Proceedings of the Estonian Academy of Sciences,
2014, **63**, 2S, 210–221
doi: 10.3176/proc.2014.2S.02
Available online at www.eap.ee/proceedings

E-sail test payload of the ESTCube-1 nanosatellite

Jouni Envall[a,b*], Pekka Janhunen[a], Petri Toivanen[a], Mihkel Pajusalu[c], Erik Ilbis[c], Jaanus Kalde[c], Matis Averin[c], Henri Kuuste[c], Kaspars Laizans[b,c], Viljo Allik[b], Timo Rauhala[d], Henri Seppänen[d], Sergiy Kiprich[e], Jukka Ukkonen[d], Edward Haeggström[d], Taneli Kalvas[f], Olli Tarvainen[f], Janne Kauppinen[f], Antti Nuottajärvi[f,g], and Hannu Koivisto[f]

[a] Finnish Meteorological Institute, P.O. Box 503, FI-00101 Helsinki, Finland
[b] Tartu Observatory, Observatooriumi 1, 61602 Tõravere, Tartumaa, Estonia
[c] Institute of Physics, Faculty of Science and Technology, University of Tartu, Tähe 4-111, 51010 Tartu, Estonia
[d] Electronics Research Laboratory, Department of Physics, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland
[e] National Science Center, Kharkov Institute of Physics and Technology, 1 Akademicheskaya St., Kharkov, UA-61108, Ukraine
[f] Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland
[g] Current affiliation: Department of Chemistry and Bioengineering, Tampere University of Technology, FI-33720 Tampere, Finland

Received 13 August 2013, revised 17 April 2014, accepted 27 April 2014, available online 23 May 2014

Abstract. The scientific mission of ESTCube-1, launched in May 2013, is to measure the electric solar wind sail (E-sail) force in orbit. The experiment is planned to push forward the development of the E-sail, a propulsion method recently invented at the Finnish Meteorological Institute. The E-sail is based on extracting momentum from the solar wind plasma flow by using long thin electrically charged tethers. ESTCube-1 is equipped with one such tether, together with hardware capable of deploying and charging it. At the orbital altitude of ESTCube-1 (660–680 km) there is no solar wind present. Instead, ESTCube-1 shall observe the interaction between the charged tether and the ionospheric plasma. The ESTCube-1 payload uses a 10-m, partly two-filament E-sail tether and a motorized reel on which it is stored. The tether shall be deployed from a spinning satellite with the help of centrifugal force. An additional mass is added at the tip of the tether to assist with the deployment. During the E-sail experiment the tether shall be charged to 500 V potential. Both positive and negative voltages shall be experimented with. The voltage is provided by a dedicated high-voltage source and delivered to the tether through a slip ring contact. When the negative voltage is applied to the tether, the satellite body is expected to attract the electron flow capable of compensating for the ion flow, which runs to the tether from the surrounding plasma. With the positive voltage applied, onboard cold cathode electron guns are used to remove excess electrons to maintain the positive voltage of the tether. In this paper we present the design and structure of the tether payload of ESTCube-1.

Key words: space research, propulsion, satellite, nanosatellite, electric solar wind sail, E-sail, ESTCube-1.

Acronyms and abbreviations

ADC – analogue-to-digital converter
ADCS – Attitude Determination and Control System
CDHS – Command and Data Handling System
EPS – Electrical Power System
ESA – European Space Agency
FMI – Finnish Meteorological Institute
DLR – German Aerospace Center
HV – high-voltage
MCU – microcontroller unit
MOSFET – metal-oxide semiconductor, field-effect transistor
PL – payload
SPI – Serial Peripheral Interface
UH – University of Helsinki
UJ – University of Jyväskylä
UT – University of Tartu

* Corresponding author, jouni.envall@fmi.fi

1. INTRODUCTION

The scientific mission of ESTCube-1, the first Estonian satellite, is to perform an on-orbit test of the electric solar wind sail (E-sail) concept. The E-sail is a propulsion innovation made at the Finnish Meteorological Institute (FMI) in 2006 [1]. Thrust is produced by harnessing the momentum of charged solar wind particles by using long, thin, and electrically charged conducting tethers. A fullscale E-sail spacecraft is planned to have e.g. 100 tethers, each 20 km long. The sail is kept open with the help of centrifugal force, the spacecraft must therefore be kept in rotating motion. Once operational, E-sail technology is expected to revolutionize the space travel within our solar system [2–9].

The experiment conducted by ESTCube-1 marks the beginning of the space test era for the E-sail [10]. The ESTCube-1 payload (PL) includes one E-sail tether, deployable to ~10-m length. The tether is stored on a motorized reel and can be reeled out upon request from the ground. The principle of tether deployment is similar to the proposed principle of larger E-sails, i.e. the satellite is spun around its axis of the maximum moment of inertia and the exiting tether is stretched by the effect of centrifugal force. This force is enhanced by placing a small end mass at the tip of the tether. Successful deployment of the tether is verified by observing a noticeable drop in the satellite spin rate. In addition, a visual verification shall be obtained by imaging the tether and its end mass with the onboard camera during the tether deployment. Once deployed, the tether shall be charged with a voltage of 500 V. Both positive and negative voltages, corresponding to positively and negatively charged E-sails, respectively, shall be tested. Because of its orbit (a low-Earth orbit with 660–680 km altitude) ESTCube-1 is not influenced by solar wind. Instead, the charged tether shall interact with the ionospheric plasma, through which the satellite is travelling with its orbital speed of 7.5 km/s. When the on and off cycles of the tether voltage are correctly synchronized to the satellite's spin rate, the E-sail effect between the tether and the plasma can be observed as a cumulative change in the spin rate. The change can be chosen to be in either direction, depending on the on/off cycling.

In this paper we give an overall technical description of the onboard apparatus which shall be used to perform the E-sail experiments. The satellite was launched into orbit on 7 May 2013 (UTC), but at the time of writing it had not yet entered the tether experiment phase of its mission.

2. APPARATUS

The PL apparatus is divided on two separate circuit boards, the motor board and the high-voltage (HV) board. Figure 1 depicts the internal connections of the PL, as well as the interactions between the PL and the Command and Data Handling System (CDHS) and the Electrical Power System (EPS) of the satellite. Figure 2 shows how the circuit boards are fitted into the assembled satellite. The motor board is responsible for the tether deployment. It is where the tether is stored prior to the

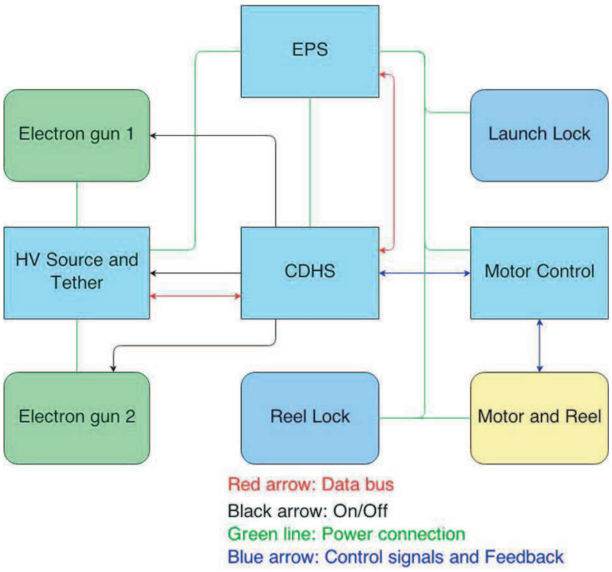


Fig. 1. Block diagram depicting the data and power interactions between PL parts, CDHS, and EPS.

