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Overview of electric solar wind sail applications

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Abstract. We analyse the potential of the electric solar wind sail for solar system space missions. The applications studied include flyby missions to terrestrial planets (Venus, Mars and Phobos, Mercury) and asteroids, missions based on non-Keplerian orbits (orbits that can be maintained only by applying continuous propulsive force), one-way boosting to the outer solar system, off-Lagrange point space weather forecasting, and low-cost impactor probes for added science value to other missions. We also discuss the generic idea of data clippers (returning large volumes of high-resolution scientific data from distant targets packed in memory chips) and possible exploitation of asteroid resources. Possible orbits were estimated by orbit calculations assuming circular and coplanar orbits for planets. Some particular challenge areas requiring further research work and related to some more ambitious mission scenarios are also identified and discussed.

Key words: advanced propulsion concepts, electric solar wind sail, space plasma physics, solar system space missions.

1. INTRODUCTION

The electric solar wind sail (E-sail) is an advanced concept for spacecraft propulsion, based on momentum transfer from the solar wind plasma stream, intercepted by long and charged tethers [1]. The electrostatic field created by the tethers deflects trajectories of solar wind protons so that their flow-aligned momentum component decreases. The flow-aligned momentum lost by the protons is transferred to the charged tether by a Coulomb force (the charged tether is pulled by the plasma charge separation electric field) and then transmitted to the spacecraft as thrust. The concept is attractive for applications because no propellant is needed for travelling over long distances. The E-sail's operating principle is different from other propellantless propulsion technologies such as the solar photon sail [2] and the solar wind magnetic sail. The former is based on momentum transfer from sunlight (solar photons), while the latter is based on a large loop-shaped superconductive

wire whose magnetic field deflects solar wind protons from their originally straight trajectories [3].

The main purpose of this article is to analyse the potential of E-sail technology in some of the envisaged possible applications for solar system space activities. To a limited extent we also adopt a comparative approach, estimating the added value and other advantages stemming from E-sail technology in comparison with present chemical and electric propulsion systems and (in some cases) with other propellantless propulsion concepts. When making such comparisons a key quantity that we use for representing the mission cost is the total required velocity change, Δv, also called delta-v.

The Sail Propulsion Working Group, a joint working group between the Navigation Guidance and Control Section and the Electric Propulsion Section of the European Space Agency, has envisaged the study of three reference missions which could be successfully carried out using propellantless propulsion concepts. In particular, in the frame of the Working Group, the

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following reference missions are studied: mission to asteroids, mission to high inclination near-Sun orbits (for solar polar observation), and a mission requiring non-Keplerian orbits, i.e. orbits which can be maintained only by applying continuous propulsive thrust. The possibility of applying the E-sail technology to these missions is also discussed in this paper.

Currently, the demonstration mission ESTCube-1 is being developed by the University of Tartu to provide a practical proof of the E-sail concept in a low Earth orbit (LEO) [4]. In LEO the E-sail would sense a plasma stream moving at a relative velocity of ∼ 7 km/s which is much slower than in the solar wind (300–800 km/s), but at the same time with much higher plasma density (about 10^{10}–10^{11} m^{-3} versus about 5×10^6 m^{-3} in the solar wind). After the LEO demonstration of ESTCube-1 it is important to carry out a mission in the free-streaming solar wind outside the Earth's magnetosphere in order to fully demonstrate the feasibility of the E-sail concept. One possibility for such a solar wind test mission could be a six-unit (6U) CubeSat based on ESTCube-1 1U heritage, but launched to a geostationary transfer orbit and then raised to a solar wind intersecting orbit by an onboard butane cold gas thruster.

The related concept of electrostatic plasma brake for deorbiting a satellite [5] is only briefly touched upon in Section 3, otherwise it is left out of the scope of this paper.

2. MATHEMATICAL BACKGROUND

The orbital calculations presented in this paper are based on assuming circular and coplanar planetary orbits. For a semi-quantitative discussion this approximation is sufficient, although some care is needed with Mercury whose eccentricity is rather significant.

For computing impulsive propulsion Δv values for orbital changes we use the so-called vis-viva equation which is valid for elliptical Keplerian orbits,

$$v = \sqrt{GM\left(\frac{2}{r} - \frac{2}{r_1 + r_2}\right)}. \tag{1}$$

Here G is Newton's constant of gravity, M is the mass of the central object, r_1 is the orbit's perigee distance, r_2 is the apogee distance, r is the instantaneous radial distance within the orbit ($r_1 \leq r \leq r_2$), and v is the orbital speed at r.

When an impulsive chemical burn is performed within the gravity well of a massive body, the orbital energy changes more than in free space far from massive bodies. This so-called Oberth effect is central to orbital dynamics and it is a direct consequence of the conservation of energy. For example, assume that a spacecraft is in a parabolic (marginally bound or marginally escaping) orbit around a planet and that it makes an impulsive burn of magnitude Δv at distance r

from the planet's centre along its instantaneous orbital velocity vector so that the spacecraft is ejected out from the planet with hyperbolic excess speed v. If the spacecraft is in a parabolic (zero total energy) orbit with respect to a central body of mass M, its orbital speed at distance r from the body is equal to the local escape speed

$$v_e = \sqrt{\frac{2GM}{r}}, \tag{2}$$

as can also be deduced from Eq. (1) by setting $r_2 = \infty$. After the impulsive burn we obtain by energy conservation

$$\frac{1}{2}v^2 = \frac{1}{2}(v_e + \Delta v)^2 - \frac{GM}{r}. \tag{3}$$

Solving for the resulting hyperbolic excess speed v, we obtain

$$v = \sqrt{(\Delta v)^2 + 2v_e \Delta v}. \tag{4}$$

Conversely, if we need to find the magnitude of the burn Δv which yields a given hyperbolic excess speed v, the answer is

$$\Delta v = \sqrt{v^2 + v_e^2} - v_e. \tag{5}$$

For example, if a spacecraft is in a parabolic Earth orbit, it needs a heliocentric Δv of 3 km/s to enter a Mars transfer orbit. To accomplish this requires a near-Earth burn of only 0.4 km/s magnitude. For a heavy object such as Jupiter whose escape speed is 60 km/s the effect is even larger: a burn of 0.4 km/s made on a parabolic orbit near Jupiter gives a heliocentric Δv of 7 km/s.

