

ESTCube-1 In-Orbit Experience and Lessons Learned

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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 ESTCube-1 has been a collaborative effort with many international partners. The satellite is shown on Figure 1 [1].

The main scientific mission objective of the satellite was to perform the first in-orbit electric solar wind sail (E-sail) experiment [1]–[3]. Implemented according to the one-unit CubeSat standard [4], it has physical dimensions of approximately $10 \times 10 \times 10$ cm and mass of slightly over 1 kg. ESTCube-1 consists of the following subsystems: electrical power system (EPS) [5]; communication system (COM); command and data handling system (CDHS) [6]; attitude determination and control system (ADCS) [7]–[9]; camera system [10]; and the E-sail experiment payload [11]. 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.

1. Characterize novel subsystems (EPS, ADCS, and camera).
2. Spin-up the satellite to one rotation per second.
3. Test tether deployment.
4. If deployment successful, charge the tether synchronously with the satellite spin and measure changes in the spin rate

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Manuscript received March 5, 2015 and ready for publication June 15, 2015.

DOI No. 10.1109/MAES.2015.150034.

Review handled by M. Jah.

0885/8985/15/\$26.00© 2015 IEEE

caused by Coulomb drag interaction between the tether and the ionospheric plasma.

5. Characterize on-board electron guns.

CubeSats have been proven to be capable of providing an excellent platform for educational and in-orbit demonstration (IOD) projects that are at the same time challenging from the engineering point of view [12]. The CubeSat standard and the associated philosophy allow for rapid development [13] and provide the benefit of quickly accumulating knowledge and expertise. Several CubeSat programs have demonstrated how lessons learned from previous missions benefit subsequent projects within the program. For example, three-unit CubeSats RAX-1 and RAX-2 performed studies of large plasma formations in the ionosphere

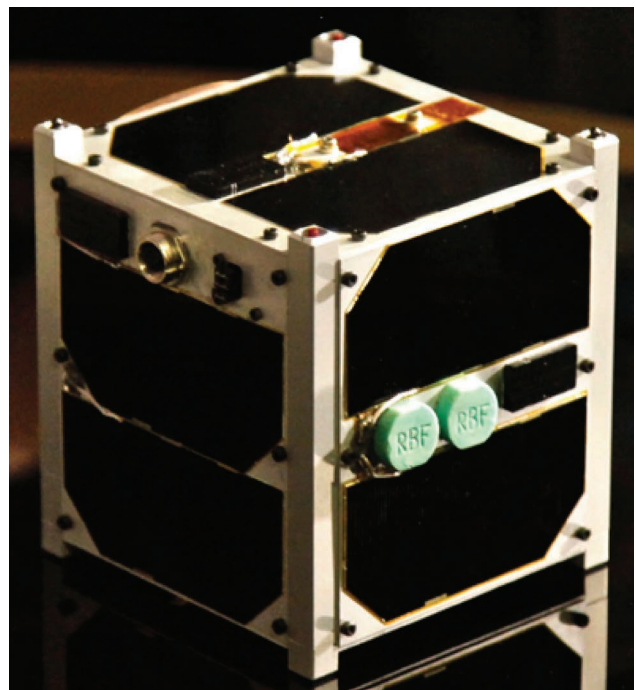


Figure 1. ESTCube-1 satellite before delivering it to the launch provider.



[14], [15]. Gradual degradation of solar panels caused the RAX-1 mission to end two months into the mission after it was launched in November 2010 [16]. However, the fault in the design of RAX-1 responsible for the solar panel damage was identified, and the fault was corrected on RAX-2 that was launched at the end of 2011 [15]. The RAX team has also developed an ADCS by learning from the previous experience [17], [18]. Similarly, review of mission outcomes and focus on compiling a list of lessons learned has allowed for the AAUSAT program from Aalborg University to be successful and continue for more than ten years [19]–[21]. Examples of other successful CubeSat series include the satellites constructed by Delft University of Technology, such as Delfi-C3 and Delfi-n3Xt [22], [23]; the BeeSat series operated by the Berlin Institute of Technology [24], [25]; the CP CubeSats from California Polytechnic University [26]; the two DICE satellites from Utah State University [27]; the Cute series from Tokyo Institute of technology [28], [29]; and the UWE series from the University of Würzburg [30].

