Electric
solar
wind
sail

ESAIL D61.1
E-sail mission document

Work Package: **WP 61**
Version: **Version 1.0**

Prepared by: Tartu Observatory, Urmas Kvell
Time: Tõravere, November 26th, 2013
Coordinating person: Urmas Kvell, urmas.kvell@to.ee

(List of participants:)

Participant no.	**Participant organisation**	**Abbrev.**	**Country**
1 (Coordinator)	Finnish Meteorological Institute	FMI	Finland
7	Tartu Observatory	Tartu	Estonia
9	Alta S.p.A.	Alta	Italy

Table of Contents

1. Applicable documents

AD-1: Deliverable D53.2 "Refined design concepts document"

AD-2: Deliverable D62.1 "Orbit calculations supporting WP 6.1"

AD-3: Deliverable D23.1 "Tether space environment requirements"

AD-4: Deliverable D22.1 "Tether coating report"

2. Introduction

In WP61, preliminary analysis was performed for a number of electric solar wind sail (E-sail) missions from which the most relevant, interesting and promising mission concepts were selected for further analysis. Refined concept of E-sail from WP53 [AD1] was used for mission analysis. The purpose of this deliverable is to present a selection of mission candidates where E-sail propulsion either would be enabling technology or would provide significant benefits. Main results of this work are published in scientific journals [1]. The necessary orbital calculations and optimisations were performed in WP62 and are presented in [AD2].

3. Baseline E-sail

E-sail is highly scalable for a variety of mission profiles, as a reference, we can consider a full-scale E-sail to have 2000 km total tether length (for example, one hundred 20 km long tethers) with 25 kV potential. At 1 astronomical unit (au) distance from the Sun, this E-sail configuration provides 1 N thrust level. We consider E-sail design to be suitable for 30…1000 kg payloads but in principle, it is flexible to support any payload size with required spacecraft acceleration. Table 1 lists specific E-sail configurations for payloads ranging from 100…1000 kg and for required spacecraft accelerations ranging from 0.1…1 mm/s^2 [AD1].

The required radial distance range in the solar system for E-sail technology to work is set as 0.9…4 au. This range covers all near-Earth missions, all asteroid main belt missions, Mars missions and missions where E-sail acts as a booster stage for an outer solar system mission. With relatively minor modifications, the radial distance could be shifted to go inward or outward in the solar system to support other types of missions, for example ranging 0.25…1.1 au or 0.4…8 au [AD1]. Maximum mission lifetime requirement is set as 5 years [AD3]. Additional requirements for the E-sail hardware might imply in mission specific cases, e.g., flying through planetary shadow, E-sail operation or deployment far from the Sun, impulsive acceleration during operation, etc.

The magnitude of E-sail thrust depends on its distance from the Sun; it scales as 1/r where r is the solar distance [2]. Although the solar wind is highly variable, E-sail can provide a stable thrust output by controlling the tether potential accordingly in-flight [2]. By inclining the sail, the direction of thrust vector can be changed up to 30 degrees [2]. Together with thrust throttling capability, the E-sail can navigate accurately in the solar system [3].

Table 1: Specific E-sail configurations for 100 - 1000 kg payload and 0.1 - 1 mm/s^2 accelerations from [AD1]. TM stands for the spacecraft telemetry system.

Acceleration 0.1 mm/s^2				
Payload + TM	100 kg	200 kg	500 kg	1000 kg
E-sail tethers	12 x 4.0 km	16 x 5.7 km	24 x 9.2 km	34 x 12.9 km
Thrust at 1 au	0.03 N	0.05 N	0.13 N	0.25 N
Total mass	280 kg	535 kg	1290 kg	2535 kg
Acceleration 0.3 mm/s^2				
Payload + TM	100 kg	200 kg	500 kg	1000 kg
E-sail tethers	16 x 6.3 km	24 x 8.0 km	36 x 12.7 km	50 x 17.9 km
Thrust at 1 au	0.06 N	0.11 N	0.27 N	0.52 N
Total mass	296 kg	558 kg	1329 kg	2597 kg
Acceleration 1 mm/s^2				
Payload + TM	100 kg	200 kg	300 kg	
E-sail tethers	44 x 15.3 km	62 x 19.4 km	86 x 20.0 km	
Thrust at 1 au	0.39 N	0.70 N	1.00 N	
Total mass	391 kg	696 kg	996 kg	

4. Mission concepts

The number of potential E-sail applications is large, in principle, E-sail could replace the propulsion systems of most missions to date as well as enable new types of missions, which are not feasible with conventional means. Here we have categorised missions into following groups:

(1) asteroids,
(2) non-Keplerian orbits (e.g., solar wind monitoring),
(3) near-Sun missions,
(4) terrestrial planets,
(5) one-way boosting to outer solar system,
(6) Interstellar Heliopause Probe,
(7) impactors or penetrators,
(8) “data clippers” carrying data as payload.

Outside Earth's magnetosphere, E-sail propulsion can be used almost everywhere in the solar system. It is possible to spiral inward or outward in the solar system by inclining the sail appropriately, thus, tacking towards the Sun is possible. As E-sail thrust depends on the distance from the Sun, E-sail can provide high acceleration for missions in the 0.9…4 au distance range and to missions to outer solar system. E-sail as a stand-alone system does not enable a speedy return from the outer solar system because of the low acceleration when starting from the outer solar system. However, when combining E-sail with a modest chemical propulsion system, it is possible to speed up the return trip from the orbits around the gas giants. By performing a chemical burn near the planet and thus utilising the Oberth effect, the spacecraft is injected towards the inner solar system at significant speed and then E-sail could be used for precise navigation for Earth rendezvous. This would bring a technological challenge, currently out of scope of the ESAIL project as to whether the sail can withstand the impulsive chemical burn without breaking or becoming entangled.

All E-sail mission need to start from near or full escape orbit as E-sail needs to be outside of Earth's magnetosphere (in the solar wind) before it can generate propulsive thrust. The magnetosphere boundary is closest to Earth on the dayside, where it resides on average at 10 Earth radii. Increasing the orbital apogee above 20 Earth radii requires 2.9 km/s velocity change from a 300 km altitude orbit, while reaching the Moon distance (60 Earth radii) requires 3.1 km/s and marginally escaping from the Earth-Moon system 3.2 km/s [1]. In many cases, E-sail propulsion system on the spacecraft would enable the use of Soyuz class launchers for interplanetary missions. The altitude and inclination of the low Earth orbit or the escape orbit are not essential because E-sail can easily correct its course after reaching the solar wind. This brings an improvement in spacecraft design and development process, as they are no longer dependent on the exact launch window and mission trajectory. In mission planning, the strict requirements on launch window are also more relaxed; one only needs to consider availability of launch vehicles and resulting E-sail travel time to mission target. In addition, multiple E-sail missions can share the same launcher to the initial escape orbit.

