ESTCube-1 student satellite in-orbit experience and lessons learned

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Abstract ESTCube-1 is a one-unit CubeSat that has been in orbit since May 2013. It was launched to a Sun-synchronous 670 km altitude polar low Earth orbit, and its primary mission objective was to centrifugally deploy a tether as a part of the first in-orbit demonstration of electric solar wind sail (E-sail) technology. The electrical power system, the communication system and the command and data handling system remain fully functional after almost two years in orbit. The camera, developed to image the end-mass of the tether, has taken more than 270 images for camera characterization, for validating the attitude determination system, and for public outreach purposes. The attitude determination accuracy is better than 1.5°, and the attitude control system is able to spin up the satellite to more than two rotations per second around an axis that suits the E-sail experiment. In this article, we present our in-orbit experience of operating and preparing the satellite for the experiment, as well as the most important lessons learned.
Keywords: ESTCube-1, CubeSat, nanosatellite, lessons learned, in-orbit experience.

1. Introduction

ESTCube-1 is a student satellite project lead by the University of Tartu, Estonia and supported by the European Space Agency (ESA) via Plan for European Cooperating States (PECS). Development of the satellite has been a collaborative effort with many international partners. It is shown on Figure 1. [1]

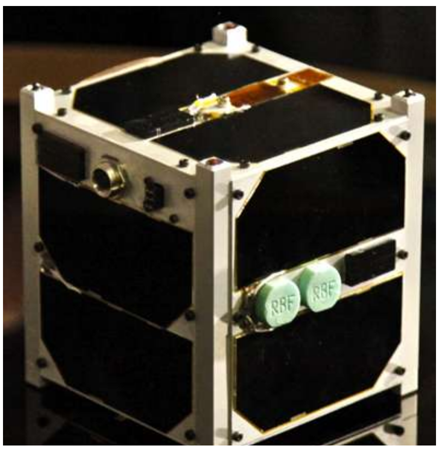

Figure 1 ESTCube-1 satellite before delivering it to the launch provider.

The main scientific mission objective of the satellite was to perform the first in-orbit electric solar wind sail (E-sail) experiment [2, 3]. Implemented according to the one-unit CubeSat standard, it has physical dimensions of approximately 10×10×10 cm and mass of slightly over 1 kg. ESTCube-1 consists of the following subsystems: Electrical Power System (EPS)

[4]; Communication System (COM); Command and Data Handling System (CDHS) [5]; Attitude Determination and Control System (ADCS [6, 7, 8]; Camera System [9]; and the E-sail experiment payload [10]. All subsystems and payloads were custom-built mostly using Commercial Off-The-Shelf (COTS) components. The satellite was intended to prepare for and to perform the E-sail experiment consisting of the following phases [1].

- In-orbit validation.
- Characterize novel subsystems (EPS, ADCS and camera).
- Spin-up the satellite to one rotation per second.
- Test tether deployment.
- If deployment successful, charge the tether synchronously with the satellite spin and measure changes in the spin rate caused by Coulomb drag interaction between the tether and the ionospheric plasma.
- Characterize on-board electron guns.

ESTCube-1 project started without prior in-house experience. Nevertheless, the project has achieved most of its objectives. The satellite has worked as expected; except for the following issues — a larger than expected decrease in energy production during the mission; a need for in-orbit recalibration of attitude determination sensors; ferromagnetic materials aligning the satellite frame with the geomagnetic field; and problems with reeling out the tether. However, from developing all subsystems in-house and operating the satellite, the team has gained valuable experience that could decrease the development time and improve the overall quality of the follow-up missions.

In this article, we report on the in-orbit experience — an overview of ESTCube-1 operations from the launch until the experiment, as well as on the most important lessons learned. Full analysis of lessons learned are presented in an article submitted to the IEEE Aerospace and Electronic Systems Magazine [11]. Detailed flight results of ESTCube-1 will be provided in dedicated articles. We hope that other teams can benefit from our experience.

2. In-orbit experience

ESTCube-1 was launched on May 7, 2013 on board the Vega rocket by Arianespace. After successful early operations, several software updates took place — the satellite was launched with minimal software functionality to eliminate the risk of activating certain mission-related components too early. For example, prematurely enabling the high voltage supply, unlocking the tether reel or the tether end-mass.

The EPS firmware has been gradually improved by adding functionality: power saving methods, including satellite-wide timed sleep modes and battery level thresholds for automatically turning off other subsystems; variety of data logging functions; a callable timed beacon function for public outreach purposes; stability updates; and experiment-related functions.

Similarly to the EPS, the CDHS has been improved by adding functionality: power saving mode, variety of data logging functions, high time-resolution functions for sensor measurements, experiment-related functions, additional pre-processing of attitude measurements, as well as attitude determination and control algorithms. While ADCS sensors are placed on a dedicated board, all calculations take place on the CDHS microcontroller (MCU).

