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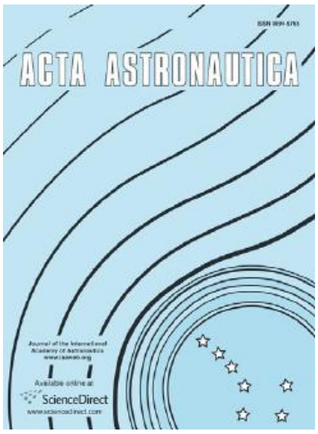

E-st@r-I experience: valuable knowledge for improving the e-st@r-II design

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Abstract

Many universities all over the world have now established hands-on education programs based on CubeSats. These small and cheap platforms are becoming more and more attractive also for other-than-educational missions, such as technology demonstration, science applications, and Earth observation. This new paradigm requires the development of adequate technology to increase CubeSat performance and mission reliability, because educationally-driven missions have often failed. In 2013 the ESA Education Office launched the *Fly Your Satellite! Programme* which aims at increasing CubeSat mission reliability through several actions: to improve design implementation, to define best practices for conducting the verification process, and to make the CubeSat community aware of the importance of verification. Within this framework, the CubeSat team at Politecnico di Torino developed the e-st@r-II CubeSat as follow-on of the e-st@r-I satellite, launched in 2012 on the VEGA Maiden Flight. E-st@r-I and e-st@r-II are both 1U satellites with educational and technology demonstration objectives: to give hands-on experience to university students and to test an active attitude determination and control system based on inertial and magnetic measurements with magnetic actuation. This paper describes the know-how gained thanks to the e-st@r-I mission, and how this heritage has been translated into the improvement of the new CubeSat in several areas and lifecycle phases. The CubeSat design has been reviewed to reduce the complexity of the assembly procedure and to deal with possible failures of the on-board computer, for example re-coding the software in the communications subsystem. New procedures have been designed and assessed for the verification campaign accordingly to ECSS rules and with the support of ESA specialists. Different operative modes have been implemented to handle some anomalies observed during the operations of the first satellite. A new version of the on-board software is one of the main modifications. In particular, the activation sequence of the satellite has been modified to have a stepwise switch-on of the satellite. In conclusion, the e-st@r-I experience has provided valuable lessons during its development, verification and on-orbit operations. This know-how has become crucial for the development of the e-st@r-II CubeSat as illustrated in this article.

Keywords

CubeSat; CubeSat verification; Spacecraft Design; Spacecraft lifecycle; Assembly Integration and Verification; Space Engineering Education

1 Introduction

The number of CubeSats in Earth orbit has increased since 2003, when six of them were deployed in the first multiple CubeSat launch [1]. The CubeSat standard was born within the academia with a pure educational purpose [2]. Low-cost and fast-delivery features were key parameters playing a crucial role for the standard definition. These factors led to a high number of CubeSats developed by universities in the first decade, mainly with education as primary objective; technology demonstration, scientific experiments and/or Earth observation have been secondary objectives for most of them [3]. However, in the last years space agencies and private companies recognised CubeSats as attractive space platforms to accomplish technology demonstration and scientific experiments, with a significant cost reduction and a relatively faster development time, from design to operations, compared with traditional larger-satellite missions.

CubeSats allow to build brand new architectures, which would be unattainable with bigger satellites. Constellations of nano-satellites in LEO are becoming a reality [4] [5], while the CubeSat community is exploring the possible applications of CubeSats for interplanetary missions [6] [7], and one unit for technology demonstration of future missions to the Moon has already been launched [8].

Despite the number of developed CubeSats increased substantially during the last years, around half of the total launched CubeSats have suffered a failure. Their mission's rate of success still is unacceptable in view of the opening possibilities for science and Earth observation missions.

A possible way to increase the rate of success is to evaluate previous missions gathering lessons learned, extract possible failures and drawbacks, and deduce possible improvements for future projects. This activity has been conducted by the CubeSat Team at Politecnico di Torino [9] after the launch of our first CubeSat, e-st@r-I.

The Team was founded at the beginning of 2006 with the objective of giving hands-on experience opportunities to engineering students in the area of space missions and systems design. The activities are focused on the development of CubeSats and small platforms for technology demonstration, and on the definition of testing methodologies and tools. Scientific missions are being studied in collaboration with international partners [10]. To conduct these activities, the Team works in the Systems and Technologies for Aerospace Research Laboratory (STARLab), located in the Department of Mechanical and Aerospace Engineering (DIMEAS).