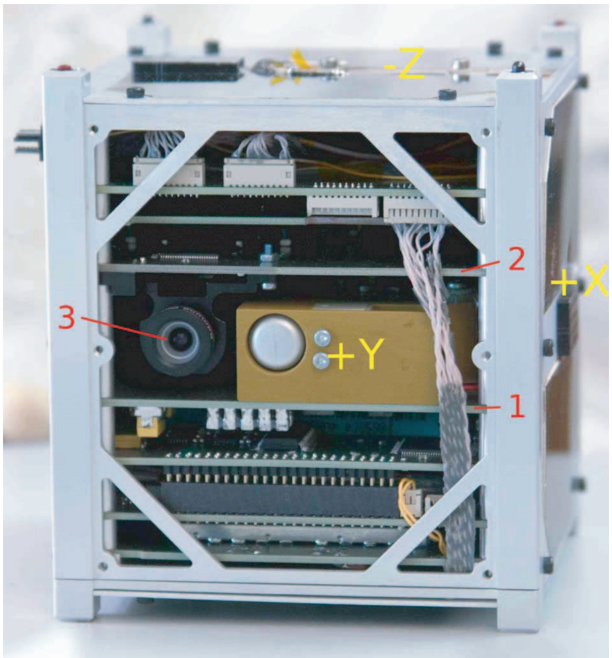


Fig. 2. Assembled satellite with side panels removed. Labels: (1) motor board, (2) HV board, (3) onboard camera. The yellow labels denote the directions of the X, Y, and Z axes of the satellite's coordinate system.

deployment and it also includes the hardware and electronics needed to reel out the tether. The HV board provides the ±500 V voltages needed during the E-sail experiment. In addition to the circuit boards, two cold cathode electron guns are attached on ±Z sides of the satellite, one on each side.

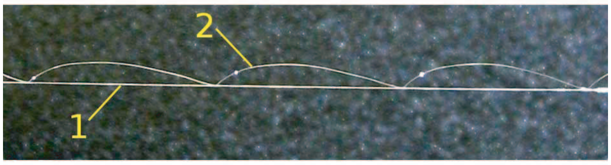
The HV board does not have its own microcontroller unit (MCU). The HV operations are directly operated and commanded by the CDHS. The CDHS is able to switch the high voltage on or off and select which of the electron guns, if any, are operational. These operations are commanded via simple digital on/off signals. In return, the HV board provides the CDHS with the signals for current measurement (see Section 2.8 for details). Both the tether current and the (electron gun) anode current are measured throughout the E-sail experiment. The former provides scientific data needed for the full understanding of the E-sail phenomenon, while the latter provides information about the performance of the electron guns.

The motor board includes an MCU, but the communication between the motor board and the CDHS is nevertheless handled via low-level on/off signals. The CDHS commands the motor on or off and in return it gets a pulse sequence, corresponding to the amount which the motor has turned.

2.1. Tether

The tether is one of the core technologies of E-sail development. The tether manufacture is being carried out by the Electronics Research Laboratory at the University of Helsinki (UH). Currently E-sail tethers are made of 25–50 μm aluminium wires, which are ultrasonically bonded together to form multifilament tethers. The UH has developed a specific ultrasonic wire-to-wire bonding technology to achieve this goal [11,12]. The reason for using the multifilament design is to make the tethers more resistant to micrometeoroid bombardment. The tether onboard ESTCube-1 consists of two parts; a 3.5-m two-filament Heytether part and a 16-m single-filament part. The physical properties of the Heytether part enable proper demonstration of E-sail tether outreeling, and it also provides protection against micrometeoroids for the outer end of the tether. The single-filament part enables the overall length of the tether to be lengthened up to 19.5 m. Nominally the ESTCube-1 mission is designed to operate a 10-m tether. Figure 3 illustrates the Heytether structure. It consists of a 50-μm basewire and a 25-μm loop wire.

(a)



(b)

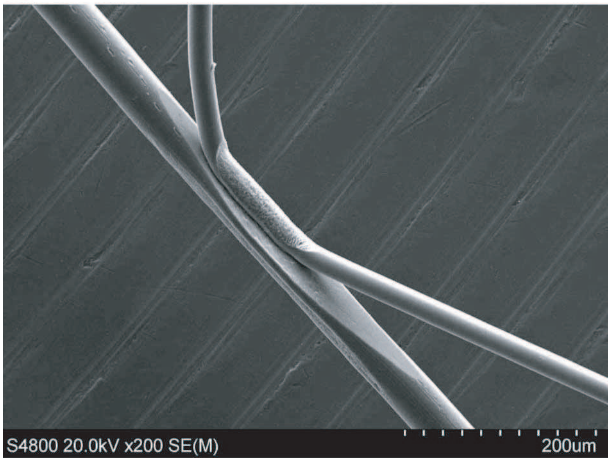


Fig. 3. Two-filament Heytether. (a) Photograph of the tether. Labels: (1) basewire, (2) loop wire. Distance between bonds is 10 mm. (b) Scanning Electron Microscope (SEM) image of an ultrasonic wire-to-wire bond.

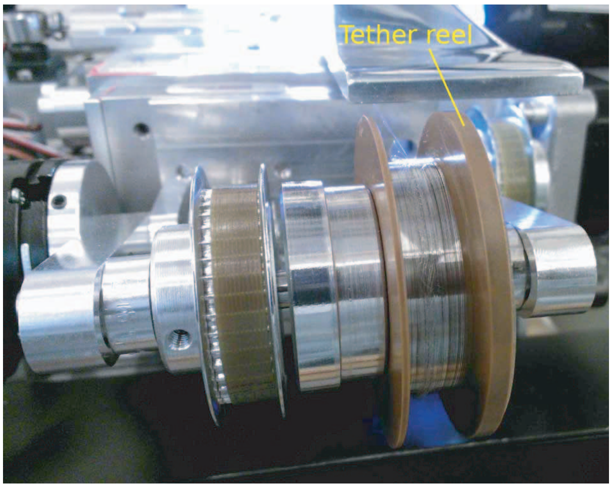


Fig. 4. Tether being manufactured on the reel at the UH on 15 January 2013.

