Lessons learned of a systematic approach for the e-st@r-II CubeSat environmental test campaign

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LESSONS LEARNED OF A SYSTEMATIC APPROACH FOR THE E-ST@R-II CUBESAT ENVIRONMENTAL TEST CAMPAIGN

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CubeSat-standard satellites have become more and more popular during last years. Education objectives, mainly pursued in the first CubeSat projects, have given way to the design of missions with other-than-education objectives, like Earth observation and technology demonstration. These new objectives require the development of appropriate technology. Moreover, is necessary to ensure a certain level of reliability, because education-driven mission often failed. In 2013 the ESA Education Office launched the Fly Your Satellite! Initiative devoted to provide six university teams with the support of ESA specialists for the verification phase of their CubeSats. Within this framework, the CubeSat Team at Politecnico di Torino developed the e-st@r-II CubeSat. E-st@r-II is a 1U satellite with educational and technology demonstration objectives: to give hands-on experience to university students; to demonstrate the capability of autonomous attitude determination and control, through the design, development and test in orbit of an A-ADCS; and to test in orbit COTS technology and in-house developed hardware and software (as UHF communication subsystem and software for on-board and data handling subsystem). The paper describes the application of a systematic approach to the definition, planning and execution of environmental test campaign of e-st@r-II CubeSat and the gathered lessons learned. The approach is based on procedures designed and assessed for the vibrations and thermal-vacuum cycling tests of a CubeSat accordingly to ECSS rules and with the support of ESA specialists. Concretely, ECSS application, tailored to fit a CubeSat project, allowed to define a test plan oriented to reduce verification duration and cost, which lead to a lean verification execution. Moreover, the interaction with ESA thermal and mechanical experts represented a valuable aid to increase the Team know-how and to improve and optimise the verification plan and its execution. The planning encompasses the analysis of the requirements to be verified that have been gathered in such a way that the tests duration has been reduced. The required tests, like thermal-vacuum cycling and bake-out tests, have been combined in order to speed-up the verification campaign. The tests outputs shown that the satellite is able to withstand launch and space environment. Furthermore, satellite expected functionalities have been tested and verified when the CubeSat is subjected to space environment, in terms of temperature and vacuum conditions. In conclusion, it has been successfully demonstrated that the proposed approach allows executing a lean CubeSat verification campaign against environmental requirements following a systematic approach based on ECSS.

I. INTRODUCTION

The use of small-satellites as platforms for fast-access to space with a relatively low cost has increased in the last years [1]. In particular, many universities in the world have now permanent hands-on education programs based on CubeSats, as at Politecnico di Torino [2]. Small and cheap platforms are becoming more and more attractive also for other-than-educational missions, such as for example technology demonstration, Earth observation [3] and science application [4]. These new objectives require the development of adequate technology to increase CubeSat performances. Furthermore, it is necessary to improve mission reliability. In fact, the number of developed CubeSat during last years is increasing, as well as the complexity of objectives. However, CubeSats' mission rate of success remains unacceptable for these new objectives [5]. Generally speaking, more than half of CubeSats have suffered a failure. This number increases until three-quarters if unknown status of CubeSats are considered as failures.

Authors have identified some possible activities to improve reliability:

- *guidelines for CubeSats life-cycle activities*, that is actions to be conducted by CubeSat developers during all phases of the project, so a fault prevention technique
- *redundancies at system level*, i.e. new mission architectures that can lead to achieve mission objectives even if reliability of each CubeSat of the constellation remains lower than conventional satellites. It is based on fault tolerance technique
- *verification-standards tailoring*, so fault removal technique applies.

The paper focuses on the last activity, which was applied to conduct the environmental test campaign of e-st@r-II CubeSat, designed and developed entirely by students at Politecnico di Torino. Traditional satellites projects are usually based on a distribution of resources in terms of cost, time and personnel to each of the space program development phases (i.e. design, development, integration and verification). On the contrary, CubeSats projects usually accelerate design and development to save time, manpower, and financial resources for Assembly, Integration and Verification (AIV) phase.

