Project No: 262733

Project Acronym: ESAIL

Project Full Name: Electric sail propulsion technology

Periodic Report

Period covered: from 01/12/2011 **to** 30/11/2012

Start date of project: 01/12/2010

Project coordinator name:
Dr. Pekka Janhunen

Version: 1

Date of preparation: 15/01/2013

Date of submission (SESAM): 22/01/2013

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:	2nd
Period covered - start date:	01/12/2011
Period covered - end date:	30/11/2012
Name of the scientific representative of the project's coordinator and organisation:	Dr. Pekka Janhunen ILMATIETEEN LAITOS
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Project website address:	http://www.electric-sailing.fi/fp7

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	22/01/2013

This declaration was visaed electronically byPekka JANHUNEN(ECAS user name njanhupe) on 22/01/2013

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

The ESAIL project is mostly a TRL 4-5 prototyping and hardware development activity. In all important respects, we are fully on schedule and have met or exceeded the expectations:
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 is nearing completion. Environmental tests for it are scheduled in February 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 only about 10%. 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, 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. Similar tests for 4-wire tether were also carried out.

An operative version of a dynamic mechanical simulator software exists.

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 2, most of the ESAIL project's goals have already been achieved (production of 1 km tether, design and prototyping a lightweight Remote Unit, prototyping of auxiliary tether). Remaining work involves completion of Remote Unit environmental tests and prototyping of main tether reel.

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 guidel ines	1.0	10	ILMATIETEEN LAITOS	Report	PU	1	17/03/2011	Submitted	
2	Periodic report	0.0	10	ILMATIETEEN LAITOS	Report	PU	12	30/11/2011	Not submitted	
3	Periodic report	0.0	10	ILMATIETEEN LAITOS	Report	PU	24	30/11/2012	Not submitted	
4	Periodic report	0.0	10	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	
5	Final report	0.0	10	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	
1	Tether factory (100 m) de sign and implementation a nd 100 m tether productio n	1.0	21	HELSINGIN YLIOPISTO	Report	PU	14	13/03/2012	Submitted	
2	Tether factory (1 km) req uirements	0.0	21	HELSINGIN YLIOPISTO	Report	PU	18	31/05/2012	Not submitted	
3	Tether factory (1 km) des ign and implementation an d 1 km tether production	0.0	21	HELSINGIN YLIOPISTO	Report	PU	32	31/07/2013	Not submitted	
1	Tether coating report	0.0	22	ILMATIETEEN LAITOS	Report	PU	17	30/04/2012	Not submitted	
1	Tether space environment 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	0.0	23	ILMATIETEEN LAITOS	Report	PU	26	31/01/2013	Not submitted	
1	Auxiliary tether report	1.0	24	ILMATIETEEN LAITOS	Report	PU	7	01/02/2012	Submitted	

1	Requirements specificatio ns of the tether reeling tests	1.0	31	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	6	01/06/2011	Submitted	
2	Reeling tests plan	1.0	31	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	6	01/06/2011	Submitted	
3	Reeling test results	1.0	31	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	6	23/06/2011	Submitted	
45	Reeling test results - Fi rst amendment	1.0	31	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	13	05/12/2011	Submitted	
1	Requirements specificatio n of the main tether reel	1.0	32	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	12	03/11/2011	Submitted	
2	Design description of the main tether reel	1.0	32	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	12	11/01/2012	Submitted	
3	Main tether reel test pla n	0.0	32	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	18	31/05/2012	Not submitted	
4	Main tether reel test res	0.0	32	DEUTSCHES	Report	PU	30	31/05/2013	Not submitted	

	ults			ZENTRUM FUER LUFT - UND RAUMFAHRT EV						
1	Requirements specificatio n of the auxiliary tether reel	1.0	33	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	7	09/09/2011	Submitted	
2	Design description of the auxiliary tether reel	1.0	33	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	11	01/12/2011	Submitted	
3	Auxiliary tether reel tes t plan	1.0	33	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	18	21/05/2012	Submitted	
4	Auxiliary tether reel tes t results	0.0	33	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV	Report	PU	30	31/05/2013	Not submitted	
1	Requirements specificatio n of the Remote Unit	1.0	41	UPPSALA UNIVERSITET	Report	PU	7	30/06/2011	Submitted	
2	Design description of the Remote Unit	1.0	41	UPPSALA UNIVERSITET	Report	PU	13	17/02/2012	Submitted	
3	Remote Unit test plan	1.0	41	UPPSALA UNIVERSITET	Report	PU	20	13/08/2012	Submitted	
4	Remote Unit test results	0.0	41	UPPSALA UNIVERSITET	Report	PU	32	31/07/2013	Not submitted	
1	Final report of Remote Un it power system	0.0	42	TARTU OBSERVATORY -ESTONIAN MINISTRY OF	Report	PU	30	31/05/2013	Not submitted	

				EDUCATION AND RESEARCH						
1	Final report of Remote Un it control and telemetry	0.0	43	UPPSALA UNIVERSITET	Report	PU	30	31/05/2013	Not submitted	
1	Final report of Remote Un it tether jettison	0.0	44	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND RESEARCH	Report	PU	30	31/05/2013	Not submitted	
1	Final Report of Remote Un it gas thruster	0.0	45	NANOSPACE AB	Report	PU	30	31/05/2013	Not submitted	
1	Simplified FEEP design re port	1.0	46	ALTA SPA	Report	CO	18	28/05/2012	Submitted	
2	Simplified FEEP test repo rt	0.0	46	ALTA SPA	Report	PU	30	31/05/2013	Not submitted	
3	Cost assessment for indus trial production	0.0	46	ALTA SPA	Report	PU	30	31/05/2013	Not submitted	
1	Simulator user guide	0.0	51	ILMATIETEEN LAITOS	Report	PU	30	31/05/2013	Not submitted	
2	Report of performed runs	0.0	51	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	
1	Conceptual E-sail designs and specifications for c omponent development	1.0	52	ILMATIETEEN LAITOS	Report	PU	3	17/03/2011	Submitted	
1	Failure mode and recovery strategies analysis repo rt	0.0	53	ILMATIETEEN LAITOS	Report	PU	26	31/01/2013	Not submitted	
2	Refined design concepts d ocument	0.0	53	ILMATIETEEN LAITOS	Report	PU	32	31/07/2013	Not submitted	
1	E-sail mission document	0.0	61	TARTU OBSERVATORY -ESTONIAN MINISTRY OF EDUCATION AND	Report	PU	36	30/11/2013	Not submitted	

				RESEARCH						
1	Summary of orbit calculations supporting WP 61	0.0	62	UNIVERSITA DI PISA	Report	PU	36	30/11/2013	Not submitted	
1	Scientific deliverables a s defined in WP 20 – WP 60.	0.0	70	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	
1	Public outreach report	0.0	80	ILMATIETEEN LAITOS	Report	PU	36	30/11/2013	Not submitted	

Milestones

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

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	
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:	01/12/2011
Period covered - end date:	30/11/2012
Name	
Date	22/01/2013

This declaration was visaed electronically by Pekka JANHUNEN (ECAS user name njanhupe) on 22/01/2013

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 X 3rd ☐ 4th ☐

Period covered: from Dec 1, 2011 to Nov 30, 2012

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.