Recent projects include the CubeSat e-st@r-I, which was designed, developed, tested and launched in 2012 as first Italian CubeSat in orbit. The second unit, e-st@r-II, has been developed within the ESA's *Fly Your Satellite!* programme. It has already conducted functional verifications at ambient condition, and it is waiting for an available slot at the environmental test facilities at ESTEC for thermal-vacuum and vibration testing. 3STAR, a triple-unit CubeSat integrating a GNSS remote sensing payload [11], is also being designed in the STARLab.

In the present paper the authors describe the results and lessons learned from past activities and how they have been turned into design implementation for current and future projects. In Section 2, an overview of the e-st@r programme at Politecnico di Torino and a description of the e-st@r-I CubeSat is provided. Lessons learned from the e-st@r-I project are detailed in Section 3. Section 4 describes how the team applied the previous experience to improve the e-st@r-II design, verification plan and execution, and in-orbit operations plan. Finally, conclusions are drawn in Section 5.

2 E-st@r programme

The e-st@r programme is the main activity led by the CubeSat Team. The programme has been set to give hands-on experience to university students, concurrently exploring the possibilities of novel space mission concepts and technology innovations. The first unit of the family, e-st@r-I, was a 1U CubeSat driven by educational and technology demonstration goals. The flight model is shown in Figure 1.

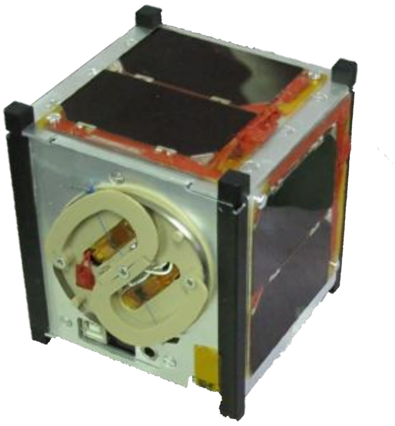


Figure 1: flight model of e-st@r-I CubeSat

The detailed description of the e-st@r-I platform is given in [12]. The satellite was manufactured using mainly COTS components. The payload was an active-attitude determination and control subsystem aimed at demonstrating autonomous attitude control capabilities based on magnetic actuation [13]. The satellite bus was equipped with a fully customized communications subsystem (COMSYS) based on the commercial transceiver BHX2 from Radiometrix [14] data sheet/url], while the antenna system was developed from scratch by the students [15]. The Electrical Power System (EPS) includes a Clyde Space Ltd distribution unit [16] and an in-house developed daughter-board, devoted to provide 1) mechanical and electrical connection between the batteries and the EPS motherboard, and 2) telemetry data to the bus.. The On-Board Computer (OBC) board was procured off-the-shelf from Pumpkin Inc. [17], while the software has been developed and tested in house by the team. The team also designed the structure, the manufacturing being provided by an external company. The launch of e-st@r-I took place on February 2012 from Centre Spatial Guyanais in Kourou, as part of the ESA's *Educational CubeSats on the VEGA Maiden Flight* programme.

A new launch opportunity to take place in mid-2013 was offered to the team a few weeks later. The available time between this communication and the expected launch date was too tight, and the development of a new CubeSat resulted unfeasible. Consequently, the team decided to develop e-st@r-II as follow-on of e-st@r-I, improving its design and verification activities in order to increase its chances of mission success. During the development of the satellite the launch was indefinitely postponed. In the meantime, ESA launched the *Fly Your Satellite!* programme [18]. The e-st@r-II project was selected as one of the six CubeSats to participate in the Phase 1 of the *FYS!* Programme. E-st@r-II successfully completed the first phase in October 2013. At the date this paper was submitted (November 2014), e-st@r-II is one of the three CubeSats that completed the development and functional testing in ambient conditions during Phase 2, and it will be subjected to environmental test campaign at ESTEC facilities soon.

3 LESSONS LEARNED

Lessons learned have been gathered during the whole e-st@r-I lifecycle. Depending on the type of information, each of them has been classified in three main groups: technical, management and educational aspects.

It is worth remarking that speaking about lessons learned is a common usage to think about negative aspects. However, not only drawbacks but also positive feedbacks have been obtained from e-st@r-I project.