Low thrust transfer between circular orbits needs a Δv which is simply equal to the difference of the orbital speeds. Thus, slowly spiralling out from LEO to escape, e.g., by electric propulsion requires a total Δv of 7.7 km/s, although the same task done with an impulsive near-Earth burn needs only 3.2 km/s. While proceeding via an elliptical orbit would make the low thrust Δv somewhat smaller than 7.7 km/s, doing so would necessitate turning the thruster off part of the time, which might be wise in case of electric propulsion, but not necessarily wise in case of the E-sail where propellant consumption is not an issue. Similar considerations hold for a transfer between heliocentric orbits if the transfer is slow. Thus, a low thrust propulsion system generally needs to have a higher specific impulse than an impulsive method to provide practical benefits. The electric sail fulfills this requirement nicely because being a propellantless method, its specific impulse is infinite.

3. E-SAIL PERFORMANCE AND OTHER PROPERTIES

Performance estimates of the E-sail are based on numerical simulation [1,6,7] and semiempirical theory derived from them [6,8]. In laboratory conditions mimicking LEO plasma ram flow, the electron sheath shape and width were measured by [9] and one can

calculate that the result is in good agreement with theoretical formulas given by [6].

Mass budgets of E-sails of various thrust levels and for different scientific payload masses were estimated and tabulated by [10]. For example, to yield characteristic acceleration (E-sail thrust divided by total spacecraft mass at 1 au distance from the Sun in average solar wind) of 1 mm/s^2, the spacecraft total mass was found to be 391 kg (including the 20% margin), of which 143 kg is formed by the E-sail propulsion system consisting of 44 tethers of 15.3 km length each. Characteristic acceleration of 1 mm/s^2 corresponds to 31.5 km/s of Δv capability per year.

Outside the Earth's magnetosphere, the E-sail can provide propulsive thrust almost everywhere in the solar system. The only restrictions are that the thrust direction cannot be changed by more than about $\pm 30^o$ and that inside giant planet magnetospheres special considerations are needed. The E-sail thrust magnitude decays as $\sim 1/r$, where r is the solar distance. Notice that the E-sail thrust decays slower than the photonic sail and solar electric propulsion thrust because the latter ones decay as $1/r^2$. The reason is that while the solar wind dynamic pressure decays as $1/r^2$, the effective area of the sail is proportional to the electron sheath width surrounding the tethers, which scales similarly to the plasma Debye length that in the solar wind scales as $\sim r$. Since the E-sail thrust is proportional to the product of the dynamic pressure and the effective sail area, it scales as $1/r$.

The solar wind is highly variable and at first sight one might think that this would set restrictions to applying the solar wind as a thrust source for space missions. However, if the electron gun voltage is controlled in flight so as to produce maximal thrust with available electric power, the resulting E-sail thrust varies much less than the solar wind dynamic pressure and accurate navigation is possible [11].

As mentioned above, by inclining the sail the thrust direction can be modified by up to $\sim 30^o$. This makes it possible to spiral inwards or outwards in the solar system by tilting the sail in the appropriate direction to decrease or increase the heliocentric orbital speed, respectively. Thus, even though the radial component of the E-sail thrust vector is always positive, one can still use the system also to tack towards the Sun. A similar tacking procedure is possible also with photonic sails. Unlike most photon sails, the E-sail thrust can be throttled at will between zero and some maximum by controlling the power of the electron gun.

4. E-SAIL APPLICATIONS

The number of potential E-sail applications is large. Here we use a categorization into five main groups: (1) asteroid and terrestrial planets, (2) non-Keplerian orbits (e.g., off-Lagrange point solar wind monitoring to achieve longer warning time for space weather forecasts), (3) near-Sun missions, (4) one-way boosting to the outer solar system, and (5) general ideas for impactors or penetrators, "data clippers" carrying data as payload and in situ resource utilization.

The E-sail needs to be raised beyond the Earth's magnetosphere before it can generate propulsive thrust. The position of the magnetosphere boundary (magnetopause) varies according to solar wind dynamic pressure, but resides on average at $\sim 10\ R_E$ in the dayside and much farther in the nightside (here R_E is the Earth's radius 6371.2 km). Lifting the orbital apogee to 20 R_E requires a 2.9 km/s impulsive boost from LEO assuming a 300 km initial altitude, while lifting to the Moon distance (60 R_E) requires 3.1 km/s and marginally escaping from the Earth–Moon system 3.2 km/s. One could in principle start an E-sail mission from a 20 R_E apogee Sun-oriented elliptical orbit, but it would necessitate some 1–2 km/s of E-sail thrustings near the apogee to raise the nightside orbit from LEO to 20 R_E and beyond. Because the E-sail is about fast travel in the solar system, one typically wants to start the mission fast. Therefore in this paper we adopt 3.2 km/s (injection from LEO to a marginal Earth escape orbit) as the size of the impulsive chemical burn that must be made at LEO to start an E-sail mission. The altitude and inclination of the LEO orbit are not essential because once the E-sail has reached the solar wind, it can correct its course. Also, multiple E-sail probes targeted to different destinations can share the same launcher to the initial escape orbit.