Five milestones were to be reached during Periodic 1:

MS1: Remote Unit design parameters fixed
MS2: First tether sample delivered to reeling test
MS3: Construction of Remote Unit component prototypes start
MS4: 100 m tether produced
MS5: Reeling of tether demonstrated

During Period 1, all these milestones except MS3 were reached, some (MS4, MS5 and partly MS1) were reached ahead of time.

We agreed in the first Evaluation Meeting (March 2012) to postpone prototyping of the main tether reel (WP32) because to find its optimal geometric parameters one needs more experience from long (1 km) tether production and its reeling. We also decided to use some of the DLR resources to environmental testing of the Remote Unit (WP41) at DLR which has good facilities for the purpose.

In the DoW, no new milestones were scheduled to be reached during Period 2. The remaining six milestones are all scheduled during Period 3:

MS6: Main tether reel prototype tested
MS7: Remote Unit prototype tested
MS8: Gas thruster prototype tested
MS9: FEEP thruster prototype tested
MS10: 1 km tether produced
MS11: Concrete E-sail designs and missions using them analysed

During Period 2, we have started (and almost finished) the construction of the prototype Remote Unit, thus MS3 has been reached. We have already produced a 1 km long four-line tether (end of November 2012), so MS10 has been reached about 8 months ahead of expected time.

3.2.2 Work progress and achievements during the period

WP21 Tether factory

The tether factory work has received a major emphasis during Period 2. Design and construction of an automatic Tether Factory capable of producing kilometre scale tether commenced. By gradual improvements the work progressed through the year and culminated in a successful production of a 1 km long tether in November 2012. The production of the 1 km continuous four wire tether took about 2 weeks. During the production,, the base wire was deliberately cut three times and the parts were rejoined by manual ultrasonic bonding. This was done to demonstrate robustness of the tether production process towards accidental failures: If the base wire breaks (for any reason) after producing e.g. 900 m of a required e.g. 1 km tether, one doesn't have to abandon the 900 m already produced, but one can simply continue after rejoining the wires. Thus, the main goal of WP21 was reached and further ongoing work deals with “polishing” the Tether Factory and improving its online quality assurance features.
The Deliverables where this work is documented have not yet been written (its due date is in July 2013). In December and January the tether team was busy with producing the flight model tether for the ESTCube-1 nanosatellite which is scheduled to be launched onboard Vega from Guyana in April 13 2013.
A press release was made of the successful production of a 1 km long E-sail tether in January 2013. It was reported by tens of online and other media all over the world. Further press releases concerning ESTCube-1 flight will be made soon.

WP22 Tether coating

Tether coating has not been further pursued during Period 2. We decided to prioritise the tether production (WP21) because a long tether is absolutely necessary for the E-sail while coating it is an option which might or might not be beneficial or needed. From the preliminary work done in Period 1 we already know that atomic layer deposition (ALD) aluminium oxide coating process works at least to some extent with the tether production process. The selection of possible coating processes is in our case mostly limited by the fact that for optimum quality of the tether, we want to reel it on the flight model reel immediately after production at the factory, and the output reel is integrated to the factory with only about 20 cm distance separating it from the bonding site. Inserting any kind of coating process in this tight space and doing it without disturbing the tether factory process is challenging for many reasons. With ALD, however, we can take the reeled tether after production and put it in the ALD reactor and take it out. By its very nature, the ALD process excels at producing a uniform thickness coating even when the coated body has a very complicated shape, as in our case where the airspaces between layers of wires on the reel can be very narrow. Because in ALD the reactor is filled by a different gas mixture for each atomic layer of the coating, the thickness of the coating has the same number of monolayers in all places where gas molecules have access.

We haven't yet tested experimentally if a long ALD-coated tether can be reeled out without problems, i.e. without the wires getting stuck together to a harmful extent by the coating. If this turns out to be a problem, the tether could be produced on a different, less compact reel at the factory, then ALD-coated on that reel, then re-reeled on the flight model reel. Possible small adhesion by the coating would then be broken controllably during re-reeling rather than in space. The potential drawback with this approach is, of course, that re-reeling the tether can always break some bonds and make it more difficult to control the placement of the loop wires on the reel.

WP23 Tether testing

Work on tether testing was done in Period 2. Deliverables were not yet made, but the work is documented in Appendix A of this document. At the moment WP23 is waiting for the tether team to supply coated wire samples for further testing runs.

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. At the moment, 1 km tether has been produced on a small reel (which is very encouraging in terms of compact storage of the tethers) and we can measure e.g. the overall density of the reeled material from this experiment to yield experiment-based scaled estimates of volume and mass requirements of the main tether reels required to store a given length of tether. A decision about the main tether reel geometric parameters should be made as soon as we get the relevant people present from their other duties, so that WP32 could commence.

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 kept us busy during the year. In early 2012, a very significant mass saving effort was done on the structural parts at ÅSTC by Sven Wagner. In summer 2012, ÅSTC struggled with challenges in finding a workshop willing to manufacture some of the more challenging complex aluminium parts at reasonable price. There was a danger that the budget of this WP was about to be exceeded. Finally suitable subcontractors were found, but to save money it was necessary to decide to manufacture only one Remote Unit prototype (up to that point, the cold gas and FEEP versions of the Remote Unit had been progressed in a symmetrical way). We decided to build the cold

gas one first because it is less complex, more lightweight and because its performance seems sufficient for small E-sail missions. The decision whether to build the ionic liquid FEEP version later was postponed until we know the financial situation after Period 2. A testing plan for the Remote Unit was made and tests are scheduled to be made mainly at DLR premises in February 2013. Overall, the Remote Unit work is in schedule and the mass goal of 0.5 kg was almost reached with the cold gas version. Assuming the tests go well, we will have a lightweight (0.56 kg) design of the Remote Unit at TRL 5 at the end of the project which fulfills the project's goal of raising the TRL to 4-5. Because the cold gas and FEEP versions of the Remote Unit only differ in some mechanical characteristics, it is of lesser significant if one of the models is not physically built to completion and tested.
Optimising the mass of the Remote Unit was important because it reduces the costs of testing the technology in space. All grams of the Remote Unit are multiplied by the number of tethers and the spacecraft bus mass needed to host the items which are “payload” from the spacecraft bus point of view. Also, there was no question already from the start that a functionally complete Remote Unit could be built. The question was at what mass this is possible at present. We have now come a long way towards showing (basically only pending the environmental tests) that it is possible to do at low mass, satisfying the original dry mass goal of 0.3-0.5 kg almost completely. The mass could be further optimised by e.g. space qualifying a smaller battery than the one we are using now. The present battery has lots of excess capacity that the Remote Unit does not need, and the selection of the battery was based not on capacity but on availability and qualification status considerations.

