	EUROPEAN COMMISSION RESEARCH AND INNOVATION DG	Periodic Report

Project No: 262733

Project Acronym: ESAIL

Project Full Name: Electric sail propulsion technology

Periodic Report

Period covered: from 01/12/2012 **to** 30/11/2013

Start date of project: 01/12/2010

Project coordinator name:
Dr. Pekka Janhunen

Version: 1

Date of preparation: 11/02/2014

Date of submission (SESAM):

Project coordinator organisation name:
ILMATIETEEN LAITOS

Periodic Report

PROJECT PERIODIC REPORT

Grant Agreement number:	262733
Project acronym:	ESAIL
Project title:	Electric sail propulsion technology
Funding Scheme:	FP7-CP
Date of latest version of Annex I against which the assessment will be made:	06/12/2010
Period number:	3rd
Period covered - start date:	01/12/2012
Period covered - end date:	30/11/2013
Name of the scientific representative of the project's coordinator and organisation:	Dr. Pekka Janhunen ILMATIETEEN LAITOS
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Declaration by the scientific representative of the project coordinator (1)

I, Dr. Pekka Janhunen ILMATIETEEN LAITOS , as scientific representative of the coordinator of the project ESAIL and in line with the obligations as stated in Article II.2.3 of the Grant Agreement declare that:

The project has fully achieved its objectives and technical goals for the period.

The attached periodic report represents an accurate description of the work carried out in this project for this reporting period.

The public website is up to date.

To my best knowledge, the financial statements which are being submitted as part of this report are in line with the actual work carried out and are consistent with the report on the resources used for the project (section 6) and if applicable with the certificate on financial statement.

All beneficiaries, in particular non-profit public bodies, secondary and higher education establishments, research organisations and SMEs, have declared to have verified their legal status. Any changes have been reported under section 5 (Project Management) in accordance with Article II.3.f of the Grant Agreement.

Name	Dr. Pekka Janhunen ILMATIETEEN LAITOS
Date	

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

1. Publishable summary

Summary description of project context and objectives

The Electric Solar Wind Sail (E-sail) is a recent invention of ultra-efficient propellantless in-space propulsion technology. It uses the solar wind charged ions as natural source for producing spacecraft thrust. The E-sail is composed of a set of long, thin, conducting and positively charged tethers which are centrifugally stretched from the main spacecraft and kept electrically charged by an onboard electron gun powered by solar panels.
The E-sail concept is an enabling technology for reducing significantly the time, cost and mass required for spacecraft to reach their destinations. It has been estimated that it has the potential to improve the state of the art of propulsion systems by 2 to 3 orders of magnitude if using the lifetime-integrated total impulse versus propulsion system mass as the figure of merit. Furthermore, the E-sail propulsion technology is truly a green propellantless method reducing significantly the mission launch masses and the amount of chemical propellant burnt in the atmosphere. As an electromechanical device it does not need any poisonous, explosive or radioactive substances or dangerous construction procedures.
In the ESAIL project we develop the key E-sail technologies (tethers, tether reels, spinup and guidance/control method based on gas and FEEP thrusters) to prototype level. The goal is that after the project, the decision to build and fly the first E-sail demonstration mission in the solar wind can be made. As a secondary technological goal, the project will raise the FEEP and gas thruster readiness level for general-purpose satellite attitude control purposes.

Description of work performed and main results

After Period 3 we have reached all goals of the project. An automatic ultrasonic tether bonding factory has been designed and built. The factory runs without user intervention and produces 2-wire or 4-wire E-sail tether, currently at a rate of about 3 metres per hour. The factory was successfully used in November 2012 to produce a 1 km long continuous four-wire tether which was the officially stated goal.

A prototype Remote Unit (small autonomous device sitting on tip of each main tether) has been designed and underwent environmental testing in March 2013. We adopted 0.9-4 AU as the required operational solar distance range for the Remote Unit, which will allow a broad range of E-sail missions with the prototyped Remote Unit design, including near-Earth missions, asteroid missions and outer solar system missions. The Remote Unit prototype's mass exceeds the original 0.5 kg goal by 20%. If needed, the mass could be reduced e.g. by using custom-made battery (at the moment the Remote Unit prototype has a COTS space-qualified battery which has unnecessarily high capacity and is therefore unnecessarily heavy for the purpose).

