Proceedings of the Estonian Academy of Sciences,
2014, **63**, 2S, 258–266
doi: 10.3176/proc.2014.2S.07
Available online at www.eap.ee/proceedings

Accommodating the plasma brake experiment on-board the Aalto-1 satellite

Osama Khurshid*, Tuomas Tikka, Jaan Praks, and Martti Hallikainen

Aalto University, 02150 Espoo, Finland

Received 15 August 2013, revised 19 April 2014, accepted 22 April 2014, available online 23 May 2014

Abstract. This paper presents an overview and the current status of hosting the electrostatic plasma brake (EPB) experiment on-board the Finnish Aalto-1 satellite. The goal of the experiment is to demonstrate the use of an electrostatically charged tether for satellite attitude and orbital maneuvers. The plasma brake device is based on electrostatic solar sail concept, invented in Finnish Meteorological Institute (FMI). The electrostatic solar sail is designed to utilize the solar wind charged particles to propel the spacecraft by using long conductive tethers, surrounded by electrostatic field. Similar phenomenon can be used in low Earth orbit plasma environment, where the relative motion between the electrostatically charged tether and the ionospheric plasma can produce a significant amount of drag. This drag can be utilized for deorbiting the satellite. The Aalto-1, a multi-payload CubeSat, will carry, among others, the plasma brake payload. Plasma brake payload consists of a 100 m long conductive tether, a reel mechanism for tether storage, a high voltage source, and electron guns to maintain the tether charge. The experiment will be performed in positive and negative tether charge modes and includes a long term passive deorbiting mode. The experiment hardware, the satellite mission and different phases of the experiment are presented.

Key words: plasma brake, Aalto-1 satellite, de-orbiting, attitude control.

1. INTRODUCTION

The increasing amount of orbital debris is a growing concern and a challenge for future space missions. Satellites generally stay in the orbit until removed by natural deorbiting process. Usually, it takes a very long time for satellites to deorbit, leading to an increasing amount of bodies orbiting the Earth and larger risk for collisions. This can be a major issue for spacecrafts in the future space missions. The low Earth orbit (LEO) region of 600–1000 km needs special attention, because of its active usage for Earth observation missions. Therefore, it is necessary to take effective measures, which will help to reduce the amount of debris in the future. One efficient measure against the future debris buildup would be the possibility to bring satellites down from the orbit right after their active mission has ended. This would require a sufficient amount of fuel, if active propulsion is used, and a fully operational spacecraft. Due to additional requirements, this solution would increase cost and complications. This leads to the increasing interest towards alternate deorbiting methods such as utilization of drag enhancing surfaces, solar sails [1] and using high efficiency electric propulsion [2].

The invention of electric solar sail [1] has provided new means for propellantless propulsion, and efforts are being made to utilize the concept also for deorbiting satellites [3,4]. This technology could be especially suitable for providing the deorbiting means to increasing amount of small satellites. Nanosatellites have a short development time in comparison to conventional satellites and they provide low-cost access to space. However, the shorter mission lifetime and lower cost also translate to contribution towards rapidly increasing LEO debris because most of the nanosatellites are launched to this region. With international agreements, the maximal decay lifetime of this satellite class has been restricted to 25 years. Therefore, the deorbiting technologies for small satellites have high importance for space technology future.

---

* Corresponding author, osama.khurshid@aalto.fi

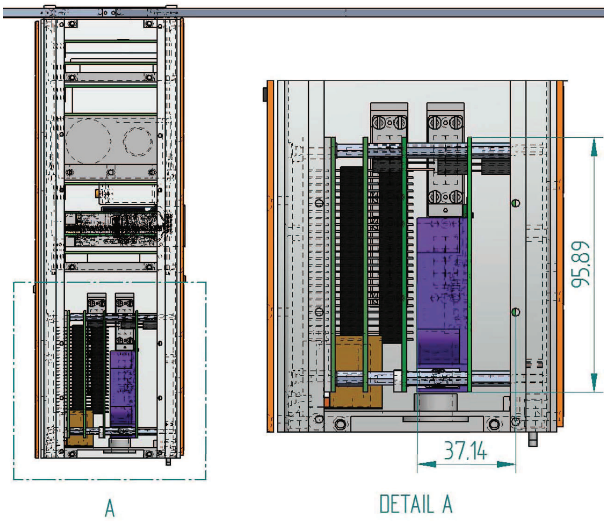

Fig. 1. CAD drawing depicting the placement of the plasma brake module in the satellite. The satellite is depicted on the left and detailed view of the PB payload placement on the right.

Aalto-1, weighing 4 kg and measuring 10 × 10 × 34 cm, is a 3U CubeSat being developed at Aalto University in collaboration with several Finnish institutes [5,6]. The main payload of the mission is a miniature spectral imager [7]. Aalto-1 will accommodate an electrostatic tether-based deorbiting experiment and will contribute to the development of affordable and reliable deorbiting solutions for nanosatellites. Aalto-1 is the second mission after ESTCube-1 [8] carrying e-sail experiment to space. The cross-section of the satellite and the close-up of the PB payload is shown in Fig. 1.