2.2. Tether reel and isolation

At the beginning of the mission the tether is stored on a dedicated reel. The overall diameter and height of the reel are 50 mm and 14 mm, respectively. The inner cylindrical face, around which the tether is stored, has the dimensions of 36 mm and 10 mm for diameter and height, respectively. Packing the tether on the reel is a delicate process, which currently can only be performed by the tether factory at the UH. The tether is packed directly onto the target reel while being manufactured. Figure 4 shows this work in progress. Onboard the satellite the reel is attached directly on the motor which runs it. Surrounding the reel there is a block called

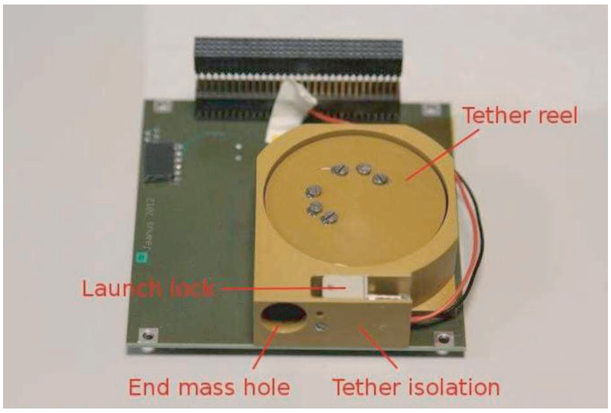


Fig. 5. Motor board partly assembled. The two electric wires on the right are used for releasing the launch lock. They were not connected to their terminals on the circuit board at the time of this photograph.

tether isolation. The purpose of this block is to offer mechanical platform for the tether end mass and its launch lock. Also, the tether isolation block ensures that the exposed high-voltage tether is electrically isolated from its surroundings. Figure 5 shows the tether isolation mounted around the reel. The material of both the reel and the tether isolation is Tecasint 4011 [13]. As a polyimide it is known to have favourable mechanical, thermal, and electrical properties for space use. It also comes with prior flight heritage. These mechanical parts were designed and produced by the German Aerospace Center (DLR), Bremen.

2.3. Reel motor and control electronics

A closed loop precision piezo rotator ANR101/RES from Attocube corporation was chosen as the tether reel motor. In Fig. 6a the motor can be seen attached on the motor board. The design and dimensions of the motor allowed it to be placed inside the tether reel, thus saving space on the circuit board, as shown in Fig. 6b. The motor is controlled with custom-designed control electronics. The design of the control electronics, as well as the circuit board layout and manufacture, were carried out by the University of Tartu (UT).

2.4. Slip ring

Because the tether needs to be charged with a high voltage during the experiment, an electrical contact is needed between the tether and the HV source. To establish such a contact from the circuit board onto a rotating reel, a slip ring structure is used. Figure 7a shows the slip ring. It is constructed of circuit board material with a gold alloy pattern etched on it. In Fig. 7b the slip ring is shown attached on the bottom of the reel with six screws. The four slip ring contacts can be seen

(a)

(b)

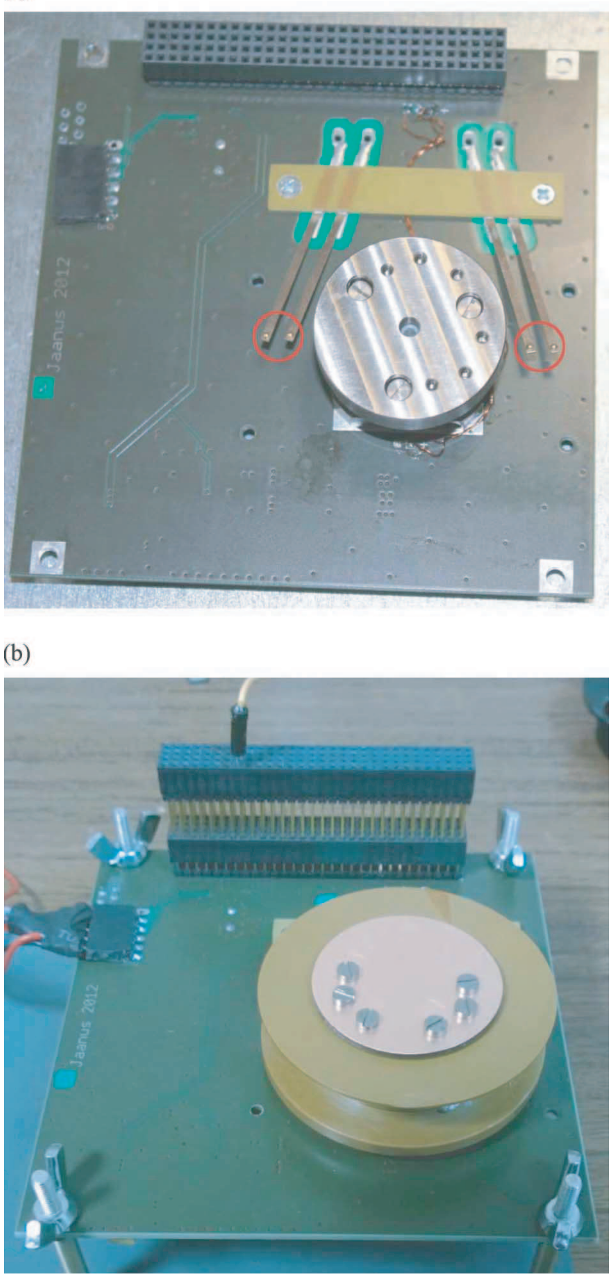
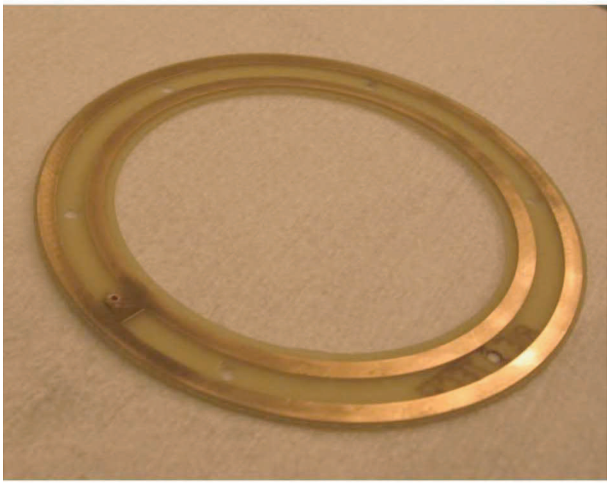


Fig. 6. Different stages of motor board assembly. (a) Reel motor attached on the circuit board. Shown circled are the four slip ring contacts. (b) Tether reel attached on the motor.

in Fig. 6a connected on the board and surrounding the motor on both sides. The material of the slip ring contacts is copper, with the contact points at the tip coated with gold alloy.

Figure 8 depicts how the tether is contacted to the slip ring. The root of the tether's basewire emerges through a hole. Three gold wires had been bonded to the basewire and subsequently all four wires were bonded to the slip ring. The reason for adding the gold wires was the difficulty of producing high-quality bonds between

(a)



(b)