A miniature butane cold gas thruster suitable for the Remote Unit has been designed, built and tested, to be flight-tested on the QB-50 CubeSat mission.

A miniature ionic liquid FEEP thruster for the Remote Unit was successfully built and tested in a vacuum chamber, and the plasma plume angular characteristics were measured.

Multiple reel in/reel out cycles of 10 m 2-wire Heytether were successfully demonstrated without breaking any bonds of the tether. Two 100 m long 4-wire tethers were made and tested for reel-out. One of the filled tether reels underwent vibration testing before reel-out. Bond strength was measured by extensive sampling afterwards. It was found that vibration test did not weaken the bonds.

Two complementary versions of a dynamic mechanical simulator software were completed.

Expected final results and potential impacts

The main goal is to demonstrate TRL 4-5 prototypes of the key components of the electric sail, scalable to 1 N thrust with 100-200 kg propulsion system mass and 0.9-4 AU operational solar distance range. Specifically, this includes building and testing a laboratory prototype of the Remote Unit and its components (butane gas thruster, ionic liquid FEEP thruster, motorised auxtether reels, etc.) and producing at least 1 km of qualify-controlled final-type 4-wire Heytether made of 25/50 um aluminium wire.
If we succeed, it means that the door is open to a novel, general-purpose breakthrough method of moving in the solar system without consuming propellant. The next step after that must be a solar wind test mission for flight validation. The outcome could be enormous, for it has the potential to literally open up the solar system's scientific and economic treasures in a way which was not even dreamt about only five years ago.

At end of Period 3, the project's goals have been achieved: production of 1 km tether; design, prototyping and space environment testing a lightweight autonomous Remote Unit; demonstration of MEMS cold gas and ionic liquid FEEP micropropulsion thrusters; prototyping of auxiliary tether; showing that electron bombardment does not harm tether; showing reelability of tether after simulated launch vibrations.

Project public website address:	http://www.electric-sailing.fi/fp7

2. Core of the report

Project objectives, Work progress and achievements, and project management during the period

The Project Summary Pdf document contains the core of the report.

3. Deliverables and milestones tables

Deliverables (excluding the periodic and final reports)

Del. no.	Deliverable name	Version	WP no.	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I (proj month)	Actual / Forecast delivery date	Status	Comments
1	Project management gu idelines	1.0	10	ILMATIETEEN LAITOS	Report	PU	1	17/03/2011	Submitted	
2	Periodic report	1.0	10	ILMATIETEEN LAITOS	Report	PU	12	30/11/2011	Submitted	
3	Periodic report	1.0	10	ILMATIETEEN LAITOS	Report	PU	24	30/11/2012	Submitted	
4	Periodic report	1.0	10	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	
5	Final report	1.0	10	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Submitted	
1	Tether factory (100 m) de sign and implemen tation and 100 m teth er prod uction	1.0	21	HELSINGIN YLIOPISTO	Report	PU	14	13/03/2012	Submitted	
2	Tether factory (1 km) req uirements	1.0	21	HELSINGIN YLIOPISTO	Report	PU	18	19/08/2013	Submitted	
3	Tether factory (1 km) des ign and implement ation and 1 km tether produc tion	1.0	21	HELSINGIN YLIOPISTO	Report	PU	32	28/05/2013	Submitted	
1	Tether coating report	1.0	22	ILMATIETEEN LAITOS	Report	PU	17	11/11/2013	Submitted	
1	Tether space environm ent requirements	1.0	23	ILMATIETEEN LAITOS	Report	PU	8	17/08/2011	Submitted	
2	Tether vacuum-testing set up	1.0	23	ILMATIETEEN LAITOS	Report	PU	12	07/11/2011	Submitted	
3	Tether vacuum-testing res ults	1.0	23	ILMATIETEEN LAITOS	Report	PU	26	07/11/2013	Submitted	
1	Auxiliary tether repo rt	1.0	24	ILMATIETEEN LAITOS	Report	PU	7	01/02/2012	Submitted	