E-sail needs solar wind or another fast plasma stream to work; therefore, it cannot be used in practice inside Earth's magnetosphere where the plasma rather stationary. However, the satellite orbital motion relative to the plasma would enable E-sail technology to be used for deorbiting purposes; this will be discussed in detail in a later chapter. In gas giants’ magnetospheres, the plasma corotates rapidly with the planet and this might provide some way of E-sail propulsion usage inside the magnetospheres, but this will need further research. Mars and Venus have no magnetospheres; Mercury has a weak and small magnetosphere so E-sail can be used in principle, but not necessarily down to the lowest orbits. In planetary missions, E-sail can of course pass through magnetospheres without any limitations, but generating thrust while inside the magnetosphere is limited.

When E-sail is used around planets, the capability of the sail to withstand eclipse periods and radiation environment needs to be analysed in specific mission designs. The long E-sail tethers may experience significant contraction and elongation due to rapid changes in thermal environment when eclipsing, this might cause dynamical oscillations in the tether rig [1].

5. Asteroid missions

Asteroids have been chosen as mission targets usually as a side objective if the mission trajectory and on-board instrumentation allow for an asteroid fly-by. There have been only a few successful missions to specific asteroids; most notable past and existing missions are listed in table 2 [4…12]. The American mission NEAR Shoemaker was the first spacecraft to land on an asteroid [13]. The Japanese Hayabusa mission concluded on 13 June 2010 when it returned a material sample from asteroid 25143 Itokawa back to Earth [14]. Still ongoing Dawn mission has successfully orbited Vesta and is currently on route to Ceres, scheduled to arrive in February 2015 [15]. In light of these recent missions, the scientific community has renewed its interest in studying asteroid in near-Earth region, in the main asteroid belt and the Jupiter Trojan asteroids. A number of missions are currently in planning and in development, for example Don Quijote (ESA), Hayabusa 2 (JAXA), MarcoPolo-R (ESA) and OSIRIS-Rex (NASA) [10, 16…19].

Asteroids are interesting scientifically and, more to that because of the impact threat, resource utilisation and for potential manned exploration [20, 21]. Main concepts for asteroid missions are:

1) fly-by observations,
2) reaching asteroid orbit for mapping,
3) landing and sample return,
4) asteroid deflection
5) in situ resource utilization,
6) capturing and returning an asteroid.

E-sail represents an interesting option for asteroid missions, because transfers for these missions usually either require a considerable propellant mass or complicate manoeuvres such as planetary flybys. In addition, E-sail would offer flexibility in the launch window and target selection.

Table 2: Past and existing missions to small bodies in our solar system.

Name	NEAR	Cassini	Deep Space 1	Stardust
Launch	1996	1997	1998	1999
Target	Eros	Titan	9969 Braille	5535 Annefrank
Dry mass	487 kg	2523 kg	373 kg	300 kg
Wet mass	800 kg	5600 kg	486 kg	380 kg
Power (at 1 au)	1800 W	640 W	2500 W	330 W
Propulsion	chemical propulsion	chemical propulsion	ion engine	chemical propulsion

Name	Genesis	Hayabusa	Rosetta	Dawn
Launch	2001	2003	2004	2007
Target	Earth-Sun L1	25143 Itokawa	2867 Steins, 21 Lutetia, Comet Churyumov-Gerasimenko	Ceres, Vesta
Dry mass	494 kg	380 kg	1300 kg	725 kg
Wet mass	636 kg	510 kg	3000 kg	1217 kg
Power (at 1 au)	254 W	2600 W	8700 W	10 000 W
Propulsion	chemical propulsion	electric and chemical propulsion	chemical propulsion	electric propulsion

5.1. Single near-Earth object

E-sail mission to a single near-Earth object as a fly-by or for a rendezvous would interest asteroid science and mapping for potential manned exploration. Currently detected near-Earth asteroids range up to approximately 32 km in diameter and their discovery rate is expected to increase rapidly within the next 10 years. There exists a scientific need for close distance observations of asteroids to complement Earth-based observations. Asteroid selection for good mission candidates has been done in various studies, for example the ESA Advanced Concept Team has identified near-Earth asteroids that will be accessible for human exploration from 2020 – 2035 [21]. From mission planning perspective, it would be easier than a multi-target mission and would enable spacecraft design reusability for future missions (e.g. when choosing another single target, or building a multi-target mission) [22].

Considering the scientific purpose of the mission concepts for asteroid observation, the goal would be to observe the asteroid from a close position and, if possible, to make a few revolutions around the target to get significant measurement data, technical approaches for doing that are:

1) using a non-Keplerian orbit (or "hovering") in case of a small asteroid,
2) using a terminator orbit around a large asteroid.

Terminator orbits are near perpendicular to the Sun direction and thus are preferred to provide better electrical power production due to constant illumination of the solar panels and less perturbations due to constant solar radiation pressure. For maintaining a precise orbit around the asteroid for a longer time, an additional propulsion system can be considered on the spacecraft for eliminating small perturbations.

E-sail technology specific concern is that near the asteroid, the gravity potential may bend the tethers and affect the performance of the sail. The spinning of the spacecraft may pose a problem for scientific missions that require optical instruments; this should be further investigated.

A single target E-sail mission to a near-Earth asteroid has been identified by the Electric/solar sail working group as a feasible candidate for a future ESA mission proposal. Main features of the initial mission design are described in table 3. Main objective of the mission is a low mass/cost demonstration mission to reach a single near-Earth asteroid (e.g. Apophis) as a precursor mission for human exploration or asteroid deflection.

Table 3: Initial design for E-sail mission to asteroid Apophis by Electric/solar sail working group.

Target	Apophis
Orbital parameters	1) aphelion = 1.0987 au 2) perihelion = 0.7460 au 3) eccentricity = 0.191 4) inclination = 3.33 degrees 5) orbital period = 323.6 days
E-sail parameters	1) characteristic acceleration = 0.3 mm/s^2 2) number of tethers = 10 3) tether length = 3 km 4) transfer time = 300 days
Spacecraft mass	269 kg
Spacecraft power	1318 W
Payload mass	25 kg
Payload power	450 W
Instruments	1) cameras 2) near-IR imager or spectrometer 3) thermal IR instrument

5.2. Near-Earth objects tour

Since E-sail is designed to work in a specific solar distance range, the logical step from single-asteroid missions would be multi-asteroid touring missions. The only limit to mission duration and the number of asteroids studied is set by the durability of the equipment. In a touring mission, there are two possibilities for visiting a target asteroid:

1) rendezvous mode, which provides a close encounter with extended duration and zero relative velocity,
2) fly-by mode, which provides a close encounter with short duration and nonzero relative velocity.