While we have learned from the aforementioned mission, the 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 lessons learned from five years of development and almost two years of operations. Lessons are identified from the point of view of system engineering, electrical engineering, mechanical engineering, software engineering, testing and measurements, payload, and management. Detailed flight results of ESTCube-1 will be provided in dedicated articles. We hope that other teams can benefit from our experience.

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 preprocessing 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 on May 15, 2013. During its lifetime, ESTCube-1 has downlinked 300 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 was the team 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.

Attitude determination sensors were prelaunch calibrated in the laboratory [8] 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



Figure 2.

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

output were used to fine-tune correction functions and to validate the system. The accuracy of the system is better than 1.5° [9].

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.

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 (see Section VIII for more details). 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 [31]. 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

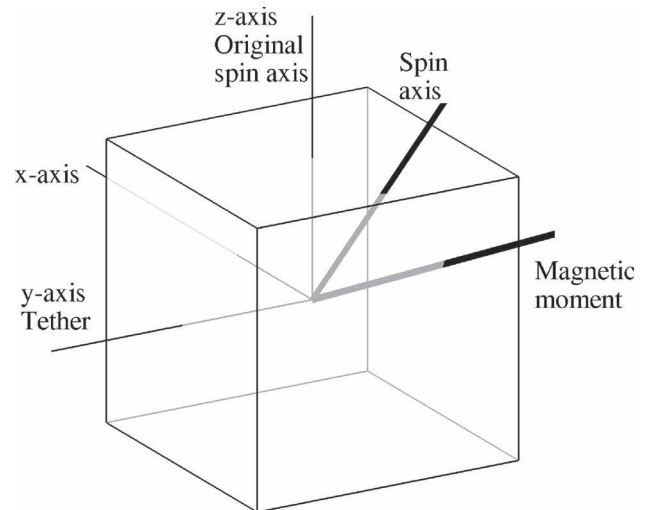


Figure 3.

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. The spin axis is determined from in-orbit attitude measurements. The magnetic moment is determined in a laboratory using the engineering model which did not have electron guns and could be magnetized differently from the flight model. Axes x, y and z are orthogonal and aligned with sides of the satellite.

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).

After two years and two weeks of being operational, due to insufficient amount of energy produced, the satellite entered energy-negative mode and consumed the available energy stored in the batteries to keep operating. Once the batteries were drained, the satellite did not have enough energy available to be operational.

SYSTEM ENGINEERING

MODEL PHILOSOPHY

The ESTCube-1 team used a protoflight model philosophy [32] to deliver the satellite on time. On August 2012 the schedule was accelerated by moving the delivery date from May 2013 to January 2013. The decision was a trade-off between engineering risks and securing a launch opportunity. The protoflight tests can increase the risk of components becoming damaged before the launch. In the case of ESTCube-1, the first vibration test caused the tether reel to turn and break the tether into small pieces, which covered some inner components of the satellite. While the problem was solved (solution in Section VIII), in the future, we plan to use a model philosophy of engineering, qualification, and flight models. Due to budgetary restrictions, expensive parts of the satellite (parts of the payload, reaction wheels, thrusters) might not be included in all models.

STANDARDIZATION

During ESTCube-1 development, each subsystem team was able to make design decisions independently. Such approach did not cause any major problems, but we think that all subsystems should follow a unified architecture and use common components and development tools where applicable, to allow reusability, to save development time, and to facilitate mobility of team members between subsystems. For example, just two MCU architectures can be used—one for computation-intensive subsystems and another for subsystems with low computational and high uptime requirements.