1	Requirements specific ations of the tether r ee ling tests	2.0	31	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	6	01/06/2011	Submitted	
2	Reeling tests plan	1.0	31	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	6	01/06/2011	Submitted	
3	Reeling test results	1.0	31	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	6	23/06/2011	Submitted	
1	Requirements specific ation of the main tet her reel	1.0	32	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	12	03/11/2011	Submitted	
2	Design description of the main tether reel	1.0	32	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	12	11/01/2012	Submitted	
3	Main tether reel test plan	1.0	32	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	18	11/11/2013	Submitted	
4	Main tether reel test res ults	1.0	32	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	30	31/05/2013	Submitted	
1	Requirements specific ation of the auxiliar y t ether reel	1.0	33	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	7	09/09/2011	Submitted	
2	Design description of the auxiliary tether r eel	2.0	33	DEUTSCHES ZENTRUM FU	Report	PU	11	01/12/2011	Submitted	

				ER LUFT - UND RAUMFAHRT E V						
3	Auxiliary tether reel test plan	1.0	33	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	18	21/05/2012	Submitted	
4	Auxiliary tether reel test results	1.0	33	DEUTSCHES ZENTRUM FU ER LUFT - UND RAUMFAHRT E V	Report	PU	30	20/08/2013	Submitted	
1	Requirements specific ation of the Remote Un it	1.0	41	UPPSALA UN IVERSITET	Report	PU	7	30/06/2011	Submitted	
2	Design description of the Remote Unit	1.0	41	UPPSALA UN IVERSITET	Report	PU	13	17/02/2012	Submitted	
3	Remote Unit test plan	1.0	41	UPPSALA UN IVERSITET	Report	PU	20	13/08/2012	Submitted	
4	Remote Unit test resu lts	1.0	41	UPPSALA UN IVERSITET	Report	PU	32	07/05/2013	Submitted	
1	Final report of Remote Unit power system	1.0	42	TARTU OBSE RVATORY -E STONIAN MI NISTRY OF EDUCATION AND RESEAR CH	Report	PU	30	14/06/2013	Submitted	
1	Final report of Remote Unit control and telem etry	1.0	43	UPPSALA UN IVERSITET	Report	PU	30	20/06/2013	Submitted	
1	Final report of Remote Unit tether jettison	1.0	44	TARTU OBSE RVATORY -E STONIAN MI NISTRY OF EDUCATION AND RESEAR CH	Report	PU	30	26/09/2013	Submitted	
1	Final Report of Remote Unit gas thruster	1.0	45	NANOSPACE AB	Report	PU	30	11/11/2013	Submitted	

1	Simplified FEEP design report	1.0	46	ALTA SPA	Report	CO	18	28/05/2012	Submitted	
2	Simplified FEEP test rep ort	1.0	46	ALTA SPA	Report	PU	30	25/06/2013	Submitted	
3	Cost assessment for in dustrial production	1.0	46	ALTA SPA	Report	PU	30	25/06/2013	Submitted	
1	Simulator user guide	1.0	51	ILMATIETEEN LAITOS	Report	PU	30	27/05/2013	Submitted	
2	Report of performed r uns	1.0	51	ILMATIETEEN LAITOS	Report	PU	36	07/11/2013	Submitted	
1	Conceptual E-sail desi gns and specifications for component develo pment	1.0	52	ILMATIETEEN LAITOS	Report	PU	3	17/03/2011	Submitted	
1	Failure mode and reco very strategies analys is report	1.0	53	ILMATIETEEN LAITOS	Report	PU	26	18/02/2013	Submitted	
2	Refined design concep ts document	1.0	53	ILMATIETEEN LAITOS	Report	PU	32	28/08/2013	Submitted	
1	E-sail mission docume nt	1.0	61	TARTU OBSE RVATORY -E STONIAN MI NISTRY OF EDUCATION AND RESEAR CH	Report	PU	36	02/12/2013	Submitted	
1	Summary of orbit calcu lations supporting WP 61	1.0	62	UNIVERSITA DI PISA	Report	PU	36	05/11/2013	Submitted	
1	Scientific deliverable s as defined in WP 20 – WP 6 0.	1.0	70	ILMATIETEEN LAITOS	Report	PU	36	02/12/2013	Submitted	
1	Public outreach report	1.0	80	ILMATIETEEN LAITOS	Report	PU	36	20/11/2013	Submitted	

