	EUROPEAN COMMISSION RESEARCH AND INNOVATION DG	Final Report

Project No: 262733

Project Acronym: ESAIL

Project Full Name: Electric sail propulsion technology

Final Report

Period covered: from 01/12/2010 **to** 30/11/2013

Start date of project: 01/12/2010

Project coordinator name:
Dr. Pekka Janhunen

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Project coordinator organisation name:
ILMATIETEEN LAITOS

Final Report

PROJECT FINAL REPORT

Grant Agreement number:	262733
Project acronym:	ESAIL
Project title:	Electric sail propulsion technology
Funding Scheme:	FP7-CP
Project starting date:	01/12/2010
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Final Report

Please note that the contents of the Final Report can be found in the attachment.

4.1 Final publishable summary report

Executive Summary

Efficient planetary exploration with high scientific return and especially sample return missions call for improved in-space propulsion technologies. The electric sail is a new European invention which has the potential to improve the state of the art by 2-3 orders of magnitude if using the lifetime-integrated total impulse versus propulsion system mass as the figure of merit. The electric sail is a propellantless method which uses the natural solar wind's momentum flux for producing spacecraft propulsion. In the ESAIL project we designed, built and tested prototypes of the key electric sail components (tethers, reels, spinup and guidance/navigation) needed to build a large electric sail ultimately capable of ~1 newton thrust and having ~100 kg propulsion system mass. Specifically, we produced a 1 km long sample of final-type E-sail tether, built and enviromental-tested a laboratory prototype of the so-called Remote Unit (an active nanosatellite-type device installed on the tip of each E-sail tether), built dynamical simulations of how the E-sail flies in real time-varying solar wind, analysed quantitatively how much an E-sail system of given thrust would weigh and made rigorous orbit calculations a large number of E-sail missions in the solar system.

Summary description of project context and objectives

How to move a spacecraft in the solar system is a fundamental problem of space activities. Our present techniques (chemical rockets and ion engines) solve the problem only partially because they enable a total delta-v capability for the spacecraft which is not sufficient to perform some of the more ambitious missions. Also in many cases which are technically possible with the traditional techniques, the cost is nevertheless high because the propulsion system is heavy in comparison to the payload that must be moved.

The electric solar wind sail (electric sail, E-sail) is a novel propellantless propulsion method which is based on harnessing the solar wind for producing spacecraft propulsion. The main objectives of the ESAIL project were the following:

1) Produce 1 km piece of final-type E-sail tether, to prove that manufacturing kilometre length thin and micrometeoroid-resistant multi-wire tethers is possible by University of Helsinki's unique wire-to-wire ultrasonic bonding technique.

2) Demonstrate successful and reliable reeling in and reeling out of the tether, also after the reeled tether has been shaken in a vibration test bench to simulate launch vibrations.

3) Assess coating options for the E-sail tether. A coating is not absolutely necessary, but using a non-metallic coating would reduce the equilibrium temperature of the tethers in space and thus enable shorter solar distances for the mission. A coating would also likely decrease the probability of cold welding on the reel during launch

vibrations (which is however small anyway) and improve optical visibility of the tethers which would be useful although not necessary for diagnostics.

4) Design and build a prototype "Remote Unit": a small autonomous device which hosts the auxiliary tether reels and small thrusters for initiating and controlling the spin of the E-sail tether rig. Furthermore the Remote Unit must be lightweight, it must stay operational in a sufficiently wide solar distance range and it must tolerate the usual launch vibration and space vacuum and thermal environment conditions. Our prototype Remote Unit the solar distance range is 0.9-4 au which we consider a good achievement. Our Remote Unit and other hardware built in the ESAIL project does not contain any radioactive or otherwise dangerous or poisonous substances.

5) Produce and test a piece of prototype auxiliary tether. The auxiliary tether connects together the tips of the main tethers to guarantee dynamical stability of the E-sail tether rig despite solar wind variations.

6) Design, build and test a prototype main tether reel. The main tether reel that we built will be flight-tested in the Aalto-1 CubeSat mission after the project.

7) The Remote Unit is designed with two complementary propulsion options: miniaturised MEMS technology cold gas thruster and similarly miniaturised ionic liquid FEEP thruster. The thrusters are complementary in the sense that the cold gas thruster is at somewhat higher technical readiness level (TRL) while the ionic liquid FEEP thruster has much higher total impulse capability. Both types of thrusters developed in this project, in addition to their use in E-sail Remote Units, are directly applicable for generic attitude and orbit control tasks of satellites and other spacecraft. Because the thrusters are miniaturised, they are in fact enabling technology for small autonomous spacecraft (needed e.g. in economical in situ exploration of asteroids) and for affordable low mass tight formation flying satellite constellations (needed e.g. in more advanced Earth observation and telecommunication applications). The cold gas and ionic liquid FEEP thrusters can also be used as replacements for heavier traditional thrusters in almost any satellite application or spacecraft which needs micropropulsion in the relevant parametre range.

8) Develop software for dynamical simulation of the E-sail in realistic, time-dependent solar wind. The software acts as a "flight simulator" which was used extensively during the project for comparing flight properties of different geometric design options for the E-sail tether rig.

9) Develop quantitative concept for an E-sail spacecraft, including mass budget of its various subsystems. We published our mass budget analysis in a peer reviewed journal.

10) For a wide range of possible E-sail missions, search the mathematically optimal orbits and thrusting schedules for obtaining e.g. the mission flighttimes to different planets and asteroids, as function of E-sail thrust (tether rig size).

11) Public outreach: media interest towards the E-sail invention is

high andwe had a large number of dissemination events and publicity during the project.

Description of main S & T results/foregrounds

See attached file "achievements.pdf". For approximate resource usage, see attached file "approximate-resource-usage.pdf".

Potential impact and main dissemination activities and exploitation results

The E-sail is a device which produces a significant level of propellantless inexhaustible thrust from a system which is lightweight and in principle straightforward to build, and also safe and without poistonous, dangerous or radioactive components. The E-sail could have at least the following direct applications:

1) Enable spacecraft that can tour near-Earth objects and asteroids indefinitely in flyby and rendezvous mode. This is a dramatic improvement over present propulsion methods which allow only one or at most few targets to be explored by one mission before running out of propellant.

2) Enable getting a spacecraft to in principle any target in the solar systemk, with reasonably short traveltime and without increasing the launch mass.

3) Enable also two-way missions for many targets (although not for the outer solar system).

4) Enable missions that hover in an unnatural non-Keplerian orbit for specific tasks such as monitoring the solar wind with longer warning time or to have a permanent view to Earth's or other planet's or Sun's polar region.

5) Enable efficient and safe deorbiting of a satellite, for solving the increasingly acute problem of space debris in low Earth orbit.