Based on potential scientific return for asteroid science, planetary defence or asteroid resource utilization, some asteroids would be visited in the rendezvous mode and others would be observed in the flyby mode.

A multi-asteroid mission requires extremely high velocity change over mission lifetime and for conventional propulsion systems would pose strict limitations on possible launch windows [23]. Thus, previous asteroid missions have been limited to only one or at most a few asteroids as their primary targets and additional remote observations of other asteroids were performed only if they happened to be close to the optimal spacecraft trajectory.

A technologically feasible mission length from 6 months up to 2 years would enable to study tens of asteroids with a single E-sail mission in near-Earth region. To date, there are over 600 000 asteroids and comets discovered, from which over 10 000 reside in the near-Earth region. The spacecraft thermal design and telemetry system design would be rather simple or even reusable from other missions. The order of mission targets could either be based on scientific value or from technical perspective, so that E-sail navigates from one asteroid to the next one going always farther from the Sun, thus making use of the solar wind pressure force.

5.3. Main belt asteroid tour

The main asteroid belt, ranging from 2.3…3.3 au, contains the majority of discovered asteroids. The near-Earth E-sail asteroid tour concept could be applied to the asteroid main belt without any changes needed in the propulsion system. However, other spacecraft systems and especially the telemetry system would need to be redesigned accordingly. With a given mission lifetime between 6 months and 2 years, much more asteroids could be visited as compared to the near-Earth region. Spacecraft navigation would be more challenging and E-sail technology specific concern would be the increased amount of micrometeoroids in specific regions of the asteroid belt that might damage or cut the tethers. Nevertheless, the existing micrometeoroid models for interplanetary space environment are still under significant development and one could consider a higher safety margin for tether design in this type of missions, for example, using a 5-wire Heytether instead of a 4-wire Heytether.

5.4. Trojan asteroid tour

There are over 6000 discovered Jupiter Trojans to date, some of which are believed to contain water ice. This type of a mission would be more challenging than NEO or main belt asteroid tour, but scientifically very interesting. Due to increased interest in Trojan asteroids, several mission proposals have already been made to space agencies:

1) using electric propulsion technology, a Jovian orbiter and a mother spacecraft that would observe Trojan asteroids in a fly-by mission, earliest potential launch in 2021 (JAXA) [24],

2) using electric propulsion technology, a 50 kg payload, 1600 kg spacecraft mission to rendezvous with 4 Trojan objects, ESA M-class mission type, 15.6 years total mission time, earliest potential launch in 2026 (DLR) [25],
3) using chemical propulsion, a 50 kg payload, 3070 kg spacecraft mission to perform multiple fly-by’s of Trojan asteroids, proposal to the ESA M-class missions call of 2010, potential launch window was in 2011 (ESA) [26].

E-sail mission would provide significant cost reduction and a flexible choice of the launch window. However, depending on the exact payload power requirements, the spacecraft could require the use of a radioisotope power supply for this mission type.

5.5. Asteroid deflection

E-sail could be used to deflect an Earth threatening asteroid from its course. Near-Earth objects for which closest Earth approach distance is smaller than 0.05 au are classified as Potentially Hazardous Asteroids (PHAs); to date, there are over 1400 currently known PHAs [20, 27]. The potential threat posed by PHAs of impacting Earth may be catastrophic, but the annual likelihood of such event is extremely small. Due to the relatively small size of PHAs and possible perturbations, the precise distance of the future close approaches are extremely difficult to calculate far in advance. As one solution for better tracking PHAs, it is proposed to tag these asteroids with a radio transponder [1]. This would increase tracking accuracy and thus could help decide when an asteroid deflection mission is required. E-sail could be used for constructing identical low-cost spacecraft for PHAs tagging with single-target or multi-target missions [28].

For the actual asteroid deflection, there are two promising approaches. In the first scenario, given a sufficient warning time, an E-sail mission can be launched to reach the asteroid, attach the spacecraft to the asteroid and use E-sail thrust to alter its orbit [29]. In the second scenario, one or more E-sail spacecraft could be placed in a retrograde orbit around the Sun at 1 au solar distance. These spacecraft would passively be available for mitigation before a threat is identified and after that, the E-sail spacecraft can be navigated to impact with the asteroid. The retrograde orbit enables a significantly high impact energy even with relatively lightweight spacecraft [30, 31]. Very high velocity change is required to reach this type of retrograde orbit and thus it would be impractical for conventional propulsion systems.

5.6. Asteroid resource utilization

E-sail technology would enable visiting asteroids repeatedly and to transport payloads with very low propulsion system mass, as such, it would be well suited for mining water and other volatiles on asteroids. This would enable manufacturing of asteroid-derived propellants in space based on liquid hydrogen and oxygen to support future interplanetary missions with chemical propulsion systems that are either leaving from Earth or that need refuelling for a return trip [1]. Manned Mars exploration is one area that would greatly benefit from asteroid resource utilization as returning from Mars could become cost-effective and besides the propellant, mining could provide water for drinking water and breathing oxygen.

Metal asteroids also contain significant concentrations of platinum group metals that may be economically feasible to mine them on asteroid and return to Earth [1]. E-sail technology could provide an economical and flexible transportation solution for carrying necessary mining equipment to asteroids and for returning mined payloads. An alternative approach would be to use E-sail for transporting whole asteroids to an Earth orbit for (possibly manned) mining. This mission concept has been recently studied by NASA for returning a selected 10 000 kg near-Earth asteroid with electric propulsion system by 2025 [32]. With a 5-year mission time, the spacecraft would rendezvous with the asteroid, capture and detumble it, and transport it to the International Space Station for planetary defence research and asteroid resource utilization experiments.

6. Non-Keplerian orbit missions

Due to the E-sail’s ability to provide continuous thrust, the spacecraft can be put on non-Keplerian orbits [33]. This concept originates from the solar photon sail studies, but applies to all sail-based propulsion systems. Solar electric propulsion systems can achieve a similar effect but only for a short limited mission time. Thus, E-sail is enabling technology for this category of missions.

6.1. Helioseismology from lifted orbit

An E-sail spacecraft on an orbit lifted above the ecliptic plane would have a continuous view of the polar regions of the Sun [1]. This would provide continuous long time-scale helioseismological measurements. The orbit solar distance could be 1 au, which would keep the spacecraft relatively close to Earth (as the orbit period would be similar to Earth) for a low-cost telemetry link.