WP51 Dynamical simulation

During Period 2, the dynamical simulator continued to serve as one of the basic tools we use at FMI to analyse E-sailing. Enhancements were made as needed.

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

We had a meeting in Pisa in autumn 2012 about WP53 (refined design concepts) and WP61 (mission scenarios). We are also in active telecon and visiting contact with the “E-sail Working Group” which was formed by Jose Gonzalez del Amo at ESTEC. We also submitted a paper “Electric solar wind sail mass budget model” (Janhunen, P., Quarta A. and Mengali, G.) to *Geosci. Instrum. Methods Data Syst*. The paper is still under review; we think that it will soon be accepted. We also published the paper “Photonic spin plane control of the electric sail” (Janhunen, P. Acta Astronaut. 83, 85-90, 2013) which relates to a more advanced E-sail concept using Remote Units with photonic blades instead of cold gas or FEEP thrusters, and also including the possibility of leaving out auxiliary tethers. We also wrote paper “Electric sail, photonic sail and deorbiting applications of the freely guided photonic blade” (Janhunen, P., Acta Astronaut., submitted, 2013) which further explores the auxtether-free E-sail variant and points out “spinoff” applications of the freely guided photonic blade (FGPB) concept to a novel type of photonic heliogyro sail (more efficient packing factor) and for E-sail derived plasma brake and/or atmospheric drag based scalable and efficient satellite deorbiting applications.
Concerning mission scenarios, we have discussed the various pros and cons (technical, scientific, financial and others) of many different E-sail mission categories together with the ESTEC E-sail Working Group. A multi-asteroid touring mission seems to be the

strongest candidate at the moment. We also filed a proposal to ESA's call AO7359 “Requirements and concepts for IOD missions for breakthrough concepts and approaches” named “Demonstration of Electric Sail's Applicability (DESA)”. The cost cap of such ESA technology demonstration mission is 50 M€. Our DESA mission would cost 37 M€. The subcontractors of the DESA proposal are ÅSTC, Nanospace and OHB-Sweden.
The E-sail can be applied to many widely different purposes and at different levels of performance, ambition and cost. The limitations of which mission to pursue are mostly not technical, but due to resources (the same team cannot pursue all interesting missions at the same time) and due to scientific, technical and political emphasis areas of ESA and the rest of the space community. In any case, all applications of E-sail technology to medium or large ESA missions require a demonstration mission in the solar wind such as DESA.
The University of Pisa group has supported us along the way by their unique capability to produce mathematically optimised trajectories for low thrust propulsion such as the E-sail. Two papers were recently published: “A graphical approach to electric sail mission design with radial thrust” (Mengali, G., Quarta, A. and Aliasi, G., Acta Astronautica, in press, 2013), and “Electric sail for near-Earth asteroid sample return mission: case 1998 KY26” (Quarta, A., Mengali, G. and Janhunen, P., J. Aerospace Eng., in press, 2013).

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.

While some deliverables at late from the originally planned schedule, overall the project is in the Coordinator's opinion exceeding its expectations. If we once again discuss this in terms of the eleven Milestones, we can assess the situation it in the following way. Milestones that have been *reached* or *essentially reached* are typeset in *italic:*

MS1: Remote Unit design parameters fixed. Done.
MS2: First tether sample delivered to reeling test. Done.
MS3: Construction of Remote Unit component prototypes start. Done.
MS4: 100 m tether produced. Done, ahead of time.
MS5: Reeling of tether demonstrated. Done, also independently at DLR and UH, and the ESTCube-1 test mission with tether is delivered on January 21, 2013 to the launch provider and will be launched onboard Vega on April 13 2013.
MS6: Main tether reel prototype tested. Not yet done, because main tether reel WP was decided to be postponed until optimal design parameters are known from other WPs.
MS7: Remote Unit prototype tested. Not yet done, tests are scheduled in February 2013.
MS8: Gas thruster prototype tested. Formally not yet done, but similar thrusters have been fired and even flown (PRISMA).
MS9: FEEP thruster prototype tested. Done, although not yet reported in a Deliverable.
MS10: 1 km tether produced. Done, ahead of time.
MS11: Concrete E-sail designs and missions using them analysed. A lot of work has already been done and will continue until end of the project.

We are particularly proud of the successful production of 1 km tether and successful low-mass design of the Remote Unit because the items are a backbone of the E-sail technology. The most important remaining tasks are to complete the Remote Unit environmental testing successfully, to fix the main tether reel design parameters and to complete its design work, and overall to allocate the remaining budgetary and time resources in the most beneficial way during the third and final period of the project.

3.2.3 Project management during the period

The consortium management was usually unproblematic, but we were challenged by the fact that it seemed in summer 2012 that the Remote Unit work was going over budget if implemented in the originally planned breadth, and therefore we had either to reallocate resources from some other WPs or to descope the Remote Unit prototyping activity. We tried to find candidate WPs that could have been descoped in benefit of the Remote Unit work, but this turned out to be difficult to do. Thus we were forced to decide to build only one Remote Unit prototype and not two as it was planned at one point of the project. (In the DoW we did not explicitly state the number of Remote Unit prototypes that we would build to completion and testing, so this does not mean descoping the the DoW.) Partially the decision was also forced by the fact that we needed to decide rather rapidly how many Remote Unit structural parts to order from the workshop, and not having any spare funds in this type of project we had to act conservatively and ordered only one unit. After receiving the budgetary reports from all partners for Period 2 (which has not yet happened when writing this), we will look into the budget situation and decide about the most beneficial and efficient use of resource during Period 3.
The following project meetings were held during the period (Dec 1 2011- Nov 30 2012):