Secondarily, the above-listed enabled technical capabilities could in turn enable the following novel kinds of larger application areas:

i) Economically feasible asteroid mining, because the E-sail solves the transportation problem. Asteroids could be mined e.g. for water, platinum group metals and iron and nickel structural materials. Water transported by E-sails to Mars orbit, for example would enable one to make the manned mission return propellant there, thus reducing the cost of manned Mars exploration by a large factor, also potentially enabling reusable vehicles that carry people and freight in both directions between the planets. Platinum group metals are valuable enough to be returned to Earth for direct selling. Iron and nickel from metallic asteroids could be used for large space constructions using e.g. remotely operated 3-D printing technology. In all the cases, the role of the E-sail is to transport the materials between asteroids and Earth or other planet.

ii) A traditional planetary mission requires a dedicated launch because the launcher upper stage typically gives the heliocentric kick towards the chosen planet. Because escape orbit capable launchers are all rather big and therefore expensive (the smallest one is currently Soyuz), this effectively means that a small planetary mission is not possible. When using the E-sail, this limitation is removed because

any escape orbit is a possible starting orbit for any E-sail mission. Thus, several small E-sail probes could be launched with one escape-capable launcher, and the probes can be destined to different targets in the solar system. Thus, the E-sail is enabling technology for small, affordable deep space missions.

People and media have recognised these capabilities, broadly speaking. The media interest towards the E-sail is consistently high. We are interacting with the media often and the news spread far and wide. Some details are available in the Dissemination activities list included in this Final Report which contains 108 entries. The list is not complete because we are not practically able to keep track of all media attention that the E-sail project is receiving. As a recent example, our Estonian project partner Dr. Mart Noorma was selected the "citisen of the year 2013" in Estonia the launch of the E-sail testing satellite ESTCube-1 was voted as the "event of the year", and the prime minister of Estonia (Andrus Ansip) covered ESTCube-1 and the E-sail invention in his yearly speech to the Estonian Parliament in December 2013.

In short, the societal importance is that the E-sail could revolutionise space technology. Up to this point (TRL 4-5) the development has gone well and no potential show stopper are seen. The needed next step is testing and validation in space.

Address of project public website and relevant contact details

ESAIL-specific website: http://www.electric-sailing.fi/fp7
General electric sail website: http://www.electric-sailing.fi
Finnish language general audience E-sail blog: http://www.electric-sailing.blogspot.fi
Contact: Pekka Janhunen, pekka.janhunen@fmi.fi, +358 29 539 4635

4.2 Use and dissemination of foreground

Section A (public)

Publications

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES											
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Permanent identifiers (if applicable)	Is open access provided to this publication ?	Type
1	Invited Article: Electric solar wind sail: Toward test missions http://dx.doi .org/10.1063/1.3514548	P. Janhunen , P. K. Toivanen , J. Polkko , S. Merikallio , P. Salminen , E. Haeggstro#m , H. Seppa#nen , R. Kurppa , J. Ukkonen , S. Kiprich , G. Thornell , H. Kratz , L. Richter , O. Kro#mer , R. Rosta , M. Noorma , J. Envall , S. La#tt , G. Mengali , A. A. Quarta , H. Koivisto , O. Tarvainen , T. Kalvas , J. Kauppinen , A. Nuottaja#rvi	Review of Scientific Instruments	Vol. 81/Issue 11	American Institute of Physics Inc.	United States	01/01/2010	111301		Yes	Peer reviewed

		, A. Obraztsov									
2	One kilometer (1 km) electric solar wind sail tether produced automatically 10.1063/1.481 9795	Henri Seppa#nen , Timo Rauhala , Sergiy Kiprich , Jukka Ukkonen , Martin Simonsson , Risto Kurppa , Pekka Janhunen , Edward Hæggstro #m	Review of Scientific Instruments	Vol. 84/Issue 9	American Institute of Physics Inc.	United States	01/01/2013	095102			Peer reviewed
3	Electrostatic Plasma Brake for Deorbiting a Satellite 10.2514/1.475 37	Pekka Janhunen	Journal of Propulsion and Power	Vol. 26/Issue 2	American Institute of Aeronautics and Astronautics Inc. (AIAA)	United States	01/03/2010	370-372		Yes	Peer reviewed
4	Spin Plane Control and Thrust Vectoring of Electric Solar Wind Sail 10.2514/1.B34 330	Petri K. Toivanen , Pekka Janhunen	Journal of Propulsion and Power	Vol. 29/Issue 1	American Institute of Aeronautics and Astronautics Inc. (AIAA)	United States	01/01/2013	178-185		Yes	Peer reviewed
5	Wire-to-wire bonding of µm-diameter aluminum wires for the Electric Solar Wind Sail 10.1016/j.mee .2011.07.002	Henri Seppänen , Sergiy Kiprich , Risto Kurppa , Pekka Janhunen , Edward Hæggströ m	Microelectron ic Engineering	Vol. 88/Issue 11	Elsevier	Netherlands	01/11/2011	3267-3269		Yes	Peer reviewed
6	Electric solar wind sail mass budget model 10.5194/gi-2- 85-2013	P. Janhunen , A. A. Quarta , G. Mengali	Geoscientific Instrumentation, Methods and Data Systems (GI)	Vol. 2/Issue 1	Copernicus GmbH (Copernicus Publications)	Germany	01/01/2013	85-95		Yes	Peer reviewed
7	Electric sail missions to potentially hazardous asteroids http://dx.doi .org/10.1016/j.actaastro. 2009.11.021	Alessandro A. Quarta , Giovanni Mengali	Acta Astronautica	Vol. 66/Issue 9-10	Elsevier Limited	United Kingdom	01/05/2010	1506-1519		Yes	Peer reviewed
8	Optimal interplanetary rendezvous combining electric sail and high thrust propulsion system http://dx.doi .org/10.1016/j.actaastro. 2010.01.024	Alessandro A. Quarta , Giovanni Mengali , Pekka Janhunen	Acta Astronautica	Vol. 68/Issue 5-6	Elsevier Limited	United Kingdom	01/03/2011	603-621		Yes	Peer reviewed
9	Moving an asteroid with electric solar wind	S. Merikallio	Astrophysics and Space Sc	Vol. 6/Iss	Copernicus Group	Germany	01/01/2010	41-48		Yes	Peer revie