6.2. Remote sensing of Earth and Earth's environment

Similarly to the helioseismological mission, an E-sail lifted close to Earth orbit could be used for Earth and near-Earth environment remote sensing. Several types of non-Keplerian orbits near the Earth would be applicable for E-sail technology that are based on extensive research done for solar photon sail and electric propulsion missions, one example is a polar sitter orbit [34]. One potential application is observing small asteroids that are temporarily captured by Earth’s gravity [1]. This mission would need a relatively small telescope as the asteroids come very close to the Earth. Main limitation of E-sail technology for Earth remote sensing is that the spacecraft orbit cannot be in the magnetosphere where there is no solar wind.

6.3. Giant planet auroras

E-sail would enable a mission to study the effect of solar wind on the auroras of gas giants [35]. In Jupiter’s example, the spacecraft could establish a non-Keplerian orbit lifted above the Jupiter-Sun Lagrange L1 point, to provide continuous and simultaneous measurements of the solar wind parameters and Jupiter’s pole [1]. A traditional mission design would require several spacecraft for this mission: one at the L1 point for measuring the solar wind and additional ones in a Jupiter polar orbit, which provide more-or-less continuous measurements of the auroras. The Jupiter orbiters would have to be tolerant against the hard radiation environment in the polar orbit whereas the radiation levels in L1 distance are considerably low.

6.4. Off-Lagrange point space weather surveillance

Sail-based propulsion systems would enable continuous space weather measurements for Earth satellite services much closer to the Sun, as current missions are limited to the Earth-Sun Lagrange L1 point [1]. Existing missions like NASA’s ACE and ESA’s SOHO at the L1 point provide us with a 1-hour warning time for large solar flares [36, 37]. At the same time, new missions have to be planned that continue these measurements [38, 39]. E-sail could place the spacecraft at a stable orbit in the Earth-Sun line much closer than L1, thus providing a significantly increasing the warning time of magnetic storms. Main challenge for this type of mission is the risk of high electric field of active E-sail tethers or the electron gun disturbing the sensitive plasma and magnetic field measurements. There are different ways to overcome this by either interleaving the propulsion system and measurement instruments, using multiple spacecraft or by placing the measurement instruments further away from the sail with booms or tethers. The exact technical solution should be chosen together with measurement instruments.

7. Near-Sun missions

Near-Sun missions pose technical challenges for spacecraft design mainly due to increased thermal radiation environment. The high temperature brings its technical challenges for everything, including E-sail technology. The aluminium tethers might not tolerate the thermal environment so close to the Sun unless they are coated with a well emitting layer for cooling [AD4]. Alternatively, copper could be used as tether material since it can tolerate much higher temperatures; the ultrasonic tether bonding process for aluminium would be applicable to copper as well [1].

When operating E-sail closer to the Sun than 1 au, the maximum thrust output would increase, as it is inversely proportional to the distance from the Sun. However, to realise this thrust increase, more power is needed, as solar panels tend to degrade at high temperatures. Operating E-sail at full voltage near the Sun may not be possible.

7.1. Solar polar orbiter

A dedicated solar physics and helioseismology mission requires achieving a high inclination and low altitude, meaning less than 0.5 au, orbit around the Sun. Achieving a target orbit that satisfies these requirements is highly demanding on total velocity change of the mission, thus being suitable for E-sail propulsion. The latest mission development in this area is ESA's Solar Orbiter, which aims to use a chemical propulsion system, and multiple Earth and Venus gravity assist manoeuvres to reach a nominal 25 degree inclination, 0.28 au perihelion distance and 0.91 au aphelion distance (reaching beyond Venus at farthest point) [40, 41]. Extending the mission time by 3 years, could enable increasing the inclination with additional gravity assist manoeuvres up to 36 degrees.

Reaching higher inclinations or even a circular orbit around the Sun at 0.28 au is economically feasible only with E-sail or solar photon sail technology [1, 42, 43]. A polar orbit around the Sun would provide invaluable measurement data for helioseismology and E-sail would be enabling technology for such a mission. Due to E-sail tethers being charged, E-sail should be turned off to allow for clean scientific measurements, but this can be done after reaching target orbit.

7.2. Mercury

Mercury is a technologically very challenging mission target, as it is difficult to reach, due to its low mass it is hard to perform a capture manoeuvre and the thermal environment is harsh because of the closeness to the Sun and the high thermal radiation from the planet. Existing missions include NASA's Messenger and ESA's BepiColombo, from which the latter is still under development [44…46]. Both missions have long transfer times, for example BepiColombo plans to achieve a 6-year transfer by combining chemical propulsion and ion engines.

Given the technical challenges, E-sail could reduce mission costs by providing a lightweight propulsion system for the mission as well as potentially reduce transfer time. Travelling to Mercury requires tacking towards the Sun with E-sail that is not as efficient as travelling away from the Sun. Thus, making a return trip from Mercury would be an attractive option for E-sail use; this could provide an economically feasible Mercury sample return mission. Similar mission case has been studied for solar photon sail before [47].

8. Terrestrial planet missions

Terrestrial planet missions offer an interesting option for interplanetary mission transfers with E-sail, especially if it is combined with a high-thrust propulsion system. Such a combination would reduce the total propellant mass required by traditional missions and would allow to avoid complex gravity assist manoeuvres. Venus, Mars and the moons of Mars are ideal mission candidates because they lack a planetary magnetosphere and the thermal environment is friendlier than in a Mercury mission that was described before.

8.1. Venus

Venus is the most nearby planet and thus easiest to access in terms of required total velocity change. However, for a traditional scientific Venus mission, the benefits of using E-sail would be rather small when compared other propulsion systems which numerous past Venus missions have used [2].

However, similarly to the Mercury E-sail return mission concept, an E-sail spacecraft could be used to make a low-cost return trip from Venus to Earth for a sample return [48]. Such a mission could bring a more comprehensive understanding of Venus surface composition and there have been previous studies that have dealt with the technological challenges of sample collecting on Venus surface [49…52].

8.2. Mars

Mars missions have been a key development of many NASA and ESA activities with the long-term perspective of manned Mars exploration. Extensive studies have been carried out of the feasibility and benefits of replacing chemical propulsion systems with solar electric propulsion systems in different Mars mission concepts [53]. Therefore, there is definitely a need to reduce the costs of future Mars missions by introducing more lightweight propulsion technologies. E-sail would not necessarily reduce the mission transfer times because of the closeness of Mars, but would have a saving in spacecraft mass. A manned exploration program for Mars requires that the cost per kilogram to transfer equipment or supplies from Earth to Mars would be significantly lower; E-sail or electric propulsion systems could enable that cost reduction. One example use is for water transportation, which is needed for drinking water, radiation shielding and making breathing air.