In order to correctly perform the verification campaign, the use of standards and procedures is crucial to carry out it in a systematic way. However, most of procedures are difficult to be applied on small-satellites projects, and specially to CubeSat projects. Standards key-points for verification activities have been identified and European Cooperation for Space Standardization (ECSS) standards have been adapted to fit CubeSats projects taking into account their main drivers (i.e. low cost and fast delivery).

II. E-ST@R-II CUBESAT

E-st@r-II is a 1U CubeSat equipped with an Active-Attitude Determination and Control System (A-ADCS) based on magnetic actuation and with innovative algorithms as regards the determination [6]. The commissioning phase foresees that the payload is deactivated leaving the satellite in its free tumbling motion, without any attitude stabilization. The A-ADCS starts its work when commanded from Ground Control Station (GCS) by detumbling angular velocities. The project was selected by ESA Education Office for "Fly Your Satellite!" initiative [7], which is now at the end of Phase 2 "Test your Satellite".

The stowed configuration of e-st@r-II is an aluminium-alloy cube-shaped box, 100 mm per side, with 5 out of the 6 faces occupied by solar panels. The sixth external surface hosts the antenna system and the access ports for ground operations. After the satellite activation, the antenna system deploys two arms of the dipole that remain attached to the CubeSat structure.

E-st@r-II is actually derived from the e-st@r-I design [8-9]. E-st@r-I Flight Module was built after the corresponding Engineering Qualification Model was successfully verified. E-st@r-I was selected by ESA and was injected into orbit during the Vega Maiden Flight held on February 13th 2012. For e-st@r-II a protoflight approach has been adopted, relying on lessons learned and the experience gathered with e-st@r-I.

II.I Fly Your Satellite! Program

The 'Fly Your Satellite!' programme is an exciting initiative from the Education and Knowledge Management Office of the European Space Agency (ESA) focused on CubeSat projects run by university students. The programme is one of the several hands-on opportunities offered by ESA Education and provides experience of the full life-cycle of a space project. ESA provides the CubeSat teams with direct support from ESA technical specialists and access to state-of-the-art environmental test facilities. ESA will also procure a launch opportunity for selected CubeSat(s). More information is available on the following website: http://www.esa.int/education/flyyoursatellite.

III. STANDARDS TAILORING

CubeSats reliability could be increased, of course, testing the whole system's functionality in all possible operational conditions that will face during its life-cycle. This approach, however, clashes with reality, usually characterized by a very limited budget, as for e-st@r-II CubeSat. Due to time constraints, limited cost budget and quick schedule, it is rare that component are tested at equipment level; the functional and operational tests are mainly performed at subsystem level and environmental tests are conducted only at system level.

To conduct such verifications, CubeSat developers normally try to follow international standards that, however, have been stated for large-conventional satellites projects, with longer time schedules and higher budget. Hence, a tailoring of these standards is required to allow their application to CubeSat projects.

For e-st@r-II, ECSS standards were studied and tailored to adapt them to the project. The ECSS standards are normative documents that encompass a comprehensive set of documents addressing all essential aspects of the three major space project branches for the successful implementation of space programmes and projects, i.e., engineering, project management and product assurance.

Verification process guidelines are reported in ECSS-E-ST-10-02C, and required tests in ECSS-E-ST-10-03C. In particular:

- ECSS-E-ST-10-02C establishes the requirements for the verification of a space system product, defines the fundamental concepts of the verification process and the criteria for defining the verification strategy, and specifies the requirements for the implementation of the verification programme. It includes also the list of the expected documentation

- ECSS-E-ST-10-03C addresses the requirements for performing verification by testing of space segment elements and space segment equipment on ground prior to launch. The document is applicable for tests performed on qualification models, flight models (tested at acceptance level) and protoflight models.

A study on the content of ECSS-E-ST-10-03C was conducted to assess the minimum required tests to be conducted on e-st@r-II CubeSat at system level and, specially, to propose an optimised lean test schedule to obtain a time and cost effective verification phase.