Milestones

Milestone no.	Milestone name	Work package no	Lead beneficiary	Delivery date from Annex I	Achieved Yes/No	Actual / Forecast achievement date	Comments

1	Remote Unit design p arameters fixed	33,41,42,43,44,45,46	5	31/03/2011	Yes	10/02/2011	
2	First tether sample deliv ered to reeling test	21,31	2	31/03/2011	Yes	12/04/2011	
3	Construction of Remote Unit component prototy pes starts	33,41,42,43,44,45,46	5	30/11/2011	Yes	01/04/2012	Design and manufacture overlapped significantly, therefore not possible to give firm date
4	100 m tether produced	21	2	30/11/2011	Yes	15/07/2011	Date when tether was made, not when it was re ported
5	Reeling of tether de monstrated	31	4	31/08/2011	Yes	29/03/2011	
6	Main tether reel pro totype tested	32	2	31/05/2013	Yes	15/01/2014	Lead beneficiary cha nged and activity pushed forward in agreement with Project Officer
7	Remote Unit prototype tested	33,41,42,43,44,45,46	5	31/05/2013	Yes	29/04/2013	
8	Gas thruster prototype te sted	45	6	31/05/2013	Yes	08/11/2013	Date of D45.1
9	FEEP thruster prototype tested	46	9	31/05/2013	Yes	13/06/2013	Lead beneficiary number typo in DoW
10	1 km tether produced	21	2	31/07/2013	Yes	24/11/2012	
11	Concrete E-sail designs and missions using them analysed	51,52,53,61,,62	1	30/11/2013	Yes	26/11/2013	

4. Explanation of the use of the resources

The **explanation on the use of resources** was removed from the scientific periodic reports in SESAM. These deta ils now have to be entered in the cost statement forms in FORCE instea d.

Attachments	report.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
Period covered - start date:	01/12/2012
Period covered - end date:	30/11/2013
Name	
Date	

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

PROJECT PERIODIC REPORT (Core)

Grant Agreement number: 262733

Project acronym: ESAIL

Project title: Electric Sail Propulsion Technology

Funding Scheme: Collaborative Project

Date of latest version of Annex I against which the assessment will be made:

Periodic report: 1st ☐ 2nd ☐ 3rd X 4th ☐

Period covered: from Dec 1, 2012 to Nov 30, 2013

Name, title and organisation of the scientific representative of the project's coordinator[1]:

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Project website[2] address: http://www.electric-sailing.fi/fp7

1 Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .

2 The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

3.2 Core of the report for the period: Project objectives, work progress and achievements, project management

3.2.1 Project objectives for the period

The Electric Solar Wind Sail (E-sail) is a recent invention of ultra-efficient propellantless in-space propulsion technology. It uses the solar wind charged ions as natural source for producing spacecraft thrust. The E-sail is composed of a set of long, thin, conducting and positively charged tethers which are centrifugally stretched from the main spacecraft and kept electrically charged by an onboard electron gun powered by solar panels.

The E-sail concept is an enabling technology for reducing significantly the time, cost and mass required for spacecraft to reach their destinations. It has been estimated that it has the potential to improve the state of the art of propulsion systems by 2 to 3 orders of magnitude if using the lifetime-integrated total impulse versus propulsion system mass as the figure of merit. Furthermore, the E-sail propulsion technology is truly a green propellantless method reducing significantly the mission launch masses and the amount of chemical propellant burnt in the atmosphere. As an electromechanical device it does not need any poisonous, explosive or radioactive substances or dangerous construction procedures.

In the ESAIL project we develop the key E-sail technologies (tethers, tether reels, spinup and guidance/control method based on gas and FEEP thrusters) to prototype level. The goal is that after the project, the decision to build and fly the first E-sail demonstration mission in the solar wind can be made. As a secondary technological goal, the project will raise ionic liquid FEEP thruster and evaporative gas thruster readiness level for general-purpose satellite attitude control purposes.