This paper presents the mission and the requirements for the satellite to successfully execute and achieve the goals of the plasma brake experiment on-board Aalto-1. The main focus will be on the satellite system designed to perform the experiment. The paper is divided into seven sections. The first section gives a short motivation and introduction to the subject. The second section presents the principle of the solar sail concept and the aims of the experiment. The third section presents the system requirements defined by the experiment. The fourth section presents the design of the developed plasma brake payload. The fifth section presents the mission phases in which the experiment will be executed and the last section provides the conclusions of the paper.

2. THE EXPERIMENT

The plasma brake device in the Aalto-1 satellite has been designed and manufactured by FMI. It is based on the solar sail concept, recently invented in the same institute. The solar sail is a recent invention in the domain of propellantless propulsion of the spacecraft [1], based on electrostatic Coulomb force. The force results from the momentum exchange between the flow of ions or electrons and the positively charged or negatively charged conductive body, respectively.

The electric solar sail was first developed to utilize solar wind as the momentum source for propulsion in interplanetary space [1]. It was proposed that a number of centrifugally stretched conductive tethers could be used to create a large area with necessary electric field with relatively small amount of material. As the current in such a tether would be very small, very thin tethers could be used. Later on, the same principle was proposed to be used for the LEO orbit, where the plasma plays the major role instead of the solar wind [4]. The effect, caused by even a single tether, can be sufficient to bring a small satellite to a lower orbit. The first test equipment was built by a consortium led by FMI for the Estonian nanosatellite ESTCube-1 [8]. The satellite was successfully launched in May 2013.

The backbone of the EPB experiment during Aalto-1 mission is a 100 m, conductive tether attached to the satellite. The equipment for Aalto-1 is similar to the payload developed for ESTCube-1 with a few differences. The device is designed to deploy a long thin tether in space. The currently designed experiment aims at testing both the positive and negative charged tether modes.

A positively charged tether can collect momentum from the ions in plasma stream. The plasma electrons try to neutralize the positive charge on the tether. The positive charge mode needs the tether to be kept at a continuous positive potential. Therefore, the collected electrons must be continuously removed from the tether. This can be achieved by connecting the tether to an electron emitting device through a voltage source. The use of electron guns can provide a feasible solution to maintain the required positive potential. The electron current, collected by the tether, is important in this case as it determines the characteristics of electron guns.

Similarly, a negatively charged tether can also collect momentum from electrons in the plasma stream, if the tether's negative potential is maintained at a certain level. A negatively charged tether attracts plasma ions and repels electrons, thus forming an ion sheath around the charged tether. These ions have to be removed through an ion gun in order to maintain the required negative potential. This concept is more complex to realize than the positive potential mode [2]. However, in certain conditions, using a larger conductive recombination area could be sufficient to perform the experiment, as electrons and ions have different energies and thus different mobilities.

Several aspects have to be considered while conducting such an experiment in LEO environment. A charged tether, when placed in plasma, does not only experience the forces due to the charged tether's interaction with plasma, but also with the magnetic field. A conductive tether in a magnetic field experiences the Lorentz force. The net force and its direction depend upon the magnetic field and the current in the conductor. Also, the density of the ionospheric plasma varies significantly with altitude, thus varying the amount of the force produced. In very low orbits the atmospheric drag force, acting on the satellite, can be more dominant than the Coulomb effect. All these factors, put together, complicate the experiment.

For Aalto-1, the primary aim of the plasma brake mission is to quantify the force, acting on the electrostatically charged tether moving with respect to the ionospheric plasma, and to validate the concept. The secondary aim of the experiment is to deorbit the satellite. The deorbiting time will be determined by the force, quantified in the initial phase of the experiment.

The most important part of the electrostatic plasma brake is the heytether. Space tethers have found several applications over the period of time. These applications include attitude stabilization, propulsion [1,2], satellite formation flight [9], satellite deorbiting [10], and also some futuristic concepts as space elevator. The tether has to be robust in order to stand the micrometeoroid and other orbital debris impacts. Therefore, the tethers cannot be made up of single wires [11]. The tether used in Aalto-1 EPB experiment is specially designed, comprising of a base wire to which three interleaving looping wires are ultrasonically bonded. The aim of heytether design is to manufacture the tether with a maximum sustainable pull strength exceeding 50 mN for 99% of the bonds [12]. Space tethers, due to multiple looping wires, have a greater physical impact resistance. During the deployment of tether from the satellite, the moments of inertia of the satellite are greatly altered. A small mass, attached to the end of a deployed tether, has a pronounced effect on the satellite attitude dynamics. The result is a collection of forces acting on the satellite, affecting its attitude. Therefore, an active attitude control system is required during all the phases of the experiment.

3. REQUIREMENTS FOR EXPERIMENT HARDWARE

The main challenges and their implications on the satellite system are listed in this section. These challenges are mainly related to the attitude dynamics of the satellite, high power requirements for tether charging, and timing of the switching of the tether voltage. This section also explains the required experiment setup and its complexities.

