ESAIL: project achievements summary Pekka Janhunen, Nov 21, 2013

The following table lists the WP-specific objectives from the Description of Work and the corresponding achievements reached at the end of the project.

WP	Objective of WP from the Description of Work	Description of achievement at end of project
WP21	Design and implement a Tether Factory and produce 1 km long and 2.5 cm wide 4-line Hoytether out of 25-50 μm diameter aluminium wire with it.	Achieved ahead of time. One kilometre long tether was produced in autumn 2012 and later published (Seppänen et al., Rev. Sci. Instrum. 84, 095102, 2013). Here and elsewhere, the originally envisioned U.S. Hoytether geometry was replaced by our own Heytether geometry (named after Henri Seppänen, while Hoytether was named after Robert Hoyt of Tethers Unlimited Inc.) which is easier to manufacture while providing similar micrometeoroid tolerance.
WP22	Assess materials and processes for tether coating which minimise the potential for launch vibration induced cold welding on the reel and possibly improve optical visibility and thermal emission properties of the tether.	Done. Several coatings were studied and Al_2O_3 ALD coating was found which satisfies the requirements apart from a moderate sticking problem. Cold welding does not seem to be a problem even without coating, but thermal emissivity enhancement would be required if Sun-approaching missions are desired. Search for suitable coatings continues with other funding after ESAIL project.
WP23	Vacuum-test the durability and ageing of tether materials by simulating the effect of the solar wind.	Achieved. Bare and ALD coated tethers were subjected to electron bombardment simulating a biased E-sail tether in solar wind. No adverse changes were seen in the tests. Novel theoretical arguments were found that as a potential adverse effect, in the high vacuum of outer space (which is unreachable on ground-based laboratories), outgassing of oxygen from Al_2O_3 might possibly occur.
WP24	Assess different materials and possibilities for the auxiliary tether. The auxiliary tether must provide a mechanical connection between the Remote Units, but it need not be electrically conducting. The auxiliary tether must survive throughout the mission in the space environment i.e. in the presence of micrometeoroids, radiation, vacuum and temperature changes. The absolute strength requirement of the auxiliary tether is not high. There are two variants: centrifugally	Achieved. Several auxtether concepts were analysed and the perforated kapton tape concept was selected for experimental study. A piece of perforated kapton tape was manufactured and its elasticity coefficient was determined, thus establishing that it is possible to tailor the elasticity by perforation. By using more resources, a roll-to-roll process would be possible to develop. We think that the found auxtether solution satisfies essentially all requirements. - The “advanced” stretched

	stabilising (baseline) and elastically stabilising (advanced option) auxiliary tether. According to preliminary mechanical simulations, the elastic option may provide higher performance, but is technically more complex	auxtether option was made into the new baseline during the first half year of the ESAIL project.
WP31	Demonstrate (TRL 3-4) reliable reeling of the tether (WP 21). Test different ways of reeling the Hoytether (e.g. direct and folded) as well as different values for the reeling parameters (e.g. sideways motioning) and come out with recommended values. The baseline is to reel the tether out only once in space. Retraction-capable reeling may be tested also as an option.	Goals exceeded because TRL is higher (the experiment is already in orbit). Hoytether was replaced by operationally equivalent Heytether. Reeling tests were made in two places and several times with different types and lengths of tether, at DLR and at the University of Helsinki. As a torture test, one 10-m tether sample was reeled in and out five times in succession: some of its bonds broke in the process, but the tether did not break. It was discovered that with the tether isolation (housing) in place, unreeling succeeds reliably with as small pull force as 0.02 grams. A 10 m tether is flying with ESTCube-1 and its deployment in orbit will be attempted soon.
WP32	Design and build TRL 4 prototype reel for the tether (WP 21) using experience gained in WP 31. The device should include everything that a flight model would (motors, brakes, electric interface, etc.), but not all components need to be space-qualified in case they are expensive.	Goals were exceeded because achieved TRL is higher: ESTCube-1 reel (10 m tether) is already in orbit and Aalto-1 reel (100 m tether) will be launched in late 2014.
WP33	Similarly to WP 32, build TRL 4 prototype reel for the auxiliary tether (WP 24). The baseline is that the auxiliary tether will be tape-like and therefore easier to reel than the main tether.	Achieved. The constructed auxtether reel satisfied strict mass goals and passed environmental tests both alone and as part of the Remote Unit prototype.
WP41	Design and build prototype of the Remote Unit. The Remote Unit at the tip of each tether hosts the reel of the auxiliary tether, the thruster (gas thruster or FEEP thruster) and a signalling LED (optical beacon) that can be imaged from the main spacecraft. It obeys simple (mostly on/off type) radio commands from the main spacecraft and may send back simple housekeeping data such as temperature readings. The design criteria are minimum mass and reliability. All functions of the unit must work at 1 au distance where deployment is typically carried out. The thrusting function should work at wider solar distance range if possible. The keep-alive and LED functions should work at as wide solar distance range as	Prototype Remote Unit was made and it passed all functional and most of the environmental tests. Because of a trivial mistake made in assembly, the cold end thermal tests did not pass. The tests were not repeated because the test facility also had shortcomings and renting an external test facility would have exceeded the budget. Careful, innovative and successful mass optimisation of the Remote Unit was done. The operational radial distance range 0.9-4 au was selected in the beginning of the project. Although some tests formally failed, we think that overall the Remote Unit project met or exceeded its goals because of the wide radial distance range specification that was