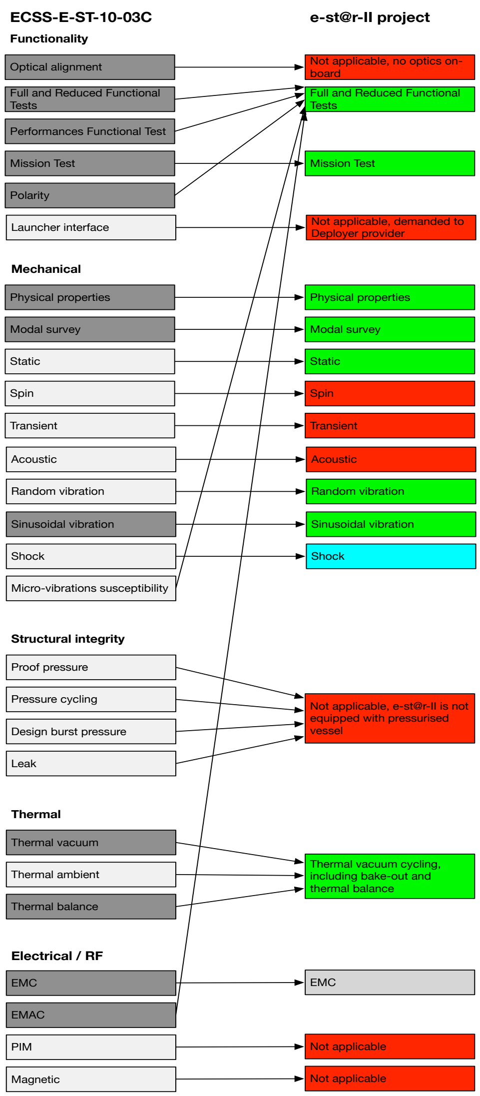

Fig. I: ECSS vs verification approach for e-st@r-II: in dark grey the ECSS required verifications; in light grey the ECSS optional ones; in red the verifications not required for e-st@r-II; in green the performed ones; and in cyan the one performed by analysis.

Fig. I shows the whole required and optional tests as defined in the ECSS standard on the left side. On the right side, the verification approach for e-st@r-II is depicted: it is based on the combinations of some verifications. In fact, several full and reduced functional test procedures are planned to include more than one verification (i.e. performance functional test, micro-vibrations susceptibility and polarity). Moreover, a single thermal test includes the three ECSS thermal verifications plus bake-out.

IV. ENVIRONMENTAL TEST CAMPAIGN

The environmental verifications at system level consists of evaluating through test and analysis the capability of the CubeSat to withstand launch and space environment in terms of mechanical, temperature and pressure loads. Within the "Fly Your Satellite!" initiative, ESA Education Office provided not only the facilities and test operators to conduct the tests, but also the support of ESA experts. Their contribution was very relevant because of their knowledge and experience, first in the analysis that preceded the tests and which provided the basis for testing, and then in the verification planning and test setup definition.

In accordance with ESA it was decided to verify:

- *Launch environment* (i.e. quasi-static loads, random vibrations and sinusoidal vibrations) by means of test
- *Thermal environment* by means first of analysis performed with self-developed Matlab code and ESATAN software, and then of test
- *Pressure environment* by means of test.

The environmental tests require that the functionalities and the operations of the satellite are checked before, sometimes during, and after each main activity foreseen by the test (e.g. after the assembly of the satellite on the shaker or in the thermal-vacuum chamber). For this purpose, also health-check activities and functional tests were planned and performed.

Taking into account the previous mentioned limitation in terms of schedule and costs, the tests were planned in order to be less time consuming and cheap. For this reason, two main groups of test were defined: *Vibrations test*, which includes the mechanical tests, and *Thermal Vacuum Cycling test* (TVC), which includes thermal and pressure environment tests.

Tests were planned and then executed following the same order the satellite will experience during the launch, i.e. first vibrations and then thermal-vacuum environment. A flow-chart that depicts the environmental tests campaign is presented in Fig. II: the main activities are reported, including shipments and inspections.