3.1 Technical aspects

The CubeSat Team focused its attention mainly on the activities in the technical domain (i.e. CubeSat design, manufacture, verification and operations). Hence, it is in this framework that most of the lessons learned have been gathered.

Positive outcomes have been achieved thanks to the e-st@r-I project. The development of the CubeSat increased the space missions and systems design know-how of the team. This knowledge is essential for the development of future projects. In particular, the team developed a bus platform, completely tested on-ground and partially on-orbit. This platform (including structure, electrical harness, solar panels, antenna deployment system, OBC, COMSYS and EPS boards) represents the basis for the development of the next nano-satellites. Moreover the software development and integration are invaluable engineering skills acquired with the experience, and led the know-how to grow to the extent to make the difference between stacking together a series of components or assembling an integrated functional product.

A portable ground control station has also been designed, manufactured and tested by the students. It is composed by an omnidirectional antenna, transportable radio and TNC, and a laptop with in-house developed software. This station is a key element for the verification campaign due to its reduced weight and volume. It can be transported everywhere and it was fundamental to conduct functional verifications of the CubeSat. It also works as a backup of the main ground control station.

Finally, methodologies and tools for the CubeSat design and its assessment were also defined. The team developed software models and simulations that were crucial in the iteration processes of subsystems and system design. Two examples of them are the mathematical models of the solar cells and of the attitude determination and control system. Further, verifications were conducted on different models at component, subsystem and system levels.

Criticalities were observed specifically during Assembly, Integration and Verification (AIV), and operations phases. The AIV activities gave valuables hands-on experience to team members. In particular, students established verification plans, specifications and procedures based on ECSS standards, tailoring them whenever necessary on the basis of the project nature, i.e. low-cost and fast-delivery. However, a lack of experience in this domain was encountered in conducting these activities.

The main concern regarding the e-st@r-I assembly was the internal complexity of the satellite. The reduced volume of a 1U CubeSat introduced a challenge on the internal layout. Concretely, the satellite was characterised to accommodate a significant volume of wires (from the antenna, magnetorquers, solar panels and batteries) that was not properly been taken into account during the design. Moreover, the internal layout complexity was increased by the installation of the magnetorquers inside the structure. Once the problem was observed, a possible reduction of the number of wires was evaluated. However, adopting such solution would have implied an in-depth re-design of the system that was unfeasible due to time and cost constraints. A precise cables layout was then studied and established using the e-st@r-I CAD model. This solution, even if not optimal, allowed to partially reducing the assembly complexity of the satellite.

As far as the functional and environmental verifications are concerned, they were mainly conducted through analysis and test. In particular, Hardware-In-The-Loop (HIL) method was applied to verify full satellite functionality, simulating space environment and dynamics that could not be reproduced on ground, due to unavailability of some resources at the STARLab (e.g. sun simulator) [19]. E-st@r-I models at system level (i.e. qualification and acceptance models) successfully passed the required functional and environmental tests.

Nevertheless, some drawbacks were observed in their planning and execution. The low-cost constraint notably influences the environmental test campaign, which usually is one of the most expensive phases of a CubeSat project, together with launch cost. The team was not able to afford the cost of a complete ECSS-compliant environmental verification campaign. Hence, also for verification execution, ECSS standards were tailored following a good-sensitive engineering approach in accordance with ESA programme requirements in which e-st@r-I project was involved. In particular, only sinusoidal and random vibrations, followed by thermal-vacuum cycling (TVC) tests were conducted on qualification and acceptance models.

Vibration tests were executed at Politecnico di Torino with the support of laboratory technicians. The use of a novel shaker, together with the students' reduced experience on environmental tests execution, led to an added difficulty for that test. Moreover, dry-testing using a satellite's mass dummy was required to augment the knowledge about vibration test execution before conducting the tests on the qualification and acceptance models.