For a sample return mission to Mars or one of its moons, i.e. Phobos or Deimos, the E-sail would provide benefit in the trip towards the target, depending on the science requirements for the mission, there might be a need to deliver the samples back to Earth rather fast [1, 54]. If this were the case, then E-sail would enable a very cost-effective way to carry a separate, relatively high mass, chemical propulsion system to Mars orbit that is intended for a quick return trip.

9. Outer solar system missions

E-sail is well suited for fly-by missions in the outer solar system as it would significantly reduce the costs and travel time of reaching an object beyond 4 au solar distance as well as increase the flexibility of available launch windows. When combined with a high-thrust propulsion system, the spacecraft would be able to perform impulsive orbit insertion manoeuvres. The E-sail mission trajectory could be tailored to provide a specific velocity on arrival to the target object at the cost of increased travel time [55].

In the current FP7 project, E-sail technology requirements are set for the 0.9…4 au solar distance range, this would enable E-sail missions, where the propulsion system is used as a booster stage for reaching outer solar system objects. Payload in these mission scenarios would definitely need a radioisotope based power supply.

9.1. Fly-by missions

A fly-by mission of a remote target in the outer solar system would provide a relatively low cost single shot opportunity. Potential targets in the outer solar system include the gas giants Jupiter, Saturn, Uranus, Neptune and their moons, the Jupiter Trojan asteroids and the Centaur objects. A fly-by mission has limited science capability, but only a small number of missions have so far reached outer solar system bodies. A low-cost science opportunity would be to launch a number of E-sail spacecraft at different targets in the outer solar system; each spacecraft would carry identical measurement instruments, potentially reused from past missions.

9.2. Giant planet atmosphere probes

An advanced mission scenario from the fly-by mission type would be to launch atmosphere probes to Jupiter, Saturn, Uranus, Neptune and possibly Titan as well [1]. The atmospheric properties of the gas giants are well known only for Jupiter, which were measured by NASA’s Galileo entry probe [56]. Galileo probe also demonstrated a successful high-speed atmospheric entry at 47.8 km/s. Up to four E-sail spacecraft could be launched together, each carrying a probe to a different gas giant. Depending on the heat shields of the probes, mission trajectory could be planned to achieve a short travel time and thus have a higher probe atmospheric entry speed. Various planetary entry probe designs have been researched as part of ESA CDF studies that support different selections of measurement instruments. In principle, an E-sail mission can cope with any probe mass (preferably up to 1500 kg), as it only affects the travel time. This mission could be combined with a separate E-sail spacecraft that is used for telemetry relay from the probes, which later continues towards the Kuiper belt.

9.3. Giant planet missions

The giant planets provide a sufficiently large Oberth effect that enables planetary insertion with a modest-sized chemical propulsion system [1]. This opens the possibilities for lowering cost of planetary orbiters, moon missions and even sample return for Jupiter, Saturn, Uranus and Neptune. E-sail technology could provide low-cost solution for navigation and boosting towards the planets at up to 4 au solar distance and similarly in the return trip to reach Earth. With additional technology development, this range could be increased to 10 au with minor modifications.

Past mission studies include ESA’s Europa study for a Jovian Minisat Explorer [57, 58]. The main disadvantage of these missions are the overall high cost of the spacecraft development and high radiation environment near the planets. With E-sail, the mission launch windows would become more flexible and the mission trajectories would no longer need gravity assist manoeuvres [55]. From E-sail technology perspective, actual sailing inside the planetary magnetospheres could be researched in the future.

9.4. Kuiper belt probes

E-sail technology could enable a mission for a swarm of Kuiper belt probes for fly-by measurements [1]. This is similar to the Jupiter Trojans tour, but with cheaper payloads, as only fly-by monitoring is envisaged. Regarding existing missions, there is only the NASA’s New Horizons spacecraft, which will arrive at Pluto in 2015, and if successful, will continue on to study another currently undetermined Kuiper belt object. The preferable second target would be 40…90 km in diameter and ideally white or grey, in contrast to Pluto's reddish colour [59].

9.5. Outer solar system missions

A mission to the outer Solar System boundaries would enable in situ measurements to gain valuable insight of the heliosphere and the nearby interstellar medium. Traditionally, it requires long transfer times, i.e. the Voyager missions and Pioneer 10 and 11 [60…62].

Voyager 1 is the farthest spacecraft from Earth to date, with 126 au distance and 36-year mission time. E-sail technology could significantly shorten the transfer time for heliosheath and heliosphere missions, which require 100 au distance from the Sun.

10. Interstellar heliopause mission

A mission to the heliopause region, 200 au from the Sun, has a scientific aim to analyse the heliopause and the interstellar medium through in situ measurements [63…65]. E-sail would be enabling technology for this mission type. Previous studies on this mission include a 2006 ESA technology reference study, which considered the solar photo sail for reaching the heliopause in 25 years [66]. However, at least a 150 m radius sail would have been needed and the mission trajectory required two close fly-bys of the Sun (at 0.25 solar distance) [67, 68]. A 25 kg and 15 W highly miniaturized and integrated instrumentation package was proposed for the mission.

E-sail technology could provide an overall lighter propulsion system and possibly faster transfer time for the mission [1]. The launch window and navigation accuracy are not relevant for the mission as the goal is just to reach 200 au distance. The main emphasis is on the spacecraft design and finding ways to shorten the travel time to reduce the required spacecraft design lifetime. From E-sail technology perspective, tacking towards the Sun will not probably give a benefit as compared to simply spiralling outwards in the solar system from 1 au [55]. Depending on the scientific instrumentation, the sail might interfere with the measurements and it should be jettisoned before leaving the solar system; this would need further analysis. Main disadvantages in spacecraft design is the need for a radioactive power supply and a deep space communication link, but these requirements apply independently of the chosen propulsion system.

11. Impactor

An E-sail spacecraft could be used to complement a scientific mission by impacting a target atmosphereless body while another spacecraft is performing measurements of the impact plume [1]. This would be a low-cost method to increase the scientific output of existing or planned missions significantly. The spacecraft design would be rather simple, as no scientific instruments are needed on the E-sail spacecraft. An example mission would be ESA's Jupiter Icy Moon Explorer (JUICE) that is planned to perform a fly-by of Europa in 2030 [69]. A small E-sail spacecraft could perform a controlled impact with Europa at the same time with JUICE measurements to provide additional information about the Jupiter's moon.