The E-sail needs the solar wind or other fast plasma stream to work. Therefore the E-sail cannot in practice be used inside the Earth's magnetosphere where the plasma generally does not stream rapidly. An exception to this limitation is that one can use an E-sail like apparatus for plasma braking in LEO [5], utilizing the ~ 7 km/s speed difference between the orbiting satellite and nearly stationary ionosphere and the fact that the plasma density in LEO is high so that the process is relatively efficient even though the speed difference is much less than the solar wind speed of 400–800 km/s. In giant planet magnetospheres the plasma corotates rapidly with the planet, which might enable some form of E-sailing also inside giant planet magnetospheres; this question should be addressed in future studies. Mars and Venus have no magnetospheres, thus only some modifications to E-sail propulsion are imposed by the existence of the plasma wake around those planets. Mercury has a weak and small magnetosphere, so E-sailing can be in general used, although not necessarily down to the lowest orbits. We remark that the E-sail can obviously fly through magnetospheres without limitations, only its ability to generate propulsive thrust inside those regions is limited or absent, depending on the case as described above.

When manoeuvring around planets, the capability of the E-sail tether rig to tolerate eclipse periods should be analysed on a case by case basis. Depending on the orbit's geometry and on the planet's atmosphere and surface properties, the long E-sail tethers may experience significant contraction due to rapid cooling

if the spacecraft flies into eclipse, and corresponding elongation takes place when the eclipse period ends. If thermal contraction of the tethers is rapid, it might cause harmful dynamical oscillations of the tether rig. In this paper we do not take such possible restrictions into account, but assume that E-sails can operate around planets either by avoiding eclipses or by having the tether rig engineered so as to tolerate the effects of thermal contraction.

As mentioned in Section 2, the E-sail performance has been estimated and tabulated earlier in various configurations [10]. The obtainable performance (characteristic acceleration) depends on how large fraction the E-sail propulsion system forms of the spacecraft total mass. There is also a practical upper limit of E-sail size beyond which complexity would increase and performance would drop. At the present level of technology this soft limit is likely to be $\sim$ 1 N thrust at 1 au solar distance. For small and moderate payloads up to a few hundred kilograms of mass, high performance is typically available, of order 1 mm/s^2 characteristic acceleration corresponding to $\sim$ 30 km/s of Δv capability per year. The numbers must be scaled by $1/r$ when going beyond 1 au.

In the following subsections we survey various solar system applications for the E-sail. In each case, we discuss how much chemical Δv could be saved by using the E-sail. In some cases we also make comparisons with electric propulsion (ion engines, Hall thrusters, and other low thrust electric rocket devices).

4.1. Terrestrial planets and asteroids

4.1.1. Venus

Venus is the closest planet and the easiest to access in the Δv sense by impulsive kicks. An injection from a marginal Earth escape orbit to a Venus transfer orbit requires a 0.3 km/s near-Earth kick and capturing from the Venus transfer orbit to a high Venus orbit requires 0.4 km/s near Venus. If the target is a low Venus orbit, orbit lowering needs additional 3.0 km/s or alternatively propellantless gradual aerobraking. An E-sail could do any or all of these manoeuvres with no propellant consumption. The transfer time is slightly longer but comparable to impulsive kick Hohmann transfer [12]. For example, if the target is a low Venus orbit, using the E-sail would save 0.7 km/s impulsive burns and make an aerobraking device unnecessary, typically with comparable transfer times.

4.1.2. Mars and Phobos

For Mars, the injection from a marginal Earth escape orbit to a Mars transfer orbit requires a 0.4 km/s perigee burn and settling from the transfer orbit to a high Mars orbit another 0.7 km/s. Reaching a low Mars orbit needs

additional impulsive 1.4 km/s or aerobraking. Thus, getting a spacecraft to a low Mars orbit with an E-sail would save 1.1 km/s of impulsive Δv and make aerobraking unnecessary.

If one wants to rendezvous with Phobos (6000 km orbital altitude), aerobraking is less attractive because it would necessitate a 0.5 km/s circularizing burn to raise the perigee back up from the atmosphere. Without aerobraking, Phobos rendezvous impulsive Δv distance from a high Mars orbit is about 1 km/s.

A Phobos sample return mission therefore requires a total impulsive Δv of 2.1 km/s for landing on Phobos and another 1.7 km/s for the return trip, if a high-speed hyperbolic Earth reentry is tolerated by the sample capsule. In Phobos sample return, an E-sail would save 3.8 km/s of impulsive Δv and enable a lighter Earth reentry shield because reentry could occur from a marginal Earth escape orbit without hyperbolic excess speed. Saving 3.8 km/s of Δv is equivalent to saving about 2/3 of the initial mass if bipropellant hydrazine with 3.4 km/s specific impulse is employed. One also saves the mass of the tanks and rocket engine, but on the other hand, must include the E-sail. Roughly speaking, we expect these mass items to be of comparable magnitude, so to a first approximation one can say that the chemical propellant mass is saved.

One could also travel to Mars or Phobos by electric propulsion. However, the total Δv then becomes larger because the Oberth effect is no longer utilized. The Δv from a marginal Earth escape to a high Mars orbit is then equal to the Earth–Mars orbital speed difference 5.7 km/s and rendezvous with Phobos needs a further 2.1 km/s. The total Δv for a Phobos sample return using electric propulsion is then 15.6 km/s. For example, with a typical 3000 s specific impulse Hall thruster the xenon propellant fraction would then be 40%. Including the mass of the required high-power electric power system and solar panels would probably increase the initial mass near the chemical propulsion value. Indeed, the Russian Phobos–Grunt sample return mission which recently failed in the Earth orbit did not use electric propulsion but hydrazine.

The E-sail must produce the same total Δv as electric propulsion (or larger, because the controllability of the E-sail thrust direction is more limited). However, being propellantless and needing only modest electric power, the E-sail can deliver such high Δv without increasing the initial mass. The operability of the E-sail in the vicinity of Mars has not been analysed in detail yet. Expectedly the planet's plasma tail modifies the E-sail effect in the nightside, but likely this does not change the above results qualitatively. Because Mars does not have a strong intrinsic magnetic field, its plasma environment is compact, not much wider than the planet itself.