	sail 10.5194/astra -6-41-2010	, P. Janhunen	iences Transactions	ue 1							wed
10	Electric Sail Mission Analysis for Outer Solar System Exploration 10.2514/1.470 06	Alessandr o A. Quarta , Gi ovanni Men gali	Journal of Guidance, Cont rol, and Dynamics	Vol. 33/Is sue 3	American Institute of Aeronautics and As tronautics Inc. (AIA A)	United States	01/05/2010	740-755		Yes	Peer revie wed
11	Photonic spin control for solar wind ele ctric sail http://dx.doi .org/10.1016/j.actaastro. 20 12.10.017	Pekka Janh unen	Acta Astronautica	Vol. 83	Elsevier Limited	United Kingdom	01/02/2013	85-90		Yes	Peer revie wed
12	Electric sail, photonic sail and deorbiting a pplications of the freely guided photonic blade http://dx.doi .org/10.1016/j.actaastro. 20 13.07.041	Pekka Janh unen	Acta Astronautica	Vol. 93	Elsevier Limited	United Kingdom	01/01/2014	410-417		Yes	Peer revie wed
13	Electric sail for near-Earth asteroid sample return mission: case 1998 KY26	Quarta, A., G. Mengali and P. Janhunen	Journal of Aerospace Engi neering	In press	American Society of Civil Engineers (ASC E)		31/12/2014	Not known yet		Yes	Peer revie wed
14	A graphical approach to electric sail mi ssion design with radial thrust http://dx.doi .org/10.1016/j.actaastro. 20 12.03.022	Giovanni M engali , Alessa nd ro A. Qu arta , Gen eroso Aliasi	Acta Astronautica	Vol. 82/Is sue 2	Elsevier Limited	United Kingdom	01/02/2013	197-208		Yes	Peer revie wed
15	Status report of the electric sail in 2009 http://dx.doi .org/10.1016/j.actaastro. 20 10.02.007	Pekka Janh unen	Acta Astronautica	Vol. 68/Is sue 5-6	Elsevier Limited	United Kingdom	01/03/2011	567-570		Yes	Peer revie wed

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Press releases	ILMATIETEEN LAITOS	EU project to build Electric Solar Wind Sail	09/12/2010	Finnish Meteorological Institute	Medias	1000	All
2	Presentations	ILMATIETEEN LAITOS	Development of electric solar wind sail propellantless propulsion for solar system access	08/12/2010	Brussels, FP8-SPACE Hearing Event	Industry - Policy makers	300	All European
3	Interviews	ILMATIETEEN LAITOS	Estonian TV interview ("Pealtnägija" show, 10 min)	10/12/2010	Finnish Meteorological Institute	Civil society	500000	Estonia
4	Articles published in the popular press	ILMATIETEEN LAITOS	Popular article in "Tekniikan Maailma" (World of Technology)	18/02/2011	Most popular big audience technology magazine of Finland, "The world of Technology"	Civil society	551000	Finland
5	Presentations	ILMATIETEEN LAITOS	Electric solar wind sail technology	09/02/2011	Tartu Observatory Science Center	Scientific community (higher education, Research) - Policy makers - Medias	80	Estonia
6	Articles published in the popular press	ILMATIETEEN LAITOS	Long interview of E-sail scientists	10/04/2011	Uusimaa newspaper	Civil society	120000	Finland
7	Articles published in the popular press	ILMATIETEEN LAITOS	Article on E-sail technology	18/04/2011	Tähdet and Avaruus (Stars and Space), the most popular astromagazine of nordic countries	Civil society	75000	Finland
8	Presentations	ILMATIETEEN LAITOS	Talk in URSA seminar series	15/03/2011	Helsinki, Finland	Civil society	50	Finland
9	Presentations	ILMATIETEEN LAITOS	Talk in URSA seminar series	22/03/2011	Helsinki, Finland	Civil society	50	Finland
10	Presentations	ILMATIETEEN LAITOS	Talk in URSA seminar series	30/03/2011	Helsinki, Finland	Civil society	50	Finland

11	Presentations	ILMATIETEEN LAITOS	Talk in Finnish Geophysical Society s meeting	22/03/2011	Helsinki, Finland	Scientific comm unity (higher educat ion, Research) - Civ il society	30	Finland
12	Presentations	ILMATIETEEN LAITOS	Public talk of E-sails possibilities	17/04/2011	Helsinki, Finland	Civil society	20	Finland
13	Oral presentation to a wider public	ILMATIETEEN LAITOS	Oasis of Excellence, Innovation seminar	14/05/2011	Caribbean	Industry	40	USA, Finland
14	Articles published in the popular press	ILMATIETEEN LAITOS	interview of an ESAIL -scientists	05/01/2012	APU -magazine	Civil society	180000	Finland
15	Presentations	ILMATIETEEN LAITOS	Presentation for Rot ary eClub	24/01/2012	international online talk broadcasted fr om Helsinki, Fi nland	Civil society - Poli cy makers	200	All
16	Articles published in the popular press	ILMATIETEEN LAITOS	Aalto-1, story on Fi nlands first satellite and its payload	03/09/2011	Turun Sanomat, reagional newsp aper	Civil society	250000	Finland
17	Articles published in the popular press	ILMATIETEEN LAITOS	"Sailing to the edges of our solar system" - newspaper story	05/10/2011	Kouvolan Sanomat, regional newspaper	Civil society	70000	Finland
18	Presentations	UPPSALA UN IVERSITET	Presentation for the university's Division of Microsystems T echnology	01/03/2011	Uppsala, Sweden	Scientific comm unity (higher educat ion, Research)	30	Sweden
19	Presentations	UPPSALA UN IVERSITET	Talk for two highsch ool classes from Uppsala	03/10/2011	Uppsala, Sweden	Civil society	60	Sweden
20	Presentations	UPPSALA UN IVERSITET	presentation for ÅSTC steering committee	01/04/2011	Uppsala, Sweden	Scientific comm unity (higher educat ion, Research) - Pol icy makers	20	Sweden
21	Presentations	UPPSALA UN IVERSITET	presentation for ÅSTC steering committee	03/10/2011	Uppsala, Sweden	Policy makers	20	Sweden
22	Presentations	UPPSALA UN IVERSITET	presentation for ÅSTC steering committee	16/01/2012	Uppsala, Sweden	Policy makers	20	Sweden
23	Organisation of Conference	UNIVERSITA DI P ISA	presentation for 7th IAA Symposium on	12/07/2011	Aosta, Italy	Scientific comm unity (higher educat	40	International