A secondary objective of the ESTCube-1 mission was to take images of Estonia. Firstly, to validate the camera for this purpose, images of the Earth were taken. The first fully downlinked image was taken already on May 15, 2013. During its lifetime, ESTCube-1 has downlinked more than 270 images for scientific and public outreach purposes. These images have been used to characterize the camera and to validate on-board attitude determination. Due to challenges with the ADCS, taking an image of Estonia proved to be difficult and only at the one-year anniversary the team was able to present an image of Estonia, Latvia and a part of Finland (Figure 2). The most important software updates for the camera were histogram analysis that allowed automatic detection of the Earth and clouds, and optimization of power consumption.

Figure 2 A composite image showing Estonia, Latvia and a part of Finland taken on April 23, 2014.

Attitude determination sensors were pre-launch calibrated in the laboratory [7] but had to be recalibrated using in-orbit measurements. For calibration, statistical methods were used, and attitude determined from on-board images as well the Kalman Filter output were used to fine-tune correction functions and to validate the system. The accuracy of the system is better than 1.5° [8].

Due to ferromagnetic steel structural components and battery casings, as well as ferromagnetic nickel anode and cathode of electron guns, the satellite body aligns with the geomagnetic field. Tests with the engineering model and Helmholtz coils in an anechoic chamber revealed that the residual magnetic moment is larger than the on-board coils can produce and the direction is roughly diagonal from one edge to another. Under stable unactuated conditions the spin axis of the satellite is roughly aligned with its internal magnetic moment vector (see Figure 3) which in turn follows the geomagnetic field. The latter causes precession of the spin axis. In-orbit attitude control experiments showed ability to spin up around the z-axis of the satellite and align the spin axis with the polar axis of the Earth (as required by the E-sail experiment [1]) but the rotation is not stable and over time the satellite returns to its natural motion of following the geomagnetic field. By controlling the spin rate around the axis that follows the geomagnetic field, the team was able to reach the spin rate of 360 deg/s.

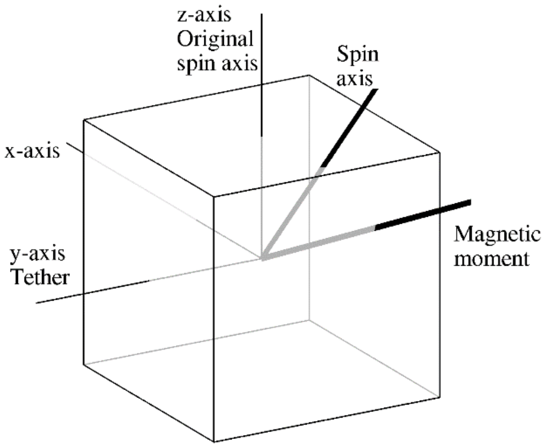

Figure 3 Alignment of the spin axis under stable unactuated conditions as well as the originally intended spin axis (aligned with z-axis), the tether (aligned with y-axis) and the magnetic moment under unactuated conditions.

Since the natural spin axis still provides the required centrifugal force to deploy the tether and to perform the experiment with relaxed requirements, multiple attempts to deploy the tether took place. However, deployment of the tether was neither confirmed by camera nor angular velocity measurements. The most probable reason is that the tether reel is not rotating because either the rotator is jammed or reel lock deployment has failed. To enhance the centrifugal pull force of the end-mass in an attempt to release the possible mechanical jam, the spin rate was increased to as high as possible which resulted in 840 deg/s.

Another part of the E-sail experiment was testing of the field-emission based electron guns, intended to charge up the satellite [12]. While E-sail tether deployment failed, the electron guns were still tested by powering up the high-voltage source and applying a potential difference of around 510 V between the electron gun anode and cathode. Currents going to electron guns measured during these experiments showed that applying the anode voltage increases the cathode current, indicating that electron guns function. A voltage of 510 V produced a cathode current of 300 μA. The reliability of the technology still seems to be of concern. One of the electron guns appears to have disconnected from the power supply and the functioning one short circuited during tests (after the successful measurement of the cathode current).

3. Lessons learned

3.1. Electrical power

A serious problem we encountered in orbit was faster than expected solar panel degradation (about 60% decrease during the first year). Some form of solar panel degradation will take place during every satellite mission and this often determines the mission lifetime. Therefore, we suggest for a highly granular power distribution system in which components and subsystems can be powered off independently, conserving power while saving critical functionality. We also used automatic battery voltage thresholds, which caused automatic subsystem turn-off when power level becomes critical. This system can be developed to automatically achieve power positivity, even in case of communication problems. To further save power, we also used timer-based sleep modes, in which only the EPS was powered. Still, great care must be taken so that the system exits these modes reliably (even in the case of memory overflows, which might overwrite sleep parameters). For example, we used control areas before and after critical memory sections, in addition to checksums of these sections. It is also a good idea to implement an automatic system to hard-reset the whole satellite if the satellite has not been successfully communicated with for some time. We used a 12-hour timer for this.

Solar panel cover glass should be used to avoid rapid degradation of solar cells. In the case of ESTCube-1, we did not use cover glass, since its in-house application is complex and it reduces the beginning-of-life efficiency of solar panels. We also underestimated the extent of degradation during the time required to complete the mission. Lack of solar panel cover glass was likely the main cause of the rapid solar panel degradation on ESTCube-1, and in the hindsight we strongly suggest using cover glass, even for shorter missions, and especially on polar orbits (higher amount of trapped particles encountered).