3.1. Challenges in attitude control

Attitude control, during and after the deployment of a flexible tether, is a critical task for the success of the experiment. There are multiple ways the tether can be deployed. A comparison [13,14] of different deployment techniques shows that it is more feasible to spin the satellite and use the centrifugal force to reel the tether out than to use a gravity gradient or thruster based system. This type of spinning motion, however, has its own complications.

A key requirement in the deployment phase is to keep the tether tension within certain limits, in order to avoid the tether damage. The tether in the Aalto-1 mission can withstand a tension up to a maximum of 50 mN. If the tension is maintained between 20 and 25 μN, the tether would avoid bending or over-stretching. The required spin rate ω_{req} to achieve sufficient tension depends on the end mass, attached to the tether tip, according to Eq. (1). The satellite should be rotated around the axis with the highest moment of inertia to achieve a stable spinning system. The method is described well in [15–17]:

$$\begin{aligned} T_{\text{tether}} &= m_{pm} l \omega_{\text{req}}^2, \\ \omega_{\text{req}} &= \sqrt{\frac{T_{\text{tether}}}{m_{pm} l}}, \end{aligned} \tag{1}$$

where T_{tether} is the tether tension, m_{pm} is the mass attached at the end of the tether, and l is the tether length.

The angular velocity required to maintain the tether tension at 25 mN, with a 0.5 g end point mass, is shown in Fig. 2.

A small satellite in LEO can be spun with considerable ease using magnetorquers. Any other mechanism such as using a heavier end mass, ejected with a higher initial velocity, is not suitable for this experiment in a nanosatellite due to its higher mass and power requirements. Also the use of chemical propulsion, as in [13], is generally restricted for nano- and picosatellites due to piggy-back launches.

A steady deployment velocity is important for the tether. The angular velocity of the satellite provides the required force that pulls the tether out of the reel. Abrupt changes in the angular velocity cause sudden stretching of the tether and can break it. This danger exists primarily during the initial phase of the deployment, for first few centimetres and metres. It can be avoided by strengthening the first few centimetres or metres of the

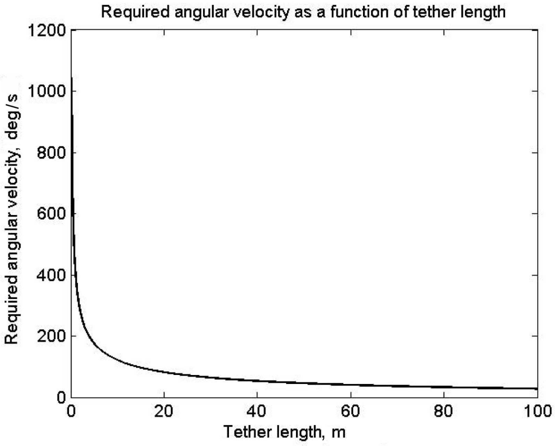

Fig. 2. Tether tension as a function of angular velocity.

tether. However, this would complicate the manufacturing process. The uniform and small changes in the angular velocity of a spinning satellite provide uniform changes in the centrifugal force and thus a uniform deployment process.

The deployment, and the experiment itself, constrains the attitude for the satellite spin. In order to have a stable system, the spin axis has to be the axis of maximum moment of inertia. A satellite might have very small differences in the moment of inertia about two of its principal axes, as is the case with Aalto-1. Thus, the moment of inertia should be taken into consideration during the design process of the structure and subsystem placement. Therefore, the Aalto-1 frame structure is designed to provide maximum moment of inertia about Y-axis, minimum moment of inertia about Z-axis and intermediate moment of inertia about X-axis.

The experiment also requires the control of the angular velocity, nutations, and precession motion during the phases when the satellite is spinning. The experiment's scientific aims do not imply any requirement for the duration of the spin-up phase. Therefore, the power budget and the efficiency of the spin-controller are the key aspects to be considered during the spin-up phase. The spin axis of the satellite has to be maintained parallel to the Earth's spin axis, as shown in Fig. 3, in order to avoid disturbances caused by additional Lorenz force due to magnetic field line alignment in relation to the tether spin axis.

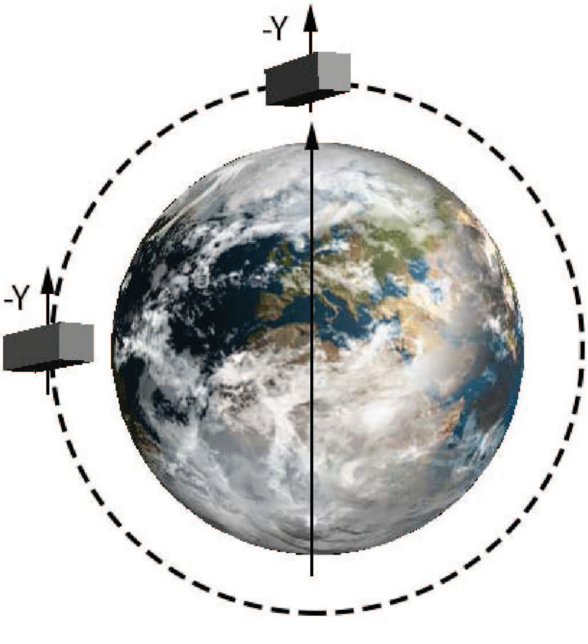

Fig. 3. Attitude of the Aalto-1 satellite over poles and equator during the plasma brake experiment. The arrows show the direction of Aalto-1 rotaion axis.