	possible.	achieved. The achieved dry mass for the cold gas version of the unit was 595 grams (measured by weighing the prototype).
WP42	Design, build and test the solar panel based power system of the Remote Unit, including power distribution.	Successfully achieved and integrated with the rest of the Remote Unit.
WP43	Design and build controller and telemetry for the Remote Unit. The Remote Unit controller and telemetry unit needs to be able to receive simple on/off type commands from the main spacecraft and by default also to send back housekeeping data such as temperature values. The unit controls the auxiliary tether reel motor, the thruster and a signalling LED installed on the Remote Unit. The required telemetry rates are low (few bits per second at most) and the nominal maximum distance to the main spacecraft is 20 km. Design targets are reliability, low mass and low power. Modularity in the sense of being compatible with possibly different Remote Unit designs is also a goal.	Successfully achieved and integrated with the rest of the Remote Unit.
WP44	Design, build and test a pyrotechnic device, which can be used to jettison a tether if needed. The device will be placed at the outer end of each tether, in contact with the Remote Unit. The device will provide the thrust needed for the jettisoning of the tether, and it will also serve as an end mass to help the controlled removal of the tether. The jettisoning device may be used only under abnormal conditions, e.g., if a main or auxiliary tether reel gets stuck during deployment or if a main tether breaks during deployment or flight.	Successfully achieved and integrated with the rest of the Remote Unit.
WP45	Design and develop the key propulsion components, based on compressed gas or vaporising liquids as propellant, needed to deploy the electric sail and control its position during flight. In more detail, the objectives of this WP are twofold: 1.To design a propulsion system for the Remote Unit (i.e. on the tip of each tether) suitable to perform the tasks to produce the angular momentum to deploy the tethers and later during the mission to have the capability to modify the spin rate of the tethers if needed.	Successfully achieved. In addition to being compatible with the E-sail Remote Unit (actually slightly "over-compatible"), the produced cold gas propulsion module was made compatible with CubeSat form factor to facilitate flight testing in a CubeSat as part of the QB-50 project or a standalone CubeSat.