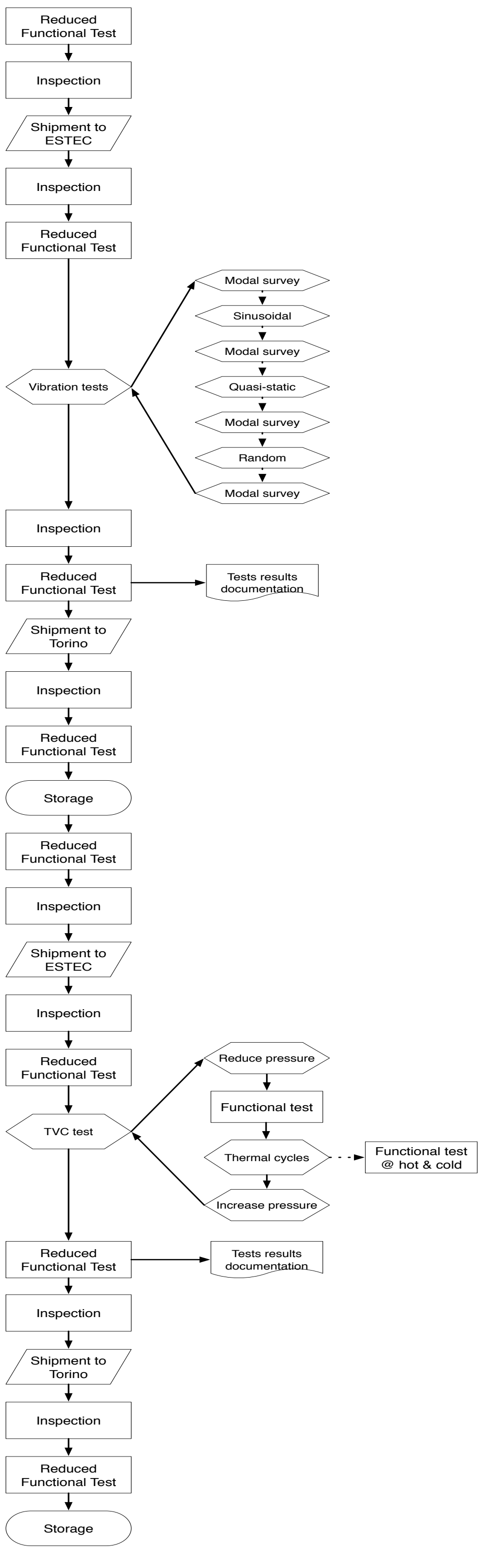

Fig. II: Environmental tests campaign activities flow-chart.

IV.I Vibrations

The vibration tests encompassed the following solicitations:

- modal survey (resonance search) was performed before and after each vibration test to determine the resonance frequencies and to evaluate the CubeSat equipment integrity. A pure low-amplitude sinusoidal signal is input into the vibration table for resonance search. The low-amplitude sinusoidal sign up logarithmically from 50-2000 Hz and lasts approximately three minutes for a protoflight approach
- sinusoidal vibrations simulate the low-frequency sinusoidal dynamic loads. The sinusoidal tests were performed to verify the spacecraft structure dimensioning under the flight limit loads. A pure sinusoidal signal is input into the vibration table for the range of frequencies defined by the Team in accordance with ESA (see Table I). Sine tests sweep up logarithmically from 5 to 125 Hz. On the shaker, the sinusoidal enforced acceleration is applied to a structure with a sweep rate of four octaves/min; this quantity is the velocity at which the frequency domain is scanned

Frequency [Hz]	Amplitude [g]
5 – 100	2.5
100 – 125	1.25
Sweep rate	**4 oct/min**

Table I: Sine vibration profile.

- quasi-static acceleration simulates an equivalent static acceleration for a combination of spacecraft launch, steady-state longitudinal and lateral accelerations, including corresponding low frequency transients. The applied level is 10.8 g.