The ESAIL project had 11 planned and scheduled Milestones which were reached as follows (the relevant ones have already been discussed in earlier Periodic Reports 1 and 2; notice that no Milestones were scheduled to be reached during Period 2):

Milestone	Status
MS1 Remote Unit parameters fixed	Was reached as planned during Period 1
MS2 First tether sample delivered to reeling test	Was reached as planned during Period 1
MS3 Construction of Remote Unit component prototypes starts	Was reached as planned during Period 1
MS4 100 m tether produced	Was reached as planned during Period 1
MS5 Reeling of tether demonstrated	Was reached as planned during Period 1
MS6 Main tether reel prototype tested	Necessary measurements have been completed, pending D32.4 will be finalised and submitted as soon as possible
MS7 Remote Unit prototype tested	Completed in April-March 2013 (D41.4)

MS8 Gas thruster prototype tested	Completed and reported (D45.1)
MS9 FEEP thruster prototype tested	Completed and reported (D64.2)
MS10 1 km tether produced	Completed ahead of time in Nov 2012 (D21.3)
MS11 Concrete E-sail designs and missions using them analysed	Completed and reported (D61.1)

3.2.2 Work progress and achievements during the period

WP21 Tether factory

The tether factory work has continued intensively also in Period 3 after the 1 km tether was made in Nov 2012. Systematic work has been accomplished to improve the quality of the produced tether, as well as intensive research into non-destructive testing methods about how to monitor tether quality during production. Also the previous period achievements were written into Deliverables during Period 3. A 10 m flight model reel was made for the ESTCube-1 satellite which was successfully launched in May 2013 onboard Vega from French Guiana. Several 100 m long flight capable tethers were made in autumn 2013 for the upcoming Aalto-1 CubeSat mission where also the reel (WP32, see below) will be flight-tested. One 100 m tether for Aalto-1 was unreeled after production, another 100 m tether was also vibration tested in Tartu before unreeling.

WP22 Tether coating

We coated one 10 m long reeled tether with 100 nm Al_2O_3 coating in the atomic layer deposition (ALD) reactor of the Department of Chemistry of the University of Helsinki. A special property of ALD is that objects with arbitrarily complicated shape (such as a reeled multi-wire E-sail tether) can be coated by uniform thickness because the coating is built one molecular monolayer at a time. When testing reel-out of the ALD-coated tether, we found that the alumina coating has slightly glued the different wires together. This is not surprising given that the coating is applied when the tether is already on its storage reel. It was possible to pull out the tether out of the reel without breaking it, however: the maximum required pull force was 1 gram while the tether is designed to withstand 5 gram pull plus margin. Although in principle sufficient, we think that this margin of success (factor 5) is too narrow, that there is a risk that with a longer tether, more sticking might occur locally at some point so that the tether might fail to come out of its reel.

Also some spray coatings were tested, but were not found promising because of incomplete adherence and other issues.

It seems that a feasible coating method should be integrated with the tether factory so that the coating is applied after the tether is bonded but before is reeled. There are spatial versions of ALD which in principle would be suitable; however, spatial ALD apparatuses are expensive and hence not our preferred option. Further E-sail coating research is planned with wet bath methods (e.g., anodising) and other alumina coating to be performed, outside of the ESAIL project, in University of Roma Tre by group of prof. Edoardo Bemporad.

