any propellant. Although the thrust generated by an E-Sail is low, it can be applied continuously over a period of years (depending on the mission type), and can push a 500 kg spacecraft to tremendous velocities—as high as 12 AU per year—making the voyage to 600 AU in as few as 50 years after launch. The NASA Marshall Space Flight Center recently completed a NASA Innovative Advanced Concept (NIAC) study in which all of the major system- and subsystem-level aspects of an E-Sail-propelled vehicle were assessed and a maturation plan developed. If implemented, E-Sail propulsion could be realized and deployed as a viable option for space missions within a decade.

Keywords: in-space propulsion, electric sail, spacecraft propulsion

Nomenclature

Symbol	*Definition*	*Units*
L_w	Length of Wires	
m_p	Proton Mass	
n_e	Electron Density	
n_p	Number Density	
N_w	Number of Wires	
P	Proton Impact Parameter	
T_e	Electron Temperature	
v_p	Velocity	
λ_D	Debye Shielding Distance	
ϕ	Electrical Bias on Wire	

Acronyms/Abbreviations

AU	Astronomical Unit
E-sail	Electrostatic Sail
NIAC	NASA Innovative Advanced Concept
TRL	Technology Readiness Level

1. Introduction

The Electrostatic Sail (E-Sail) is a revolutionary propulsion technology that uses the naturally occurring solar winds to produce thrust without the expense (mass) of propellants, enabling trip times to the edge of the solar system that are half of those offered by any alternative system. In addition to these benefits (reductions in launch costs and travel times to solar system targets), this system will enable new types of missions that employ non-Keplerian orbits.

The E-Sail taps the momentum flux of the natural solar wind for spacecraft propulsion with the help of long, positively charged wires (Fig. 1). The system produces a thrust vector that points away from the Sun, but that can be turned at will within a cone of approximately 30°, and whose magnitude can be easily adjusted.

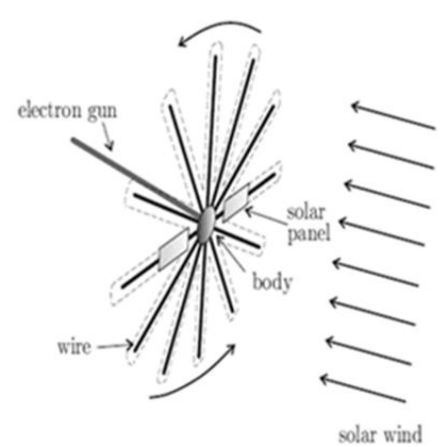

Fig. 1. The Electric Sail produces thrust by the interaction of the solar wind with its positively charged wires extending multiple kilometers out from the spacecraft hub.

The thrust produced by an E-sail declines at a rate of $1/r^{7/6}$ (where r is the solar distance), and the system provides acceleration to distances of 20 AU. In comparison, the thrust of a solar sail propulsion system declines at a rate of $1/r^2$ and is only capable of accelerating a spacecraft at a maximum radius of ~5 AU. E-Sail velocities are 25% greater than solar sail options, due to the reduced rate of acceleration decline. Consequently, an E-Sail mission to the Heliopause can be accomplished within 15 years (Fig. 2), a feat Voyager 1 took 29 years to accomplish.

E-Sail propulsion exceeds the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU per year. In more human terms, the E-Sail technology will bring the time frame of Heliopause missions to well within that of an investigator's career. It may be difficult for a young researcher to decide to pursue a Heliopause mission with today's propulsion technology, knowing they may be at the end of a 30-year career before they see any results from the mission. E-Sail technology would supply results to an investigator with plenty of time to follow up with second or third missions that build upon the conclusions and discoveries of earlier missions.

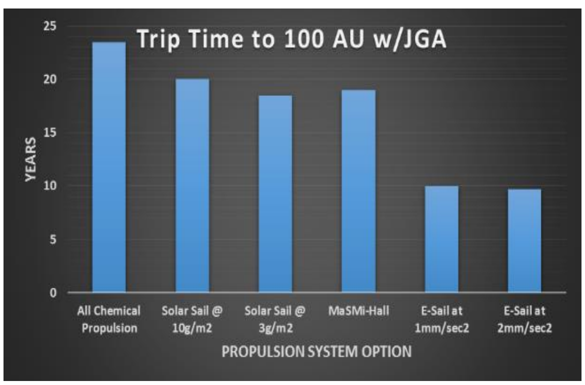

Fig. 2. E-Sail propulsion can significantly reduce travel time to 100 AU compared to more conventional propulsion systems.

2. E-Sail Propulsion Concept of Operations

The E-Sail acquires momentum from the hypersonic solar wind and can provide propulsion throughout the heliosphere. Consistent with the concept of a "sail", no propellant is needed as electrostatic forces capture a small "push" from the solar wind that, over a period of months, accelerates a spacecraft to enormous speeds—on the order of 100-150 km/s (~ 20-30 AU/yr).