It is well known that, among environmental verifications, the TVC test is one of the most expensive. The STARLab is not equipped with a thermal-vacuum (TV) chamber. The e-st@r-I TVC tests (both at qualification and acceptance levels) were conducted at the Aerospace Engineering Department of Politecnico di Milano thanks to an agreement between the two universities. However, only two complete thermo-vacuum cycles (hot-cold, cold-hot) were conducted due to TV chamber availability and time constraints. During the test planning a second problem was identified, i.e. the necessity to activate/deactivate the satellite during TVC test in order to conduct functional verifications. To cope with this late-discovered issue, it was decided to disassemble and replace the deployment switch (DS) with two wires that were taken outside the TV chamber through electrical connector. The activation/deactivation of the satellite was manually controlled from the exterior of the chamber. Unfortunately, this activity implied the necessity of re-assemble the DS after environmental verifications. The desire to measure internal temperature during the TVC test also emerged late in the development process, when the satellite was already assembled. Internal temperatures were then measured through the on-board temperature sensors devoted to gather temperature data during orbit operations, limiting measurements to when the satellite was active. Moreover, it has not been possible to correlate real temperatures with those measured by the on-board sensors, and verify their correct functionality.

Despite all the previous drawbacks, the acceptance model passed the functional and environmental verifications and became the flight unit, which was completely operative when integrated in the deployer.

Regarding operations in orbit, the first contact with the satellite was established one day after launch. Nonetheless, the contact was intermittent and the telemetry packets have not been completely decoded.

The Team conducted a root cause analysis to identify the origin of the partial failure on communications. Two possible failure causes were identified: 1) the antenna remained folded, 2) low batteries state-of-charge occurred. The antenna deployment system was widely tested on-ground and a mechanical failure was excluded. Should a failure on this system had occurred, it could have been due to a very low battery state-of-charge. Batteries state-of-charge was identified as the most possible cause of the communication problem. The analysis was then extended to investigate the origin of the low state-of-charge of the batteries. The team suspected that the satellite could be released from the deployer with a spin rate higher than that assumed during the design phase. Besides, the activation sequence of the satellite was designed in a way that, just after the insertion in orbit, the CubeSat started a de-tumbling phase to stabilise the satellite, leading to high electrical power consumption. Moreover, the satellite remained stored inside the deployer for approximately three months before launch, without batteries recharge. This led to the possibility that the batteries were not fully charged when the satellite was launched. Then, the combination of these three factors: 1) Battery not fully charged when e-st@r-I was launched, 2) De-tumbling phase just after deployment and 3) Unexpected high tumbling rate, led to a fast battery depleting from a non-complete state-of-charge and hence, to the impossibility to receive radiofrequency signal strongly enough to decode the telemetry packet.

To recover from the failure, the operative mode of the satellite was switched from ground from basic mode (all subsystems active) to save energy mode (only vital functions carried out). The link was never recovered and few months later, the CubeSat Team declared the cessation of emissions and mission conclusion.

Lesson learned	Description
#1	Establishing a permanent space project in universities increases the space mission and systems design know-how of students and professors. Experience is valuable for future projects
#2	The internal components disposition shall be carefully assessed. It is suggested to reduce the amount of wires inside the satellite. Prefer connectors mounted on the boards instead of free-wires
#3	Execute environmental verification with the support of experts. If not possible, operator shall follow a training at least before the execution of the test on the flight system
#4	Implement in the design the possibility to switch-on/off the satellite by means of ground support equipment and not only mechanically through deployment switch

#5	Plan thermocouples installation on the proper PCBs, that will be devoted to measure temperature during environmental tests
#6	Implement a step-by-step activation of the satellite in orbit in order to first establish and stabilise the communication link, second assess the status of all subsystems, and then activate the payload
#7	Use batteries with low or zero self-discharge rate, because it is possible that the satellite remains stowed inside the deployer for long periods without the possibility to be recharged
#8	Implement an operative mode in which the satellite uses as less energy as possible to allow batteries recharge

Table 1: Technical lessons learned

3.2 Management aspects

The first issue encountered in the area of project management was related to the problem of knowledge transfer. A frequent turnover is the consequence of the high number of students involved in the project and the limited time for which they remain into the team for completing their thesis or collaboration activity. This point was taken into account highlighting the importance of properly writing documentation since the very beginning phases of the project. Students usually do not like paperwork, but systematically planning internal reports, logbooks and proper technical documentation is the only way to keep track of project advancements and to help future person involved with guidelines as legacy of the work done. At the end of e-st@r-I development, the project design was well documented, mainly for the part concerning the CubeSat design. The reason also resides in the fact that most of the theses addressed this part of the project lifecycle.

On the other hand, the same observation does not apply to the Assembly, Integration and Verification (AIV) process. Not all verifications were properly planned and documented. The consequence of the lack of documentation of this phase was that some results were lost or forgotten, leading to the need of performing some verification again. As an example of this problem, during e-st@r-I design, the antenna deployment system was tested at subsystem level. The system functionality was successfully verified, however the results were not written down and after a few weeks the test was required to be conducted again to verify again the correct functionality of this system.