	2.To build and test a prototype model of the gas thruster with the objective to demonstrate key performance parameters. The objective of this WP is to reach TRL 4 for the key propulsion components.	
WP46	Design simplified FEEP propulsion subsystem, to be installed on the Remote Unit (WP 4) and suitable for deploying the E-sail and thereafter to optionally control the relative position and velocity of the tether tips during E-sail flight. Build and test a prototype model of the simplified FEEP with the objective to demonstrate key performance parameters. Assess recurring costs of production of the simplified FEEP units at industrial scale.	The ionic liquid FEEP thruster was successfully developed. It was realised that providing current balance for the thruster is nontrivial in the E-sail case. Running thrusters in different Remote Units in alternating polarity modes and balancing their currents through the main tethers was developed as a conceptual solution for dealing with this issue. Another solution would be to install two thrusters per Remote Unit, but that would increase the mass. The developed FEEP thruster was made CubeSat compatible to facilitate flight testing in a CubeSat.
WP51	Provide dynamical simulation of E-sail tether rotation and control for WP 5X .	Two dynamical simulators with mostly complementary properties were programmed and extensively used during the project to assess the flight dynamics of the various study concepts.
WP52	Develop E-sail design concepts at start of project, to obtain specifications according to which component development in other WPs shall take place so that maximum genericness is obtained.	Several tether rig geometries were considered and the stretched auxtether concept was selected at the beginning of the project.
WP53	Refine design concepts of WP 52 to take into account information on the actual prototypes developed in WP 2x-4x, outputting mass budget, power budget and failure scenario analysis for each design.	E-sail mass and power budgets were analysed and published (Janhunen et al., Geosci. Instrum. Method. Data Syst., 2, 85-95, 2013).
WP61	Analyse a number of E-sail missions using refined concepts of WP 53. The ultimate usability of the developed E-sail designs of WP 53 can only be seen when concrete missions are designed around them. For a given E-sail design, the main additional parameters needed to define a mission are the target, the orbit and the payload mass. The payload mass is motivated by the ability to do a useful amount of science at the target (or to return a useful amount of asteroid material in an asteroid resource utilisation mission, etc.). The necessary orbital calculations and	D61.1 has not yet been delivered, but several scientific publications have been made on E-sail mission analysis, the topic is coordinated with ESA's E-sail Working Group and when soon delivered, D61.1 will provide a comprehensive summary of the subject.

	optimisations are performed in WP 62.	
WP62	Do the necessary orbit calculations and optimisations required by WP 61	D62.1 is extensive document and considers the minimum time to achieve a given (large) solar distance, optimal 3-D trajectories to the heliosheath, the Interstellar Heliopause Probe application (nowadays called IP, Interstellar Probe), missions to inner planets, missions to outer planets, rendezvous access times to all potentially hazardous asteroids (PHAs), special study of Apophis, nodal flybys with near-Earth asteroids, sample return case study with 1999 KY-26 and non-Keplerian orbit artificial equilibrium points in the Earht-Moon system.
WP70	Coordinate scientific and technical aspects of the project.	Coordination was successful since all technical WPs achieved or exceeded their goals and we finished the project on time while keeping the budget. The project led to publication of eleven (11) scientific papers in high quality peer-reviewed journals.
WP80	Do common public outreach activities (in addition to normal scientific publishing done by the partners)	Media especially in Finland and Estonia but also in other countries has high interest towards our work, to the point of almost making the E-sail into a household word. The number of listed dissemination activities is 108. As a recent example, the biggest daily newspaper in Finland (Helsingin Sanomat) published a 3-page story of our work in October 2013, and they are using the story in their own major advertising campaigns (with the slogan "The story that got me shine in the coffee table"). Our work has also been covered by magazines such as Scientific American (2 times), New Scientist, Astronomie Heute, Air et Cosmos, Die Welt, Allt om vetenskap and many others.

E-sail status after ESAIL project

The baseline output concept from the project is the **stretched auxtether E-sail with cold gas Remote Units** and with uncoated tethers. Apart from some environmental testing this concept is ready to fly. It has two limitations which were discovered during the project:

i) There is a secular change of the spin-rate if the mission's orbit revolves around the sun with the sail inclined. Remote Unit thrusters must counteract this effect which scales by the tether length and thus by the square root of the total thrust. With default cold gas tank (50 grams of butane), a 10 mN E-sail with 10 tethers each 2 km long could fly for 1 year with sail inclined and orbiting the sun. A fast outer solar system mission or off-Lagrange point near-Earth mission is not affected by this issue because in those cases the spacecraft does not orbit the sun with inclined sail.

ii) The smallest allowed solar distance is roughly 0.9 au, because uncoated aluminium tethers become too warm near the sun.

The secondary output of the project is that the cold gas thrusters could be replaced by **ionic liquid FEEP thrusters**. The total impulse capability of FEEP thrusters is large enough to resolve the secular spin-rate issue (up to 1 N mission which orbits the sun for 5 years). The drawback is that FEEP thrusters are heavier than cold gas thrusters and using them requires current balancing through the main tethers which complicates the operations because different Remote Unit thruster modes must be synchronised.