STANDARDS AND DOCUMENTATION

While we think that standards of the European Cooperation for Space Standardization (ECSS) can be used as a best practice, submissive following of the ECSS standards introduces too much overhead for CubeSat projects which usually use agile development methods and which take five years or less to develop a satellite. However, the team must use standards and conventions that are agreed with external parties, for example, amateur radio standards (e.g., [33]) have to be followed by CubeSat teams operating on amateur radio frequencies.

We consider an interface control document as the most important because it defines links between subsystems and payloads. Documents must be well written and maintained regularly. We suggest using web-based documentation tools and/or versioning and revision control systems. In that case all members can easily access the newest version (as well as the history of versions) and maintaining versions is much easier.

Every development should start with requirements specification and requirements should have a hierarchy—every requirement, except the system level ones, should have a parent requirement. For example, ADCS requirements should stem from system requirements and Sun sensor requirements should stem from ADCS requirements. In a perfect case, subsystem teams should know top-level subsystem requirements before design decisions are made. For example, the CDHS was developed with a functionality to log a static set of housekeeping data, but for in-orbit debugging, dynamic logging of various parameters was required and implemented in one of the software updates.

Interface documents must contain detailed descriptions of electrical, mechanical, and software interfaces. For example, we experienced a faulty software interface as a discrepancy of measurement units (radians and degrees) between functions implemented by different developers. We were able to solve the issue by updating software. The units must be agreed beforehand but, as a safety measure for such a risk, a team can introduce correction coefficients—updatable gains and offsets.

In addition to the recommendations listed above, we would suggest paying attention to the specific conditions due to student workforce, if student workforce is used (see Section IX for specific suggestions). We have also learned new aspects that are critical for the mission and have to be taken into account when writing requirements for the next missions, for example, related to solar panel degradation, attitude determination and control, as well as payload.

INTEGRATION

The ESTCube-1 team, similar to other CubeSat teams, faced many challenges when fitting various wires and cable harnesses into the satellite. We suggest using as few wires as possible and include them in computer-aided design (CAD) mechanical models. Integration of subsystems and components should be practiced before integration of the engineering model. We would suggest maintaining as fully functional as possible a prototype of the satellite that contains the latest subsystems to test prototypes of new subsystems. In this case, many problems could be detected right when the new revision of the component is inserted into the satellite assembly. Another option is assembling as complete a model of the satellite as possible on a periodical basis and performing conformity tests.

In which order the side panels attach to the satellite frame should be considered. For example, one might need to attach a side panel before all connections under that side panel have been made. We would suggest making the integration order of side panels as independent of each other as possible to reduce the effect of these problems.

To remember to integrate all components, they should be laid out on a table. A simple but effective way to ensure a successful integration is to make a checklist of all components and processes. Development of the checklist should start early and all subsystems should be involved.

Prior to the integration in the cleanroom all the components have to be cleaned thoroughly to meet the standards required by the launch provider and the middlemen, and to ensure that the components like solar panels and lenses will not become contaminated. Contamination can accumulate on lenses, causing artifacts on images, and on solar panels, reducing the amount of solar photons that can reach solar cells (therefore, effectively reducing the efficiency). Using protective films while integrating and removing them before the launch can help to avoid contamination.

In the case of ESTCube-1, the satellite was successfully integrated and some of the suggestions listed above were followed but by fully following them the integration process can be optimized further and made more time efficient.

ELECTRICAL ENGINEERING

COMMERCIAL OFF-THE-SHELF COMPONENTS

The electronics on-board ESTCube-1 were assembled solely from COTS components, a market which is developing rapidly, and therefore high performance components can be obtained quickly and at low cost. To ensure reliability, automotive or industrial-grade components were used, where possible, and several redundancy measures were applied to assure that a component failure would not jeopardize the mission and also several tests were performed (see Section VII).

The in-flight experience shows that this approach was a success because the failures experienced (for example, a failed sensor and a failed memory) did not cause any larger problems due to redundant counterparts of components. Applying redundant

measures also had other benefits—from better measurement results due to a larger amount of sensors to better electrical efficiency due to power electronics components working in parallel and sharing the load.