			Realistic Near-Term Advanced Scientific Space Missions			ion, Research)		
24	Publication	UNIVERSITA DI PISA	"Artificial equilibrium points for a generalized sail in the circular restricted three-body problem"	12/07/2011	Article in Celest. Mech. Dyn. Astr.	Scientific community (higher education, Research)		International
25	Publication	UNIVERSITA DI PISA	A Graphical Approach to E-sail Mission Design with Radial Thrust	11/07/2011	A Paper submitted to 7th Symposium on Realistic Advanced Scientific Space Missions	Scientific community (higher education, Research)		international
26	Organisation of Conference	ILMATIETEEN LAITOS	"2011 Electric Solar Wind Sail: Discovering solar system further and faster"	02/09/2011	FinCospar conference, Kemiö, Finland	Scientific community (higher education, Research)	50	Finland
27	Posters	ILMATIETEEN LAITOS	Sailing with E-Sail to the outer planets	03/10/2011	European Planetary Science Conference EPSC, Nantes, France	Scientific community (higher education, Research)	500	International
28	Posters	ILMATIETEEN LAITOS	Jupiter, Saturn, Uranus and Neptune; gas giants one launch away	04/10/2011	European Planetary Science Conference EPSC, Nantes, France	Scientific community (higher education, Research)	500	International
29	Posters	ILMATIETEEN LAITOS	Asteroid touring mission with Electric Solar Wind Sail	06/10/2011	European Planetary Science Conference EPSC, Nantes, France	Scientific community (higher education, Research)	500	International
30	Presentations	UNIVERSITA DI PISA	Electric sail performance with purely radial thrust	13/04/2011	Italy, Pisa, Department of Aerospace Engineering	Scientific community (higher education, Research)	35	Italy
31	Presentations	UNIVERSITA DI PISA	Mission Applications for Low-Thrust Spacecraft Configurations	23/09/2011	University of Pisa, Faculty of Engineering, Italy	Scientific community (higher education, Research)	80	Italy
32	Organisation of Conference	UNIVERSITA DI PISA	Electric Sail Mass Breakdown for High-Energy Missions	28/04/2011	Torino, Italy	Scientific community (higher education, Research)	100	Italy
33	Thesis	UNIVERSITA DI PISA	Electric Sail mass breakdown model	12/07/2011	University of Pisa, Faculty of Engi	Scientific community (higher educat	40	Italy

					neering, Italy	ion, Research) - Civ il society		
34	Organisation of Workshops	HELSINGIN YLIOPISTO	Multifilament T ether for Electric S olar Wind Sail	14/07/2011	IMAPS Workshop on Wire Bonding, San Francisco, USA	Scientific comm unity (higher educat ion, Research)	100	International
35	Organisation of Conference	ILMATIETEEN LAITOS	2nd EU Space Co nference	16/11/2012	Larnaca, Cyprus	Scientific comm unity (higher educat ion, Research) - Ind ustry - Policy makers	60	International
36	Organisation of Conference	ILMATIETEEN LAITOS	Electric Solar Wind Sail (E-sail) mission to asteroids	15/07/2012	39th COSPAR Sci entific Assembly, Mysore, India	Scientific comm unity (higher educat ion, Research)	200	International
37	Publication	ILMATIETEEN LAITOS	Space Research in F inland, report to CO SPAR 2012	01/07/2012	Printed report, download available at www.cospar.fi	Scientific comm unity (higher educat ion, Research) - Ind ustry - Civil society - Policy makers	5000	International
38	Organisation of Workshops	ILMATIETEEN LAITOS	Electrostatic plasma brake for satellite deorbiting	24/04/2012	SOSTC AIAA, Imp roving Space Op erations Workshop, Jet Proppulsion Laboratory, Pas adena, USA	Scientific comm unity (higher educat ion, Research) - Ind ustry	200	International
39	Publication	HELSINGIN YLIOPISTO	Wire-to-wire bo nding of um-dia meter aluminum wires for the Electr ic Solar Wind Sail	01/01/2011	Microelectronic Engineering, 88, 32 67-3269, 2011	Scientific comm unity (higher educat ion, Research)		International
40	Publication	ILMATIETEEN LAITOS	Spin plane control a nd thrust vectoring of electric solar wi nd sail by tether po tential modulation	01/11/2012	J. Prop. Power, 29, 178-185, 2013	Scientific comm unity (higher educat ion, Research)		International
41	Publication	UNIVERSITA DI P ISA	A graphical approac h to electric sail m ission design with r adial thrust	01/11/2012	Acta Astronautica, 82, 197-208, 2013	Scientific comm unity (higher educat ion, Research)		International
42	Publication	UNIVERSITA DI P ISA	Electric sail for ne ar-Earth asteroid sa	01/11/2012	J. Aerospace Eng.	Scientific comm unity (higher educat		International

			mple return mission: case 1998 KY26			ion, Research)		
43	Publication	ILMATIETEEN LAITOS	Photonic spin contr ol for solar wind el ectric sail	01/01/2013	Acta Astronautica, 83, 85-90, 2013	Scientific comm unity (higher educat ion, Research)		International
44	Organisation of Conference	ILMATIETEEN LAITOS	Attitude dynamics analysis of Aalto-1 satellite during de-or biting experiment wi th Plasma Brake	01/10/2012	63rd Int. Astronauti ca. Congress, N aples, Italy, Oct 1-5 2012, IAC-12-B4.2. 11, 2012.	Scientific comm unity (higher educat ion, Research) - Ind ustry		International
45	Organisation of Conference	ILMATIETEEN LAITOS	Possibilities opened by electric solar w ind sail technology	01/10/2012	63rd Int. Astronauti ca. Congress, N aples, Italy, Oct 1-5 2012, IAC-12-D4.1.4, 2012	Scientific comm unity (higher educat ion, Research)		International
46	Organisation of Conference	ILMATIETEEN LAITOS	PIC simulation of E lectric Sail with ex plicit trapped elect ron modelling	13/07/2012	ASTRONUM-2 011, Valencia, Spain, June 13-17, ASP Conf. Ser. 4 59, 271, 2012	Scientific comm unity (higher educat ion, Research)		International
47	Publication	ILMATIETEEN LAITOS	Electric solar wind sail propulsion syst em development	11/11/2011	International Electr ic Propulsion C onference IEPC-2011-058, Wiesb aden, Germany	Scientific comm unity (higher educat ion, Research)		International
48	Presentations	ILMATIETEEN LAITOS	Electric sail and pl asma brake for effic ient interplanetary propulsion and satel lite deorbiting	30/11/2012	Finnish Meteoro logical Institute - UK Space Agency Colloquium	Scientific comm unity (higher educat ion, Research) - Ind ustry - Policy makers - Medias	100	Finland, UK
49	Interviews	HELSINGIN YLIOPISTO	How do one expe riment the E-sail?	12/03/2013	Tiede -magazine 3/2012	Civil society	290000	Finland
50	Presentations	ILMATIETEEN LAITOS	Sailing in the solar system - presentati on for finnish MENSA	07/02/2013	Hotel Arthur, H elsinki	Civil society - Poli cy makers	30	Finland
51	Articles published in the popular press	ILMATIETEEN LAITOS	Finnish Electric sail heading towards sp ace on board an Esto nian satellite.	01/04/2013	Helsingin sanomat	Civil society - Poli cy makers	1000000	Finland
52	Web sites/Appli	ILMATIETEEN	The remote unit	25/03/2013	www.verkkouutis	Civil society - Medi	30000	Finland