The E-sail consists of 10-100 electrically conducting wire strands, each many kilometers in length. These strands are deployed from the main spacecraft bus, and the spacecraft rotates to keep the strands taut. An electron gun is used to keep the spacecraft and the strands in a high positive potential. The electric field around the strands interacts with the solar wind, which is a plasma that flows radially away from the sun, moving at speeds between 300 and 700 km/s. The high voltage potential applied to the wires interacts with the solar wind to deflect the positive particles, transferring momentum from the solar wind to the vehicle in the process.

Unlike other propellantless concepts, the electric sail does not rely on a fixed area to produce thrust. In fact, as the electric sail moves away from the sun, the electron Debye length increases, permitting a commensurate growth in the size of the positive electric field, which increases the apparent area of the virtual sail. This results in thrust decreasing as $\sim 1/r^{7/6}$.

The magnitude of the total thrust generated is related to the effective cross-sectional area over which the solar wind is perturbed. This is proportional to the total length of the wires, but it also is highly dependent on the efficiency of the interaction between the biased wires and the solar wind. The wires themselves are less than 0.1 mm in diameter. However, the effective radius—the range of the imposed electric field—is much greater. This range is characterized by a proton impact parameter, P, which is directly proportional to the magnitude of the applied positive potential and the Debye shielding distance, λ_D, of the solar wind plasma ($\lambda_D \approx T_e^{1/2}/n_e^{1/2}$, where T_e and n_e are electron temperature and density, respectively). The total force on the wire array is given by:

$$F = m_p n_p v_p^2 N_w P(\phi, \lambda_D),$$

where; m_p, n_p, and v_p are proton mass, number density, and velocity; N_w and L_w are the number and length of the wires; and ϕ is the electrical bias on the wire. Therefore, as the vehicle moves away from the sun and the solar wind density decreases as $1/r^2$, the proton impact parameter increases—which helps maintain the thrust level, partially compensating for the reduced plasma pressure.

The important components of the propulsion system are: the wire array, kept in tension by a slow rotation; a wire deployment system; an electron gun to maintain the positive bias on the wires; a programmable high-voltage power supply that can individually adjust the voltage on every wire; and a power distribution system. The bias of each wire must be individually controlled to enable thrust vectoring. Critical wire design parameters include material, diameter, total length, count, electrical bias, and configuration (single vs. multiple strand and deployed geometry).

Speeds in excess of 50 km/s (10.5 AU/yr) are predicted in early calculations by Quarta and Mengali [1]. Work by Stone [2] included experimental data that was used to calculate a thrust level. This level is of the same order of magnitude as—but is approximately 3.5 times higher than—predictions by Janhunen [3].

This concept is very flexible and adaptable. The previously discussed parameters allow mission/vehicle designers to trade the effects of the wire lengths on performance, number of wires, and applied voltage levels to determine sensitivity variations for the integrated spacecraft design. The bias of the wires can be modulated as the vehicle rotates, to provide thrust vectoring over a wide range of angles relative to the incident solar wind. This provides for mission concepts that involve visits to multiple planets or objects of interest within the solar system. Additionally, the wire array structure may provide benefits in addition to propulsion. Feedback from the wires may provide information about the structure of the solar wind, and it has been proposed to also utilize the array to supplement communications. As an example, individual wires may be biased and modulated such that they act as a large phased array .. antenna, increasing communications range and bandwidth while reducing power requirements. Individual wires may also act as a long Langmuir probe, capable of measuring the spacecraft floating potential, electron density, and temperature of the deep-space plasma environment.

The propulsion system can be sized to fit on spacecraft ranging from CubeSat-size to large-scale vehicles. However, the system is only useful for interplanetary missions and is not effective within the magnetosphere of a planet where the solar wind is significantly shielded. The effectiveness of the sail drops as it approaches to within 0.5 AU or less of the sun, due to the decreasing Debye length.

The current Technology Readiness Levels (TRL) of individual component technologies (wires, solar panels, electron gun, and satellite bus) are generally 8 or 9, but, when combined, the overall system has a TRL of 2/3, due to the uniqueness of the system-level integration and operation as a *system*. An estimate of the TRL for each major subsystem is seen in Table 1. This list was compiled to identify critical systems and components that require immediate resources to increase the TRL of the total system to TRL 3 or 4.

Table 1. The primary E-Sail subsystems are all TRL-3 or greater.