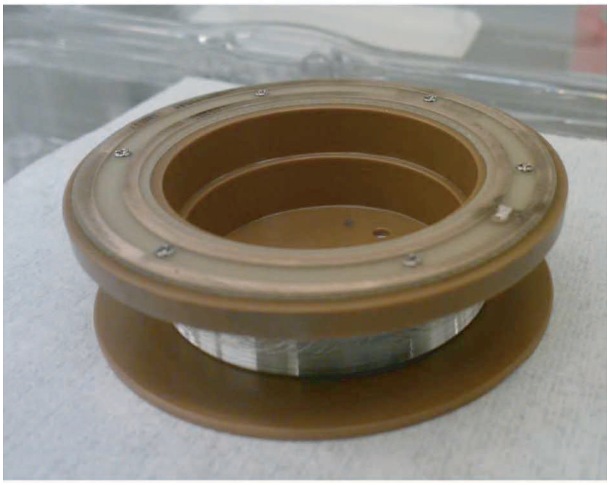


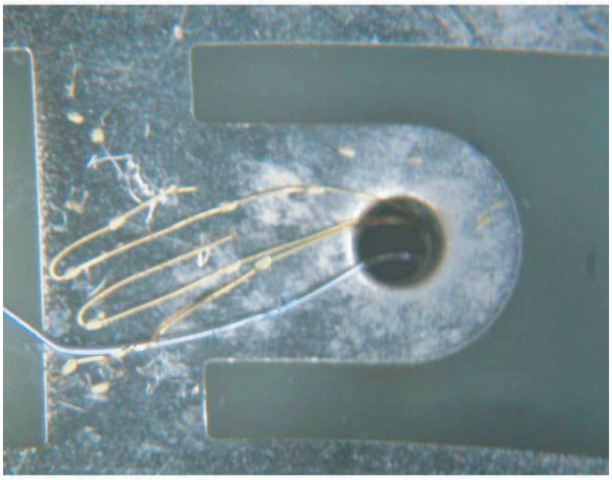
Fig. 7. Slip ring. (a) Bare slip ring. (b) Slip ring attached on the reel, tether bonded, and reeled.

the basewire and the slip ring gold alloy. Finally all bonds were covered with the conducting H20E glue from Epotek to ensure proper electrical and mechanical contact. The slip ring was designed and manufactured by the DLR, while the tether attachment was handled by the UH.

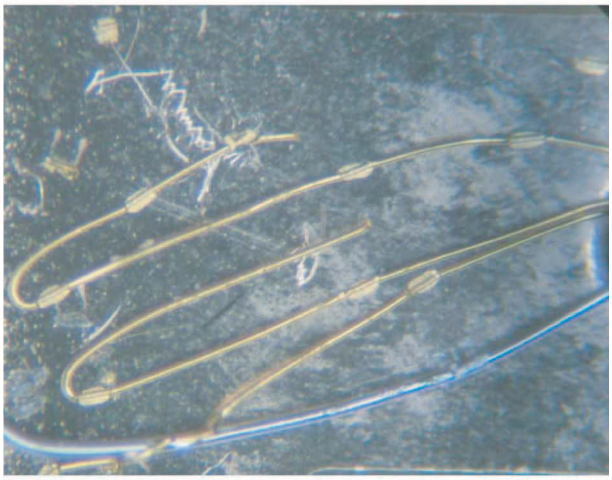
2.5. End mass

As described above, the tether is manufactured of hair-thin aluminium wires. Relying on the mass of the tether alone in an attempt to deploy it could lead to failure. To increase the centrifugal pull experienced by the tether, a 1.2-g end mass, with dimensions of 12 mm and 10 mm in diameter and length, respectively, was added at the tip. The end mass is constructed of aluminium and consists of two halves, which are attached with screws (see

(a)



(b)



(c)

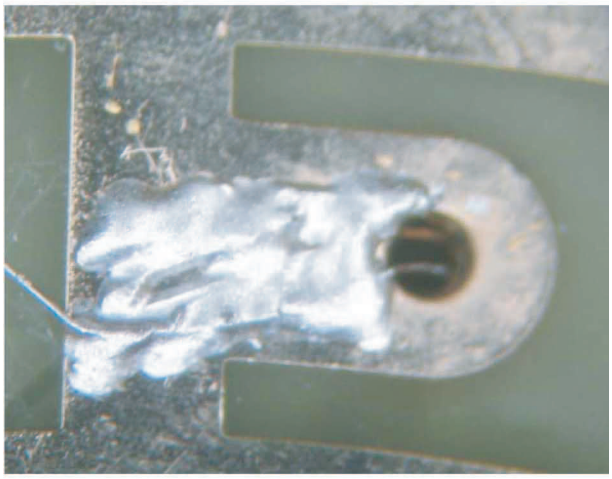


Fig. 8. Slip ring bond. (a) Basewire and three gold wires bonded on the slip ring. (b) Closeup of the same bonds. (c) All bonds covered with conducting glue.

Fig. 9a). The tether was squeezed between the two halves. Friction between the tether and the two halves was found sufficient, so no additional bonding or glueing was applied. The end mass was designed and produced at the UH. The assembled end mass can be seen hanging from the tether during PL assembly in Fig. 9b.

2.6. Launch lock

At the beginning of the mission the end mass must be locked to the tether isolation. The tensile strength of the tether is only about 50 g. Unless locked, the end mass would certainly break the tether, especially during the intense vibrations caused by the launch rocket. The launch lock can be seen in Fig. 10a. The launch lock design includes a spring loaded aluminium pin, which enters a dedicated cavity in the end mass while loaded (see Fig. 10b). The spring is kept loaded with a Dyneema string. Unlocking the reel lock is carried out by applying a current through a burn wire, which will cut the string. The launch lock was designed and produced by the DLR. The launch lock can also be seen at its final attached position in Fig. 11.

2.7. Reel lock

The reel lock is an instrument which needed to be introduced at a later stage of the satellite manufacture. Originally it was believed that the friction of the reel motor and its gear system would be sufficient to prevent the reel from turning during the launch vibrations. During the first vibration tests this assumption turned out to be faulty. In particular, it was observed that certain resonance frequencies during the vibrations would cause the piezo rotator to turn and thus break the tether. Figure 11 shows the motor board in its final form before integration to the satellite bus. The reel lock can be seen at the bottom right corner of the tether isolation block.