Meeting	Date	Location	Participants
Remote Unit component design review II	9-10 Jan 2012	Uppsala	RU team
Remote Unit electronics technical meeting	23-24 April 2012	Uppsala	ÅSTC,Nanospace, Tartu
Tether testing planning meeting	16 May 2012	Jyväskylä	UJ, FMI
Mission and E-sail design kickoff	29-30 Sep 2012	Pisa	FMI,Alta,Pisa,Tartu

The ESAIL project public website was set up and the address is http://www.electric-sailing.fi/fp7. In addition, private ESAIL Team Pages were set up which contain more information for internal use, at address https://www.electric-sailing.fi/fp7s. The Team Pages are password protected and the password has been communicated to the Evaluator and the Project Officer separately. In particular, the Team Pages contain the agendas, the minutes, the presentations and some photographs from each project meeting. The Team Pages also contain copies of the delivered deliverables, a template for new deliverables, list of the WP descriptions, the full DoW and different versions of the ESAIL project logos for partners to 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: Hardware delivery Jan 21 2013, Launch April 13 2013)
- Aalto-1 nanosatellite project (Aalto University, FMI, UH, UJ, DLR: launch in 2014)

- SWESTCube ("Solar Wind Electric Sail Test Cubesat") nanosatellite project (early planning stage; Tartu,FMI,Nanospace), target launch is 2015, purpose is to lift 3U or 6U CubeSat to hieh elliptic orbit by GTO piggyback launch and advanced evaporative gas thruster and measure the E-sail effect in the solar wind
- 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€
- 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)

Appendix: Emissivity measurements

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Introduction

The basic idea for measuring the emissivity of the tether wire is to heat up the wire in vacuum conditions while measuring voltage drop across the wire for getting a resistance value, which is a function of the wire temperature. The emissivity value has a strong effect on the thermodynamics of the wire because the wire is long compared to its diameter and therefore the heat conduction is low compared to radiated heat. Because of the boundary effects, non-constant resistivity of aluminium, power-law dependence of radiation, etc. the only way to get the emissivity of the wire is to compare the experimental data to data from a computer simulation.

Emissivity measurement setup

The measurements are done in a vacuum chamber shown in figure 1 with low 10^{-7} mbar pressure. The wire under measurement is bonded to 15x10x1 mm^3 aluminium plates (plate A) at each end, which are bolted to a larger aluminium plates (plate B) used to mechanically connect the measurement wire to a rigid support frame keeping the wire approximately straight. The plate B at each end is used to connect the measurement wires coming from the vacuum feed-throughs (see figure 2). Outside the vacuum the electronics shown in figure 3 is connected to the measurement wires. The electronics uses a four-wire connection. Two of the wires are used for the bias current and two of the wires are used to voltage measurement. Therefore the biggest other contribution to the measured resistance comes from contact resistance between plate A and the wire (the bonded contact). The measurement electronics is connected to computer control/DAQ system National Instruments PCI-6229, which is used to collect data at 10 kHz sample rate. Calibration of the device was done with 100 ohm (± 1 %) resistor and Fluke 87 IV multimeter by driving the measurement current through the resistor and measuring the voltage drop with the multimeter. Current setting and voltage reading calibration coefficients were set accordingly.

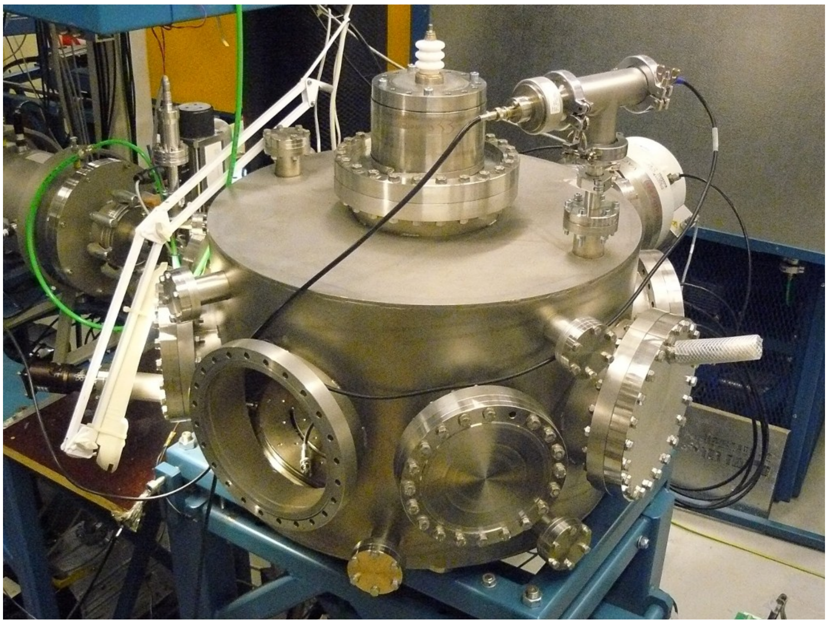

Figure 1. The vacuum chamber for making the tether testing.

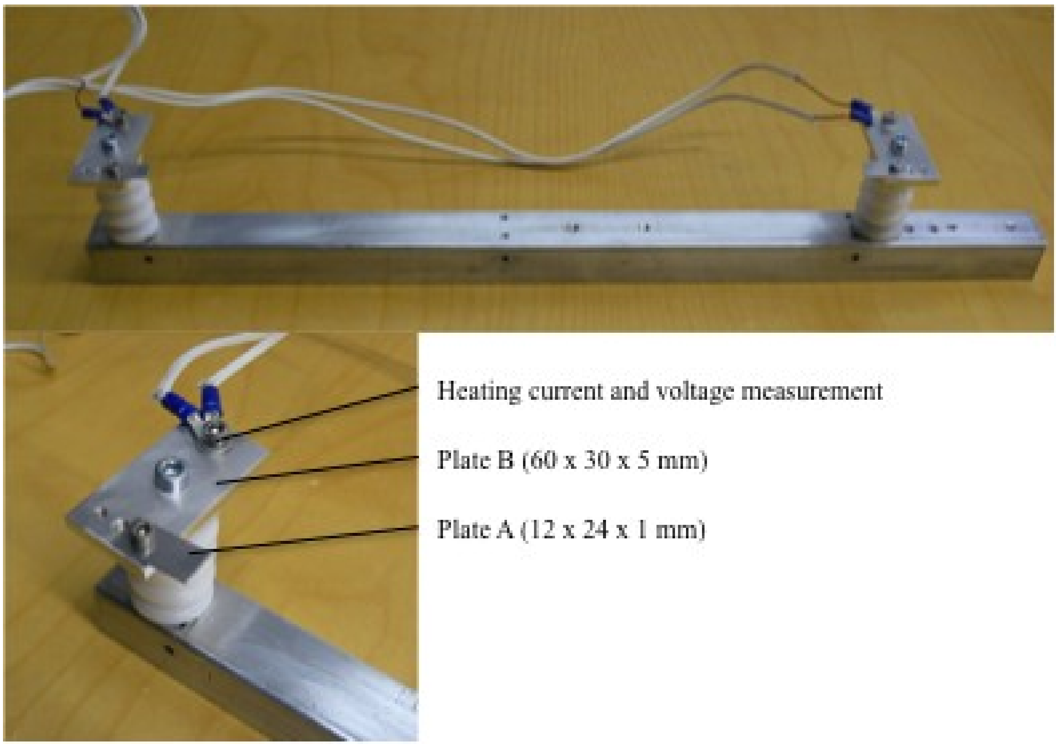

Figure 2: Setup for the emissivity measurements.