Looking into future 1: how to improve the baseline concept

1) Although it was not part of the Description of Work and therefore was not formally studied during the project, it seems clear than one can resolve the secular spin rate changing issue by replacing the Remote Unit cold gas or FEEP thruster by a photonic blade. The required area of the blade is 3-4 m^2 and it scales with the tether length. The (triangular or rectangular) blade should be installed on the inner side of the Remote Unit so that the centrifugal force acting on the Remote Unit tends to keep the blade stretched. The blade must be actuated by a single axis twisting actuator. No attitude control system is required because the auxiliary tethers are keeping the Remote Unit in the right orientation. A large enough number of the twisting actuators in different Remote Units must stay operational throughout the mission.

2) If operational range below ~0.9 au is required, one must either develop a suitable aluminium tether coating or one must use some other metal such as copper. The temporal ALD coating method which was investigated during the project has a moderate sticking problem: to counteract sticking, 1 gram pull force was required, while tether tolerates 5 gram pull. We are planning to investigate how to integrate anodisation coating as part of the tether factory. Presumably this would eliminate any sticking problems because the coating is then applied before reeling while in temporal ALD is it applied after reeling. There are also spatial ALD methods which would resolve the sticking issue. However, those methods are rather expensive. Alternatively, replacing aluminium with copper would resolve solar distance range thermal issues directly without any coating. Ultrasonic bonding of copper requires ~+200 C temperature. Integrating this level of local heating with the tether factory would be possible, but would introduce some technical complexity.

3) For missions requiring significantly less thrust than 1 N, the baseline concept must be scaled down. To avoid redesigning the Remote Units, scaling must be done by reducing the tether length and the number of tethers by the same factor. With shorter than 20 km tethers, the thrust produced by each tether is (linearly) smaller while the mass of the Remote Unit and its associated auxiliary tether does not change. Hence as a result of downscaling, performance (thrust per mass) is reduced in comparison to the 1 N system, scaling roughly as the square root of the total thrust. For example a 100 mN E-sail would be about 3 times more lightweight than a 1 N system.

Outside the project, the freely guided photonic blade concept (FGPB) was developed to improve the scaling for smaller than 1 N systems. A hybrid FGPB-auxtether also looks possible. The hybrid approach might retain the robustness of the auxtether concept while reaching improved scaling.

Improved scaling also implies less expensive flight demonstration.

Looking into future 2: what are the needed next steps

While many relevant things could be done, the following tasks have the highest priority (listed in arbitrary order):

1) Maintain and scale up tether production capability upwards from 1 km. This is an acute administrative challenge since the relevant persons are employed on soft money.
2) Measure the E-sail/plasma brake effect in LEO. This is an ongoing effort with ESTCube-1 (currently flying) and Aalto-1 (launch late 2014) CubeSat missions.
3) Measure the E-sail effect in the authentic environment i.e. in the solar wind. Together with Estonians, we are planning to do with with a 3-U CubeSat using a single 1 km tether.
4) Decide upon the preferred tether rig type (auxiliary tethers only, freely guided photonic blades only, their hybrid etc.) and demonstrate its deployment in LEO or in the solar wind. In case of the freely guided photonic blade option, the demonstration might be possible with a nanosatellite (1-10 kg) using a single tether. In the other cases, multiple tethers and a microsatellite platform (10-100 kg) is needed.

Presently, it is not straightforward to get a small demonstration spacecraft into the solar wind at low cost. Therefore with respect to step (3) above, we are monitoring piggyback possibilities may need to tailor the mission architecture according to specific opportunities.

Non-E-sail goals of the ESAIL project

Besides supporting E-sail development, the ESAIL project had as additional goals to support the development of miniature cold gas and ionic liquid FEEP thrusters. Both types of thrusters are enabling technology for nanosatellite sized self-propelled spacecraft which are in turn required e.g. in formation flying Earth orbiting satellite cluster missions and in affordable exploration of near-earth objects for the purpose of planetary protection, asteroid resource prospecting and scientific exploration, among other things (e.g., small autonomous CubeSat sized NEO landers which are deployed by the main spacecraft hovering nearby and acting as radio link). These goals were fully reached: the TRL of both miniature cold gas and ionic liquid FEEP thrusters was raised and both thruster types are nearing their first flight experiments.