12. Data clipper

High volume data transmission in interplanetary and deep space missions is a major technological challenge and solutions to date are very expensive. Data transmission at large distances is extremely demanding on the spacecraft telecommunications system and power system, also, it is demanding on the ground segment, usually requiring the use of deep space communication antennas. A data-clipper mission could provide means to transport large volumes of high-resolution scientific data for interplanetary missions [48, 70]. An E-sail spacecraft could be equipped with large on-board memory storage system and could carry the data back from the mission target into Earth's vicinity for downloading to ground. The data clipper can either collect the data by its own instruments or download it in close-range from another spacecraft at the mission target. This would provide significant cost reduction as well as shorten the total data transfer time (when compared with downloading the same amount of data from mission target directly). A modest ground segment would be preferred, for example, using just one of routine ground stations that is planned for ESA's Gaia mission [71].

13. Satellite deorbiting

E-sail concept uses thin charged electrostatic tethers for turning the momentum flux of a natural plasma stream such as the solar wind into spacecraft propulsion, a similar approach can be used with ionospheric plasma in Earth orbit [72]. The Coulomb drag interaction with the ionospheric plasma that is moving with respect to the satellite due to the satellite’s orbital motion will produce thrust in roughly the same magnitude. This electrostatic plasma braking technique could be used as a stand-alone deorbit system for satellites weighing up to 100 kg. For heavier satellites, the most effective use of plasma brake would be in combination with another propulsion system [73]. ESTCube-1 nanosatellite, launched in mid-2013, will perform the first in-orbit demonstration of E-sail technology in low Earth orbit [74].

It is a promising option for the low Earth orbit protected region, which extends from the surface to 2000 km altitude. As it is the closest to Earth, it is a highly populated region and falls under the European Code of Conduct for Space Debris Mitigation to limit the orbital lifetime of satellites to up to 25 years [75]. For satellites below 650 km altitude, the natural atmospheric drag is sufficient, satellites in the 650…1500 km altitude range are usually brought down to the 650 km limit. For satellites in the 1500…2000 km altitude range a reorbiting approach is usually taken to increase the altitude just above the 2000 km limit. E-sail technology based plasma brake deorbiting system could provide a lightweight solution that provides a 3 year deorbit time for the nanosatellite and small satellite segment.

14. Conclusion

We have given an overview of a variety of mission candidates where E-sail propulsion either would be enabling technology or would provide significant benefits. Main results of the preliminary analysis and more detailed analysis together with orbital calculations and optimisations are published in scientific journals [1, AD2]. E-sail can be used to reduce costs on most missions by providing a lightweight propulsion system or shortening required mission lifetime or even both at the same time.

E-sail can be used either as a stand-alone propulsion system or be combined with another type of propulsion system (e.g. chemical propulsion) on the spacecraft. E-sail is a promising technology for asteroid missions where mission costs have been high for the amount of useful science (for example, when comparing with planetary missions). As a hybrid system, E-sail can make sample return missions much more feasible. E-sail could be used as a booster stage for spacecraft in outer solar system missions. As an enabling technology, multi-asteroid missions and non-Keplerian orbit missions are now possible.

From technology perspective, there are two categories of missions feasible for near future:

1) single-asteroid and multi-asteroid missions near Earth and in main asteroid belt,
2) missions to outer solar system where E-sail is used as a booster mechanism up to 4 au radial distance, these include gas giants, Kuiper belt, heliopause or impactor missions.

The 0.9…4 au radial distance requirement for E-sail hardware is suitable for these missions. With slight modifications 0.4…1 au, 4…8 au or 6…10 au ranges would be achievable to enable flexible use of E-sail in Mercury, Venus, Jupiter and Saturn missions. Advantage of E-sail technology is that it allows spacecraft design and development to be independent from launch windows in mission planning. However all E-sail missions need to start from near or full escape orbit.

In the longer run, E-sail technology might provide significant cost reduction in interplanetary missions, thus enable economic asteroid resource utilisation, manned Mars and asteroid exploration.

References

[1] Janhunen, P., Toivanen, P. K, Envall, J., Merikallio, S., Montesanti, G., Gonzalez del Amo, J., Kvell, U., Noorma, M., Lätt, S. Electric solar wind sail applications overview. *Proceedings of Estonian Academy of Sciences*, submitted, 2013.

[2] Janhunen, P., Toivanen, P. K., Polkko, J., Merikallio, S., Salminen, P., Haeggström, E., Seppänen, H, et al. Invited Article: Electric solar wind sail: Toward test missions. *Review of scientific instruments,* 2010, 81(11), 111301-111301.

[3] Toivanen, P.K., Janhunen, P. Electric sailing under observed solar wind conditions. *Astrophysics and Space Sciences Transactions*, 2009, 5(1), 61-69.

[4] Veverka, J., Robinson, M., Thomas, P., Murchie, S., Bell, J. F., Izenberg, N., et al. NEAR at Eros: Imaging and spectral results. *Science*, 2000, 289(5487), 2088-2097.

[5] Patti, B. The Huygens mission: Design approach for an atmosphere entry probe. *Control Engineering Practice*, 1995, 3(11), 1621-1630.

[6] Porco, C. C., Baker, E., Barbara, J., Beurle, K., Brahic, A., Burns, J. A., et al. Imaging of Titan from the Cassini spacecraft. Nature, 2005, 434(7030), 159-168.

[7] Rayman, M. D., Varghese, P., Lehman, D. H., Livesay, L. L. Results from the Deep Space 1 technology validation mission. *Acta Astronautica*, 2000, 47(2), 475-487.

[8] Brownlee, D. E., Tsou, P., Anderson, J. D., Hanner, M. S., Newburn, R. L., Sekanina, Z., et al. Stardust: Comet and interstellar dust sample return mission. *Journal of Geophysical Research*, 2003, 108(E10), 8111.

[9] Lo, M. W., Williams, B. G., Bollman, W. E., Han, D., Hahn, Y., Bell, J. L., et al. Genesis mission design. *Journal of the Astronautical Sciences*, 2001, 49(1), 169-184.

[10] Kawaguchi, J. I., Fujiwara, A., Uesugi, T. Hayabusa—Its technology and science accomplishment summary and Hayabusa-2. *Acta Astronautica*, 2008, 62(10), 639-647.

[11] Glassmeier, K. H., Boehnhardt, H., Koschny, D., Kührt, E., Richter, I. The Rosetta mission: Flying towards the origin of the solar system. *Space Science Reviews*, 2007, 128(1-4), 1-21.

[12] Rayman, M. D., Fraschetti, T. C., Raymond, C. A., Russell, C. T. Dawn: A mission in development for exploration of main belt asteroids Vesta and Ceres. *Acta Astronautica*, 2006, 58(11), 605-616.