4.1.3. Mercury

Mercury is difficult to reach because it resides deep in Sun's gravity well and because its low mass provides

only a rather weak Oberth effect to assist capture by impulsive propulsion. Mercury probes have therefore made use of one or more gravity assist manoeuvres with Venus, Earth, and Mercury itself, resulting in long transfer times. Despite its small dimension and long rotation period, Mercury has a global, approximately dipolar magnetic field. The magnetopause is located between 1000 and 2000 km from the planet's surface (on average at 1.4 R_M, but might even touch the planet when the solar wind dynamic pressure is high). The strength of the field is small compared to the Earth and is ~ 300 nT at the equator.

The newest mission under construction, BepiColombo, will spend more than six years in transfer, although it makes use of both chemical propulsion and ion engines. In comparison, the E-sail could take a probe to Mercury rendezvous (high planetary orbit) in less than one year with no gravity assists [12]. Furthermore, it could accomplish a return trip in the same time without extra mass. Figure 1 shows a scenario for returning a sample from Mercury using a single E-sail in the following way: (1) the E-sail flies to Mercury and settles to orbit the planet; (2) a lander separates and lands on the surface by retrorockets; (3) the lander picks up a sample and puts it in a small capsule which is mounted on a small return rocket that was part of the lander payload; (4) the return rocket lifts off to Mercury's orbit where it jettisons the capsule which also contains a radio beacon; (5) the E-sail mother spacecraft locates the beacon signal and adjusts its orbit to rendezvous with the sample capsule. In the approach phase cold gas thrusters are used for fine-tuning the orbit. The capsule is picked up by a catcher and is moved inside an Earth reentry shield inside the mother spacecraft. Then the E-sail takes the mother spacecraft back to a nearly parabolic Earth orbit, the reentry capsule separates and returns to the Earth with the sample.

The presently developed aluminium E-sail tethers do not necessarily tolerate the high temperature encountered on a Mercury mission unless coated by a well emitting layer to assist cooling. Alternatively, aluminium could be replaced by much more heat tolerant copper. A similar ultrasonic bonding process to what we use with aluminium is possible with copper as well.

4.1.4. Asteroids

Asteroids are targets where high Δv's produced by the E-sail can be uniquely useful because being lightweight targets, asteroids provide essentially no Oberth effect to assist a capture by impulsive chemical propulsion if a rendezvous is desired. Many asteroids are essentially beyond reach for rendezvous by chemical propulsion and challenging to reach by electric propulsion. Using E-sails to reach all potentially hazardous asteroids was studied recently in [13]. The E-sail would enable multi-asteroid touring type missions where asteroids are studied in flyby and/or rendezvous modes. With the

propellantless E-sail, the only limit to mission duration and the number of asteroids studied is set by the durability of the equipment.

Asteroids are not only interesting scientifically, but also because of the impact threat, asteroid resource utilization, and as potential targets for manned exploration that need to be mapped beforehand. The E-sail's very high lifetime-integrated total impulse per mass unit could even be used to tow an Earth-threatening asteroid away from the Earth's path [14]. As an order of magnitude estimate, the baseline 1 N E-sail could tug a 150 m asteroid away from the Earth's path in seven years [14]. There is clearly a need for some further research to find out how to best attach the E-sail to asteroids of different shapes and rotation states.

In addition to deflecting a large asteroid, returning a small asteroid to the Earth's orbit for scientific study has also been proposed using electric propulsion [15]. In the mission envisaged in [15], a solar electric propulsion system is used to escape from the Earth's orbit and to rendezvous with a near-Earth object. The first phase of the mission is then devoted to the determination of the asteroid's trajectory and spin. The spacecraft must reach the same rotation speed as the asteroid, capture it, and let both masses slow down to rest. The asteroid can then be moved to another trajectory or brought to the Earth's orbit. The E-sail could be used for this kind of "extended sample return" application as well, with the advantage of saving propellant during the time needed to deflect the asteroid (depending on the asteroid mass this period can last several years).

4.2. Maintaining non-Keplerian orbits

The propellantless thrust of an E-sail can be used to maintain a non-Keplerian orbit, i.e. an orbit whose maintenance requires continuous propulsive thrust [16]. Such orbits enable a number of qualitatively new applications, examples of which are discussed next.

4.2.1. Helioseismology from a lifted orbit

The spacecraft could orbit the Sun similarly to the Earth, but in an orbit which is lifted above the ecliptic plane [16]. From such orbit one would have a continuous view to the polar region of the Sun, enabling, e.g., a long time scale uninterrupted helioseismological coverage.