Documenting the project is strongly related to information exchange among all team members and to the role of project manager. The project manager of the team acts as coordinator of the project activities, establishing the schedule and imposing milestones. Each team member should deliver a progress report of the work on a regular basis and specifically close to the design reviews. As far as schedule is concerned, since the work of all members is interrelated, the delay on one delivery will probably delay the entire project. For this reason, the design process has been divided in different small tasks that were easier to supervise. For example, the development of payload was allocated to a sub-group in which each member developed part of the subsystem (i.e. magnetorquers design and manufacturing, hardware design and software design). This approach helps in maintaining a homogeneous evolution of the project, avoiding the development of one subsystem at a different level of advancement with respect to another.

The third management issue regards the difficulty to conduct bureaucracy activities with governmental and international organisations. Usually CubeSat developers focus their attention in the technical design while disregard administrative duties. For instance, in the case of e-st@r-I, the frequency coordination and registration to the International Amateur Radio Union (IARU) and to the International Telecommunication Union (ITU) were not completely smooth. Taking into account that by the nature of the project e-st@r-I communicated in radio-amateur frequency, its frequency coordination with the IARU was easier than the ITU registration. The required information to proceed with this latter activity are established for classical space projects where great part of mission data are well known during the design phase (e.g. launcher, date of launch, orbit parameters, etc.), whereas, most of these information are not known for a CubeSat project until few months before the launch. This drawback led to a very late frequency registration to the ITU. Nevertheless, the team had the opportunity to learn the procedure to apply for the frequency registration, and this know-how revealed to be highly useful in accelerating the registration time for the subsequent project. Table 2 summarizes the lessons learned described above.

Lesson learned	Description
#9	Importance to produce adequate documentation to allow knowledge transfer among team members and to a correct description of the project design
#10	Importance to establish a precise schedule, with well-defined milestones and tasks to be completed to guarantee no/low delays
#11	Difficulties to communicate with national and international organisations. It could be useful to be informed, since the beginning of the project, of the national and international legal requirements and to be in contact with related organisations. Inform them of activities that are being conducted and any important changes (e.g. expected date of launch even if not confirmed) is key to avoiding bureaucracy delays

Table 2: Management lessons learned

3.3 Educational aspects

E-st@r-I has been a complete success from the educational point of view. More than hundred students participated in a multidisciplinary project within an international framework. Everyone actively contributed to the development of the satellite during practical lessons. The team is composed mainly by aerospace engineering students, but also mechanical, electronics, automotive, computer science and management engineering students were involved. All of them performed hands-on practice training with theoretical and laboratory exercises to design, develop, manufacture and test the CubeSat. Most took advantage of the participation in the team to conduct their M.Sc. and/or B.Sc. thesis, and some of them became effective members of the CubeSat Team after graduation.

Students had the opportunity to attend national and international workshops and conferences, (e.g. the IAC, 4S Symposium, ECS, Interplanetary Small Satellites) thanks to a project funding provided by Politecnico di Torino [20]. During these conferences and workshops, students could interact and exchange experiences and knowledge with their colleagues and with space-engineering specialists. Table 3 depicts the lessons learned from the educational point of view.

Lesson learned	Description
#12	University CubeSat projects are crucial to give hands-on experience to students in the technical and management skills
#13	CubeSats design and development are the most requested topics for M.Sc. and B.Sc. theses
#14	Students consider absolutely positive their participation in international events which allow them to grow personally and professionally

Table 3: Educational lessons learned

4 APPLICATION OF THE LESSONS LEARNED

E-st@r-I lessons learned represented a valuable knowledge to apply on future CubeSat projects. First direct application was conducted on e-st@r-II CubeSat.

Regarding the management aspects, the project manager role is still active in the team. This person continues to coordinate the team activities, enabling a smooth information exchange among team members, fixing milestones and assessing the progress of the activities. He/She also encourages students to produce the necessary documentation to assure knowledge-transfer. As far as the interaction with international organisations is concerned, the ITU proposed a time-reduced schedule for frequency registration. The new schedule fits better the purpose of a CubeSat project and appears to be feasible.