Quasi-static	Protoflight
Amplitude	10.8 g

Table II: Quasi-static acceleration level.

- random vibrations are used to qualify spacecraft parts. Random vibration tests are used to qualify flight hardware because they closely imitate the real launch environment by simultaneously exciting multiple frequencies. The duration of the random test for acceptance is 120 seconds. The input during a random test consists of a mix of frequencies between 20 Hz and 2000 Hz. The input Power Spectral Density (PSD) is controlled and measured with the aid of one or more reference accelerometers.

Frequency [Hz]	Qualification levels [g^2/Hz]
20	0.01125
130	0.05625
800	0.05625
2000	0.015
G_{RMS}	**8.683**
Duration	**2 min/axis**

Table III: Random vibrations profile.

The vibration test setup required that several accelerometers were installed on the shaker and only one was positioned on the –X face of the satellite to appreciate the behaviour of the satellite (Fig. III). No internal accelerometers were foreseen during the design of the satellite because it was not adopted a verification-oriented design approach, nor were installed before the final integration, since it would be impossible to remove them without invalidating the test just performed.

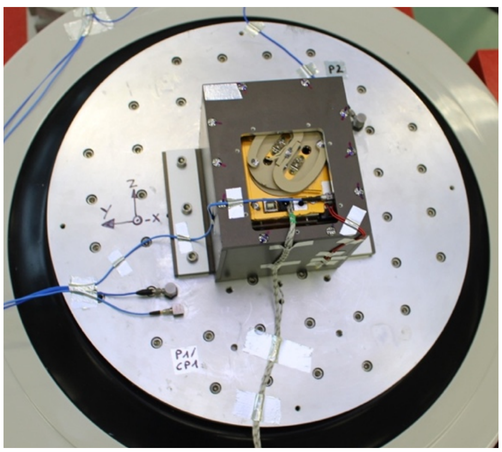

Fig. III: Satellite installed on the electro-dynamic shaker.

IV.II Thermal Vacuum Cycling

The TVC test consisted in four cycles of hot/cold temperatures under vacuum condition; in addition, for e-st@r-II, the hot plateaux were maintained for longer time to conduct bake-out test, as shown in Fig. IV. Bake-out was added to TVC and planned to be conducted during weekends, to take advantage of non-working hours. In fact, some components of e-st@r-II are not space-qualified and there were no available information regarding the outgassing features of the materials, so this test was required to increase the possibility to be accepted as secondary payload by launch organizations.

Going in-depth on the test description, during the first cycle the satellite was non-operational, while the functionalities were tested at hot and cold plateaux in the other three cycles. Moreover, a full discharge/charge cycle of the batteries at hot and cold plateaux was conducted to assess the influence of temperature on the under-voltage threshold protection. To conduct this test, four internal (i.e. one each for battery, Electrical Power Subsystem, ADCS and Communication Subsystem) and four external thermocouples (i.e. on four out of six external faces of the satellites) have been installed on the satellite. The internal thermocouples were not included during the design of the satellite, but they were added later before the final integration.