	cations	LAITOS	succesfully tested in the laboratory		et.fi	as		
53	Web sites/Applications	ILMATIETEEN LAITOS	Finnis electric sail got a remote unit.	26/03/2013	http://www.avaruus.fi/uutiset/kantoraketit-ja-satelliitit/suomalainen-sahkopurje-sai-etayksikon.html	Civil society	3000	Finland
54	Web sites/Applications	HELSINGIN YLIOPISTO	Breakthrough for the finnish E-sail: "Now we can manufacture the sail"	25/03/2013	http://www.uusisuomi.fi/comment/546383	Civil society - Medias	300000	Finland
55	Articles published in the popular press	ILMATIETEEN LAITOS	Wild vision: Finnish invention could save us from a 8.5 mega ton explosion.	27/03/2013	Uusi Suomi news paper and www-page	Civil society - Policy makers	300000	Finland
56	Web sites/Applications	UPPSALA UNIVERSITET	Elektriskt solvindsegel ett steg närmare målet	25/03/2013	www.forskning.se	Scientific community (higher education, Research) - Civil society	100000	Sweden
57	Web sites/Applications	UPPSALA UNIVERSITET	Uppsala universitet med och tillverkar rymdsegel	25/03/2013	http://evertiq.se/news/26084	Civil society	9999	Sweden
58	Press releases	ILMATIETEEN LAITOS	Sähköpurjeen et äyksikköä testattiin onnistuneesti laboratoriossa	25/03/2013	Finnish Meteorological Institute press release	Medias	1000	Finland
59	Press releases	UPPSALA UNIVERSITET	Electric solar wind sailing spacecraft an important step closer	25/03/2013	Uppsala University press release	Medias	1000	Sweden
60	Publication	ILMATIETEEN LAITOS	Electric solar wind sail mass budget model	01/01/2013	Geoscientific Instrumentation, Methods and Data Systems journal	Scientific community (higher education, Research)		International
61	Publication	ILMATIETEEN LAITOS	Electric sail, photonic sail and deorbiting applications of the freely guided photonic blade	10/01/2013	Acta Astronautica	Scientific community (higher education, Research)		International
62	Organisation of Conference	HELSINGIN YLIOPISTO	Automatic 4-wire Heytether producti	22/01/2013	International Microelectronics Ass	Scientific community (higher educat	300	International

			on for the electric solar wind sail		embly and Packing Society Topical W orkshop and Tab letop Exhibitio	ion, Research) - Ind ustry		
63	Oral presentation to a scientific event	ILMATIETEEN LAITOS	Uranus and Nept une: ice giants one launch away	18/09/2013	Uranus Workshop, Meudon Observ atory, Paris, France	Scientific comm unity (higher educat ion, Research)	90	international
64	Oral presentation to a scientific event	ILMATIETEEN LAITOS	Uranus and Neptune to be Scouted by E-sail	20/09/2013	FinCospar Confe rence, Vantaa, Finla nd	Scientific comm unity (higher educat ion, Research)	80	Finland, USA, N etherlands
65	Oral presentation to a wider public	ILMATIETEEN LAITOS	With a rover to Mars and an E-sail to Sa turn - public talk in finnish	05/10/2013	Science Fare Center Heureka, Vantaa, Finland	Civil society	250	Finland
66	Articles published in the popular press	ILMATIETEEN LAITOS	E-sail might help in asteroid conquest	19/10/2013	Helsingin Sanomat (the main daily n ews paper of Fi nland), also main news in online pa per	Civil society	1000000	Finland
67	Publication	HELSINGIN YLIOPISTO	One kilometer (1 km) electric solar wind sail tether pr oduced automati cally	01/01/2013	Review of Scien tific Instruments, v ol. 84, no. 9	Scientific comm unity (higher educat ion, Research)		International
68	Oral presentation to a scientific event	HELSINGIN YLIOPISTO	Space Tether Pr oduced to Strength S pecification.	21/07/2013	International Ultras onics Symposium (IUS), 21-25 July 2 013, Prague, Czech Republic	Scientific comm unity (higher educat ion, Research)	100	International
69	Oral presentation to a scientific event	HELSINGIN YLIOPISTO	Determining the Quality of Space Te ther in a Nondestruc tive manner	21/07/2013	International Ultras onics Symposium (IUS), 21-25 July 2 013, Prague, Czech Republic	Scientific comm unity (higher educat ion, Research)	100	International
70	Articles published in the popular press	HELSINGIN YLIOPISTO	Article on 1km E-sai l tether production	01/03/2013	Tähdet and Avar uus - magazine 2/2013	Civil society	75000	Finland
71	Press releases	HELSINGIN YLIOPISTO	1km of E-sail tether produced	07/01/2013	University of H elsinki press release	Civil society - Medi as		Finland
72	Press releases	HELSINGIN	E-Sailing at last! (	07/05/2013	University of H	Civil society - Medi		Finland

		YLIOPISTO	EstCube lauch s uccessful)		elsinki press release	as		
73	Posters	HELSINGIN YLIOPISTO	Quality assured teth er for electric solar sail	12/03/2013	Physics days 2013	Scientific comm unity (higher educat ion, Research)	200	Finland
74	Oral presentation to a scientific event	HELSINGIN YLIOPISTO	Space Tether pr oduced to Strength S pecification	22/07/2013	UFFC 2013, Prague	Scientific comm unity (higher educat ion, Research)	200	International
75	Posters	HELSINGIN YLIOPISTO	Determining the quality of space te ther in a nondestruc tive manner	21/07/2013	UFFC 2013, Prague	Scientific comm unity (higher educat ion, Research)	200	International
76	Publication	UPPSALA UN IVERSITET	Embedded i rymden	04/10/2011	Elektronik i No rden, http://www.el inor.se/index.p hp/Dow	Scientific comm unity (higher educat ion, Research) - Ind ustry	10000	Sweden
77	Press releases	UPPSALA UN IVERSITET	Uppsala universitet utvecklar miniatyrfa rkost för gigantiskt rymdsegel	07/03/2012	http://www.uu.s e/press/pressme ddelanden/press meddelande-visn ing/?id=1615&ar ea=3&typ=p m&na=&lang=sv	Medias		Sweden
78	Web sites/Appli cations	UPPSALA UN IVERSITET	Uppsala universitet utvecklar miniatyrfa rkost för gigantiskt rymdsegel	07/03/2012	Forskning (www. forskning.se)	Civil society	100000	Sweden
79	Articles published in the popular press	UPPSALA UN IVERSITET	Uppsala bygger pyttelitet segelskepp för rymden	21/08/2012	Dagens industri	Industry - Civil soc iety	2000000	Sweden
80	Interviews	UPPSALA UN IVERSITET	Jättesnabb farkost s ka segla på solvinde n	01/12/2012	Swedens radio, sver igesradio.se/sida/gr uppsida.aspx?pr ogramid=4131&gr upp=18801&artik el=5364728	Civil society	1000000	Sweden
81	Web sites/Appli cations	UPPSALA UN IVERSITET	Uppsalas ”ångst römar” ökar farten i rymden	01/10/2012	Cassiopeiabloggen No 53, http://www .astb.se/cassiopeiab loggen/?p=28401	Civil society	200	Sweden
82	Web sites/Appli	UPPSALA UN	Fråga Uppsala!	01/11/2012	Cassiopeiabloggen	Civil society	200	Sweden