[13] Veverka, J., Farquhar, B., Robinson, M., Thomas, P., Murchie, S., Harch, A., et al. The landing of the NEAR-Shoemaker spacecraft on asteroid 433 Eros. *Nature*, 2001, 413(6854), 390-393.

[14] Fujiwara, A., Kawaguchi, J., Yeomans, D. K., Abe, M., Mukai, T., Okada, T., et al. The rubble-pile asteroid Itokawa as observed by Hayabusa. *Science*, 2006, 312(5778), 1330-1334.

[15] Russell, C. T., Capaccioni, F., Coradini, A., De Sanctis, M. C., Feldman, W. C., Jaumann, R., et al. Dawn mission to Vesta and Ceres. *Earth, Moon, and Planets*, 2007, 101(1-2), 65-91.

[16] Carnelli, I., Galvez, A., Ongaro, F. Learning to deflect near-Earth objects: Industrial design of the Don Quijote mission. In *57th International Astronautical Congress*, Valencia, 2006.

[17] Barucci, M. A., Yoshikawa, M., Michel, P., Kawagushi, J., Yano, H., Brucato, J. R., et al. MARCO POLO: near earth object sample return mission. *Experimental Astronomy*, 2009, 23(3), 785-808.

[18] Barucci, M. A., Cheng, A. F., Michel, P., Benner, L. A. M., Binzel, R. P., Bland, P. A., et al. MarcoPolo-R near earth asteroid sample return mission. *Experimental Astronomy*, 2012, 33(2-3), 645-684.

[19] Lauretta, D. S., Team, O. R. An Overview of the OSIRIS-REx Asteroid Sample Return Mission. In *43rd Lunar and Planetary Institute Science Conference*, The Woodlands, 2012.

[20] Galvez, A., et al. Space mission priorities for near-Earth object risk assessment and reduction: Recommendations to ESA by the near-Earth object mission advisory panel (NEOMAP). *ESA NEOMAP Report*, Noordwijk, 2004

[21] Reddy, V., Corre, L. L., Hicks, M., Lawrence, K., Buratti, B. J., Abell, P. A., et al. Composition of near-Earth Asteroid 2008 EV5: Potential target for robotic and human exploration. *Icarus*, 2012, 221(2), 678-681.

[22] Agnolon, D., et al. Near Earth asteroid sample return: Study overview and mission analysis annex. *ESA TRS Report*, Noordwijk, 2007.

[23] Dachwald, B., Seboldt, W. Multiple near-earth asteroid rendezvous and sample return using first generation solar sailcraft. *Acta Astronautica*, 2005, 57(11), 864–875.

[24] Mori, O., Shirasawa, Y., Sawada, H., Mimasu, Y., Tsuda, Y., Funase, R., Saiki, T., Yamamoto, T., Motooka, N., Kishino, Y., Kawaguchi, J. IKAROS extended mission and advanced solar power sail mission. In *63rd International Astronautical Congress*, Naples, 2012.

[25] Maiwald, V., Braukhane, A., Quantius, D., Reershemius, S. Design of a Multi-Rendezvous Mission to Jupiter's Trojans. In *63rd International Astronautical Congress*, Naples, 2012.

[26] Lamy, P., Vernazza, P., Poncy, J., Martinot, V., Hinglais, E., Canalias, E., et al. Trojans' Odyssey: Unveiling the early history of the Solar System. *Experimental Astronomy*, 2012, 33(2-3), 685-721.

[27] Murdoch, N., et al. Asteroid impact & deflection assessment (AIDA) mission: Opportunities and tests in a US-Europe space mission cooperation. *ESA Interim Release*, Noordwijk, 2012

[28] Quarta, A.A., Mengali, G. Electric sail missions to potentially hazardous asteroids. *Acta Astronautica*, 2010, 66(9), 1506-1519.

[29] Merikallio, S., Janhunen, P. Moving an asteroid with electric solar wind sail. *Astrophysics and Space Sciences Transactions*, 2010, 6, 41-48.

[30] Dachwald, B., Wie, B. Solar sail kinetic energy impactor trajectory optimization for an asteroid-deflection mission. *Journal of Spacecraft and Rockets*, 2007, 44(4), 755–764.

[31] Dachwald, B., Kahle, R., Wie, B. Head-on impact deflection of NEAs: a case study for 99942 Apophis. In *Planetary Defense Conference*, Washington, 2007.

[32] Brophy, J. R., Gershman, R., Landau, D., Polk, J., Porter, C., Yeomans, D., et al. Feasibility of Capturing and Returning Small Near-Earth Asteroids. In *32nd International Electric Propulsion Conference*, Wiesbaden, 2011.

[33] Mengali, G., Quarta, A. A. Non-Keplerian orbits for electric sails. *Celestial Mechanics and Dynamical Astronomy*, 2009, 105(1-3), 179-195.

[34] Ceriotti, M., McInnes, C. R. Systems design of a hybrid sail pole-sitter. *Advances in Space Research*, 2011, 48(11), 1754-1762.

[35] Clarke, J. T., Grodent, D., Cowley, S. W., Bunce, E. J., Zarka, P., Connerney, J. E., Satoh, T. Jupiter's aurora. Jupiter. *The Planet, Satellites and Magnetosphere*, 2004, 1, 639-670.

[36] Bernath, P. F., McElroy, C. T., Abrams, M. C., Boone, C. D., Butler, M., Camy-Peyret, C., et al. Atmospheric chemistry experiment (ACE): mission overview. *Geophysical research letters*, 2005, 32(15), L15S01.

[37] Domingo, V., Fleck, B., Poland, A. I. The SOHO mission: an overview. *Solar Physics*, 1995, 162(1-2), 1-37.

[38] Fleck, B., Müller, D., Haugan, S., Sánchez Duarte, L., Siili, T., Gurman, J. B. 10 years of SOHO. *ESA Bulletin*, 2006, 126, 24-32.

[39] Daly, E., et al. Space Weather CDF Study Report. *ESA CDF Study Report*, Noordwijk, 2001.

[40] Müller, D., Marsden, R. G., et al. Solar Orbiter: Exploring the Sun-heliosphere connection. *ESA Assessment Study Report*, Noordwijk, 2009.

[41] Müller, D., Marsden, R. G., Cyr, O. C. St., Gilbert, H. R. Solar Orbiter. *Solar Physics*, 2013, 285(1-2), 25-70.

[42] Falkner, P., et al. The Solar Polar Orbiter. *ESA TRS Report*, Noordwijk, 2004.