Subsystem	TRL
GN&C / System dynamics	3
Thrust vector control	3
Tether Deployment	3
Plasma Acceleration / Charge Control	3
High Voltage Switching	3/4
Electron Emitter	4
High Voltage Power Supply	4
New Tether Materials State of Art (SOA) Tethers	4/5
Command, Control & Comm. (NEA Scout Heritage)	7+
Power Generation	7

3. E-Sail Propulsion: The Tethers

3.1 Wire Concept

3.1.1 Strength and Conductivity

The wire structures for the E-Sail are conductive wires or conductive fibers deployed from the spacecraft. A multi-kilovolt positive bias potential is applied to the wires so as to create a large electrostatic plasma sheath around the wires that deflects solar wind protons, thereby generating a thrust force on the wire. The positively biased wires will collect electrons from the solar wind plasma, and therefore they must provide sufficient conductivity to conduct the electrons to the central spacecraft with a minimal potential drop, so that the outer portions of the wires remain biased at a multi-kV potential with respect to the solar wind plasma. The wires must also have sufficient tensile strength to support both the electrostatic thrust and the centrifugal forces on the wire due to rotation of the system. The thrust achievable by the E-Sail scales proportionally with the wire structure's tensile strength [4]. Although the desires for conductivity and strength argue for large-diameter wires, these drivers must be balanced with minimizing the mass of the E-Sail, as well as with minimizing the power required to sustain the bias voltage. Because the thrust generated scales only very weakly with conductor diameter, while the bias power required scales with the wire diameter and the mass scales with the square of the diameter, maximizing system performance requires using the minimum possible wire diameter with a material that provides the best balance between conductivity and strength.

3.1.2 Micrometeoroid Survivability

Additionally, these multi-kilometer-long wire structures will be exposed to the interplanetary micrometeoroid environment, and impacts with these hypervelocity particles will cause cuts in the wires. A preliminary analysis of the survival probability for the wire structures, discussed in 3.1.4, indicates that a multi-line structure with multiple redundancies, such as the Hoytether structure, is necessary for missions of any significant duration. For multi-kilometer wires required to provide high survival probability for multi-year durations, this survivability requirement will drive the wire mass decision more so than the conductivity requirements.

3.1.3 Material

Table 2 compares the characteristics of several candidate conductor materials. These materials all provide sufficiently low resistivity to keep voltage drops along the wire to less than a percent of the applied bias voltage. The current collected by the biased wires and the commensurate bias power requirements scale with the diameter of the wire. Of the available materials, Amberstrand (metalized Zylon fiber) provides the highest strength-per-weight and more than adequate conductivity. It also has significantly better flexibility than aluminum or copper wire. However, the smallest Amberstrand yarn size (66 filaments) has a larger diameter than desirable for E-Sail applications. It may be possible to acquire a custom Amberstrand yarn that has fewer filaments, albeit likely at higher cost than the COTS configuration. Between the two metal wire options, aluminum provides better conductivity per mass, but copper provides superior conductivity per volume. Additionally, copper is much easier and less expensive to draw to very fine diameters, and fine copper wires are significantly more robust than fine aluminum wires.

Table 2. E-Sail tether material candidates.

	Amberstrand		CNT yarn		Aluminum	Copper
Filament count, or wire size	66	166	1	4	35 ga	35ga
Diameter (µm)	230	370			142	142
Linear mass (g/km)	56	140	10	24	43	142
Each Wire length (km)	5	5	5	5	5	5
Wire mass (g)	280	700	50	120	260	860
Wire Strength (N)	41	105	15.00	36.00	1.96	8.04
Estimated material cost ($/km)	1300	1704	10000	25000	600	800
Est. Packed Volume @ 10 wires (cc)	140	350	125	300	961	961
Resistivity (ohms/m)	9	3	160	70	1.77	1.08

The thrust achievable by the E-Sail scales proportionally with the tensile strength of the wire, making Amberstrand 66 the optimal choice, providing 20x the strength of 35-gauge aluminum, with only 30% higher linear mass.

3.1.4 Wire Structure Design and Survivability

Ensuring that the wire structures will have a high probability of surviving the micrometeoroid environment for multi-year durations will require a structure with multiple interconnected lines for redundancy, such as a Hoytether structure [5]. A Hoytether structure is composed of one or more 'primary lines' running the longitudinal length of the structure, which are periodically interconnected by 'secondary lines' using knotless connections. The periodic interconnections provide multiple redundant paths to carry loads and currents around strands that suffer cuts due to micrometeoroid impacts. Seppänen has demonstrated automated manufacture of kilometer-scale Hoytether structures composed of fine aluminum wires [6].

4. E-Sail Propulsion: Tether Deployment

4.1 Deployment Model

The system for deploying the E-Sail must be capable of extending a very large (diameter of multiple kilometers), extremely gossamer structure composed of multiple very thin wires. To keep the wires oriented perpendicular to the solar wind direction, it is necessary to set the system into rotation, so as to provide centrifugal forces to keep the wire structures in tension, countering the solar wind force trying to blow the wires 'behind' the spacecraft. Fig. 3 illustrates the notional basic configuration concept for the E-Sail.