3.2. Charging device

As mentioned earlier, the charging devices are necessary to maintain the required potential on the tether. In the positive mode, the electron removal can be performed by electron guns. The current rating of electron guns is dependent upon the current in the tether. However, the experiment can be performed even without the ion guns during the negative mode. The alternative to an ion gun is to provide high voltage source between the tether and spacecraft body, and to increase the conductive area of the satellite as much as possible. This, however, has certain consequences on power consumption and the structural frame's external surface.

According to the simulations in [1], the current in the tether will be about 2 mA in the positive mode, and only a few μA in the negative mode. This defines the electron removing capacity of the electrons guns.

3.3. Orbit determination

The force, generated during the charging of the tether inside the Earth's magnetic field, will alter the spin rate of the system, and finally decelerate the satellite causing it to lose orbital altitude. The quantity of this effect should be measured with sufficient accuracy. The orbital two-line elements (TLE) are not accurate enough for such measurements. The TLE update frequency is also one of the bottlenecks in its use. Thus, Aalto-1 needs alternate means for accurate orbit determination; for example, a GPS receiver on-board to measure changes in position and velocity.

4. HARDWARE SET-UP AND DESIGN

The EPB experiment hardware set-up on-board the Aalto-1 satellite is presented in this section. The EPB payload is controlled by the central on-board computer (OBC) [18] and the attitude of the spacecraft is controlled and measured by the attitude determination and control system (ADCS), developed in cooperation with Berlin Space Technologies [19]. The satellite carries a GPS subsystem [20], which provides accurate orbit information for the experiment.

4.1. Electrostatic plasma brake payload

The EPB payload hardware, designed and manufactured by consortium led by FMI, is similar to the payload of ESTCube-1 [8,21] with few differences. The Aalto-1 tether, manufactured by University of Helsinki, is 100 m in length. The Aalto-1 system is equipped with four electron guns, manufactured by University of Jyväskylä. The high voltage board, manufactured by FMI, will provide a higher voltage mode (1 kV) and the digital control board, manufactured by University of Tartu, will provide the command and measurement

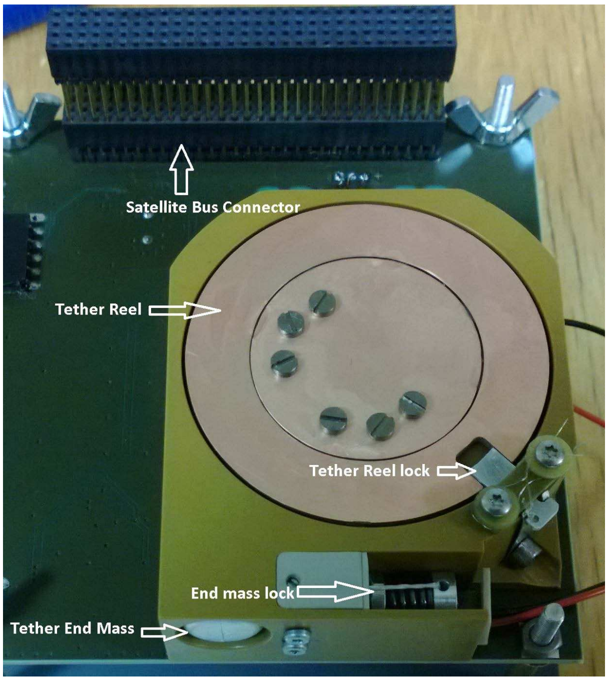

Fig. 4. PBE reel and motor assembly [22].

interface through an I^2C (Inter-Integrated circuit) bus. The reel motor, developed by DLR [23,24], is similar to ESTCube-1's and the mechanical design has only a few improvements. The EPB unit is roughly 10×10×4 cm in size and the total system weight is about 360 g. The payload integration and basic testing is performed under supervision of FMI. However, the integration and full functional testing is the responsibility of Aalto University. The set-up developed for ESTCube-1 satellite, is shown in Fig. 4.

The EPB needs a tether, having sufficient conductive properties and enough strength to withstand the micrometeorite and space debris impacts. A 100 m multiwire heytether [12] will be used for Aalto-1. The main difference between the EPB on-board Aalto-1 and ESTCube-1 [8,21] is the tether length. The experiment on-board Aalto-1 will be carried out for different lengths of the tether; from 10 to 100 m. This will also provide an opportunity to confirm the results of ESTCube-1. The tether is wound inside an isolation reel, located at the -z side inside the satellite, requiring an opening on the satellite frame. Figure 4 shows the structure of the motor and reel mechanism. The circular opening, on the reel case for the end mass, has a diameter of 12.3 mm. This is also the minimum diameter for the opening on the satellite structure's side panel.