DATA CONNECTIONS WITHIN THE SATELLITE

Within ESTCube-1, we used several different communication bus standards, both between the components of a single subsystem and between MCUs of different subsystems. Between different subsystems, we used the universal asynchronous receiver/transmitter (UART) modules within MCUs and communicated according to our in-house developed internal communication protocol (ICP). Between components within a single subsystem (e.g., analog-to-digital converters (ADCs), magnetometers, input/output (I/O) extenders, and beacon oscillator), we used interintegrated circuit (I2C) and serial peripheral interface (SPI) buses [1].

The main challenges arose from cases when the same communications bus was shared between several components, especially when the systems connected could be powered on and off separately. For example, a subsystem processor can remain partly operational due to the current supplied through a communications bus, even if the component itself is not powered through its power pins. Also, a single unpowered device on a bus can drain enough current to make the whole bus inoperable when communicating with other systems on it. We would suggest applying some form of a switch for disconnecting unpowered devices from buses or fine-tuning serial resistors on communication lines, although the latter might not always achieve the results needed.

Specific issues arose from using the I2C bus, which uses only two electrical connections, one for transferring data and the other for clock pulses. In our experience, it can very easily happen that the state machine behind I2C communications can malfunction, leading to the loss of communication capability with the component. Therefore, it should be possible to separately power off I2C devices to reset their internal state. This is not a problem with the SPI bus. It also has happened that communicating with a single device using the I2C bus causes other devices on the shared bus to receive (erroneous) data, for example our voltage-controlled oscillator chip for beacon systematically malfunctioned when an I/O extender was polled on the same I2C bus. Also, problems arise from the fact that on an I2C bus, a single data line is operated both by the bus master and the bus slave, making level conversion complicated.

All in all, we would suggest refraining from using I2C in satellites, especially for critical communications. If an I2C bus is shared between several components, it is advisable to implement some form of a chip select functionality and have an option to separately power off or reset components. As another note, SPI also offers significantly higher data rates.

MEMORY

Ferroelectric Random-Access Memory (FRAM) memory is good for nonvolatile storage of system-critical data because the underlying technology is highly radiation tolerant. However, one

should keep in mind that the storage capacity of FRAM is low compared with flash memory, for example. External parallel static random-access memory (RAM) (SRAM) or synchronous dynamic RAM (SDRAM) memory is needed for volatile storage where high-density and high data rates are required. For example, on-board file systems and compression algorithms.

For mass storage, we suggest to use flash memory devices with integrated controllers on as high a level as possible; for example, secure digital (SD) cards. This allows using third-party file systems that are possibly more efficient and more reliable than developing them in-house. However, in the case of memory devices with integrated controllers, abrupt power loss becomes an issue.

Parallel memory devices should be used where applicable. Although the current consumption of parallel memory is higher when compared with serial memory devices, parallel interface provides greater performance and makes them easier to address. Nevertheless, these are minor issues and will not influence the mission success.

ELECTRICAL POWER

Producing and distributing electrical power proved to be a challenging task both while designing the system and during operations in orbit. For more details about the design, see [5].

In the design phase, one of the largest challenges was implementing redundancy measures, especially due to the large number of components and their connections. For example, all voltage regulators were duplicated within the EPS in a hot redundant configuration. This caused high software complexity to control and to monitor redundant systems. Fortunately, no power component failures were detected during the operations period. The power production decrease experienced is expected to be due to physical damage to the solar cells, not the electronics. We would suggest critically analyzing the need for redundancy, during shorter missions—it might be safer to make a simpler system.

From satellite operations we would first stress the importance of planning for the time period after final integration of the satellite and before the launch; this time period can be easily overlooked in the design process. During this time the satellite has to be externally powered. Care must be taken to minimize the battery energy consumption when the satellite is inside the satellite deployer, since the satellite might remain in that state for months and some battery power might be required just after deploying the satellite in orbit (overdraining the batteries during this period might also cause irreversible damage).

As mentioned in Section II, one 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 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 the power level became 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.