4.2.2. Remote sensing of the Earth and Earth's environment

There are several conceivable E-sail orbits for remote sensing of the Earth or Earth's environment. For example, so-called mini moons are small asteroids that are temporarily captured by the Earth's gravity field. The mini moons are interesting, e.g., because they could be studied by a variety of astronomical instruments from the Earth at a much closer range than typical asteroids [17].
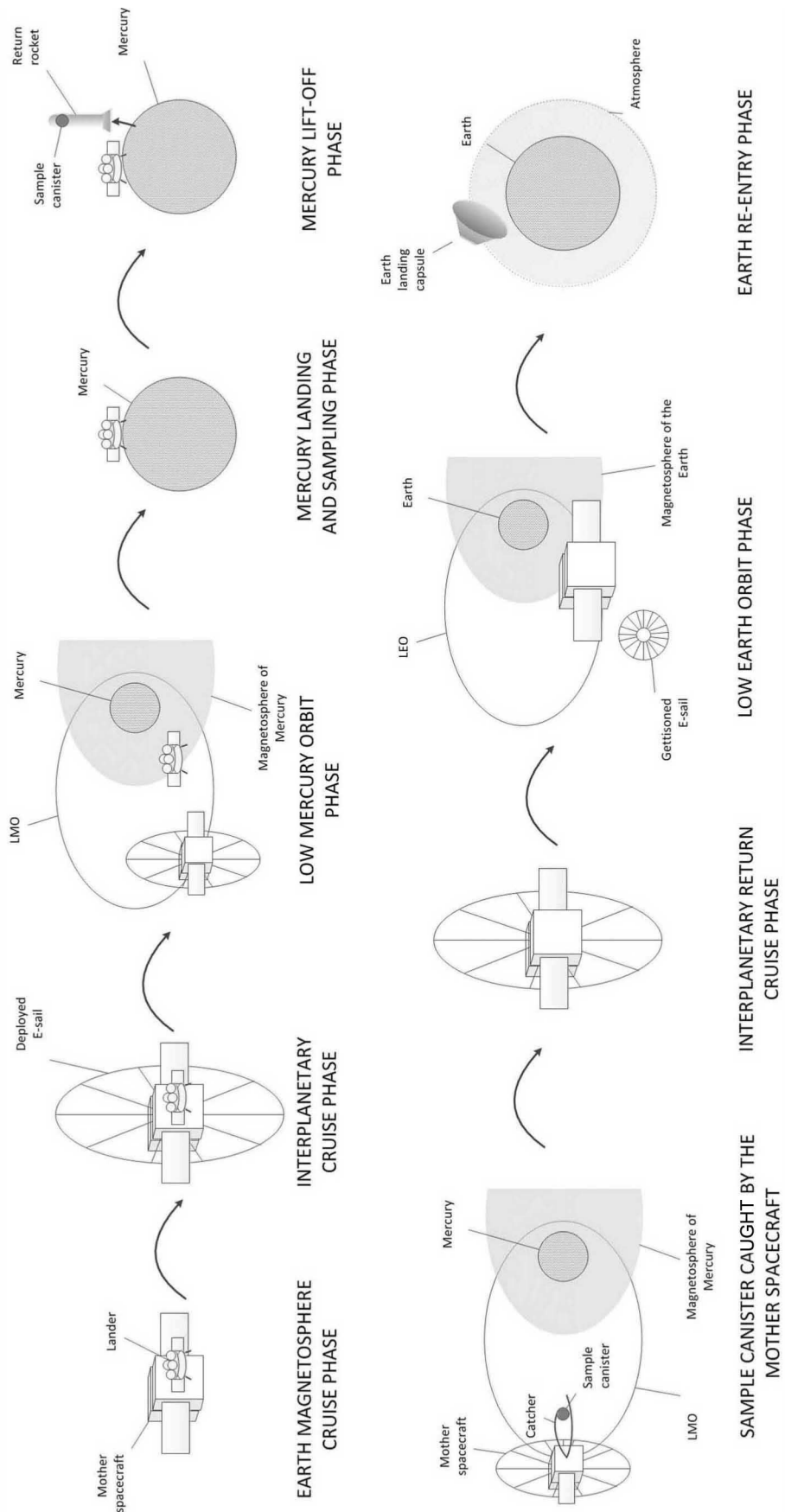
Fig. 1. Mercury sample return with a single E-sail (see text). The E-sail in relation to the main spacecraft is not drawn to scale.

Mini moons typically enter the Earth system near one of the Earth–Sun Lagrange points. Their entry could be monitored by a spacecraft located on the sunward side of the Lagrange L1 point, so that the mini moons would be visible to the spacecraft's telescope at maximum solar illumination.

Several non-Keplerian orbits for Earth remote sensing, especially for polar areas, have been investigated for solar photon sails and electric propulsion, including figure eight-shaped nightside orbits, polar sitter orbits, and non-Keplerian Molniya-type trajectories [18]. Many of the investigated orbits would also suit the E-sail which can generally produce more thrust than other low thrust methods. The E-sail can provide higher thrust than an equal mass photonic sail. The chief limitation of the E-sail in this context is its inability to produce thrust inside the magnetosphere where there is no solar wind.

4.2.3. Giant planet auroras

A planetary example of a non-Keplerian mission would be a spacecraft which is lifted above the Jupiter–Sun Lagrange L1 point so that it has a continuous view of Jupiter's north pole while being immersed in the solar wind and can monitor it. The scientific application would be to study to what extent Jupiter's auroras are driven by solar wind changes. A traditional way of reaching this science goal would be to have several spacecraft: one at the Jupiter–Sun Lagrange point for measuring the solar wind and additional ones in a polar Jupiter orbit for measuring the auroras continuously (since a single orbiter would not be enough for continuous coverage of one of the poles). Furthermore, in the traditional mission architecture the orbiters would have to be radiation hardened to survive in the intense Jovian radiation belts.

4.2.4. Monitoring of off-Lagrange point solar wind

Nowadays, short-term forecasting of magnetospheric space weather (magnetic storms) relies on continuously monitoring the solar wind plasma density, plasma velocity, and interplanetary magnetic field (IMF) at the Earth–Sun Lagrange L1 point, by satellites such as ACE and SOHO. Because it takes about 1 h for the solar wind to travel from the Lagrange L1 point to the magnetospheric nose, such monitoring can give about 1 h of warning time for preparing to the radiation belt enhancement, geomagnetically induced current, and other possible adverse effects of magnetic storms. With its ability to generate continuous thrust without consuming propellant, the E-sail could be used to "hang" a spacecraft against the gravity field of the Sun on the sunward side of the Lagrange point, for example at twice the distance from the Earth than the Lagrange point so that the warning time would be 2 h instead of 1 h.

The high electric field of active E-sail tethers tends to disturb plasma measurement and the current of the electron gun might disturb the IMF measurement. In the context of solar wind monitoring, many approaches are possible towards overcoming these problems. A straightforward approach is to alternate the propulsive and measurement phases in (say) 10 min succession. This works if the resulting data gaps are tolerated and if the E-sail can reach its full thrust within the chosen gap duration. Another simple approach is to use two identical spacecraft in nearby orbits, which together can produce a continuous realtime measurement of the solar wind. The third option is to deploy the plasma measurement package with a non-conducting ~ 500 m long tether from the E-sail mother spacecraft so that the instruments are far from the influences of the E-sail. Even when the E-sail is operating, the solar wind density can be estimated by a simple omnidirectional onboard electron detector which observes the thermal electron flux accelerated by the voltage. The solar wind dynamic pressure might also be possible to deduce from the produced thrust versus employed voltage, and the IMF measurement might be possible despite the electron gun's influence using a 5–10 m long fixed boom. In a full-scale mission the electron gun current is maximally ~ 50 mA. By the Biot–Savart law, the magnetic perturbation of such current at 10 m distance is no more than 1 nT, which is smaller than a typical IMF at 1 au of ~ 10 nT.