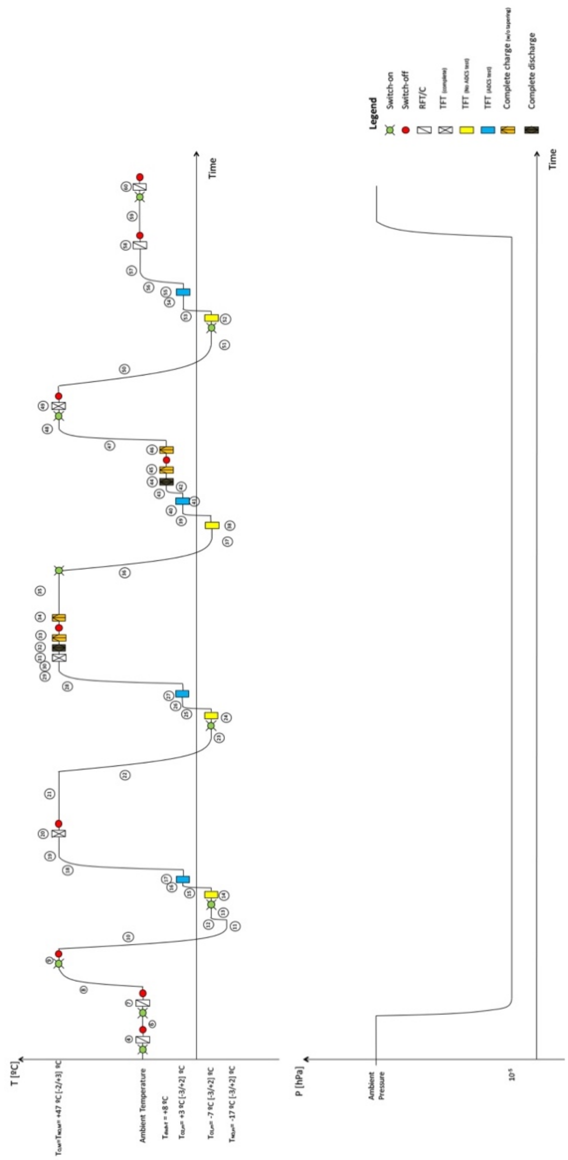

Fig. IV: TVC test sequence.

The target temperatures were obtained with a thermal analysis performed using ESATAN software and then adding twice a margin of ±10ºC: the first margin is due to the uncertainty of the modelling of the satellite (it was suggested by ESA expert) and the second is required by ECSS to obtain the qualification temperatures. Considering the results of the thermal analysis, the maximum and minimum qualification temperatures exceeded the maximum and minimum temperature at which the components can be subjected. Hence, taking into account this constraint and observing that a high uncertainty margin was assumed for the thermal analysis (10ºC instead of 5ºC as suggested in ECSS), the target temperatures ranges for non-operative cycle were defined as follow:

- Maximum non-op temperature: +47°C [-2°C / +3°C], Temperature Reference Point (TRP) on the payload (a condition to limit the target temperature based on the thermocouple located on the batteries was set)
- Minimum non-op temperature: -17°C [-3°C / +2°C], TRP on the batteries.

The most stringent range of temperature is stated by the Inertial Measurement Unit (IMU) for cold case (i.e. 0 ºC), and batteries for hot case (i.e. +50 ºC). Hence, the target temperatures for operative cycles and margins were:

- Max. target temperature: +47°C [-2°C / +3°C], TRP on the payload (a condition to limit the target temperature based on the TC located on the batteries shall be set)
- Min. target temperature #1: -7°C [-3°C / +2°C], TRP on the batteries (payload switched-off)
- Min. target temperature #2: +3°C [-3°C / +2°C], TRP on the payload (payload switched-on).

During operative cycles, all operative modes were to be tested. However, IMU has a stringent operative temperature limits and it cannot be tested below 0ºC. For this reason, it was foreseen to start Thermal Functional Test (TFT) at min target temperature #1. Then, before switching-on the ADCS, the temperature was increased up to min target temperature #2, where the ADCS was switched-on and tested.

Other general parameters defined with ESA during the test readiness review follow:

- Pressure: $P \leq 5*10^{-5}$ mbar
- Bake-out temperature: ≥ +42°C
- Temperature change rate: ≤ 10 °C/min
- Dwell time: minimum 20 minutes.

The CubeSat was hanged into the ESA-MARSIM Thermal Vacuum chamber. The installation of the CubeSat is shown in Fig. V. The thermocouples (internal and external, which were installed before the integration into the chamber) and GSE (i.e. to monitor batteries status and to switch-on/off the satellite), were connected to the interface of the chamber. Functional tests were performed via radio-frequency, using the mobile GCS installed in the laboratory.