Going in-depth on the e-st@r-II technical aspects, substantial modifications have been implemented to fill the gaps identified in the e-st@r-I CubeSat, leading to design improvement, verifications optimisation, and establishment of a detailed plan for operations.

Design modifications were assessed and applied, both on the hardware and the software. An assessment of possible improvements was done to establish what modifications were realistically easy to be implemented taking into account two main drivers: 1) reduced development time until expected launch date, and 2) limited design modifications to not deviate significantly from the e-st@r-I design.

The first problem faced by the team was the assembly and integration complexity. The position of magnetorquers in the interior of the CubeSat was critical due to the small distance between the boards edges and the structure. Hence, the team decided to install the magnetorquers on the external part of the structure, between the solar panels and the structure, as shown in Figure 2. To conduct this modification, the attachment of the solar panels has been re-designed. In e-st@r-I, the solar panels were glued and screwed on the structure faces. In detail, the solar panels have been screwed to the structure at a distance of few millimetres (assured by means of

metallic spacers), to accommodate the magnetorquers. Furthermore, this layout allows the disassembly of the solar panels if required (e.g. to conduct maintenance activities after verification campaign, if needed).
As stated before, the key factor that led to e-st@r-I failures was probably the high consumption during the detumbling phase. Hence, the team conducted the re-design with consumption reduction as principal target. Increase of antenna deployment system efficiency was conducted to reduce power consumption. The system is composed by a dipole antenna folded on a support by means of a fishing line [15]. The nylon wire is then burned by means of resistors and the antenna is unfolded. The modification regards the resistors. The twisted tungsten wire used in e-st@r-I has been replaced by two SMD resistors with lower consumption, as shown in Figure 3. Moreover, the fishing line model has been changed to another with similar mechanical properties but smaller diameter. These changes allow increasing the chances to burn the wire for the antenna deployment and to reduce electrical consumption.

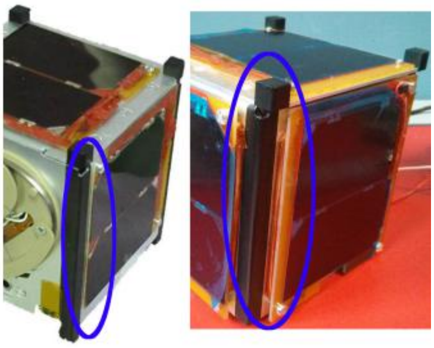
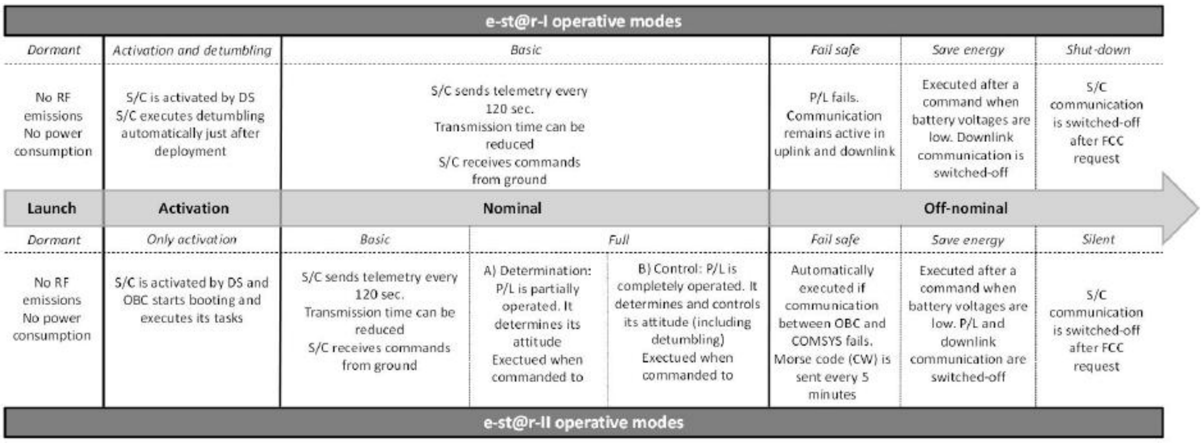


Figure 2: Comparison between e-st@r-I (left) and e-st@r-II (right) solar panel attachment and magnetorquers position

A third modification regards the electrical power storage. E-st@r-I batteries self-discharge was individuated as a cause of their possible low state-of-charge when inserted in-orbit. To reduce this value and guarantee higher performances, Li-Po batteries procured from a space company have been installed on e-st@r-II. These batteries, together with the EPS boards (i.e. both motherboard and daughter board) from the same supplier, guarantee zero self-discharge rate when the Remove Before Flight (RBF) switch is inserted in the satellite, and a negligible value without RBF.