WP23 Tether testing

Three types of tether tests were performed in a vacuum chamber of University of Jyväskylä Accelerator Laboratory. Firstly, a special setup was designed and built for measuring the thermal infrared emissivity of given tether wire. The method is based on heating the wire resistively and then monitoring the cooling curve by measuring the resistance and using the known temperature-resistance relationship. From the cooling curve it is possible to determine emissivity because practically only radiation is responsible for cooling in vacuum. About one metre long wire samples were used so that heat conduction effects at the ends were negligible. The method was applied to measuring the emissivity of bare aluminium wire and ALD alumina coated wire. It was found that 100 nm ALD coating increases the emissivity roughly by factor of two. Secondly, the coated tether was subjected to electron bombardment to simulate the accelerated solar wind plasma electron flux on high voltage biased E-sail tether. The duration of the bombardment corresponded to about 6 months time in solar wind at 1 au under +10 kV bias. No adverse effects were found from the measurement campaign, but it was theorised that electron flux might liberate atomic oxygen from Al_2O_3 and thereby make the surface of the coating metallic again. We think that there is a risk that this adverse process might occur the the solar wind, but that it cannot necessarily be simulated in laboratory conditions where there is always some amount of oxygen left in the vacuum chamber which can re-oxidise the surface. Replacing aluminium oxide by e.g. titanium oxide which is slightly conducting would be expected to be free of this potential coating issue. Thirdly, a collision of two tethers with a mutual potential difference was studied experimentally and by modelling. The practical conclusion from the collision substudy is that if a main tether breaks, it is advisable to turn off voltage from the other tethers so that should the loose piece of broken-up tether collide with another tether, the collision takes place without potential difference and therefore without sparking.

WP32 Main tether reel

By the decision made in Period 1 Evaluation Meeting (March 2012), WP32 was postponed until 1 km tether has been produced which gives us input for deciding the most proper reel geometric parameters (with and diameter) to be prototyped. Thus, no work on WP32 occurred during Period 2. In Period 3, work commenced with production of reels which are compatible with the Aalto-1 CubeSat mission to be flown later and which can hold 100 m of tether. The main test was to load the tether onto the reel, shake the reel/tether combination in vibration bench, and then try to unreel the tether. This was preceded by an easier test where the shaking step was omitted.

Without shaking, unreeling worked without problems. With shaking, some problems occurred during unreeling, but at least most of them were not due to shaking or the tether, but were instead caused by some unrelated trivial technical issues. We are currently analysing if any of the problems were due to the tether reeling itself and whether a new tether and shaking round is needed. This activity has to fall outside the project, however, which has already officially ended on Nov 30 2013. At the moment we can confirm that at least shaking did not break the tether or interfere at large with unreeling. It is possible that some more bonds broke due to shaking (in addition to those that were already broken during production) and it also cannot be excluded at the moment that shaking might have occurred some unreeling problems to occur. By unreeling problem we mean that gravity-based unreeling with the employed weight (first 0.05 g, then 0.1 g) was sometimes not enough to pull the tether out from the reel, but one had to manually touch the tether to help it proceed. It is possible that by using a larger weight, unreeling would have gone through smoothly. However, testing this would require a new tether and new shaking round.

Remote Unit related WPs (WP33 Auxiliary tether reel, WP41 Remote Unit overall design, WP42 Remote Unit power system, WP43 Remote Unit control and telemetry, WP44 Remote Unit jettison, WP45 Remote Unit gas thruster and WP46 Remote Unit FEEP thruster)

The Remote Unit work culminated at end of February 2013 to a testing campaign at DLR. For the most part the Remote Unit passed the testing. The thermal tests did not succeed completely, partly because of a trivial error made in assembly of the Remote Unit and partly because of some deficiencies of the test facility which became known only at the site. We are confident that fixing these problems would not be difficult. However, to demonstrate it in practice would have required a new test campaign in some external facility. This would have costed more money than what was allocated to the task and hence was not done. Also, in our opinion, it would not have been the most efficient use of resources. If the Remote Unit flies, such tests are necessary, but now we have reached at least TRL 4 if not more which was the goal of the project. All sub-WPs of the Remote Unit had their hardware installed in the test item. Thus, very many things could have failed in testing, but didn't.

WP51 Dynamical simulation

A user-level description of the dynamical simulator codes was written (D51.1), as well as a summary of performed runs (D51.2). Throughout the project, the dynamical simulator codes have been frequently used to test dynamical behaviour of various tether rig configurations.