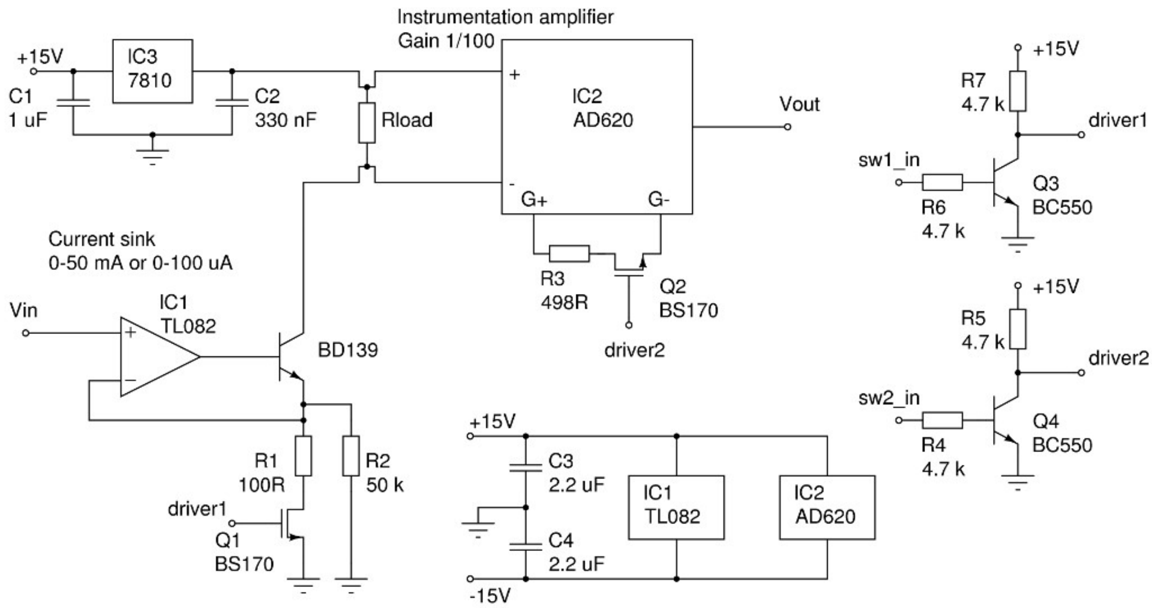

Figure 3. Circuit schematics of electronics developed for emissivity measurement. The electronics provides a four-wire resistance meter functionality with two ranges for currents and two gain settings.

Simulation program

The simulation program used for modelling the heated tether wire is based on solution of heat equation in a one-dimensional system, where resistive heating, heat conductance and radiative losses are taken in account. The simulation discretizes the wire of length L into

N (nominal value of 100) cylindrical pieces or *nodes*, which are assumed to have a temperature T_i. Each cylinder therefore has a length $dx=L/N$ and radius r. The system is iterated with dt long time steps starting from the ambient temperature T_a=297 K. At each time step, the temperature of the nodes is updated according to a local energy flow: $\Delta T_i=P\cdot dt/(c(T_i)d\cdot A\cdot dx)$, where $c(T)$ is the heat capacity of aluminium as a function of temperature, d is the density of aluminium, A is the cross section of the aluminium wire and P is the sum of power to the node. The summed power consists of 1) resistive heating component $P_{h,i}=\rho(T_i)dx\cdot I^2/A$, where $\rho(T)$ is the resistivity of aluminium and I is the current driven through the system; 2) radiative component $P_{r,i}=E(T_i)\sigma A_s(T_a^4-T_i^4)$, where $E(T)$ is the emissivity of aluminium, σ is the Stefan-Boltzmann coefficient for black-body radiation, $A_s=2\pi\cdot r\cdot dx$ is the surface area of the node cylinder; and 3) conductive component $P_{c,i}=k(T_i)A(T_{i-1}-2T_i+T_{i+1})/dx$, where $k(T)$ is the heat conductance of aluminium. The current driven through the system can be varied in a sequence similarly as is done in measurements. The simulation gives the measurable parameters resistance R and voltage V as output as a function of time. The emissivity is fed into the simulation as a linear function of temperature $E(T)=E_A\cdot T+E_B$.

The ends of the wire are assumed to be in ambient temperature. The validity of this assumption is checked in the simulation by calculating the total energy flow to the ends and converting this energy to an increase in temperature assuming that the all of the heat goes to the aluminium bonding substrates (Plate A). The energy flow might not be as assumed if the wire has been damaged in the bonding process, for example. In the typical case used in the experiments the wire is heated for 200 seconds with 20 mA and measured for 200 seconds with 50 uA measurement current. In this sequence the temperature rise of the substrate was simulated to be 0.35 K. In reality the temperature rise is smaller because the substrate is bolted to a much larger aluminium plate (plate B above) assuming that the thermal contacts from the wire to plate A and from plate A to plate B are good.

First measurement and analysis

First successful measurement has been done with plain 459 mm long 25 um diameter aluminium wire. The wire heating was done with 5 different current values: 1 mA, 5 mA, 10 mA, 15 mA and 20 mA. Each measurement consists of (a) 1 second of background measurement with zero bias, (b) 1 second of resistance measurement with 50 uA current, (c) 200 seconds of heating, (d) 200 seconds of resistance measurement with 50 uA current and (e) 600 seconds of cooling with zero current before next measurement cycle. The measurement resistances are plotted in figure 4 together with the fitted simulation results.