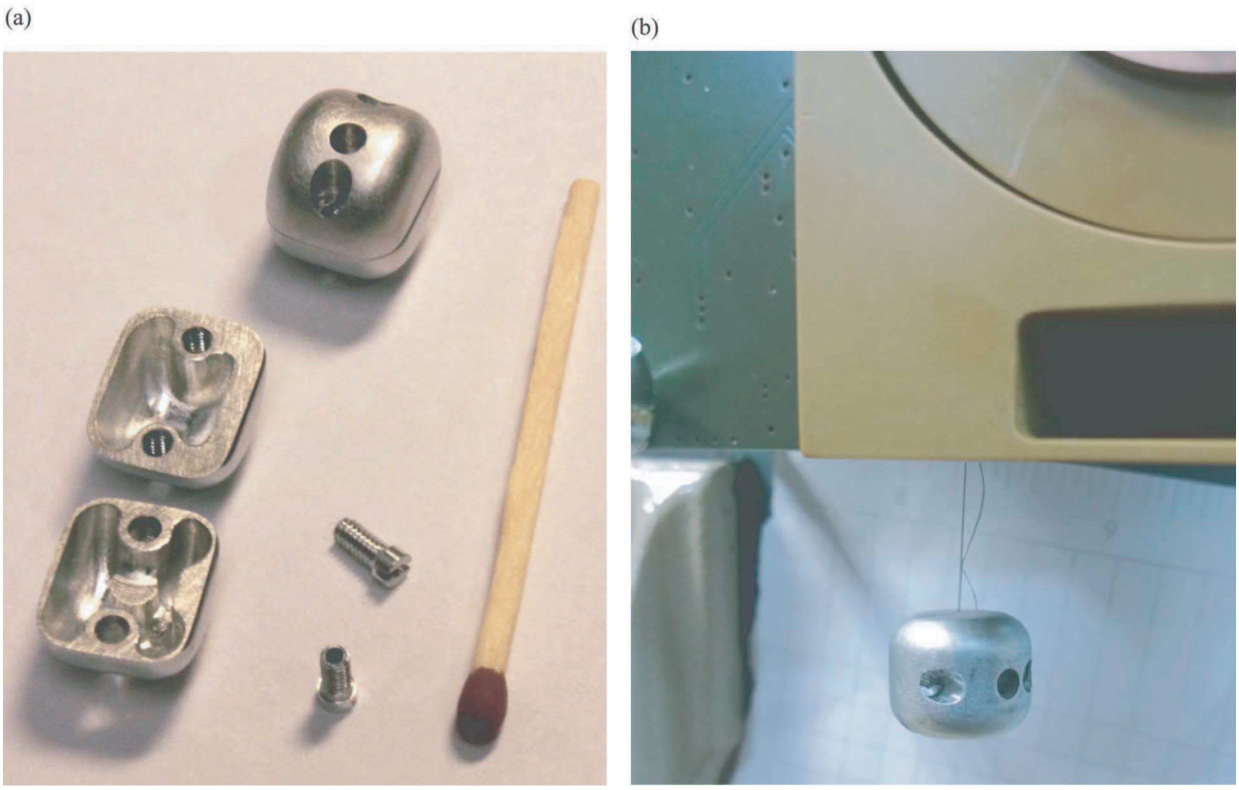


Fig. 9. (a) Assembled and stripped down view of the end mass. (b) End mass hanging from the tether during PL assembly. Tether enhanced digitally for visibility. Notice the middle hole for the launch lock pin.

(a) (b)

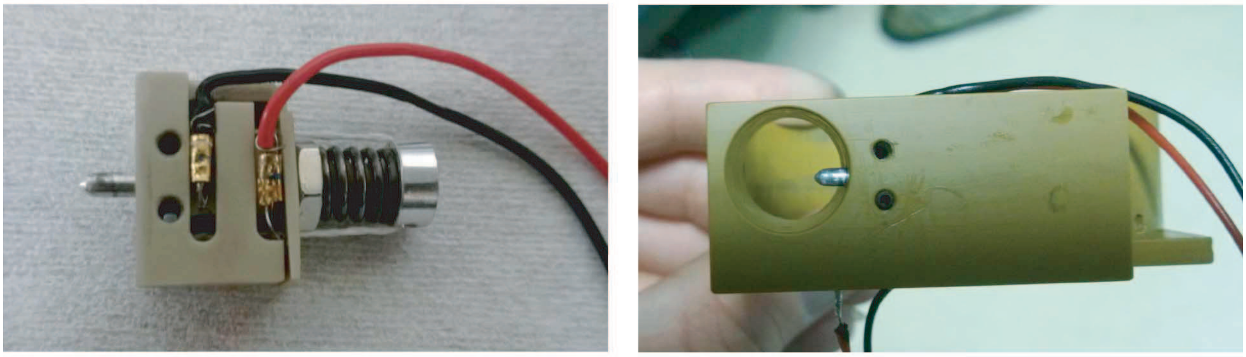


Fig. 10. (a) Launch lock, loaded. (b) Launch lock placed at its position in tether isolation. Notice the pin entering the end mass compartment.

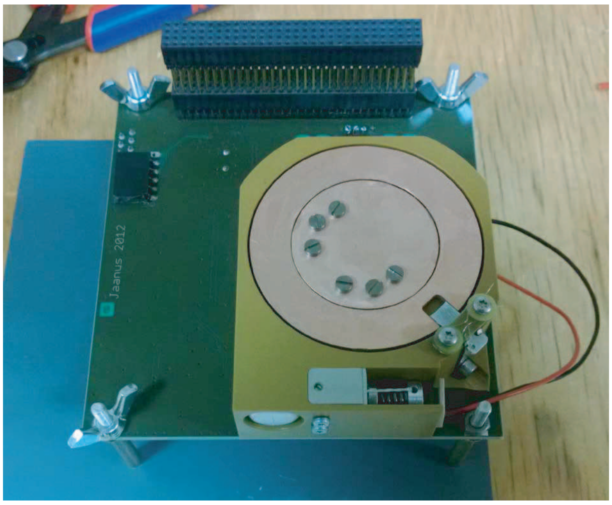


Fig. 11. Motor board fully assembled.

The locking is based on a metal bar, which is pushed into a dedicated slot in a locking ring. The locking ring consists of two coaxial parts, shown attached on top of the tether reel. The inner part is attached to the reel with the same screws which lock the reel to the motor. The purpose of this central part was to guide the outer part at the centre while being glued at its place. The reason for this complicated arrangement arose from the fact that the assembly procedure of the motor board required the end mass to be reeled in at its correct place in the tether isolation block with sub-millimetre accuracy. This in turn prevented us from predetermining the place of the locking slot on the face of the reel. The correct place would be dictated with sub-millimetre precision by the reel-in process. Therefore, the outer ring of the locking mechanism needed to be placed at its final position at the very last stage of the assembly. The unlocking is initiated by use of a burn wire to release the metal bar, which shall then be retracted by a vertically placed leaf spring. The design and manufacture of the reel lock was carried out by the UT.

2.8. High-voltage (HV) board

The HV source is responsible for generating ± 500 V $\pm 5\%$ voltage, which shall be used to charge the tether, as well as for powering the electron guns (in the positive voltage mode). All of the components for that are on the HV board in the PL section of the satellite that is powered by 3.3, 5, and 12 V lines from the EPS. Figure 12 shows the finished board.

The basic principle (see Fig. 13) is based on using an isolated 12 to 500 V DC–DC converter (12SA500 from Pico Electronics), the output of which is connected through an H-bridge between the body of the satellite, the electron guns, and the tether. The currents going into the tether and the electron guns can be monitored. The output voltage can be changed by modifying the 12 V rail voltage by $\pm 5\%$, since the output voltage of the converter depends on the input voltage proportionally.

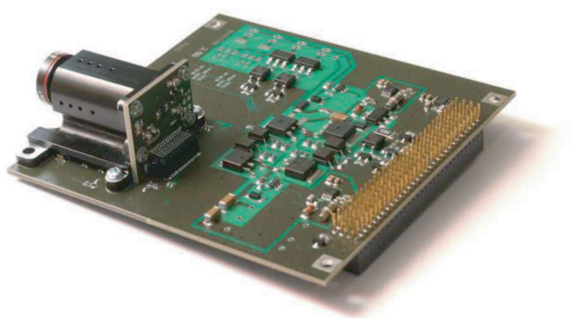


Fig. 12. High-voltage board. The large black block is the onboard camera.