3.2. Calibration and characterization

All on-board sensors have to be calibrated and characterized to gain measurement reliability. It should include as many test cases as possible to foresee. Planning of tests have to start early in the project because sophisticated test benches might be required. For example, attitude sensors should be rotated around all axes simultaneously to develop reliable calibration curves.

Our experience with COTS components is positive. Having temperature sensors in close proximity to other sensors and performing temperature-calibration for all on-board sensors can improve the accuracy of other sensor measurements remarkably.

Combining laboratory calibration with in-orbit calibration might give the best result because not all cases can be tested in a laboratory or might require testing facilities that are not available. For example, end-to-end ADCS testing might always have some limitations.

Apart from sensor-specific tests, we suggest to perform thermal vacuum and vibration tests on subsystem level before the same tests are performed as a part of launch qualification. In a perfect case, sensors must be calibrated under the conditions similar to the working conditions as close as possible. For example, Sun sensor could measure an incidence angle of light while being placed in a thermal vacuum chamber.

In the case of ESTCube-1, some sensors were well calibrated before the launch but on multiple occasions in-orbit measurements had to be used to recalibrate them. For attitude determination sensors, we were lacking test benches that would provide needed variety of tests. More temperature and voltage sensors will be used on board upcoming satellites.

Another important aspect is the timing of measurements. In the case of the EPS, for example, in telemetry collection it can easily happen that current and voltage values taken in sequence actually correspond to different power states, making calculations based on multiple sensor readings problematic. A solution would be an independent telemetry system with synchronized input buffers to be certain that all measurements correspond to the same moment of time. Filtering can also be used to reduce this problem.

3.3. Magnetism

Having ferromagnetic materials on-board the satellite has caused the biggest challenge in preparing the satellite for the experiment. It took more than half a year to partly characterize the magnetic properties of the satellite using the engineering model, to fully characterize the motion of the satellite in orbit, and to iteratively improve and test attitude controllers. Nevertheless, the spin-up maneuver could not be performed as planned for the E-sail experiment but the spin axis was oriented such that the tether would deploy without significant deflection against the satellite side (see Figure 3). We strongly suggest to characterize magnetic properties of flight components and the model prior to the launch in the case an attitude control (active or passive) is required in the magnetosphere of the Earth. Note that this issue affects not only satellites that use magnetorquers.

4. Conclusions

In this article, we presented an overview of the ESTCube-1 in-orbit experience and discuss the lessons learned. After updating and debugging software, the satellite worked as expected except for four problems.

First, faster than expected power production deterioration. However, the amount of the produced power was enough to proceed with the mission. In future, the problem can be solved by using solar panel cover glass.

Second, a need to recalibrate attitude determination sensors in orbit. After recalibrating the sensors, debugging software and fine-tuning the Kalman filter, the attitude determination system was prepared for attitude control maneuvers and the E-sail experiment. In future, all sensors have to be calibrated before the launch better than it was done on ESTCube-1, as well as full integration of the system has to be tested on the ground. However, in-orbit calibration methods can serve as a backup or can be used to fine-tune correction parameters.

Third, ferromagnetic materials used on-board aligning the satellite with the geomagnetic field. By characterizing magnetic properties of materials and by redefining the spin axis it was still possible to prepare the satellite for tether deployment. In future, the problem can be solved by pre-flight magnetic characterization of on-board materials.

Fourth, inability to deploy the tether made it impossible to measure the E-sail force. While for ESTCube-1 it was not possible to exactly determine what caused the problem, we were able to identify design improvements, some of which have already been implemented on the Aalto-1 satellite [13]. The tether deployment system has to be thoroughly tested and it has to have means to detect which part is not working (e.g., locks, the reel or the tether is broken).

A full analysis of lessons learned will be presented in [11].

Since the satellite delivery schedule was accelerated, the mission encountered delays. After launching the satellite, only preliminary validation was feasible. New software updates allowed to fully validate the on-board systems, provided full functionality and optimized power consumption.

Lessons learned, discussed in this article, have already been, and continue to be, applied to subsequent missions in the ESTCube program. While most of them are applicable for any satellite size, the target audience for this article is nanosatellite community which is not strictly following space standards. We consider standards like the European Cooperation for Space Standardization highly useful. However, they are not fully compatible with agile development methods that nanosatellite developers prefer and that provide cost-efficiency. We think that for IOD missions, that nanosatellites are often used for, the standards can be made looser to keep the cost-efficiency and short development time.

For teams that are developing satellite series for IODs and for educational proposes, we encourage to use the philosophy *fly early & fly often*. Such philosophy enables rapid technology development followed by in-orbit tests. While it increases the risk, the team can learn from mistakes and unsuccessful missions to quickly develop sequential satellites. Some of the lessons can be learned only by launching and operating satellites. *Fly early & fly often* employs the cost-efficiency of nanosatellites and COTS components. Moreover, launching a satellite soon after freezing the design allows utilization of the latest developments in the COTS market.

5. Acknowledgments

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