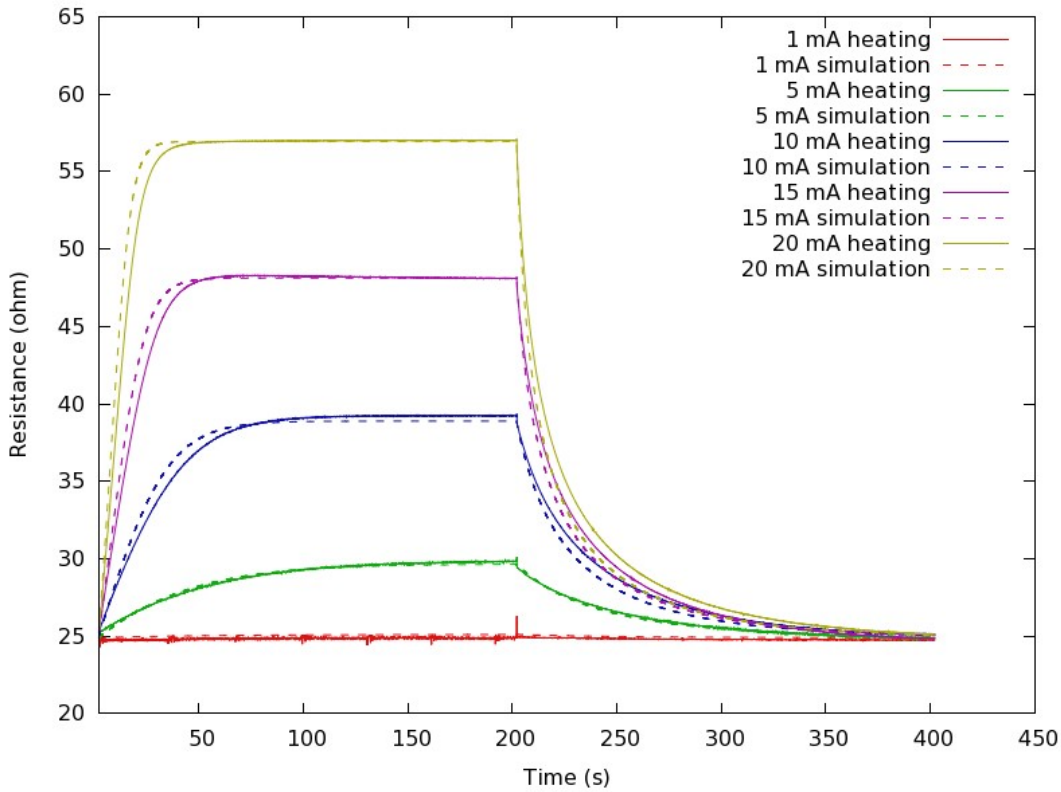

Figure 4. Emissivity measurement with 5 different heating currents plotted together with simulation results.

The data fitting with the simulation was done manually by adjusting the free parameters, which were the wire thickness and the two coefficients A and B for emissivity. Emissivity was assumed to be a linear function of temperature E(T)=A·T+B. The wire thickness was first adjusted to match the 1 mA heating curve. Emissivity coefficients were then adjusted to find the best fit to the experimental data at the static situation when heating is on (time 150-200 s). The best fit for the thickness was found to be 25.2 um. The best constants for emissivity were found to be A=1.15e-4 and B=-0.0005. The emissivity curve is plotted in figure 5 together with data from Engineering toolbox for unoxidised aluminium (http://www.engineeringtoolbox.com/radiation-heat-emissivity-aluminum-d_433.html). The temperature range, which is being used here is between 300 and 650 K as shown in figure 6, which has the spatial temperature distributions of the wire at t = 200 s.

The match to experimental data is pretty good in the static situation, but the time constant in the transitions is different by about 10-20 %. Therefore, this suggests that the heat capacity used in the simulations (from www.efunda.com) does not match reality. This error doesn't affect the validity of the analysis presented as the heat capacity doesn't have an effect the static situation, which was used for data fitting.

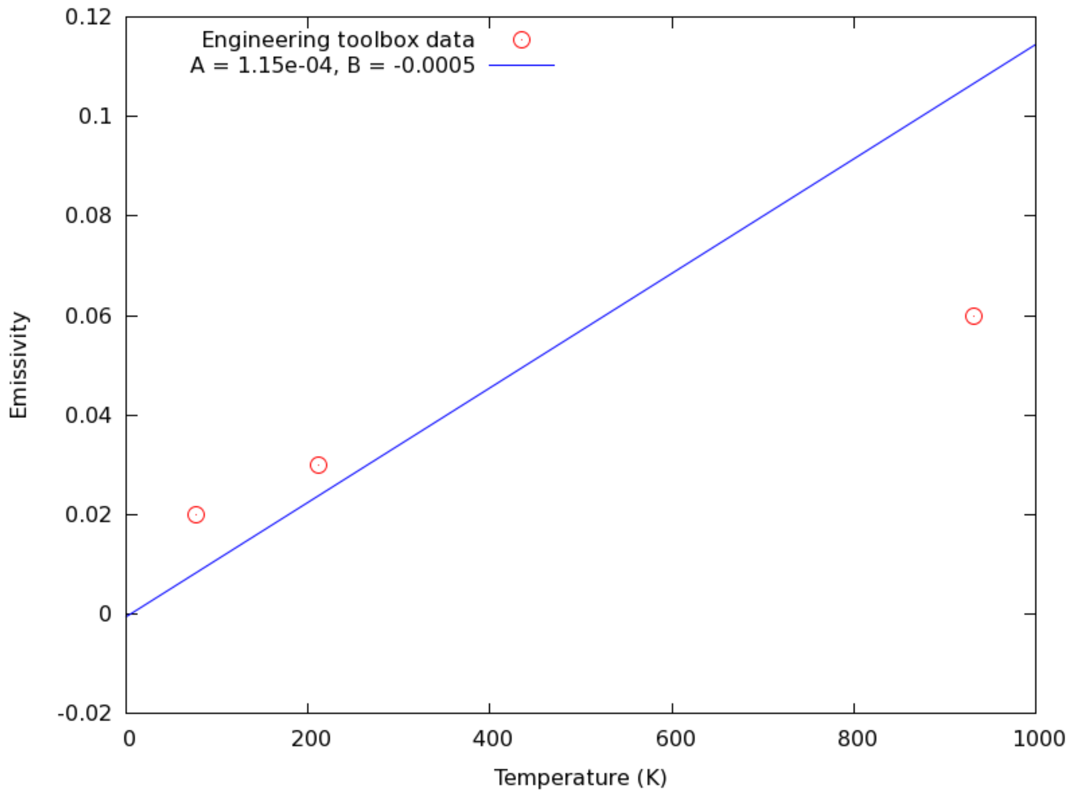

Figure 5. Best fit for emissivity for matching simulation to experimental data.