Figure 3: Comparison between e-st@r-I (left) and e-st@r-II (right) antenna deployment system

As far as the power consumption is concerned, with the constraint of reducing subsystems consumption without conducting an extreme re-design, new operative modes have been implemented. A comparison between e-st@r-I and e-st@r-II operative modes is shown in Figure 4.



e-st@r-I operative modes							
Dormant	*Activation and detumbling*	*Basic*			*Fail safe*	*Save energy*	*Shut-down*
No RF emissions No power consumption	S/C is activated by DS S/C executes detumbling automatically just after deployment	S/C sends telemetry every 120 sec. Transmission time can be reduced S/C receives commands from ground			P/L fails. Communication remains active in uplink and downlink	Executed after a command when battery voltages are low. Downlink communication is switched-off	S/C communication is switched-off after FCC request
Launch	**Activation**	**Nominal**			**Off-nominal**		
Dormant	*Only activation*	*Basic*	*Full*		*Fail safe*	*Save energy*	*Silent*
No RF emissions No power consumption	S/C is activated by DS and OBC starts booting and executes its tasks	S/C sends telemetry every 120 sec. Transmission time can be reduced S/C receives commands from ground	A) Determination: P/L is partially operated. It determines its attitude Exectued when commanded to	B) Control: P/L is completely operated. It determines and controls its attitude (including detumbling) Exectued when commanded to	Automatically executed if communication between OBC and COMSYS fails. Morse code (CW) is sent every 5 minutes	Executed after a command when battery voltages are low. P/L and downlink communication are switched-off	S/C communication is switched-off after FCC request
e-st@r-II operative modes							

Figure 4: Comparison between e-st@r-I and e-st@r-II operative modes

The main change in the operative modes regards the activation of the satellite. The *de-tumbling mode* is not any longer automatically executed in e-st@r-II as it was in e-st@r-I. Instead, after the deployment, only the OBC is activated. The OBC starts booting and after the necessary checks are passed, the antenna is deployed. Then, the ground operators wait until they are able to establish a stable communication link and receive telemetry packets. Telemetry will be then analysed and, once the assessment of correct functionality of all on-board subsystems is conducted, ground operators will execute the activation of the payload by means of a telecommand. Furthermore, the activation of the payload will be conducted in two steps: first, the attitude determination function is started by activating the Inertial Measurement Unit (IMU); second, the attitude control is activated and the CubeSat starts controlling the attitude through magnetorquers. This main modification allows the operator to increase ground authority over the satellite's functionalities.

The second change is about the fail-safe operative mode. In the e-st@r-II CubeSat, the fail-safe mode is an off-nominal mode used if communication between OBC and COMSYS fails. A new automatic communication protocol has been implemented as a backup of the main one, which is conducted with KISS AX.25 protocol. The secondary communication link automatically sends *e-st@r-II* string in CW mode every 5 minutes. However, this last modification could led to a contradiction with the requirement derived from the International Telecommunication Union radio regulation (article 22, section 1): *the CubeSat shall be fitted with devices to ensure immediate cessation of their radio emissions by telecommand, whenever such cessation is required under the provision of FCC* [21]. The nominal implemented telecommand that guarantees the transmission cessation, if required from ground, is executed by the OBC. However, if the communication between OBC and COMSYS fails, this command would result useless. To overcome this problem, another telecommand has been implemented. In this case, it will be processed by the COMSYS PIC16 microprocessor, so that the requirement is satisfied even in the occurrence that the OBC subsystem fails.

Other changes implemented in the e-st@r-II CubeSat derive from lessons learned gathered during the verification campaign carried out on the e-st@r-I platform. It has been provided to install internal thermocouples on the electronic boards of the new CubeSat so that it will be possible to measure internal temperatures during the TVC test. Specifically, four thermocouples have been bonded by means of silicon adhesive near critical components. The critical components were individuated to be the batteries, the EPS board, the radio module and the IMU. These items have the most stringent operative ranges of temperature. In particular, the operative cold temperature is constrained by the IMU while the hot temperature is constrained by the batteries. Hence, during TVC test, the thermocouple installed beside the IMU will be used as Temperature Reference Point (TRP) for cold temperature and the one near batteries as TRP for hot temperature. The second issue observed during the environmental tests of the first CubeSat was the need to activate the satellite to conduct functional tests during hot and cold plateaux of the TVC test. The e-st@r-II design does not allow to switch-on and switch-off the satellite through electrical ground support equipment, as for its parent satellite: the only way to activate/deactivate the satellite is by means of the deployment switch (DS). Hence, a relay has been installed in parallel to the DS. In this way, it is possible to control the satellite activation through electric command from the outside of the TV chamber.