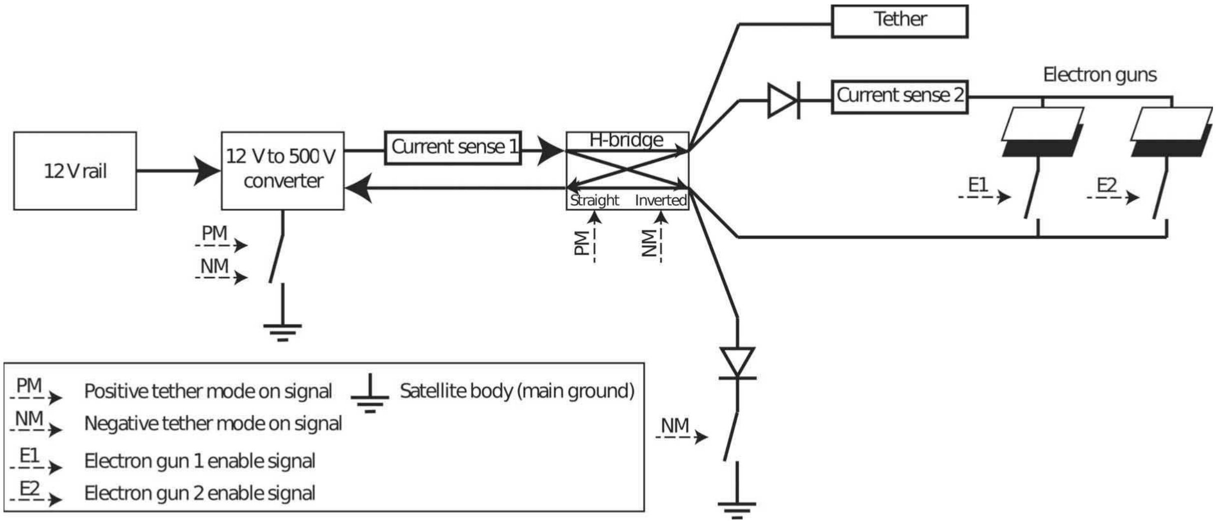


Fig. 13. Schematic presentation of the high-voltage supply.

In the positive tether mode, the H-bridge connects the positive output of the converter to the tether and to the anodes of the electron guns. In this mode the electron guns can be turned on by connecting or disconnecting the cathodes. In this case electrons are emitted through the electron guns and are absorbed by the tether.

In the negative tether mode, the H-bridge connects the negative output of the converter to the tether and the positive output is connected to the satellite body. In this case the positive ions are being gathered by the tether and electrons are being absorbed by the satellite body that is connected to the main ground connections of the satellite.

A challenge of this design is that nothing on the high-side of the 500 V converter is referenced to the satellite ground and very high voltages are involved. This especially complicates current sensing. In our approach we referenced both of the current senses to the negative output of the 500 V converter. This can be done since the current sense measuring the anode current is measuring only if it is connected through the H-bridge directly to the positive output of the 500 V input. Still, to be able to measure that current with electronics onboard the satellite, this needs to be re-referenced to the satellite ground. This was accomplished by using voltage-to-frequency converters on the 500 V side and transmitting the frequency signal to the low-voltage side using capacitive coupling. The voltage-to-frequency converters require a 5 V isolated voltage source on the 500 V side, since doing down-conversion from 500 V would introduce excessive losses. On the low-voltage side this frequency is converted back into voltage and it is referenced to the satellite ground. Further an onboard analogue-to-digital converter (ADC) is used so that the CDHS can read the voltage on the board over the Serial Peripheral Interface (SPI) bus.

Switching is also an issue on the 500 V side, since the command signals are also not referenced to a constant ground. This issue was solved by using optotriacs in the H-bridge to drive the bipolar junction transistors that do the switching. The electron gun cathodes are switched using n-channel metal-oxide-semiconductor field-effect transistors (MOSFETs) that are driven by photovoltaic MOSFET drivers (APV2121 from Panasonic). This photovoltaic driver is especially useful since it can drive n-channel MOSFETs on the low side. The photovoltaic driver is also used to connect the positive terminal of the HV source to the body of the satellite in the negative tether mode.

As a safety feature the measured current is compared to a reference value and if it is exceeded, the H-bridge is turned off.

2.9. Electron guns

The E-sail effect can be observed with either positive or negative tether voltage. In either case there shall be a flow of charge carriers from the surrounding plasma to the tether, attempting to neutralize the tether potential. This flow needs to be compensated with another flow, with an opposite direction of the electrical current between the spacecraft body and the surrounding space. In the case of the ESTCube-1 mission in a low Earth orbit the case of the negative voltage is simple from the apparatus point of view. It has been estimated that in the plasma conditions of the orbital altitude the rate at which the satellite body is able to attract electrons from the local plasma environment would be sufficient to compensate for the rate at which the tether attracts positive ions.

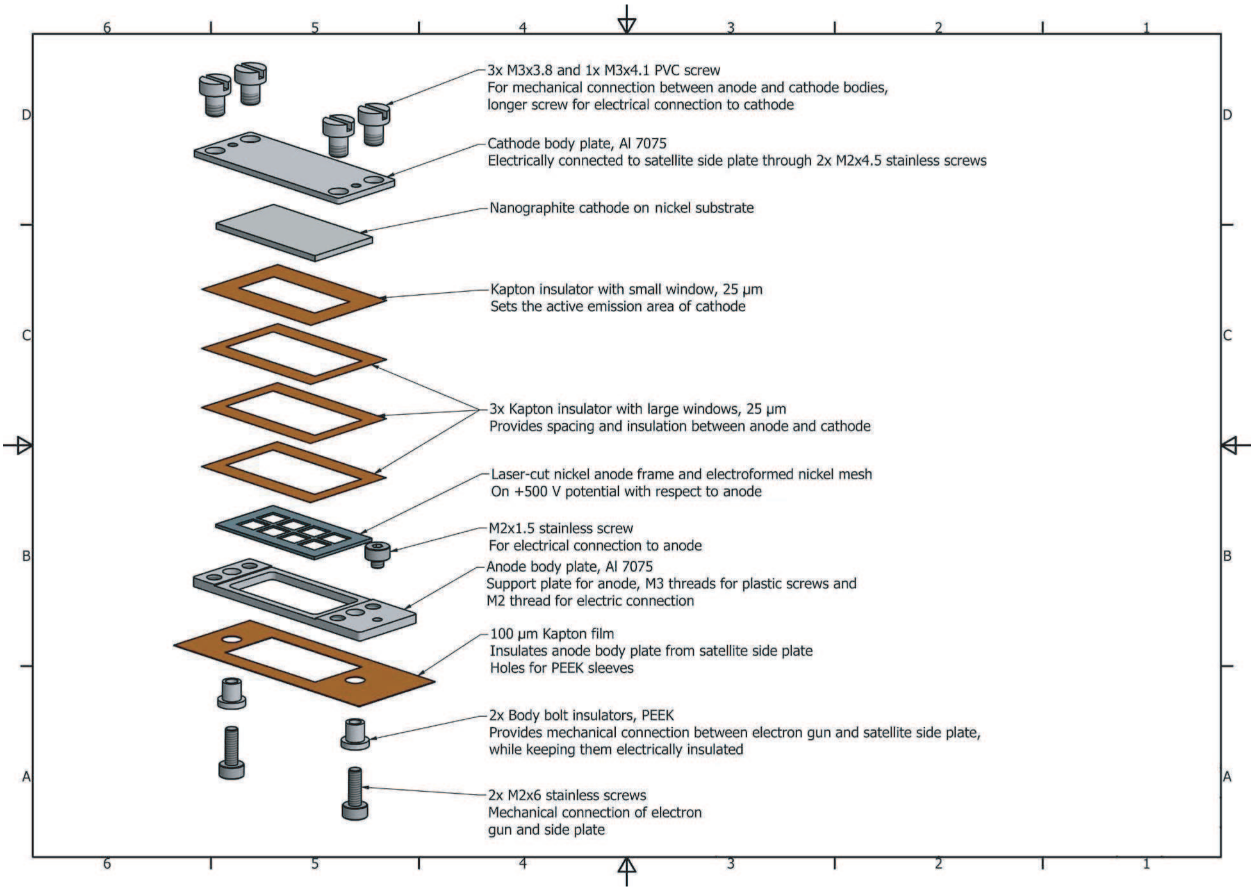
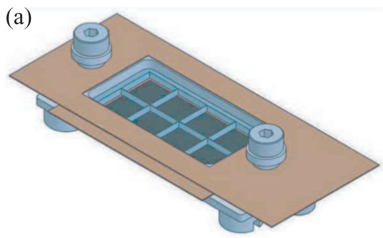


Fig. 14. Exploded view of the electron gun.