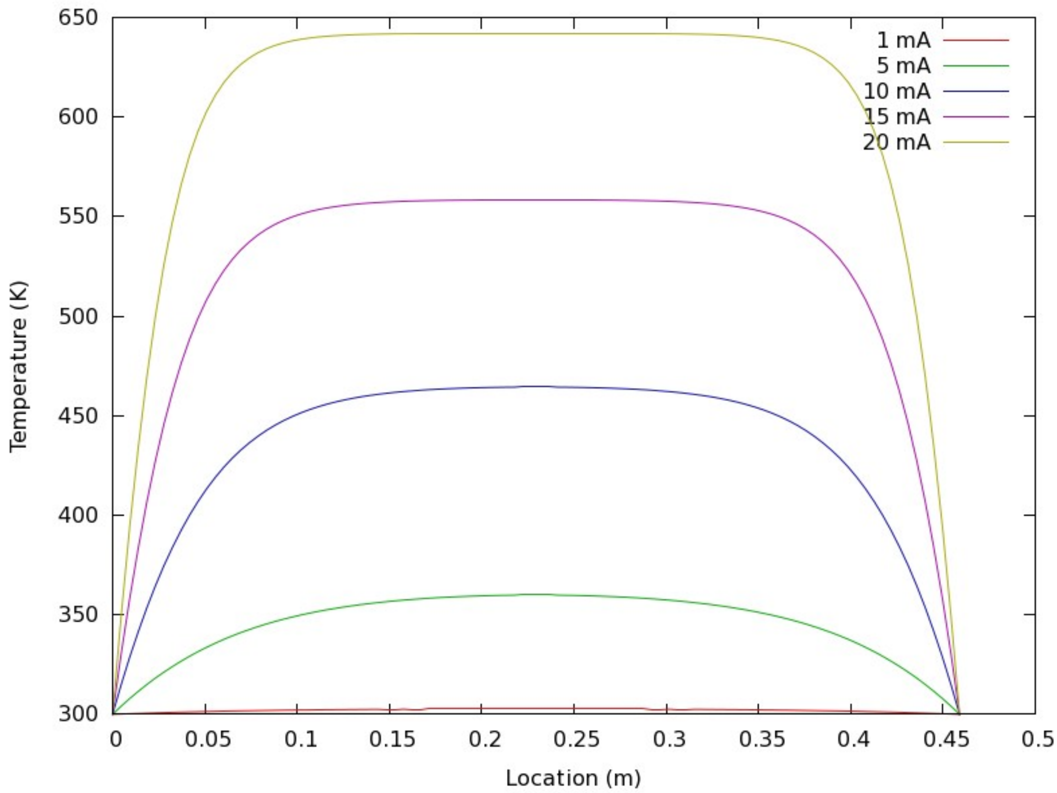

Figure 6 Spatial distribution of temperature on wire at t=200 s, before switching to lower bias current.

Second measurement with shorter wire

A second sample of bare 25 um aluminium wire was measured. This time the sample was 248 mm in length (bond-to-bond). The same measurement procedure was used as with the first measurement. This time we were able to get data from a “fresh” sample because the hardware development was done already (last time we did “blind” heating). The first measurement data is shown in figure 7.

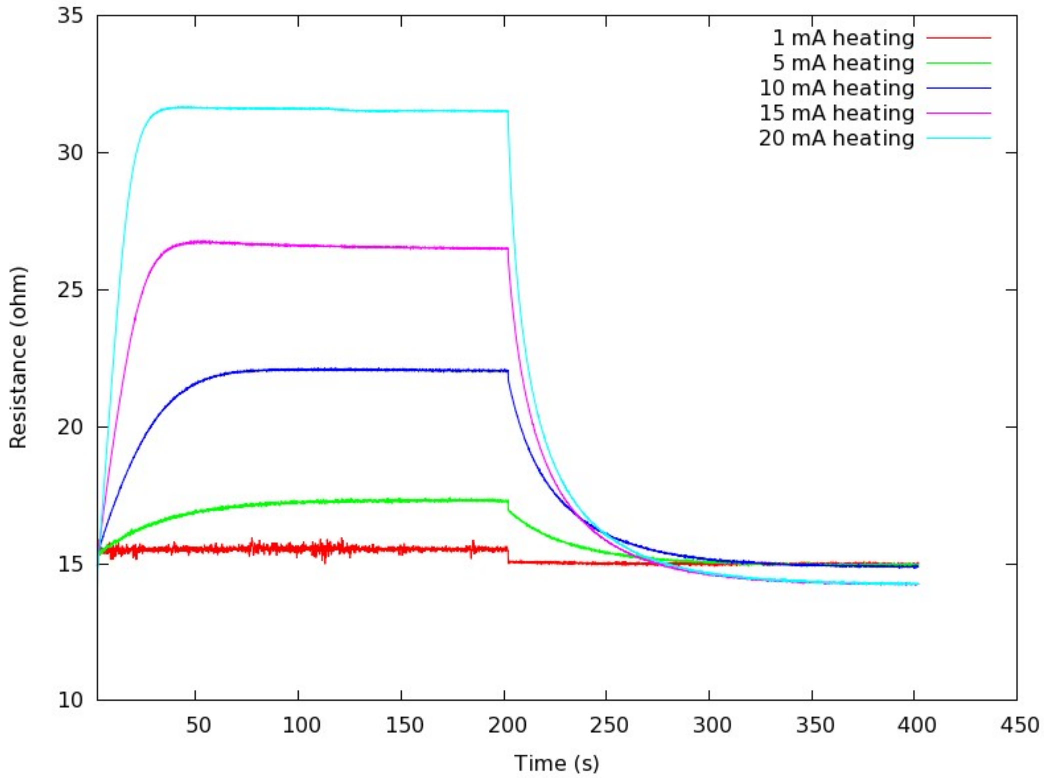

Figure 7. Resistance data from the first measurement sequence (made in order 1, 5, 10, 15, 20 mA) for 248 mm wire. Some heat induced changes happen at higher currents, which can be seen as a decreasing resistance in time 25-150 s and in the changed cold resistance value (about 1 ohm less than before heating).

Some changes in the wire or the wire bonds happened when heated. This can be seen in figure 7. Because of the observation the wire heating was cycled on and off with the following cycle: 200 s 15 mA heating current, 200 s 50 uA measurement current, 200 s 0 A current. The cycle was repeated 100 times. The resistance was still observed to decrease a bit during the cycling, until it converged to a constant value. After this sequence a new measurement with 1-20 mA heating currents was done. The results of this measurement is shown in figure 8 together with simulation results. The simulation was matched to measured data by adjusting the wire thickness and emissivity of the material. The best fit for the thickness was found to be 24.8 um and the emissivity coefficients A=1.05e-4 and B=-0.0015.