The tether is charged by a high voltage unit, which is able to produce 500 V and 1 kV voltage levels to drive the current between the tether and plasma. Four electron guns will be used for the experiment's positively charged tether mode. These electron guns are based on an advanced cold cathode design to minimize power consumption [25]. The design is comprised of a nanographite coated cathode and a silicon nitride membrane acceleration grid anode [26]. Each electron gun produces 2 mA current and consumes a total of 1.5 W, of which 1 W goes into the output beam and 0.5 W is consumed by electrons, hitting the anode instead of passing through the holes in the acceleration grid. All of the electron guns are not used simultaneously. However, four of them are incorporated into the system for redundancy.

4.2. Aalto-1 attitude determination and control system

Aalto-1 ADCS has been designed to fulfill the requirements of the EPB experiment phases. The experiment requires the satellite to provide centrifugal force to the tether end mass for deploying the tether. The required force can be produced by spinning the satellite. The spin motion will be about the axis, perpendicular to the direction in which the tether will be deployed and parallel to the axis of the tether reel motor's spin axis. Aalto-1 needs 3-axis stabilization attitude for its remote sensing mission phases prior to EPB experiment. During the experiment, the ADCS will use 3-axis magnetorquers, a 3-axis magnetometer, a 3-axis gyroscope, and six sun sensors for attitude determination and control. The ADCS modular view is presented in Fig. 5. Aalto-1 ADCS also includes reaction wheels and a star tracker; however, they cannot be used during the EPB experiment due to their limited momentum exchange capability and the satellite's high spin rate, respectively. Therefore, only magnetic control will be used for spinning the satellite and controlling its motion. The spin motion will be

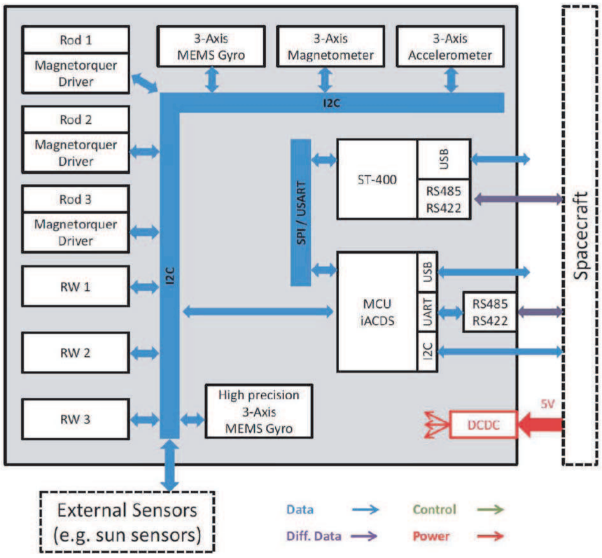

Fig. 5. ADCS modular view.

controlled using the controller presented in [27]. The simplified control equation is

$$\vec{m} = \frac{-k}{||\vec{B}||^2}[\vec{B} \times (\tilde{\vec{h}} + k_1 \vec{e}_h)], \qquad (2)$$

where $\vec{m}$ is the magnetorquer dipole moment vector in principal inertia coordinates, $\vec{B}$ is the earth magnetic field vector expressed in body principal coordinates, $\tilde{\vec{h}}$ is the satellite angular momentum error vector, $\vec{e}_h$ is the different between the required and the current momentum, and k and k_1 are the control law gains.

During the spin phase, the consumed power has to be minimized according to the power generated, which restricts the attitude control frequency. The attitude data is sent to the tether charging controller with a sufficiently high frequency to enable correct timing for turning on the power. An autonomous and active attitude control loop can keep the satellite in the desired attitude during the spin motion, which will be controlled using the mentioned controller in Eq. (2).

4.3. On-board computer control

The EPB is controlled by the satellite's on-board computer (OBC) through an I^{2}C interface. The block diagram of EPB is presented in Fig. 6. Due to possible electromagnetic interference during the tether charging, communication between all subsystems, used during the experiment, is implemented to take place only when the tether is uncharged. The tether charging should be commanded to be turned on only for a limited time interval. This is done in order to avoid losing ground station's contact with the satellite, if an anomaly occurs. The interval, when the tether is charged, can be timed according to attitude data received from the ADCS. The central OBC also stores all the necessary parameters received from the EPB module and the ADCS. These parameters are downlinked to the ground station for further analysis. These include the satellite's angular velocities, orbital altitude, tether current, and the electron gun currents. The planned mission flow, controlled by the OBC, is presented in the next section.

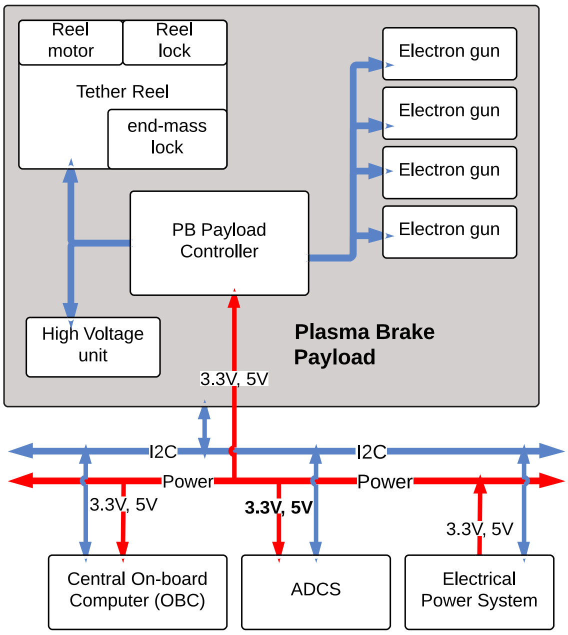

Fig. 6. Plasma brake system topology.