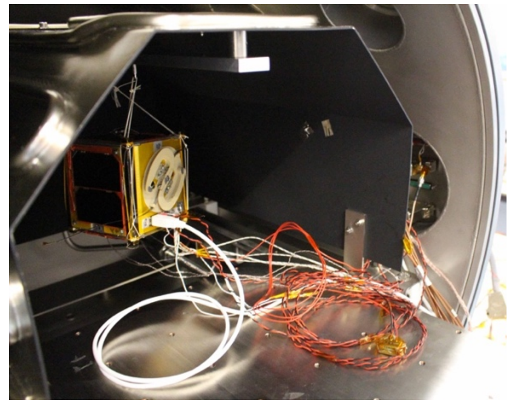

Fig. V: CubeSat installed in the TVC chamber.

IV.III Results

The test campaigns were successfully conducted at ESA-ESTEC on May and June 2015.

As regards the vibration tests, all the resonance surveys showed no relevant shift on the response of the satellite exceeded the limits (i.e. max 5% on frequency and max 10-20% on amplitude), so that means no damage was caused to the satellite by vibrations environment.

The whole test campaign was conducted as planned, with a single variation compared to the planned activities. In fact, an anomaly was observed while testing the y-axis, that was the first axis to be tested with the shaker in horizontal setup. The vibration run was automatically stopped three consecutive times by the shaker, with no malfunction caused by the CubeSat. The root cause of the non conformance was found in the large displacement of the slip table when subject to a 2.5g acceleration at 5 Hz. This event required a procedure variation, with the test level notched at 1.5g at 5 Hz, ramping up to 2.5g at 7 Hz. The levels adaptation did not have any impact on the tests since the notching occurred at frequencies lower than the first natural frequency of the CubeSat, which was above 120 Hz. Functional tests were conducted as scheduled, and they demonstrated that the satellite survived to vibration environment.

The Thermal-Vacuum Cycling test succeeded too, although there has been a non conformance on the SD memory card, which is still under investigation at the moment. The test has correctly completed within the expected schedule. During the first operative cycle, a relevant increase of the temperatures in a relative short time was observed at the switching-on of the payload. This behaviour required a procedure variation as regards the target temperature margins, which were modified as follow to assure an easier control by the test operator:

- At hot, [-2°C / +3°C] changed to [-2°C / +7°C]
- At cold, [-3°C / +2°C] changed to [-3°C / +7°C].

The test allowed the team to verify the correct functionality of the satellite in thermal-vacuum conditions, both at hot and cold conditions. In Fig. VI, the internal temperatures acquired during the full TVC test, are shown.

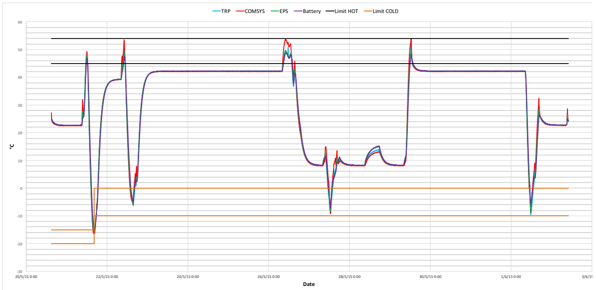

Fig. VI: Internal temperatures during TVC test

In addition, a comparison between predicted temperatures (before adding the uncertainties previously stated) and reached temperatures during TVC test, is reported in Table IV (H = hot plateaux, C = cold plateaux).

	Predicted [°C]		**Measured Non-op [°C]**		**Measured Op cycles [°C]**	
	H	*C*	*H*	*C*	*H*	*C*
ADCS (TRP)	32	2	48.2	-16	52.2	-9.6
COM SYS	32	2	49.2	-16.4	53.9	-9.2
EPS	30	0	48	-15.5	50.1	-8.5

Table IV: Predicted (without uncertainties) vs Measured temperatures.

The long duration of the TVC test campaign allowed to conduct bake-out for a cumulative total of 152 hours and 7 minutes at T ≥ +42 °C, which is far greater than the 72-hours minimum duration required by ECSS. In the following figure, the temperature profile of the TRP is shown, with the bake-out periods highlighted.