	cations	IVERSITET			No 54, 2012 http://www.astb.se/cassiopeiabloggen/?p=28447			
83	Articles published in the popular press	UPPSALA UNIVERSITET	Uppsalaforskare hissar solsegel	28/03/2013	Forskning och framsteg, http://fof.se/tidning/2013/5/artikel/uppsalaforskare-hissar-solsegel	Industry - Civil society	500000	Sweden
84	Articles published in the popular press	UPPSALA UNIVERSITET	Uppsala hissar solsegel	16/04/2013	Ny Teknik, http://www.nyteknik.se/nyheter/fordon_motor/rymden/article3676922.ece	Industry - Civil society	500000	Sweden
85	Articles published in the popular press	UPPSALA UNIVERSITET	Medvind för elektrsikt solsegel	25/06/2013	Allt om vetenskap	Civil society	135000	Sweden
86	Oral presentation to a wider public	UPPSALA UNIVERSITET	Stora krav på det lilla ... – mikroteknik för krävande miljöer, särskilt rymden	13/02/2013	Tekniska föreningen , Sweden	Civil society	20	Sweden
87	Oral presentation to a wider public	UPPSALA UNIVERSITET	Mikro- & nanoteknik för krävande miljöer	31/05/2013	Uppsala, group visits to university facilities	Civil society	200	Sweden
88	Publication	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	New satellite sail is propelled by solar protons	07/05/2013	New Scientist	Civil society	300000	International
89	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Electric Space Sail to Get Its First Test	02/05/2013	http://spectrum.ieee.org/tech-talk/aerospace/astrophysics/electric-space-sail-to-get-its-first-test	Scientific community (higher education, Research)	100000	International
90	Articles published in the popular press	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Ergma jälgib Prantsuse Guajaanas Estcube-1 starti	01/05/2013	Postimees, an Estonian news paper	Civil society	200000	Estonia

91	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	ESTCube-1 ja Robotexi meeskond pälvis ITL-i aasta auhinna	29/04/2013	http://www.ut.ee/et/uudised/estcube-1-robotexi-meeskond-palvis-itl-i-aastaauhinna	Civil society	10000	Estonia
92	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Ülevaade ESTCube-1 missioonist	24/01/2013	teadus.err.ee	Civil society	5000	Estonia
93	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	VIDEOD ja FOTOD: Eesti esimese satelliidi EstCube viimane esitlus enne teele saatmist	21/01/2013	http://forte.delfi.ee/	Civil society	50000	Estonia
94	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	PRESSITEADE: Eesti kosmosesatelliit ESTCube-1 asub teele stardipaigale	21/01/2013	http://forte.delfi.ee/	Civil society	50000	Estonia
95	Articles published in the popular press	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Jaak Kilmi: film Eesti satelliidist saab olema kriiside ajal ugu	19/01/2013	www.ohtuleht.ee/507024	Civil society		Estonia
96	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Eesti satelliit püsib grafikus	17/01/2013	http://www.teadus.ee/?p=4475	Civil society		Estonia
97	Web sites/Applications	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Eesti esimene satelliit on valmimas	14/01/2013	http://teadus.err.ee/artikkel?cat=1&id=8237	Civil society		Estonia
98	Articles published in	TARTU OBSE	Tudengisatelliit läb	10/01/2013	Tartu Postimees	Civil society		Estonia

	the popular press	RVATORY -E STONIAN MI NISTRY OF EDUCATION AND RESEARCH	ib tugevusproovi		http://www.tartupostimees.ee/1098692/tudengisatelliit-labib-tugevusproovi			
99	Web sites/Applications	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Eestlased on oma satelliidi orbiidile saatmisele väga lähedale jõudnud	05/01/2013	forte.delfi.ee	Civil society		Estonia
100	Web sites/Applications	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Tudengisatelliit EST Cube - 1 leidisriigi kogus tunnustust	21/12/2012	http://teadus.err.ee/artikkel?cat=1&id=8147	Civil society		Estonia
101	Web sites/Applications	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Tudengisatelliit EST Cube - 1	29/12/2012	http://www.ohtuleht.ee/501334	Civil society		Estonia
102	Web sites/Applications	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Eesti oma tehiskaaslane pole kogukam, kui leivapäts	23/11/2012	Maaleht http://maaleht.delfi.ee/	Civil society		Estonia
103	Web sites/Applications	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Koos tudengisatelliidiga valmib ka uus missioonijuhtimi starkvara	13/09/2011	http://teadus.err.ee/artikkel?id=5183&cat=1	Civil society		Estonia
104	Interviews	TARTU OBSERVATORY -E STONIAN MINISTRY OF EDUCATION AND RESEARCH	Eesti esimese tudengisatelliidi ehitus edeneb jõudsalt	06/09/2011	Raadio Elmar, http://www.elmar.ee/index.php?pid=4&lang=1&nid=438	Civil society		Estonia
105	Publication	UNIVERSITA DI PISA	Artificial Equilibrium Points for a	01/10/2012	Celestial Mechanics and Dynamical	Scientific community (higher educat		International

			Generalized Sail in the Elliptic Restricted Three-Body Problem		Astronomy	ion, Research)		
106	Publication	UNIVERSITA DI PISA	Trajectory Approximation for Low-Performance Electric Sail with Constant Thrust Angle	01/05/2013	Journal of Guidance, Control, and Dynamics	Scientific community (higher education, Research)		International
107	Publication	UNIVERSITA DI PISA	Optimal Interplanetary Rendezvous Combining Electric Sail and High Thrust Propulsion System	01/03/2011	Acta Astronautica	Scientific community (higher education, Research)		International
108	TV clips	ILMATIETEEN LAITOS	Sähköpurjehdusta avaruudessa	01/05/2012	YLE television broadcast, http://www.youtube.com/watch?v=WJ4yB6ow3hE	Civil society	500000	Finland

Section B (Confidential or public: confidential information marked clearly)

LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS,UTILITY MODELS, ETC.					
Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)
Patents	No		EP1989114B1	Electric sail for producing spacecraft propulsion	Janhunen, P.
Patents	No		US7641151B2	Electric sail for producing spacecraft propulsion	Janhunen, P.
Patents	No		CN101395060B	Electric sail for producing spacecraft propulsion	Janhunen, P.
Patents	No		DE602007010736D1	Elektrisches segel zur erzeugung des antriebs für ein raumfahrzeug	Janhunen, P.

OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND								
Type of Exploitable Foreground	Description of Exploitable Foreground	Confidential	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use or any other use	Patents or other IPR exploitation (licences)	Owner and Other Beneficiary(s) involved
Commercial exploitation of R&D results	Nanospace AB cold gas thruster	No		Highly miniaturised cold gas thruster suitable for satellite attitude and orbit control	Satellites, nanosatellites, space exploration	Flight qualification expected 2015, then immediatelly available for commercial exploitation	Thruster technical solutions covered by several patents	Nanospace AB, Uppsala, Sweden
Commercial exploitation of R&D results	Alta ionic liquid FEEP thruster	No		Thruster usable for satellite attitude and orbit control	Satellites, nanosatellites, space exploration	Prototype working, flight qualification under scrutiny	Not patented	Alta S.p.A., Pisa, Italy
Commercial exploitation of R&D results	Plasma brake for satellite deorbiting, Spinoff invention of the electric solar wind sail	No		Promising technique for efficient and safe deorbiting of satellites	Satellites, active space debris removal	Prototype flying, experimented scheduled soon; if successful, commercialisation can begin immediately	Not covered by patents, except those covering the electric solar wind sail	Pekka Janhunen, Finnish Meteorological Institute
General advancement of knowledge	We know that it is possible to produce long electric sail tethers and the other critical components, and we also know how.	No		The information is necessary and useful in designing and building an electric solar wind sail or plasma brake device	In-space propulsion	Looking for flight demonstration opportunities for 2016, commercialisation can begin after that	Electric sail design is patented	Pekka Janhunen, Finnish Meteorological Institute
General advancement of knowledge	Ultrasonic wire-to-wire bonding	No		General method for bonding together very thin metal wires	Electronics, mechanical engineering	Besides the E-sail/plasma brake space tether applications, we have not yet identified other (ground-based) applications.	Not patented	Electronics Research Laboratory, University of Helsinki

ADDITIONAL TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND	
Description of Exploitable Foreground	Explain of the Exploitable Foreground
Nanospace AB cold gas thruster	Cold gas thrusters are widely used for attitude and orbit control in satellites and other space vehicles. Nanospace cold gas thruster is highly miniaturised MEMS technology system so that the thruster is orders of magnitude smaller than traditional thrusters. Nanospace cold gas thruster is enabling technology for implementing a small autonomous spacecraft (satellite or other spacecraft) which is able to control its attitude without help from Earth's magnetic field,

	thus working also in deep space. This in turn is enabling technology for economical in situ robotic exploration of e.g. near-Earth objects. Nanospace cold gas thruster is also enabling technology for implementing small satellites capable of accurate formation flying. This in turn is enabling technology for Earth observation and telecom satellite clusters.
Alta ionic liquid FEEP thruster	Alta's ionic liquid FEEP thruster can be used in similar applications as Nanospace cold gas thruster (see applications above). The main difference is that the FEEP thruster has orders of magnitude higher total impulse capability than the cold gas thruster.
Plasma brake for satellite deorbiting, Spinoff invention of the electric solar wind sail	The plasma brake can be used for efficient and safe deorbiting of satellites and other space debris objects. With a single tether, the maximums debris object mass is up to few hundred kg, with multiple tethers up to several tonnes.
We know that it is possible to produce long electric sail tethers and the other critical components, and we also know how.	The electric sail is a revolutionary and general-purpose propellantless propulsion method which works outside Earth's magnetosphere.
Ultrasonic wire-to-wire bonding	The method is a general method for bonding together thin metal wires. Conceivably it might have technical ground-based applications, although we have not yet identified them.

4.3 Report on societal implications

B. Ethics

1. Did your project undergo an Ethics Review (and/or Screening)?	No
If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final reports?	

2. Please indicate whether your project involved any of the following issues :

RESEARCH ON HUMANS

Did the project involve children?	No
Did the project involve patients?	No
Did the project involve persons not able to consent?	No
Did the project involve adult healthy volunteers?	No
Did the project involve Human genetic material?	No
Did the project involve Human biological samples?	No
Did the project involve Human data collection?	No

RESEARCH ON HUMAN EMBRYO/FOETUS

Did the project involve Human Embryos?	No
Did the project involve Human Foetal Tissue / Cells?	No
Did the project involve Human Embryonic Stem Cells (hESCs)?	No
Did the project on human Embryonic Stem Cells involve cells in culture?	No
Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No

PRIVACY

Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
Did the project involve tracking the location or observation of people?	No

RESEARCH ON ANIMALS

Did the project involve research on animals?	No
Were those animals transgenic small laboratory animals?	No
Were those animals transgenic farm animals?	No
Were those animals cloned farm animals?	No
Were those animals non-human primates?	No

RESEARCH INVOLVING DEVELOPING COUNTRIES

Did the project involve the use of local resources (genetic, animal, plant etc)?	No
Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No

DUAL USE

Research having direct military use	No
Research having potential for terrorist abuse	No

C. Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	0	1
Work package leaders	1	7
Experienced researchers (i.e. PhD holders)	0	13
PhD student	1	4
Other	0	5

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	3
Of which, indicate the number of men:	3

D. Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project ?	No

6. Which of the following actions did you carry out and how effective were they?	
Design and implement an equal opportunity policy	Not Applicable
Set targets to achieve a gender balance in the workforce	Not Applicable
Organise conferences and workshops on gender	Not Applicable
Actions to improve work-life balance	Not Applicable
Other:	

7. Was there a gender dimension associated with the research content - i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?	No
If yes, please specify:	

E. Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?	Yes
If yes, please specify:	Visits to high schools and visits of high school groups to us, presentation item and lecture in public library, several amateur astronomer society lectures and one science centre public lecture. -Also a Finnish language E-sail blog with e.g. lots of video material of presentations etc., http://electric-sailing.blogspot.fi. (This belongs to E.9. but since the box does not show it we record it here.)