5. PLASMA BRAKE MISSION PHASES

The experiment phases have been divided into scientific experiment and mission phases. The scientific experiment phases include tether operation in positive and negative modes. These modes provide the scientific outcome of the experiment. The mission phases govern the sequence and the flow of the whole experiment and the state of the satellite subsystems. These are defined while considering the system constraints and design restrictions.

The flowgraph in Fig. 7 gives an overview of the mission phases. The experiment starts with the spin phase and once the required angular velocity is achieved, the tether reel and end mass locks are released. The reel motor is then turned on. This causes the tether to start reeling out with the available centrifugal force. The motor provides the means of pausing the reeling out process, if required, as well as the controlled reeling out of the tether [24].

During the reel-out process, the spin rate is continuously monitored. The spin rate decreases due to the tether reel-out [15]. If the spin rate falls below a certain threshold, the spin control algorithm reactivates to bring the satellite angular velocity back to the required level. The tether is not charged until it is reeled out up to 10 m length. At this stage, the tether can be charged to observe the phenomenon of the Coulomb force in plasma.

The tether charging has to be performed at certain sections of the spin plane. The force pushes the tether to reduce the angular velocity when the tether moves upstream with respect to plasma, and vice versa. Therefore, the tether has to be charged through 180 deg, either upstream or downstream motion, during one complete spin cycle. The change in the spin rate is detected and utilized to quantify the force, experienced by the charged tether. This procedure is executed with both the positive and negative polarity modes. The positive and negative tether modes differ in terms of the voltage polarities and levels. Also, the electron guns have to be turned on only during the positive mode.

Once the positive and negative charging of the tether has been performed at 10 m length then it is extended to the full length of 100 m. The longer the tether length, the smaller is the angular velocity required to maintain the

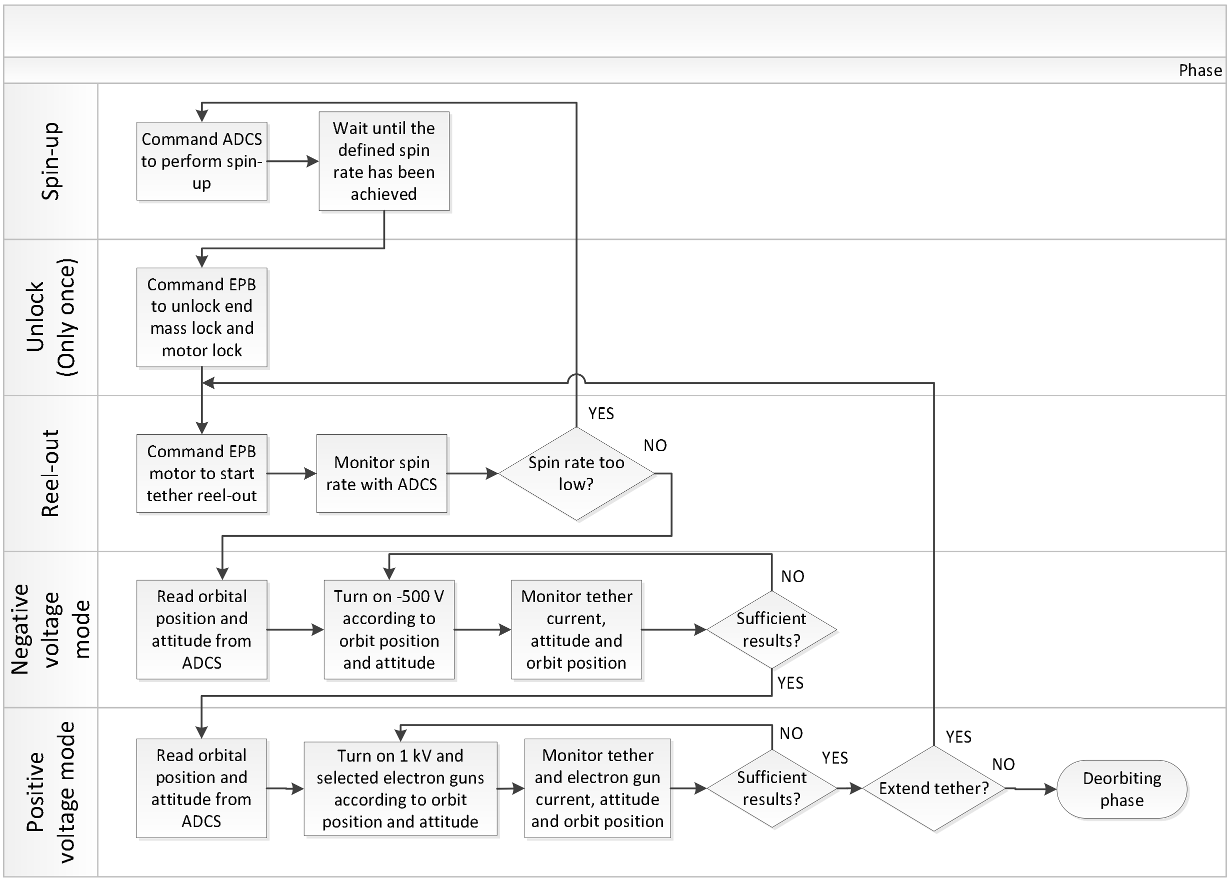

Fig. 7. Plasma brake mission phases.