WP53 Refined design concepts, WP61 Mission scenarios and WP62 Orbit calculations

For WP53, papers “Electric solar wind sail mass budget model” (Janhunen, P., Quarta A. and Mengali, G., *Geosci. Instrum. Methods Data Syst.,* 2, 85-95, 2013), “Photonic spin plane control of the electric sail” (Janhunen, P., *Acta Astronaut.,* 83, 85-90, 2013) and “Electric sail, photonic sail and deorbiting applications of the freely guided photonic blade” (*Acta Astronaut.,* 93, 410-417, 2014) were published (or, in the last case, accepted and the publication issue in 2014 already known). For WP61, the paper “Electric solar wind sail applications overview” (Janhunen, P., Toivanen, P., Envall, J., Merikallio, S., Montesanti, G., Gonzalez del Amo, J., Kvell, U., Noorma, M. and Lätt, S.) was submitted in ESTCube-1 special issue of *Proc. Est. Acad. Sci.*; the referee reports have not yet arrived. For WP62, the deliverable D62.1 “Summary of orbital calculations” is a comprehensive and precise, yet pedagogically good and readable introduction to how to use the E-sail for solar wind missions, written from the orbital dynamics perspective. It contains references to the many original papers that were published by the Pisa group and others regarding the topic. At the moment of writing this (December 17 2013), we are very close to submitting a paper about E-sail atmospheric probe missions to Uranus, to be submitted to *Plan. Space Sci.* Uranus workshop special issue. This paper has been under preparation since August.

WP70 Scientific coordination

This is the coordinator's activity (who is also the inventor of the E-sail and plasma brake) to lead the project scientifically.

During the last (third) period, the main emphasis was put to reaching all goals and submitting all deliverables before the project ends, without exceeding the total budget. At the end, everything was accomplished successfully and on time. Only one deliverable (D32.4, Main tether reel test results) was left pending after the project officially ended on Nov 30 2013, because we wanted to record results of a combined vibration followed by unreeling test into this document. This was agreed with the Project Officer. At the moment of writing this (Dec 17 2013), the unreeling itself was completed 2 days ago and analysis of the results is going on. We will submit the deliverable during the 2 month grace period after the project ends. Of course we accept that EU grants no payment for the part of work which is performed after Nov 30.

3.2.3 Project management during the period

During the last period, the principle of management was “do what you can, from where you are, with the resources you have”. We asked the partners for an extra update of their resource usage in the middle of the last period. It seems that the spending was proceeding almost normally, but in a project of this size (1.73 M€ EU contribution i.e. almost 50 k€ average spending per month), even relatively small fluctuations can become fairly large in absolute value at the end. At the moment of writing this (Dec 17 2013), we haven't yet gotten the final spending figures from the partners, hence we cannot yet say how large those fluctuations are, i.e. how well the budget balances out among the partners.

The following project meetings were held during the period (Dec 1 2012- Nov 30 2013):

Meeting	Date	Location	Participants
Remote Unit testing review	9 Apr 2013	Uppsala	RU team
ESAIL final meeting	21-22 Oct 2013	Pisa	All

As before, the ESAIL project public website is http://www.electric-sailing.fi/fp7. In addition, password protected ESAIL Team Pages exist at https://www.electric-sailing.fi/fp7s which contain more information for internal use.

Related electric sail activities outside the ESAIL project

At least the following related E-sail activities were active during Period 2:

- ESTCube-1 nanosatellite project (Tartu, FMI, UH, UJ, DLR): Successfully launched from Kourou onboard Vega on May 8, 2013
- Aalto-1 nanosatellite project (Aalto University, FMI, UH, UJ): launch in late 2014 or early 2015
- SWESTCube (“Solar Wind Electric Sail Test Cubesat”) nanosatellite project (planning stage; Tartu, FMI, Nanospace), target launch is 2015-16, lunar orbiting 3-U CubeSat, with some other high altitude and solar wind intersecting orbit a secondary option

- DESA ("Demonstration of Electric Sail's Applicability") proposal for Phase-0 study to ESA (submitted Jan 14 2013) in response to AO7359 "Requirements and concepts for IOD missions for breakthrough concepts and approaches", budget 37 M€. Decision still pending.
- Internal working group at ESA/ESTEC organised by Jose Gonzalez del Amo, whose target is to make recommendations concerning possible future scientific ESA missions using electric sail and photon sail technologies (member of the group: Urmas Kvell, Tartu)
- Academy of Finland project "Numerical and experimental investigation of electric sail and plasma brake effects in space plasma" (NumExES) 2012-2015, total budget 0.68 M€ (for FMI)