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?	Yes

F. Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?	
Main discipline:	1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
Associated discipline:	2.2 Electrical engineering, electronics [electrical engineering, electronics, communication

	engineering and systems, computer engineering (hardware only) and other allied subjects]
Associated discipline:	2.3 Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

G. Engaging with Civil society and policy makers

11a. Did your project engage with societal actors beyond the research community? (if 'No', go to Question 14)	Yes
11b. If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?	No
11c. In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	
12. Did you engage with government / public bodies or policy makers (including international organisations)	Yes, in communicating /disseminating / using the results of the project
13a. Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	Yes - as a secondary objective (please indicate areas below - multiple answer possible)
13b. If Yes, in which fields?	
Agriculture	No
Audiovisual and Media	No
Budget	No
Competition	No
Consumers	No
Culture	No
Customs	No
Development Economic and Monetary Affairs	No
Education, Training, Youth	No
Employment and Social Affairs	No
Energy	No
Enlargement	No
Enterprise	No

Environment	No
External Relations	No
External Trade	No
Fisheries and Maritime Affairs	No
Food Safety	No
Foreign and Security Policy	No
Fraud	No
Humanitarian aid	No
Human rightsd	No
Information Society	No
Institutional affairs	No
Internal Market	No
Justice, freedom and security	No
Public Health	No
Regional Policy	No
Research and Innovation	No
Space	Yes
Taxation	No
Transport	No
13c. If Yes, at which level?	International level

H. Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	15
To how many of these is open access provided?	14
How many of these are published in open access journals?	2
How many of these are published in open repositories?	1
To how many of these is open access not provided?	0
Please check all applicable reasons for not providing open access:	
publisher's licensing agreement would not permit publishing in a repository	No
no suitable repository available	No
no suitable open access journal available	No
no funds available to publish in an open access journal	No

lack of time and resources	No
lack of information on open access	No
If other - please specify	
15. How many new patent applications ('priority filings') have been made? ("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).	4

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	
Trademark	0
Registered design	0
Other	0

17. How many spin-off companies were created / are planned as a direct result of the project?	0
Indicate the approximate number of additional jobs in these companies:	0

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:	Difficult to estimate / not possible to quantify, None of the above / not relevant to the project

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:	0Difficult to estimate / not possible to quantify

I. Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?	Yes

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?	No

22. Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?	
Press Release	Yes
Media briefing	Yes
TV coverage / report	Yes
Radio coverage / report	Yes

Brochures /posters / flyers	No
DVD /Film /Multimedia	Yes
Coverage in specialist press	Yes
Coverage in general (non-specialist) press	Yes
Coverage in national press	Yes
Coverage in international press	Yes
Website for the general public / internet	Yes
Event targeting general public (festival, conference, exhibition, science café)	Yes

23. In which languages are the information products for the general public produced?	
Language of the coordinator	Yes
Other language(s)	Yes
English	Yes

Attachments	achievements.pdf, approximate-resource-usage.pdf
Grant Agreement number:	262733
Project acronym:	ESAIL
Project title:	Electric sail propulsion technology
Funding Scheme:	FP7-CP
Project starting date:	01/12/2010
Project end date:	30/11/2013
Name of the scientific representative of the project's coordinator and organisation:	Dr. Pekka Janhunen ILMATIETEEN LAITOS
Name	
Date	

This declaration was visaed electronically by Pekka JANHUNEN (ECAS user name njanhupe) on

	EUROPEAN COMMISSION RESEARCH AND INNOVATION DG	Final Report EU Financial Contribution Distribution

Project No: 262733

Project Acronym: ESAIL

Project Full Name: Electric sail propulsion technology

Final Report EU Financial Contribution Distribution

Period covered: from 01/12/2010 **to** 30/11/2013

Start date of project: 01/12/2010

Project coordinator name:
Dr. Pekka Janhunen

Version: 1

Date of preparation: 15/01/2014

Date of submission (SESAM):

Project coordinator organisation name:
ILMATIETEEN LAITOS

Final Report EU Financial Contribution Distribution

PROJECT FINAL REPORT

Grant Agreement number:	262733
Project acronym:	ESAIL
Project title:	Electric sail propulsion technology
Funding Scheme:	FP7-CP
Project starting date:	01/12/2010
Project end date:	30/11/2013
Name of the scientific representative of the project's coordinator and organisation:	Dr. Pekka Janhunen ILMATIETEEN LAITOS
Tel:	+358 9 1929 4635
Fax:	+358 9 1929 4603
E-mail:	pekka.janhunen@fmi.fi
Project website address:	

Final Report EU Financial Contribution Distribution

Distribution of the EU financial contribution between beneficiaries

Name of beneficiary	Final amount of EU contribution per beneficiary
JYVASKYLAN YLIOPISTO	72329.00
ILMATIETEEN LAITOS	498816.00
ALTA SPA	131589.00
HELSINGIN YLIOPISTO	319899.00
TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	153968.00
UNIVERSITA DI PISA	65130.00
UPPSALA UNIVERSITET	220850.00
NANOSPACE AB	172990.00
DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFA HRT EV	198725.00
Total	1834296.00

Attachments	
Grant Agreement number:	262733
Project acronym:	ESAIL
Project title:	Electric sail propulsion technology
Funding Scheme:	FP7-CP
Project starting date:	01/12/2010
Project end date:	30/11/2013
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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.

ESAIL: approximate resource usage

Pekka Janhunen, Jan 14, 2014

The following table gives the resource usage (given in terms of EU contribution) by partner. The "Planned(*)" column is the Grant Agreement EU contribution figure for each partner, amended by the 65000 € EU contribution transfer from University of Helsinki to Finnish Meteorological Institute which was agreed with the relevant parties and the Project Officer. The "Reported" column is the sum of the EU contribution equivalent costs reported by the partners; in case of ÅSTC and Alta the numbers are draft and thus not yet necessarily final. The "Balance" column is the difference Planned minus Reported.

Partner	Planned(*)	Reported	Balance
Finnish Meteorological Institute (Coordinator)	439148	498816	-59668
University of Helsinki	253427	319899	-66472
University of Jyväskylä	69960	72329	-2369
DLR-Bremen	249915	198725	+51190
ÅSTC/Univ. Uppsala	210600	220850	-10250
Nanospace AB	173016	172990	+26
Tartu Observatory	141926	153968	-12042
University of Pisa	60000	65130	-5130
Alta S.p.A.	149400	131589	+17811
TOTAL	1747393	1834296	-86904

It was also agreed with the Project Officer and relevant partners that the responsibility of two Deliverables (D32.3 "Main tether reel test plan" and D32.4 "Main tether reel test results") are transferred from DLR to University of Helsinki. Thus it is natural that the balance of Univ. Helsinki appears as negative while the balance of DLR appears as positive in the above table.

When all partners are summed together, the "Reported" is about 5% larger than "Planned".