An important conclusion from automatic power saving features is that all critical data should be kept in nonvolatile memories. In the case of ESTCube-1, we lost some camera images, for example, due to their nonvolatile storage system. Short-time power failures might also happen for other reasons, including radiation effects and software errors.

All in all, the power system implementation managed to provide enough power for the satellite to reduce the problem of solar panel degradation from a mission stopper to a minor inconvenience.

OTHER

The ESTCube-1 CDHS has two cold redundant MCUs that are selected by the EPS. To reduce intersubsystem complexity, the on-board computer can have its own low-power radiation-tolerant processor for critical administrative tasks as well as for switching the main MCUs.

Intrasubsystem buses should not be exposed to other subsystems to avoid possible compatibility issues that would affect the performance of components within a subsystem.

MECHANICAL ENGINEERING

MAIN STRUCTURE

A mono-block aluminum structure was used on ESTCube-1 because it is lightweight and it makes it easier to achieve the required tolerances. However, due to high production costs and complexity, as well as complicated system engineering and integration, we will not use a mono-block structure in the future.

A slightly different material (aluminum alloy 6082) was used for the main structure compared with the one suggested by the CubeSat standard (aluminum alloy 6061 or 7075) [4] because it was easier to order in Europe. Changes in the main structure material did not cause any problems, but the last minute change from titanium to steel bolts introduced ferromagnetic material on board. Suppliers and products should be secured early to avoid late changes.

In a perfect case, the launcher should be known during the development phase of the structure because the required tolerances change from launcher to launcher.

Unique materials should be avoided to have a chance to reproduce mechanical structures after the launch.

Apart from the ferromagnetic bolts, all ESTCube-1 issues regarding the main structure are minor.

SOLAR PANELS

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 hindsight we strongly suggest using cover glass, even for shorter missions, and especially on polar orbits (higher amount of trapped particles encountered).

SUN SENSORS

When designing Sun sensors, attention should be paid to reflectivity of the sensor mask—internal surfaces should be absorbing black to avoid stray light on position sensitive devices. In a perfect case, the mechanical design of the sensor mask would not allow the incident light to illuminate internal surfaces. In the case of ESTCube-1, the aluminum mask was anodized black and the design can be improved to avoid unwanted reflections inside the mask.

CAMERA

The basic aluminum structure of the ESTCube-1 camera lens enclosure provides a sufficient amount of radiation protection in a low Earth orbit. Radiation affects the camera RAM, which is located right behind a 1 mm thick side panel [10]. The effect can be seen by reading pixel values out of range of the ones the image sensor can produce. For ESTCube-1, these effects are not critical but, if they would be, memory devices could be protected with shielding.

The imaging sensor is also prone to radiation effects. Permanently damaged hot pixels can be avoided with the help of a shutter. To reduce the degradation of infrared (IR) filters and lenses, spectral radiation films and robust filters can be used.

MOMENT OF INERTIA

For an active ADCS, a good knowledge of the inertia matrix is critical to determine the attitude precisely when performing fine attitude maneuvers and especially when high spin rate maneuvers are required. In case attitude determination is performed without control and an attitude estimator with a prediction step is used (like Kalman filter), knowledge of the inertia matrix is still important because in the prediction step the attitude is propagated using the angular velocity and the inertia matrix. We suggest determining the inertia matrix of a satellite by measurements, instead of determining it from a CAD model. In the case of ESTCube-1, final values of the inertia matrix were estimated analyzing in-orbit measurements of the spin plane. Such approach provided required results for attitude determination for low spin rates. However, an error in the inertia matrix caused the attitude determination error to grow when the angular velocity increased.

CONNECTORS

On ESTCube-1, the system bus is based on the PC/104+ standard connector that has 4×30 pins and its stiffness makes it difficult to assemble or disassemble the satellite. The placement and stiffness of the connectors must be planned thoroughly and coordinated with the placement of printed circuit board (PCB) components, to minimize mechanical tensions during integration or disintegration. As the standard connector heights were not properly taken into account in the structure design, the pins of some connectors had to be trimmed. However, challenges with connectors did not cause any major problems.