4.3. Near-Sun missions

The E-sail may also be successfully used to drive the spacecraft to the vicinity of the Sun. Depending on the target orbit, this type of mission can be highly demanding in terms of Δv, thus opening an opportunity for the E-sail. As an example, for missions to near-Sun high-inclination orbits, such as the Solar Orbiter (SOLO), the cost related only to the orbit change manoeuvre would be at least 15 km/s for reaching an inclination of 40° [19], a high price for either a chemical or electric propulsion system.

When operating the E-sail towards the inner solar system, the thrust produced would increase inversely proportional to the distance from the Sun, providing increased performances with respect to the nominal E-sail operation at 1 au distance. To realize this thrust increase, the power consumption of the electron gun increases as the inverse square of the distance, i.e. in the same way as the solar radiation flux available to the solar panels. Since the efficiency of solar panels typically gets degraded at high temperature, finding enough electric power near the Sun to run the E-sail at full voltage may produce some technical challenges.

Due to the significant increase in temperature when cruising towards the Sun, similar considerations on the material of the E-sail as those made for the mission to Mercury may be applied (e.g., replacing aluminium tethers by copper tethers having a significantly higher tolerance for elevated temperature).

4.4. Boosting to the outer solar system

The E-sail can be used as a "booster" for missions going to Jupiter or beyond. This can be done so that the E-sail operational phase is limited to, e.g., the 0.9–4 au solar distance range where the E-sail hardware currently being prototyped is designed to operate. Thus, even though the mission payload may require a nuclear power source if it goes beyond Jupiter, the E-sail booster device can be solar powered and not even need modifications of our present E-sail component prototype specifications. Alternatively, a moderate extension of the radial distance range to, e.g., 0.9–8 au would increase the E-sail performance in beyond-Saturn missions and still be solar powered. If a nuclear power source is included onboard because of the needs of the scientific payload, its power output could be used also by the E-sail at large solar distances for somewhat increased performance. Essentially, the E-sail provides a faster and lower mass replacement for the inner planet gravity assist sequences which are used by most of the present-day outer solar system missions. An additional benefit of the E-sail is more frequent launch windows since planetary gravity assist manoeuvres as typically not used.

Potential targets for outer solar system missions include the giant planets Jupiter, Saturn, Uranus, and Neptune and their moons, Jupiter Trojan asteroids, Centaur objects, Kuiper belt objects, and beyond-heliosphere interstellar space. The giant planets provide a large enough Oberth effect to enable capture by modest-sized impulsive chemical burn followed by E-sail boosting. The small outer solar system objects such as Kuiper belt and Centaur objects provide no such capability and for them the E-sail can feasibly provide only flyby types of missions.

For example, the isotope ratios of noble and other gases in the atmospheres of the giant planets are well known only for Jupiter, because of the successful measurements by the Galileo entry probe. One could launch four E-sail equipped spacecraft, each targeted to a different giant planet, to release an entry probe near the planet (Fig. 2). The entry probe would make a high-speed atmospheric entry and then float downwards, sending data to the mother spacecraft which later sends it to the Earth. The Jupiter Galileo probe already demonstrated successfully a high-speed entry; other giant planets have smaller masses and therefore smaller entry speeds. Because of the large mass of the giant planet, the relatively high hyperbolic incoming speed of a fast E-sail probe (of order 15 km/s, for example) increases the atmospheric entry speed only slightly. For decreased costs the probes sent to the four giant planets might be identical. As with all E-sail spacecraft, any or all of the probes can be launched with any launcher that reaches an escape orbit.

In one-way outer planet missions, the E-sail could act as a plug-in replacement for present systems with no need to redesign the probe and its payload, as long as the probe's mass is not too large (not more than 1–1.5 tonnes, say) that it would be too heavy for an E-sail to carry.

5. IMPACTORS AND DATA CLIPPERS

Without any onboard science instruments, an E-sailer could be used for impacting a heavenly body at a given time, e.g., when another spacecraft is nearby and able to measure the properties of the impact plume by remote sensing. For example, we could collide a small and relatively fast E-sail with Jupiter's moon Europa, for example at the same time when ESA's Jupiter Icy Moon Explorer (JUICE) makes its flyby of the moon around 2030. The high impact speed should guarantee that the impactor's mass vaporizes completely so that there is no concern about contaminating Europa by micro-organisms. The purpose of the E-sail impactor is to increase the scientific output of another mission in a low-cost way.

The E-sail can accomplish a return trip with no propellant consumption which is beneficial for sample return missions. Within the lower-cost mission category, the ability of the E-sail to return could be utilized by "data clippers" [20]: spacecraft that carry into the vicinity of the Earth large volumes of high-resolution scientific data stored in memory. Once in the Earth's vicinity, the data can be downloaded by low-cost ground antennas since the available bandwidth scales as $\sim 1/R^2$, where R is the data transfer distance. The data clipper concept would enable a retrieval of large amounts of data from distant targets by small missions whose total cost has in principle no lower limit. The data clipper can either collect the data by its own instruments or it can download at the target from another perhaps more traditional spacecraft.