required tension [15]. The extension reduces the angular velocity of the system and increases the current in the tether due to charging. The deorbiting phase will be initiated on the condition that the previous phases have been executed successfully and sufficient satisfactory results from the experiment have been received. In the deorbiting phase, the satellite's attitude is changed to gravity gradient stabilization. The mode of tether charging for deorbiting phase will be determined, based on the obtained experimental results.

Aalto-1 EPB experiment has been designed for a spinning tethered spacecraft system moving in ionospheric plasma. In order to avoid the effects, caused by the Lorenz force, the experiment should be carried out in polar regions with the tether's plane of rotation parallel to the equatorial plane. In such a configuration, the magnetic field is perpendicular to the tether spin plane and should have the least effect to the dynamics of the satellite.

6. CONCLUSIONS

This paper presented the design of Aalto-1 satellite system to perform the EPB experiment. The EPB experiment will be performed as the last phase of the Aalto-1 multipayload mission. The small size and power requirements of the PBE subsystem make it a suitable payload to fly on-board a CubeSat. Aalto-1 will fly a 100 m tether, charged using a high voltage source to obtain the desired electric field around the tether. The experiment will be executed in multiple phases as spin-up, tether deployment, negative tether mode experiment, and positive tether mode experiment. The spin-up is a critical and most demanding phase that will determine the success of the tether deployment. After the deployment, the main challenge concerns determining the precise orbital position and satellite attitude. This information will be used for switching the voltage source on and off to control the tether charge. The PBE is based on solar sail concept and performing the experiment on-board Aalto-1 will provide further insight into the phenomenon. This concept, if successful, can be used on-board future small satellite missions for deorbiting purposes.

ACKNOWLEDGEMENTS

The authors thank Pekka Janhunen, the inventor of plasma brake concept, for his valuable input and support for developing the Aalto-1 system design, suitable for performing this experiment on-board the satellite. This work has been supported by Aalto University's Multidisciplinary Institute of Digitalisation and Energy (MIDE) and the Finnish Funding Agency for Technology and Innovation (TEKES).