SOFTWARE ENGINEERING

OPERATING SYSTEM

In order to minimize the computational overhead and memory footprint of the on-board software, a lightweight real-time operating system, FreeRTOS1, was used on the CDHS and the camera. The most important reason to use an operating system was the need for task scheduling and multitasking which is implemented in the FreeRTOS. Custom file systems had to be developed due to serial memory devices that cannot be accessed directly and due to a limited amount of RAM. The CDHS does not support delta updates (uploading only the parts that have changed), which would have been useful. If possible, we suggest using an operating system that provides most of the needed functionality, for example, a form of embedded Linux.

SOFTWARE UPDATES

A large proportion of ESTCube-1 software was written after the launch. We consider this as a bad practice because it relies on in-orbit software updates and the mission is delayed, increasing a risk of satellite failure before performing all the planned experiments. However, we think that functionality of in-orbit software updates of all active subsystems is critical for a CubeSat mission, especially for teams without prior experience. That functionality can, most importantly, save the mission and it also allows using the satellite for other purposes than initially planned. When implementing support for software updates, the bootloader must be designed to keep backup firmware images to boot when something happens to the latest image. Packet loss must be taken into account on file transfer; in the case of ESTCube-1, page-by-page uploads and verification by pagemaps and checksum have served well.

OTHER

The camera was designed following a principle of using as few components as possible, which has worked well to provide a small, simple, modular, and independent camera. However, it should be kept in mind that this approach also increases software complexity.

The CDHS is able to log a single command response to a single file at a time. The functionality of logging individual parameters to files simultaneously can ease the preparation and compression of the telemetry.

Dynamically adjustable clock frequency (without having to reset the MCU) can be used to optimize power consumption of a system.

A central communication bus is preferred so that subsystems would be able to communicate with each other without forwarding packets through each other.

Developing on-board algorithms in C can save time spent on porting. For example, ADCS functions, written in C, can be tested in MATLAB and Simulink using wrapper functions and can be directly used in on-board software.

Downlink data rate could be improved further if the COM were able to buffer several packets in its memory and transmit them in a sequence without dropping the carrier, or even better, implementing a forward error correction coding on the downlink channel.

An obvious but important lesson learned is to document the code and keep user manuals up to date.

Lessons learned presented in this subsection did not cause any major problems but can make development and operations more efficient.

TESTING AND MEASUREMENTS

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

To decrease analog sensor uncertainty, a temperature-compensated reference voltage should be measured on board.

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 the 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.

INFANT MORTALITY

Infant mortality is an early component failure caused by not testing sufficiently (wearing) a sensor before the launch. We have experienced failure of one of four hot redundant gyroscopic sensors soon after the launch and one of the two cold redundant MCUs of the CDHS suffered damage to the internal flash just three months after the launch. Two out of three SPI bus flash memory devices on the ESTCube-1 engineering model stopped working a few weeks after the integration. Flight and spare components should be stress tested before the launch. Redundant components can mitigate the risk as well. We consider this issue especially important with COTS components.

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 characterizing 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.

OTHER

A practice of early prototyping should be combined with regular subsystem-level functional tests followed by early integration tests (starting with electrical/software and later adding mechanical tests) to develop a well-functioning and reliable system.

Dedicated boards for early tests can be considered, for example, to test and perform preliminary characterization of a variety of sensors from which the best ones can be chosen for the mission.

To make debugging and diagnostics easier, test-ports can be left on a flight model and a universal serial bus (USB) connector can be used at least until an engineering model is prepared.

The power budget must account for the degradation of solar cells and batteries.

In the case of ESTCube-1, we incrementally learned lessons, listed in this subsection, and applied them to our activities on the go.

ELECTRIC SOLAR WIND SAIL (E-SAIL) PAYLOAD

The ESTCube-1 tether payload consists of a piezoelectric motor driven reel, 25 μm and 50 μm wires forming a 15 m long tether, an end-mass of the tether, a high voltage source to charge the tether, and a slip ring to connect the high voltage supply to the tether. Reeling of the tether is monitored by taking images of the end-mass. Both the end-mass and the reel are fixed with dedicated locks that use burn wires [11].