The case is more complicated when applying the positive voltage. Because of the lower thermal speed of ions the ion flow to the satellite body is insufficient to compensate for the electron flow to the tether. For this reason it is necessary to remove excess electrons from the system in order to maintain the positive tether potential. For this task we use two onboard cold cathode electron guns, placed on the top and the bottom sides, i.e. $\pm Z$ sides, of the satellite. The electron guns have been developed for our mission at the University of Jyväskylä (UJ).

Figure 14 shows the structure of the electron gun. The cathode [14] is made of graphite coated nickel substrate and the anode is made of a fine electroformed nickel mesh bonded to a laser-cut nickel frame. The gap between the anode and the cathode is of the order of 100 μm. Typical values for the tether current during the E-sail experiment are 1 mA in the positive mode and 10 μA in the negative mode. Figure 15 shows drawings depicting two views of an assembled electron gun. Figure 16 shows an electron gun attached to the satellite's side panel.

(a)



(b)

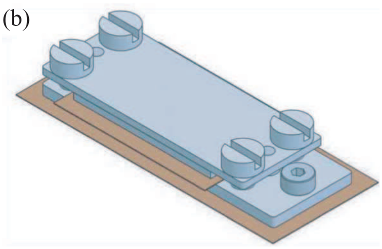


Fig. 15. Two views of the assembled electron gun. “Top” is the direction of the emitted electron beam. (a) Top view. (b) Bottom view.

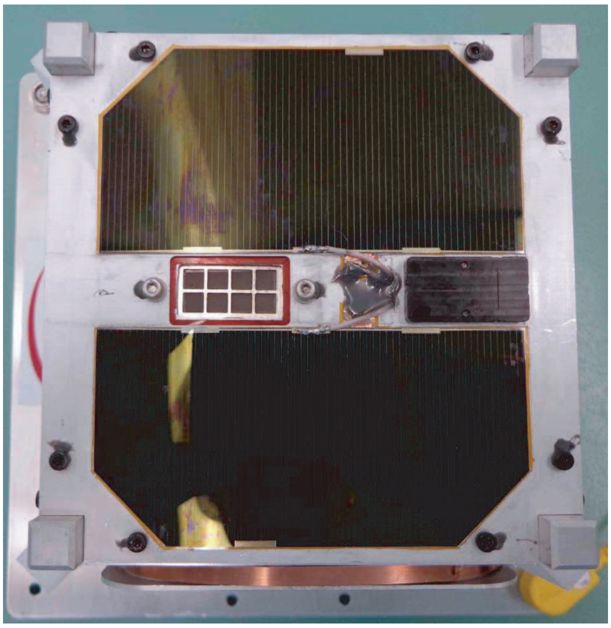


Fig. 16. Electron gun attached on the satellite side panel.

3. OPERATIONS

The principle of determining the E-sail force, acting between the charged tether and the ionospheric plasma, is based on observing the change in the satellite's spin rate as the voltage of the tether is cycled on and off with correct synchronization with the satellite's attitude and orbital position. The physics of this procedure are described with more detail in [10]. The exact sequence of events for the tether experiment is difficult to plan beforehand, as it is influenced by several factors related to orbital conditions and general behaviour of the spacecraft, which must be determined at the time of the actual experiment. The baseline sequence of events is as follows:

1. spin-up of the satellite,
2. reel lock deployment,
3. launch lock deployment,
4. tether deployment, imaging of the tether and end mass,
5. applying negative voltage to the tether,
6. observing change in the satellite's spin rate,
7. applying positive voltage to the tether,
8. observing change in the satellite's spin rate.

The tether experiment phase of the mission is begun by ramping up the satellite's spin rate to approximately 1 rev/s. The spin-up is operated by the satellite's Attitude Determination and Control System (ADCS). A more detailed description of the requirements and methods of the spin-up are given in [10,15,16]. Once the proper spin rate and axis have been obtained, the reel lock and launch lock are deployed. During and immediately after the launch lock deployment the onboard camera is used to take several pictures with sub-second intervals. This is used as a precaution if the launch vibrations have broken the tether, in which case the images should show the slowly escaping end mass. During the tether deploymet the motor is used to perform a controlled reel-out with predetermined speed. Due to its structure the tether cannot be retracted back onto the reel; the tether deployment is thus an irreversible event. The tether deployment will most probably be performed in parts. This gives the ground control team an opportunity to monitor the satellite's behaviour and correct all possible deviations from the normal operating state. Throughout the tether deployment the satellite's spin rate is monitored and the data are transmitted down to the ground station. Also the tether and the end mass are constantly imaged by the onboard camera in order to obtain an independent verification of a successful deploymet. The E-sail force is observed, as described in [10], with both positive and negative voltages. The negative mode will be tested first, because it does not require the use of electron guns and is therefore considered less risky. The essential data for the E-sail force determination are the change in the spin rate and the measured tether current, the latter giving valuable information about the local plasma environment.

4. CONCLUSIONS AND DISCUSSION

This paper has described the contents of the ESTCube-1 nanosatellite payload. The payload is used for carrying out the first space experiment of the E-sail concept.

The equipment was built and delivered to the ESTCube-1 nanosatellite team in time. The satellite was integrated to the European Space Agency's (ESA) Vega launch vehicle and the satellite was launched and delivered into orbit on 7 May 2013 (UTC) from Europe's Spaceport in Kourou, French Guiana.

The first vibration tests revealed a design flaw in the motor board. The piezo rotator was sensitive to certain resonance frequencies of the vibrations. This caused the tether reel to turn and thus break the tether. This flaw was subsequently fixed by introducing the reel lock. The reel lock itself went through some vibration testing, but the whole tether reel system did not. However, at this point we already knew almost with full certainty that the reel lock had accomplished its locking duties. A reel lock failure, or a tether breakage of any sort, would almost certainly lead to the loose tether filling the insides of the satellite, creating short cuts at several places. During its time in orbit the satellite has mostly functioned as expected. This does not support the notion of any launch failures having taken place. Also, the electron guns were not tested for vibrations. This was a planned strategy. Because of the very early stage of development of the miniaturized cold cathode electron gun technology, only flight models were available within the schedule of our mission. However, unlike the tether and its related equipment, the electron guns are not mission critical instruments. Even with no functional electron guns the negative voltage mode can still be used for the E-sail experiment.