The emissivity result is shown in figure 9 together with the emissivity result from the previous measurement.

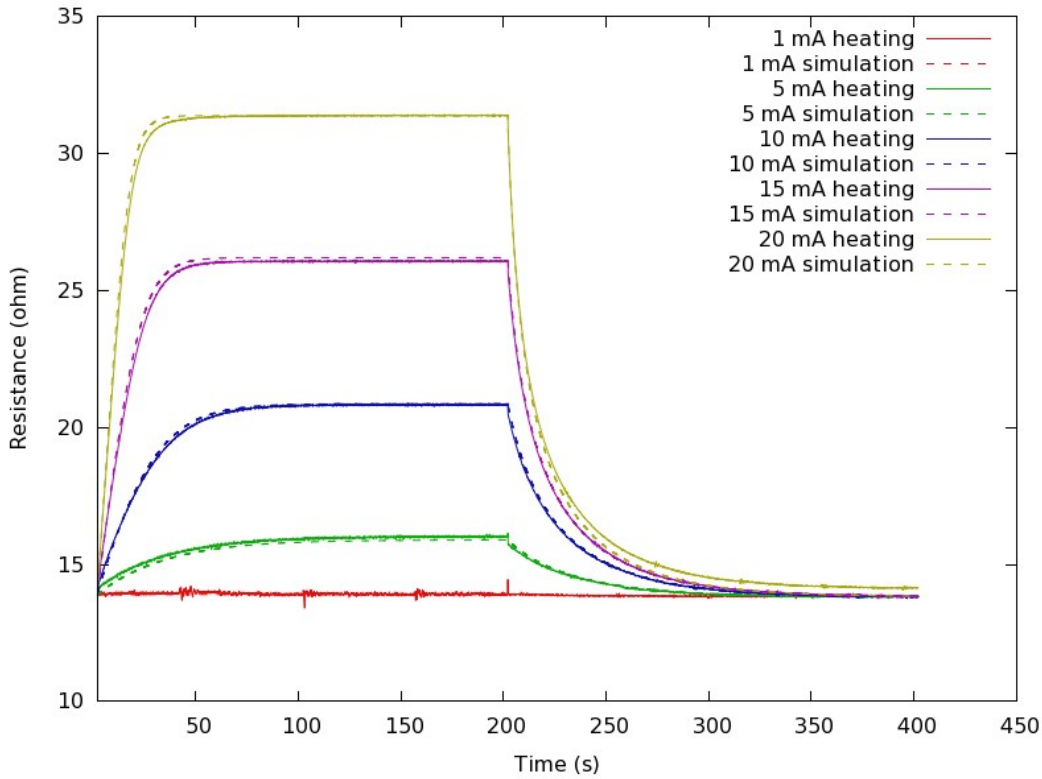

Figure 8. Resistance value from wire measurement with 248 mm wire together with simulation results best matching to the measurement.

Aluminium oxide coatings

Three samples were prepared by University of Helsinki: two longer wires and one shorter. One of the long ones was damaged during assembly of measurement setup. One long and one short were measured and the data was analysed similarly to what was described before. The fit to the short wire data was of bad quality for an unknown reason. It seemed that by fitting the wire diameter and emissivity coefficients A and B, it was not possible to get a good fit. It is possible that this behaviour is due to a damaged wire close to the bond, for example. It would be good practice to study the wire using scanning electron microscope (SEM) before emissivity measurement. The emissivity results for the tested coated wires are presented in figure 9.

According to these measurements the emissivity of the wire has increased 20-30 % at 600 K by oxidation. This should be large enough to state that an observable increase in the emissivity is achieved. To make more formal estimates of the magnitude of uncertainty, a systematic study with several identical wires should be measured.

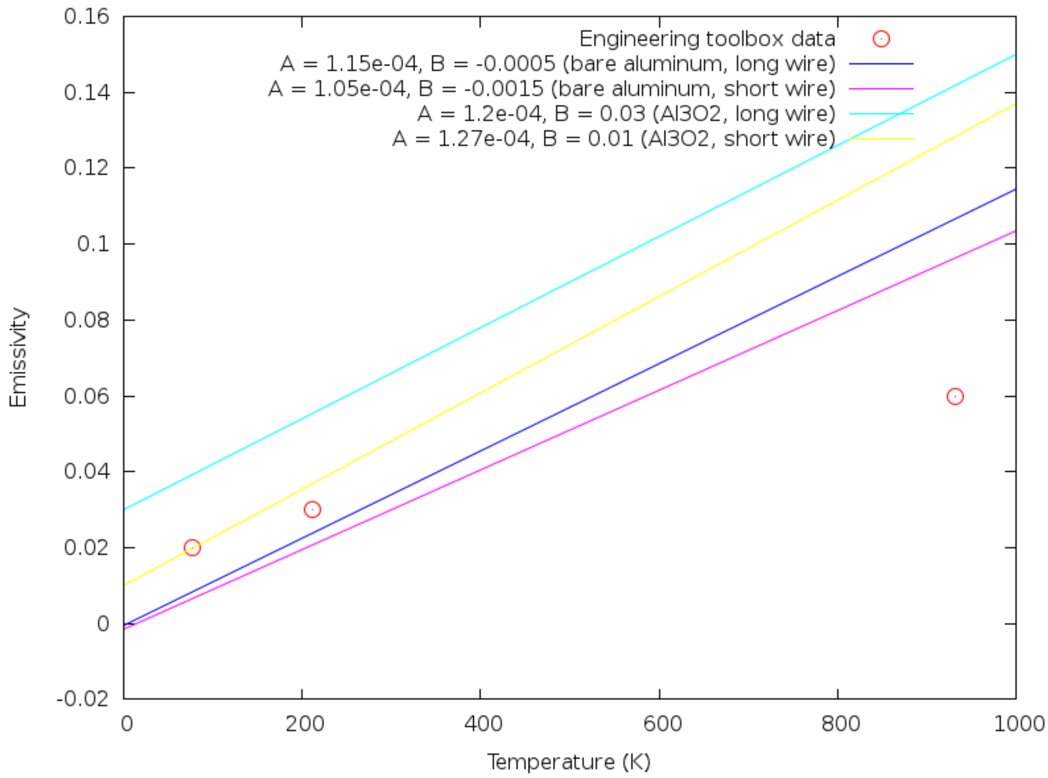

Figure 9. Emissivity of tether wire as a function of temperature from the measurements.