REFERENCES

1. Janhunen, P. Electric sail for spacecraft propulsion. *J. Prop. Power*, 2004, **20**, 763–764.
2. Janhunen, P. On the feasibility of a negative polarity electric sail. *Ann. Geophys.*, 2009, **27**, 1439–1447.
3. Ahedo, E. and Sanmartin, J. R. Analysis of bare tether systems for deorbiting Low-Earth-Orbit satellites. *J. Spacecraft Rockets*, 2002, **39**, 198–205.
4. Janhunen, P., Toivanen, P., Envall, J., Merikallio, S., Montesanti, G., del Amo, J. G. et al. Electrostatic plasma brake for deorbiting a satellite. *J. Prop. Power*, 2010, **26**, 370–372.
5. Kestilä, A., Tikka, T., Peitso, P., Rantanen, J., Näsilä, A. et al. Aalto-1 nanosatellite – technical description and mission objectives. *Geosci. Instrum. Method. Data Syst.*, 2013, **2**, 121–130.
6. Praks, J., Kestilä, A., Hallikainen, M., Saari, H., Antila, J., Janhunen, P., and Vainio, R. Aalto-1 – an experimental nanosatellite for hyperspectral remote sensing. In *Proc. IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. Vancouver, Canada, 2011.
7. Näsilä, A., Saari, H., Antila, J., Mannila, R., Kestilä, A., Praks, J. et al. Miniature spectral imager for the Aalto-1 nanosatellite. In *Proc. 4th European CubeSat Symposium*. Brussels, 2012, 24.
8. 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.
9. Chung, S. and Miller, C. D. Propellant-free control of tethered formation flight, Part 1: Linear control and experimentation. *J. Guid. Control Dynam.*, 2008, **31**, 571–584.
10. Forward, R. L., Hoyt, R. P., and Uphoff, C. The terminator tether: a low-mass system for end-of-life deorbit of LEO spacecraft. In *Tether Technical Interchange Meeting*. Huntsville, AL, 1997.
11. Seppänen, H., Kiprich, S., Kurppa, R., Janhunen, P., and Hæggström, E. Wire-to-wire bonding of um-diameter aluminum wires for the electric solar wind sail. *Microelectron. Eng.*, 2011, **88**, 3267–3269.
12. Rauhala, T., Seppänen, H., Ukkonen, J., Kiprich, S., Maconi, G., Janhunen, P., and Haeggström, E. Automatic 4-wire Heytether production for the electric solar wind sail. In *Proc. International Microelectronics Assembly and Packing Society Topical Workshop and Tabletop Exhibition on Wire Bonding*. San Jose, California, 2013.
13. Ki, K. I., Kawamoto, S., and Morino, Y. Experiments and numerical simulations of an electrodynamic tether deployment from a spool-type reel using thrusters. In *Proc. 1st IAA Conference on Dynamics and Control of Space Systems*. 2012.
14. Hoyt, R. Tether systems for satellite deployment and disposal. In *Proc. 51st International Astronautical Congress*. Rio de Janeiro, Brazil, 2000.
15. Khurshid, O., Janhunen, P., Buhl, M., Visala, A., Praks, J., and Hallikainen, M. Attitude dynamics analysis of Aalto-1 satellite during de-orbiting experiment with plasma brake. In *Proc. International Astronautical Congress*. Naples, Italy, 2012.
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.
17. 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.
18. Razzaghi, E., Yanes, A., Praks, J., and Hallikainen, M. Design of a reliable On-Board Computer for Aalto-1 nanosatellite mission. In *Proc. 2nd IAA Conference on University Satellites Missions and CubeSat Workshop*. Roma, 2013.
19. Tikka, T., Danziger, B., Engelen, S., and Hallikainen, M. Attitude Determination and Control System implementation for the Aalto-1 nanosatellite. In *Proc. 2nd IAA Conference on University Satellites Missions and CubeSat Workshop*. Roma, 2013, 676–694.
20. Leppinen, H., Kestila, A., Strom, M., Komu, M., and Hallikainen, M. Design of a low-power GPS subsystem for a nanosatellite science mission. In *Proc. 2nd IAA Conference on University Satellites Missions and Cubesat Workshop*. Roma, 2013.
21. Envall, J., Janhunen, P., Toivanen, P., Pajusalu, M., Ilbis, E., Kalde, J. et al. E-sail test payload of the ESTCube-1 nanosatellite. *Proc. Estonian Acad. Sci.*, 2014, **63**(2S), 210–221.
22. 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.
23. Krömer, O., Rosta, R., Richter, L., and Janhunen, P. SAMUEL – Space Applied Mechanism for Unreeling Electric conductive tethers. In *Abstracts of European Planetary Science Congress*. Roma, 2010, vol. 5.

24. Rosta, R., Krömer, O., Zoest, T. V., Janhunen, P., and Noorma, M. Weltraum Abrollmechanismus für dünnen electrisch leitenden draht. In *Proc. Deutscher Luft-Und Raumfahrtkongress*. Estrel, Berlin, 2012.
25. Obraztsov, A. N. and Kleshch, V. I. Cold and laser stimulated electron emission from nanocarbons. *J. Nanoelectronics Optoelectronics*, 2009, **4**, 207–219.
26. Janhunen, P., Toivanen, P. K., Polkko, J., Merikallio, S., Salminen, P., Haeggström, E. et al. Electric solar wind sail: Toward test missions. *Rev. Sci. Instrum.*, 2010, **81**, 111301, 1–11.
27. de Ruiter, A. A fault-tolerant magnetic spin stabilizing controller for the JC2Sat-FF mission. *Acta Astronaut.*, 2011, **68**, 160–171.

Plasmapiduri eksperimendi sobitamine Aalto-1 satelliidile

Osama Khurshid, Tuomas Tikka, Jaan Praks ja Martti Hallikainen

On esitatud ülevaade plasmapiduri eksperimendikorraldusest Soome Aalto-1 satelliidi pardal. Eksperimendi eesmärgiks on näidata elektrostaatiliselt laetud päikesepurje traadi kasutusvõimalusi satelliidi orbiidi manöövrite teostamisel. Plasmapiduri alamsüsteem põhineb päikesepurje efektil, mis on hiljuti leiutatud Soome meteoroloogia instituudis. Elektriline päikesepuri on loodud päikesetuule kasutamiseks kosmoselaevade kiirendamisel Päikesesüsteemis, kasutades selleks pikki elektrostaatiliselt laetud traate. Samal põhimõttel töötavat seadet võib kasutada maalähedasel orbiidil satelliidi kiiruse vähendamiseks, kuna laetud traat tekitab plasmas liikudes märkimisväärse hõõrdejõu. Jõu abil võib vähendada satelliidi kiirust ja sellisel moel on võimalik satelliit orbiidilt madalamale orbiidile või ka atmosfääri suunata. Aalto-1 on mitmeotstarbeline satelliit, mille üheks kasulikuks koormiseks on ka plasmapiduri eksperiment. Selle koosseisu kuulub 100 m pika päikesepurje traat, traadi säilitamise rull, kõrgepingeallikas ja elektronikahurid traadi laengu säilitamiseks. Eksperiment viiakse läbi nii negatiivse kui ka positiivse laenguga ja selle raames kasutatakse pikaajalist passiivset laengut satelliidi pidurdamiseks. On tutvustatud satelliidi seadmeid, satelliidi missiooni üksikasju ja eksperimendi erinevaid faase.