We carried out the tether deployment test in orbit and it was not successful. Since the payload design suffers from a lack of diagnostic measures, the exact reason why part of the payload failed is not known. Some of the future design improvements for the E-sail payload are sensors to detect whether locks have deployed, if the reel is turning, and if the end-mass is moving. By having the camera inside the tether enclosure, it will be possible to monitor the end-mass even before deployment. In the case of ESTCube-1, the end-mass would appear in the field of view only after tether deployment of a few centimeters. To improve end-mass monitoring even further, a light-emitting diode (LED) is suggested to be added near the end-mass enclosure for proximity imaging. Such LED would allow imaging of the most critical period of tether deployment without depending on sunlight and/or attitude. The ESTCube-1 camera is limited to storing a maximum of four images. More memory would allow monitoring deployment in detail. Nonvolatile memory should be used to avoid losing experiment data in the case of a reset.

As described in Section II, the reel started to turn during the qualification vibration test and the tether got broken. As a late design change, a reel lock was introduced. To avoid late design changes, subsystems have to be qualified separately before integration. In the case of the payload, vibration tests were envisaged but due to a lack of required test specifications they could not be accomplished.

To couple the tether rotation to the spacecraft spin, the tether mechanical attachment point should reside as far from the spacecraft center of mass as possible. The tether then resembles a rotating pendulum (rod attached to a spinning plate) maintaining its nominal orientation with respect to the spacecraft body. However, given the dimensions of the tether reel and one-unit CubeSat, this is hard to accomplish. Thus the ESTCube-1 tether was expected to oscillate in a cone of about 11° defined roughly by the dimensions of the end-mass opening. However, if the tether deflects more than about 20° , it would touch the conductive side panel. This would lead to wearing of the tether and even a short circuit. To avoid these risks, an additional grommet should be placed to the side panel opening. The grommet must be of antistatic material to avoid the triple junction with the plasma, high voltage, and nonconducting material. For ESTCube-1, tether movement also decreases the chance to image the end-mass as the end-mass is in the field of view only when the tether is near its nominal orientation, normal of the satellite side panel.

Another part of the E-sail payload is the high voltage (HV) supply system and the electron guns. On the HV supply side, the most conceptually difficult problem was managing which parts of the payload and the satellite are referenced to the HV source and

to the required electronics. Tests performed in orbit show that the HV supply board is operational. Developing the telemetry collection system of the HV board was a challenge due to the fact that the electrical ground level of the system floated with respect to the satellite ground, since ADCs were referenced to the satellite ground. In the future, we suggest putting telemetry collection electronics completely in the floating ground side and only using digital communication lines to interface them. This should also make the calibration of the system easier.

In the case of the electron guns, reliability remains the major concern. In our tests, one gun did not work at all (open circuit) and the other short circuited during tests (although it was confirmed to work before the short circuit). One option to improve the reliability would have been to test the whole HV and electron gun system together in the laboratory before the launch. In the time frame of ESTCube-1, this was not possible; also it would have required a rather complex vacuum chamber set-up. Another possible cause for problems was the fact that the electron guns were not covered during deployment and their surface might have gotten contaminated before their use (even a small particle could short circuit the system). This could be mitigated by using protective covers that would be removed in orbit or by increasing the distance between the cathode and the anode.

MANAGEMENT

TEAM LEADING

Having a visionary leading the team is key to successfully carrying out a technically challenging and long project, especially a project where team members must be regularly motivated by other than financial means. Team members must know and accept that an ultimate measure of success might come after years of development, after launching, and after successfully operating a satellite. However, it is up to leaders and the management team to define frequent milestones.