In addition to the matters discussed above, no particular adversities have emerged. The systems worked flawlessly in functional ground tests. At the time of the writing (June 2013) the project team in Tartu is validating the operations of the satellite in orbital conditions. Also the final flight software is being written. The schedule for the E-sail tether experiment has not yet been fixed. Once made, the experiment is also expected to provide some useful data for our next mission. In 2014 or 2015 it is time to launch the first Finnish satellite, Aalto-1. It is a 3U CubeSat designed and built by the students of Aalto University, Espoo, Finland. A similar tether payload will be included in Aalto-1 as one of its secondary payloads. The length of the tether in Aalto-1 will be 100 m.

ACKNOWLEDGEMENTS

The following persons are acknowledged for their contribution to this work: Jouni Polkko and Sini Merikallio from the FMI; Risto Kurppa, Tuomo Ylitalo, and Göran Maconi from the UH; Olaf Krömer and Roland Rosta from the DLR; Pekka Salminen from SkyTron co; Alexander Obraztsov from the University of Eastern Finland, Joensuu.

REFERENCES

1. Janhunen, P. and Sandroos, A. Simulation study of solar wind push on a charged wire: basis of solar wind electric sail propulsion. *Ann. Geophys*., 2007, **25**, 755–767.
2. Janhunen, P., Toivanen, P., Envall, J., Merikallio, S., Montesanti, G., Gonzalez del Amo, J. et al. Overview of electric solar wind sail applications. *Proc. Estonian Acad. Sci.*, 2014, **63**(2S), 267–278.
3. Janhunen, P. The electric sail – a new propulsion method which may enable fast missions to the outer solar system. *J. British Interpl. Soc.*, 2008, **61**, 322–325.
4. Mengali, G. and Quarta, A. A. Non-Keplerian orbits for electric sails. *Cel. Mech. Dyn. Astron.*, 2009, **105**, 179–195.
5. Janhunen, P. On the feasibility of a negative polarity electric sail. *Ann. Geophys.*, 2009, **27**, 1439–1447.
6. Toivanen, P. K. and Janhunen, P. Electric sailing under observed solar wind conditions. *Astrophys. Space Sci. Trans.*, 2009, **5**, 61–69.
7. Quarta, A. A. and Mengali, G. Electric sail missions to potentially hazardous asteroids. *Acta Astronaut.*, 2010, **66**, 1506–1519.
8. Janhunen, P., Toivanen, P. K., Polkko, J., Merikallio, S., Salminen, P., Haeggström, E. et al. Electric solar wind sail: towards test missions. *Rev. Sci. Instrum.*, 2010, **81**, 111301–111301–11.
9. Merikallio, S. and Janhunen, P. Moving an asteroid with electric solar wind sail. *Astrophys. Space Sci. Trans.*, 2010, **6**, 41–48.
10. Lätt, S., Slavinskis, A., Ilbis, E., Kvell, U., Voormansik, K., Kulu, E. et al. ESTCube-1 nanosatellite for electric solar wind sail in-orbit technology demonstration. *Proc. Estonian Acad. Sci.*, 2014, **63**(2S), 200–209.
11. Seppänen, H., Kiprich, S., Kurppa, R., Janhunen, P., and Haeggström, E. Wire-to-wire bonding of μm-diameter aluminum wires for the Electric Solar Wind Sail. *Microelectron. Eng.*, 2011, **88**, 3267–3269.
12. Seppänen, H., Rauhala, T., Kiprich, S., Ukkonen, J., Simonsson, M., Kurppa, R. et al. One kilometer (1 km) electric solar wind sail tether produced automatically. *Rev. Sci. Instrum.*, 2013, **84**, 095102.
13. Edelbauer, M. and Porn, M. *Tecasint Handbook*. Ensinger GmbH (available online at http://ensinger-inc.com/downloads/lit_brochures/TECASINT-handbook.pdf).
14. Obraztsov, A. N. and Kleshch, V. I. Cold and laser stimulated electron emission from nanocarbons. *J. Nanoelectron. Optoelectron.*, 2009, **4**(2), 207–219.
15. Slavinskis, A., Kulu, E., Viru, J., Valner, R., Ehrpais, H., Uiboupin, T. et al. Attitude determination and control for centrifugal tether deployment on the ESTCube-1 nanosatellite. *Proc. Estonian Acad. Sci.*, 2014, **63**(2S), 242–249.
16. Slavinskis, A., Kvell, U., Kulu, E., Sünter, I., Kuuste, H., Lätt, S. et al. High spin rate magnetic controller for nanosatellites. *Acta Astronaut.*, 2014, **95**, 218–226.

Elektrilise päikesetuulepurje katsetusmoodul nanosatelliidi ESTCube-1 pardal

Jouni Envall, Pekka Janhunen, Petri Toivanen, Mihkel Pajusalu, Erik Ilbis, Jaanus Kalde, Matis Averin, Henri Kuuste, Kaspars Laizans, Viljo Allik, Timo Rauhala, Henri Seppänen, Sergiy Kiprich, Jukka Ukkonen, Edward Haeggström, Taneli Kalvas, Olli Tarvainen, Janne Kauppinen, Antti Nuottajärvi ja Hannu Koivisto

Nanosatelliidi ESTCube-1 teaduslikuks missiooniks on mõõta elektrilise päikesetuulepurje tekitatavat jõudu Maa lähiorbiidil. Elektriline päikesetuulepuri on uudne kosmoses liikumise meetod, mis põhineb Päikesest lähtuvast plasmavoost impulsi eraldamisel pikkade elektriliselt laetud juhtmete abil. ESTCube-1 pardal on üks selline juhe

koos selle väljakerimiseks ja elektriliselt laadimiseks vajaliku aparatuuriga. Satelliidi orbiidil (660–680 km) ei ole aga otseselt päikesetuult ja selle asemel jälgib ESTCube-1 vastastikmõju laetud juhtme ja ionosfääris oleva plasma vahel. Satelliidi lastiks on 10 m pikkune osaliselt kahekiuline elektrilise päikesetuulepurje traat ja mootoriga varustatud rull, milles seda hoitakse. Juhtme väljakerimise hõlbustamiseks pannakse satelliit enne pöörlema, mistõttu mõjub juhtiva traadi otsas olevale lisamassile tugev tsentrifugaaljõud, mis omakorda tõmbab juhet satelliidist välja. Elektrilise päikesetuule eksperimendi ajal laetakse juhe 500 V potentsiaalini, kusjuures katsetatakse mõlemat polaarsust. Vajalikku kõrgepinget toodab selleks mõeldud kõrgepingeallikas ja see jõuab traadini läbi rulli küljes oleva libiseva kontakti. Kui juhtmele rakendatakse negatiivne pinge, hakkab satelliidi kere elektronide voogu ligi tõmbama ja see peaks olema piisav, et kompenseerida juhet tabavat plasma ioonide voolu. Kui juhtmele rakendatakse positiivne pinge, siis kasutatakse liigsete elektronide eemaldamiseks ja seeläbi juhtme laadimiseks satelliidi pardal olevaid külma katoodiga elektronkahureid. Selles artiklis on juttu ESTCube-1 pardal oleva eksperimendimooduli arendusest, ehitusest ja katsetustest Maa pinnal. Eksperimendimoodul sai valmis, kvalifitseeriti lennuks satelliidis kanderaketi pardal ja kosmoses ning lennutati orbiidile 2013. aasta mais.