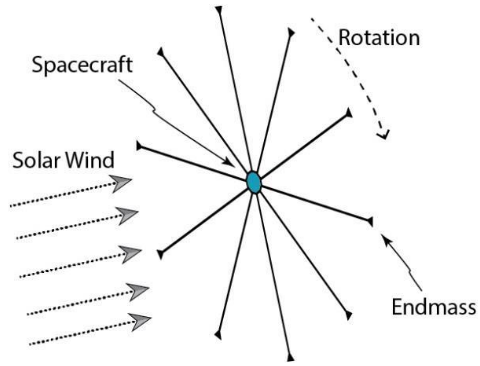

Fig. 3. Notional E-Sail concept configuration.

4.2 Basic Deployment Concept of Operations

This basic concept configuration, however, presents two significant technical challenges. To ensure the wires stay aligned mostly perpendicular to the solar wind (rather than being blown behind the spacecraft), the centrifugal tension on the wire should be roughly a factor of five times the solar wind force. This requires a spin rate on the order of once per hour, which, while slow, requires that the system provide a very large amount of angular momentum to the E-Sail structure. For a multi-kilometer wire length, a simple deployment scheme where the spacecraft is first spun up and then the wires are allowed to unspool outward under centrifugal force is not viable, because the initial spin rate required to provide the necessary final spin rate once the wires are deployed would be far too fast to be practical.

Second, because the forces on the individual wires are likely to vary depending upon orientation to the solar wind as well as due to local variations in solar wind speed, density, and direction, their rotation rates around the central spacecraft will vary. This means it is necessary to provide a means of ensuring the lines remain separated and do not collide or tangle. Janhunen's original concept [4] proposed the use of continuous controlled variation of each wire's length to maintain constant rotation rates. However, this method introduces significant system complexity and would require the wires to be continually reeled in and out, which may be problematic for a multi-line wire that will experience multiple cuts to its individual lines during its lifetime.

To simplify the concept, Janhunen [4] proposed connecting the ends of each wire line to its two adjacent lines, using non-conducting 'auxiliary wires' strung around the circumference, as illustrated in Fig. 4. At the end of each of the primary wires, a "Remote Unit" sub-satellite would be used to deploy both the main wire and the auxiliary wires. Thrusters on these remote units could accomplish the spin-up of the E-Sail system. While technically feasible, this approach presents several drawbacks. First, deployment and spin-up of the system would require tightly coordinated thrust operations of multiple Remote Units, as well as coordinated operation of all of the wire deployers on the Remote Units. Additionally, the mass of these multiple Remote Units, each with three wire deployers and multiple thrusters, will reduce the thrust-to-mass performance of the E-Sail system. Each remote unit would additionally include a cold gas thruster to enable spin-up and control of the system.

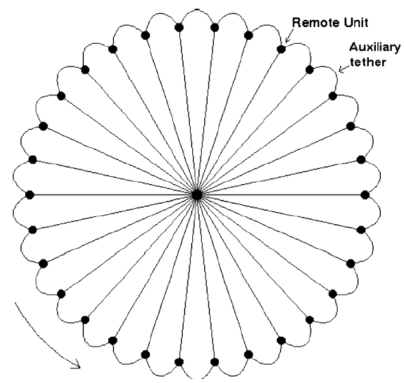

Fig. 4. E-Sail with auxiliary wires to maintain separation between the radial wires.

5. Conclusions

Though still far from being technically mature, the Electrostatic Sail, or E-Sail, propulsion system leverages the use of some high-heritage components and can benefit from the rich history of space tether and in-space antenna deployments. With its potential to provide rapid transit to the outer solar system and beyond with extremely low mass penalty, an E-Sail system merits additional analysis and experimental validation testing, first in the laboratory, and then in space.

Acknowledgements

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References

[1] Quarta, A.A. and G. Mengali, Electric sail mission analysis for outer solar system exploration, J. Guid. Contr. Dyn., 33 (2010) 740-755.

[2] Stone, N. H., The Aerodynamics of Bodies in a Rarefied Ionized Gas With Applications to Spacecraft Environmental Dynamics, NASA Technical Paper 1933, pp 97-102, November 1981.

[3] Janhunen, P.: Electric Sail for Spacecraft Propulsion, J. Propul. Power, 20(4) (2004) 763-764.

[4] Janhunen, P., et al., Invited Article: Electric solar wind sail: Toward test missions," Rev. Sci. Instr. 81, 111301 (2010).
[5] Hoyt, R.P., Forward, R.L., Failure resistant multiline tether, US pat # 6,386,484, May 14, 2002.
[6] Seppänen, et al., "One kilometer (1 km) electric solar wind sail tether produced automatically", AIP Rev. Sci. Instr., 84, 095102 (2013).