6. ASTEROID RESOURCE UTILIZATION

The ability of the E-sail to visit one or many asteroids repeatedly and to carry payloads with very low propulsion system mass fraction and zero propellant consumption would be well suited for mining water and possibly other volatiles on asteroids, making rocket fuels such as liquid hydrogen and oxygen out of them and transporting to orbits where chemical fuels are needed (Fig. 3). A chemical rocket is the only known way of lifting a payload rapidly from LEO to a higher or escape orbit. Thus expectedly there should be a market for asteroid-derived propellants in taking satellites to their orbit.
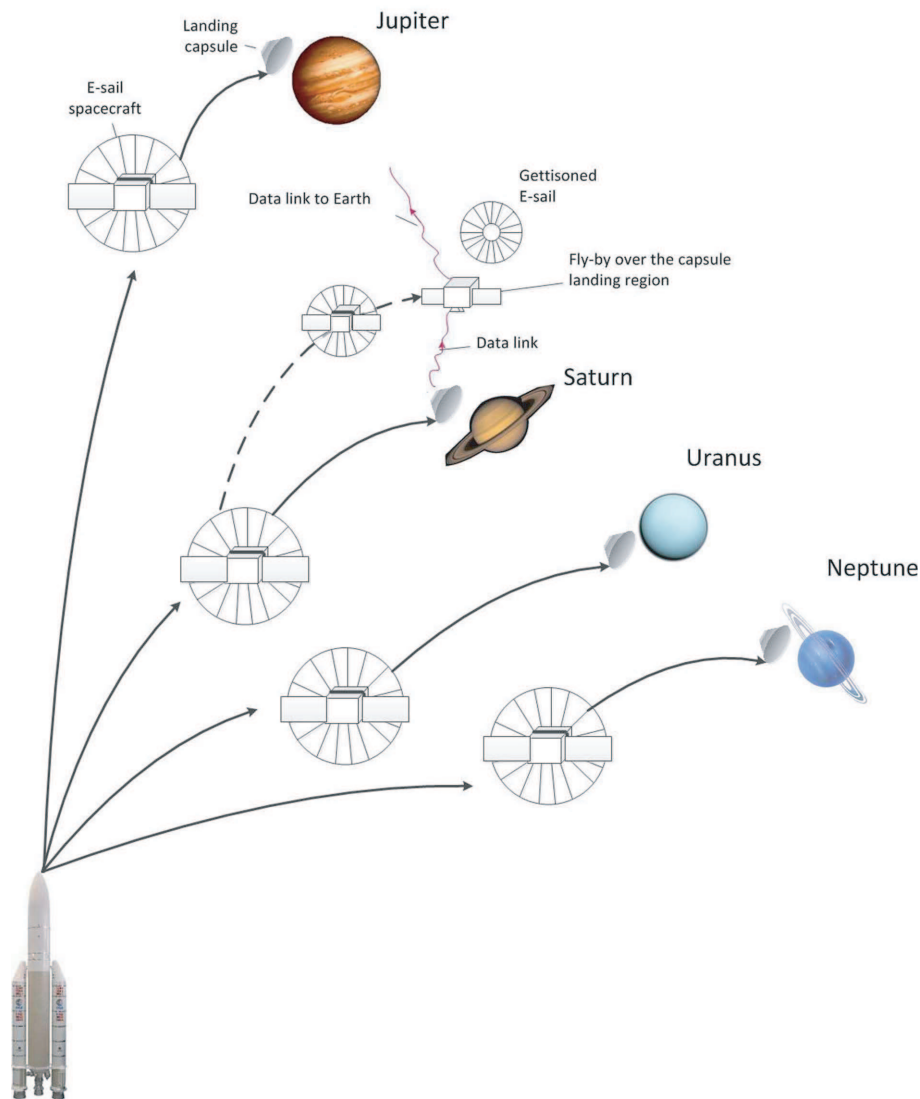
Fig. 2. Scenario for four identical atmospheric probes to all four giant planets by a single launch. For easier visualization, the details of how the data from the atmospheric probe are relayed by the E-sail mother spacecraft which flies by the giant planet are shown only in Saturn's case. Illustrative photos courtesy by Arianespace, ESA, and NASA.

Asteroid-derived propellants could also facilitate manned Mars exploration. If the rocket is refuelled for the return trip in Mars' orbit, the propellant fraction is dramatically decreased and the nuclear thermal rocket option becomes unnecessary. Besides for propellant, manned exploration also needs water for drinking water and breathing oxygen. Although one tends to circulate these substances, the circulation may not be perfect.

Metal asteroids also contain significant concentrations of platinum group metals. These metals may be precious enough to make it economically feasible to mine them on an asteroid and drop to the Earth for direct selling [21]. Ultimately, given enough automation and capital investments, a true space economy could arise where most things in space are built mainly from asteroid- or Moon-derived raw materials and not so much is needed to lift from the Earth.

The E-sail can solve the asteroid transportation problem in an economical and flexible way. Because no propellants are consumed by E-sail transportation, also rocky and metal asteroids can be mined directly without first having to transport the transportation propellant from volatile-rich asteroids, for example.