5 CONCLUSIONS

CubeSats are evolving from pure educational instruments to real science and/or service tools. Apart from the technological challenges, reliability of CubeSats is a concern for future operative missions. The reliability of the missions conducted so far is poor but can be increased to a certain extent by implementing a series of actions in several domains. One of this is to leverage the value of experience to increase the know-how of the developing teams. Learning from past projects to improve CubeSats design and increase the mission rate of success is especially crucial for academic projects. In this context, the CubeSat Team at Politecnico di Torino made a thorough analysis of the first mission (e-st@r-I) from the CubeSat design, to the manufacturing and verification processes, to mission operations, and implemented corrective actions to the new CubeSat, e-st@r-II, according to the results of these analyses.

Valuable lessons learned were gathered during all e-st@r-I lifecycle, and have been classified in three different categories: technical, management and educational. The lessons learned have been applied to the development of the second CubeSat (e-st@r-II) that is now in the acceptance process for launch by ESA.

Apart from the lessons learned that are specifically applicable to the e-st@r programme, some general conclusions can be drawn and can be of help for future CubeSat developments:

1. The design must take into account the whole system lifecycle, and not only the launch and orbit phases. This is a common mistake in university-led projects, as we are less familiar with the development process or the post-mission analysis, while we are usually more focused on the final mission and payload performance. The failure causes of most CubeSat missions are not known. This can be due in part to the lack of data from the CubeSat itself. Implementing FDIR systems of CubeSats is feasible, but very few platforms have been provided with such a system so far. Moreover, as in the case of e-st@r-I, the testing phase is sometimes overlooked. Designing the platform for testing would be mandatory in order to avoid risky and costly recovery actions. Operations is also another phase that needs to be addressed and planned carefully.
2. Documentation of the project is of paramount importance for project success. The scarcity of data is due to the real lack of information available from the system (as said above), but also to the poor documentation produced. New ways to conduct and document the design could be implemented for CubeSat projects, and they can be used as test bed for bigger systems (such as, for example, Model Based Systems Engineering methodologies for system requirements definition and traceability). Effective project documentation can help overcoming the typical quick turnover at universities, but can also support the productivity of commercial space activity.
3. Verification and Testing are crucial to mission success. This is especially true for CubeSats as it is not possible to pursue reliability increase by implementing traditional strategies such as redundancy. Improving the whole AIV/T process can represent a way to overcome the intrinsic limits of nanosatellites imposed by their size and mass. On the other hand, it is also important not to over-test these tiny systems, as they cannot be as “strong” as traditional large platforms (unless we accept to lose main CubeSat benefits such as the low cost and fast delivery). The availability of procedures and regulations specifically targeted to nanosatellites AIV/T could support the improvement in the area of nanosatellite quality assurance.
4. The positive interaction among students and professors on one side, and experts from the industry and the agencies on the other is important not only for mission success, but above all for the benefit of future space activities in general. Universities are (or should be) the cradle for new ideas and inventions, but they need to be supported in the process of making a real mission by those people who have experience and know-how. On the other hand, the industry and the agencies would benefit the fresh air and creativity from the students and researchers to think out of the box and find innovative solutions for new challenging problems.
5. Hands-on programmes are fundamental for students’ education. The value is well beyond the technical domain. For engineering students is not usual to deal with programmatic aspects, cost budget and schedule constraints, team working dynamics, and so on. The participation in international programmes helps the students to open their mind and prepare them for the professional life.

Exploiting the lessons learned and leveraging the heritage of past CubeSat projects could be a key element to increase mission success while maintaining the CubeSat’s distinctive features of low cost and fast delivery. This paper is intended to share our experience in the development of the e-st@r platforms with other universities and the other stakeholders such as the industry and space agencies, and to show how university projects can contribute to the advance of science and technology while educating students.

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