ADVISORY

Another key to success is having professional advisers to supervise and to review student work. In the case of ESTCube-1, professional advice was received in the fields of electrical engineering, radio frequency (RF) engineering, software engineering, and measurement sciences. Advisers from the amateur radio community helped to avoid many problems with practical communication and ground station set-up. Similarly, a system engineer should be a professional with a wide knowledge of involved engineering fields.

MANAGEMENT

Management of the ESTCube-1 project has been successful in carrying out some of its functions. For example, the team has access to various tools and services like the team collaboration software Confluence, the issue tracking system JIRA, the software versioning and revision control system SVN, Google services

(Mail, Documents, Hangouts, Calendar), the chat and video conference system HipChat, a remote desktop computer with access to specialized software (MATLAB, Simulink, SolidWorks), the PCB software EAGLE, etc. However, we have identified that the management team cannot consist of people whose main duties are other than management of the ESTCube-1 project. At least one person should respond to issues on a daily basis, especially during critical moments such as integration, testing, prelaunch servicing, and launch. Special attention should be paid to procurement handling. For management to be responsive, it should be supported financially.

The team should acknowledge the possibility of failures and be prepared for them. Management can play a significant role in leading the team to this understanding. Management must take into account that students can contribute only a limited amount of time to the project and that they can leave at any time.

In case the project schedule is accelerated, it should be agreed upon with external partners and subcontractors. The management team has to follow the development progress on a weekly basis in order to successfully schedule milestones and ultimately the launch.

We think that choosing a challenging scientific mission is better than a simple one (e.g., optical camera being the main payload) in an educational project. In that case, the project outcomes reach beyond the educational purposes and it works as an extra motivation. In the ESTCube team, some members have decided to continue their professional careers with the E-sail.

TEAM

A student team should be motivated and open. Students and the team will gain the most if members are able to work on various subsystems and different types of tasks, including leading, management, article writing, and outreach. Such approach will also help to avoid alienation between subsystem teams and teams in different geographical locations.

From the early stages, subsystem teams should discuss requirements as well as design choices and, most importantly, interfaces, for example, to not cause discrepancy between transmitting and receiving interfaces.

The team should have a clear understanding of the importance of the work and the priorities of its subtasks. Everybody in the team should understand and should be able to explain the mission and its requirements (Figure 4).

Opening all questions for a discussion can lead to better decisions, can contribute to team building and can serve as an informative media for updating on current progress and future plans. For example, all members should be involved in choosing the launch provider and in satellite operations.

Personal conflicts should be solved without hesitation and with the help of peers and leaders.

CONCLUSIONS

In this article, we presented an overview of the ESTCube-1 in-orbit experience and discuss the lessons learned. After updating



Figure 4.

Part of the ESTCube-1 team in a press conference dedicated for delivering the satellite to the launch provider.

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 the 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 the future, all sensors have to be calibrated before the launch better than 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 the future, the problem can be solved by preflight magnetic characterization of on-board materials.

Fourth, the 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 [34]. 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).

In addition to learning from the four major problems, we have discussed other lessons learned in the fields of system engineering, electrical engineering, mechanical engineering, software engineering, testing and measurements, as well as management.

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, provide full functionality, and optimize 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 the nanosatellite

community which is not strictly following space standards. We consider standards like the ECSS 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 using 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.

ACKNOWLEDGMENTS

The authors would like to thank everybody who has contributed to the development of ESTCube-1. The European Space Agency and the Ministry of Economic Affairs and Communication of Estonia have supported ESTCube-1 via the ESA PECS project “Technology demonstration for space debris mitigation and electric propulsion on ESTCube-1 student satellite.” We would like to thank all institutions that contributed to ESTCube-1 development. The research by Andris Slavinskis was supported by the European Social Fund’s Doctoral Studies and the Internationalization Program DoRa. The research on software engineering was supported by the European Regional Development Fund and the Investment and Development Agency of Latvia via the Latvian Electronic and Optical Equipment Competence Centre in Production Sector (agreement no. L-KC-11-0006) project number 2.9 “Receiving, validation and bootloading system of small satellite software as an enabler for safe and reliable satellite development and utilisation.” ◆

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