[43] Macdonald, M., Hughes, G., McInnes, C., Lyngvi, A., Falkner, P., Atzei, A. Solar polar orbiter: a solar sail technology reference study. *Journal of Spacecraft and Rockets*, 2006, 43(5), 960-972.

[44] Balogh, A., Grard, R., Solomon, S. C., Schulz, R., Langevin, Y., Kasaba, Y., Fujimoto, M. Missions to Mercury. *Space Science Reviews*, 2007, 132(2-4), 611-645.

[45] Benkhoff, J., van Casteren, J., Hayakawa, H., Fujimoto, M., Laakso, H., Novara, M., et al. BepiColombo—Comprehensive exploration of Mercury: Mission overview and science goals. *Planetary and Space Science*, 2010, 58(1), 2-20.

[46] Solomon, S. C., McNutt, R. L., Gold, R. E., Acuña, M. H., Baker, D. N., Boynton, W. V., et al. The MESSENGER mission to Mercury: Scientific objectives and implementation. *Planetary and Space Science*, 2001, 49(14), 1445-1465.

[47] Hughes, G. W., Macdonald, M., McInnes, C. R., Atzei, A., Falkner, P. Analysis of a solar sail mercury sample return mission. In *55th International Astronautical Congress*, Vancouver, 2004.

[48] Janhunen, P., Merikallio, S., Toivanen, P. K, Envall, J., Polkko, J. Possibilities opened by electric solar wind sail technology. In *63rd International Astronautical Congress*, Naples, 2012.

[49] Coradini, M., Scoon, G., Lebreton, J. Venus sample return: assessment study report. *ESA Report*, Noordwijk, 1998.

[50] Sweetser, T., et al. Venus Surface Sample Return: A Weighty High-Pressure Challenge. *NASA Technical Report*, Pasadena, 1999.

[51] Rodgers, D., et al. Venus Sample Return - A Hot Topic. In *IEEE Aerospace Conference*, Big Sky Montana, 2000.

[52] Kerzhanovich, V. V., et al. Dual Balloon Concept For Lifting Payloads From The Surface Of Venus. *NASA Technical Report*, Pasadena, 2005.

[53] Di Cara, D., et al. Mars Electric Propulsion: Study of Impact of Using Electric Propulsion on Future Mars Missions. *ESA CDF Study Report*, Noordwijk, 2008.

[54] Renton, D., et al. Deimos Sample Return: Executive Summary. *ESA TRS Report*, Noordwijk, 2006.

[55] Quarta, A. A., Mengali, G. Electric sail mission analysis for outer solar system exploration. *Journal of guidance, control, and dynamics*, 2010, 33(3), 740-755.

[56] Young, R. E. The Galileo probe: how it has changed our understanding of Jupiter. *New Astronomy Reviews*, 2003, 47(1), 1-51.

[57] Renard, P., Koeck, C., Kemble, S., Atzei, A., Falkner, P. System concepts and enabling technologies for an ESA low-cost mission to Jupiter/Europa. In *Small Satellites, Systems and Services*, La Rochelle, 2004.

[58] Atzei, A., Wielders, A., Stankov, A., Falkner, P. Overview of the ESA Jovian Technology Reference Studies. *ESA TRS Report*, Noordwijk, 2007.

[59] Stern, A., Spencer, J. New Horizons: The first reconnaissance mission to bodies in the Kuiper Belt. *Earth, Moon, and Planets*, 2003, 92(1-4), 477-482.

[60] Stone, E. C., Cummings, A. C., McDonald, F. B., Heikkila, B. C., Lal, N., Webber, W. R. Voyager 1 explores the termination shock region and the heliosheath beyond. *Science*, 2005, 309(5743), 2017-2020.

[61] Decker, R. B., Krimigis, S. M., Roelof, E. C., Hill, M. E., Armstrong, T. P., Gloeckler, G., et al. Voyager 1 in the foreshock, termination shock, and heliosheath. *Science*, 2005, 309(5743), 2020-2024.

[62] Hall, C. F. Pioneer 10 and Pioneer 11. *Science*, 1975, 188(4187), 445-446.

[63] Mewaldt, R. A., Kangas, J., Kerridge, S. J., Neugebauer, M. A small interstellar probe to the heliospheric boundary and interstellar space. *Acta Astronautica*, 1995, 35, 267-276.

[64] Liewer, P. C., Mewaldt, R. A., Ayon, J. A., Wallace, R. A. NASA's interstellar probe mission. In *Space Technology and Applications International Forum*, Albuquerque, 2000.

[65] Leipold, M., Fichtner, H., Heber, B., Groepper, P., Lascar, S., Burger, F., et al. Heliopause explorer—a sailcraft mission to the outer boundaries of the solar system. *Acta Astronautica*, 2006, 59(8), 785-796.

[66] Lyngvi, A., Falkner, P., Peacock, A. The interstellar heliopause probe technology reference study. *Advances in Space Research*, 2005, 35(12), 2073-2077.

[67] Lyngvi, A., Falkner, P., Kemble, S., Leipold, M., Peacock, A. The interstellar heliopause probe. *Acta Astronautica*, 2005, 57(2), 104-111.

[68] Lyngvi, A.E., van den Berg, M.L., Falkner, P. Study overview of the interstellar heliopause probe. *ESA TRS Report*, Noordwijk, 2007.

[69] Grasset, O., Dougherty, M. K., Coustenis, A., Bunce, E. J., Erd, C., Titov, D., et al. JUpiter ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the Jupiter system. Planetary and Space Science, 2012, 78, 1-21.

[70] Poncy, J., Couzin, P., Fontdecaba, J. Data Clippers: A new application for Solar sails and E-sails. In *European Planetary Science Congress*, Rome, 2010.

[71] D. Milligan, D., Rudolph, A., Whitehead, G., Loureiro, T. Gaia ground segment development and operations concept. In *SpaceOps 2010 Conference*, Huntsville, 2010.

[72] Janhunen, P. Electrostatic plasma brake for deorbiting a satellite. *Journal of propulsion and power*, 2010, 26(2), 370-372.

[73] Kvell, U., Di Cara, D., Janhunen, P., Noorma, M., Gonzales del Amo, J. Deorbiting Strategies: Comparison between Electrostatic Plasma Brake and Conventional Propulsion. In *47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, San Diego, 2011.

[74] Lätt, S., Slavinskis, A., Ilbis, E., Kvell, U., Voormansik, K., Kulu, E. et al. ESTCube-1 nanosatellite for electric solar wind sail in-orbit technology demonstration. *Proceedings of Estonian Academy of Sciences*, submitted, 2013.

[75] Di Cara, D., et al. De-Orbit: Assessment of De-Orbit Options. *ESA CDF Study Report*, Noordwijk, 2009.