7. CHALLENGING MISSIONS

In general, the E-sail does not enable a speedy return from the outer solar system, because a pure E-sail return trip would use time which is proportional to the orbiting period of the body from which the return takes place because it depends on Sun's gravity to pull the spacecraft inwards. The orbiting period increases as power 3/2 of the solar distance and varies from 1.9 years for Mars
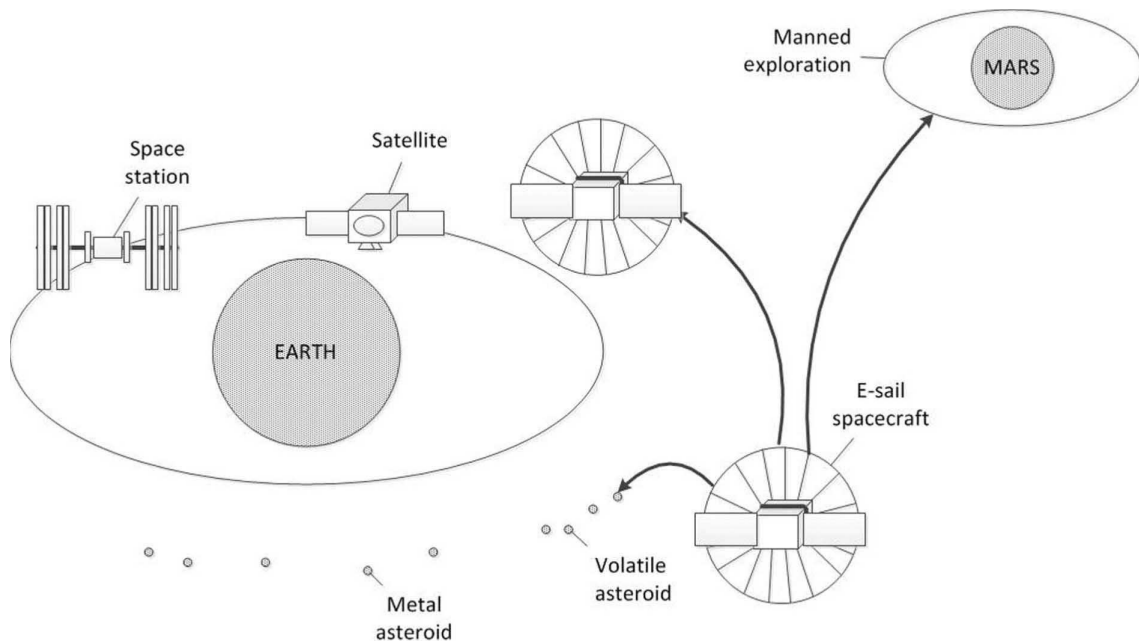
Fig. 3. Asteroid resource utilization. Resources (for example water, other volatiles, metals) are mined at asteroids and the materials are transported by E-sails to serve lifting satellites to a higher orbit and manned exploration of Mars, asteroids, and other bodies (LH2/LOX fuels, oxygen, potable water).

to as much as 165 years for Neptune. The exception is that from a nearly parabolic orbit around one of the four giant planets one can inject the spacecraft at significant speed towards the inner solar system by performing a modest chemical burn near the planet and thus utilizing the Oberth effect. The E-sail can then be used in the inner solar system to direct the probe into Earth rendezvous. Ideally, one would like to use this approach both during the forward and return trips with the same E-sail, but then the challenge is how to make the E-sail tether rig survive the impulsive chemical burn without getting broken or tangled up. A preliminary investigation of the parameters shows that survival of the tether rig is probably possible, although one may need to optimize the mass of the E-sail Remote Units or limit the heliocentric travel speed or allow some increase in the chemical fuel consumption. In principle it might also be possible to rewind the tether rig back to their reels and then reopen them. Before there is some practical experience of using the E-sail in space it may be difficult, however, to assess if such a backreeling procedure could be made reliable enough. Consequently, we are currently not planning to make any missions dependent on such reopening possibility.

If the tether rig survives the orbit insertion and de-insertion chemical burns, this method allows one to get an E-sail spacecraft into a nearly parabolic giant planet orbit and back, using the E-sail in combination with a modest amount of chemical propulsion. To rendezvous with a giant planet moon also requires a significant orbit change away from parabolic and back, however. In principle it might be possible to do this by E-sailing in the giant planet's corotating magnetospheric plasma.

More detailed analyses are needed to investigate the feasibility of E-sail-based giant planet moon sample return missions.

8. CONCLUSIONS

We have given a brief survey of some of the E-sail missions that have been thought of or analysed in more or less detail. Glossing over some details, we summarize the results as follows. The E-sail can be used to make most planetary missions cheaper or faster or both. It really excels in asteroid missions and makes two-way missions feasible (sample return and data clippers). It can also be used as a booster for outer solar system missions. The E-sail is enabling technology for multi-asteroid touring and non-Keplerian orbit missions.

All E-sail missions must start from a near or full escape orbit. Also, any escape orbit is good for any E-sail probe. Hence, E-sails can be piggybacked on other escape orbit launches and E-sails going to different targets can be launched together in any combination.

In the longer run, E-sails might enable economic asteroid resource utilization and asteroid-derived pro-pellant manufacture for satellite orbit raising, for lifting E-sail missions themselves to escape condition and for manned Mars and asteroid exploration.

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Ülevaade elektrilise päikesepurje rakendusvõimalustest kosmosemissioonidel

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Elektrilise päikesepurje tehnoloogia on potentsiaalselt rakendatav meie Päikesesüsteemis kõikidel kosmosemissioonidel. Sõltuvalt missiooni tüübist on elektrilise päikesepurje tehnoloogial selged eelised tavapäraste tõukemootorite

kasutamise ees, kõrge teaduspotentsiaaliga rakendusmissioonid on näiteks möödalennud Maa-sarnastest planeetidest, nende kaaslastest või asteroididest. Samuti võimaldaks elektriline päikesepuri soodsaid ühesuunalisi missioone Päikesesüsteemi välisosadesse ja kosmoseaparaatide hoidmist mittekeplerilistel orbiitidel, st orbiitidel, millel püsimiseks tuleb rakendada pidevat ning ühtlast tõukejõudu. Hoides kosmoselaeva orbiiti Päikesele lähemal kui Lagrange'i L1 punkt, saaks Maad tabavatest ohtlikest kiirgusvoogudest senisest varem ette hoiatada. Elektrilist päikesepurje kasutavad kosmoseaparaadid võimaldaksid täiendada olemasolevate kosmosemissioonide teadusväärtust uuritavaid taevakehi rammides ja seeläbi aineosakesi lähikosmosesse laiali lüües, kus põhimissioon neid mõõta saab. Kaugemal asuvate kosmosemissioonide juurest saaks füüsilistel andmekandjatel – näiteks mälukaartidel – Maale toimetada senisest rohkem kõrge lahutusega mõõtmisandmeid. Elektrilise päikesepurje tehnoloogia avaks võimaluse ka asteroididel leiduvate ressursside kasutamiseks.

Kirjeldatud rakendusmissioonide jaoks on esitatud hinnangulised näidisorbiidid. On analüüsitud ka edasisi tehnoloogilisi väljakutseid ja elektrilise päikesepurje kasutusvõimalusi veel ambitsioonikamatel missioonidel.