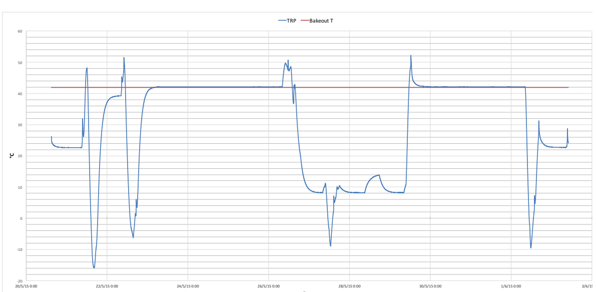

Fig. VII: TRP temperatures and bake-out

During the two test campaigns, all the interested requirements (i.e. functional and environmental) have been verified and closed-out.

V. LESSONS LEARNED

The environmental test campaign described in the previous paragraphs brought a great number of lessons learned both from the educational and technical point of view.

V.I Educational

The opportunity provided by ESA Education Office turned out to be very important for the students involved in the environmental test campaign, and consequently as heritage for the whole team. Even though compared to "traditional" satellites there were changes in the verification plan (as presented in Section III), the verifications were carried out according to the standards requirements. Moreover, being in touch with the top experts in the field, first by email and teleconference, and then side by side in the laboratories, is one of the best ways to acquire knowledge and to personally experience how to work in a professional context. Examples of experts' support are the several feedbacks for the improvement of our previous CAD sketches, FEM and thermal models, which led to a better modelling of the satellite for the analysis, to a better verification plan, and to better simulate the satellite behaviour. Other key elements were the teleconferences and reviews between the student team members and the ESA experts and managers, which represented a great outcome for all the students involved into the project because they have allowed to acquire the techniques and methodologies not only for the technical aspects but also from the relationship and project management points of view.

The main difficulty, however, is still today linked to the different knowledge background: in some cases, in fact, the reference ESA expert assumed that students have already acquired detailed knowledge on specific topics. However, sometimes that was mostly unclear for a student or actions/modifications/repairs were demanded but they were not feasible in a university project or considering the current state of the project. As example, after the tests campaign, to investigate the cause of the non conformance of the SD memory card, the expert proposed some possible additional tests which could have led to the root cause identification. Most of them required to implement an easy SW modification to be conducted: assuming that it was possible to upload a new SW, the expert indicated to proceed with the implementation. Unfortunately, this was not possible because no external interface to upload SW was considered during the design phase and a disassembling of the satellite, would invalidate the vibration tests.

V.II Technical

As regards technical aspects, various outcomes have been achieved, with a relevant increase of systems design know-how of the team to be applied in future projects.

Difficulties faced during the preparation of test campaign are to be linked primarily to a not verification-oriented design. In fact, to monitor and activate/de-activate the satellite during tests, some modifications were needed before the final integration:

- four internal thermocouples have been installed. They were not included in the original design of the satellite, so a difficulty was encountered in routing the cables outside the satellite via the only access port available
- A switch was installed in parallel with the Deployment Switch of the satellite, to be able to switch-on/off the satellite while in thermal vacuum chamber
- To be able to recharge batteries via power supply and to monitor voltage status, five additional connectors were routed to the access port.

During the test runs, the Team had the confirmation of the importance of a very detailed and comprehensive procedure, but also realized the need for promptness in evaluating and defining procedure variations. Indeed, changes may be required after starting the test, as it happened in the case of the modification of temperature margins at switch-on of the payload.

Timing is another important variable: it resulted that some tests required more time, and others less, than scheduled. In fact, the two cycles of full discharge and recharge of the batteries lasted longer since they heavily depend on the batteries status at the beginning of the cycle, which is hardly predictable. On the opposite, moving from hot to cold plateaux and vice versa was faster than planned, so anticipating the functional tests there was the possibility to respect the original planning in terms of starting and ending date.

Ground Support Equipment is another important key-aspect. It shall be procured/prepared in advance so as to allow operators to become familiar with it. Moreover, it shall be taken into account the considerable amount of cables inside the thermal vacuum chamber (e.g., internal and external thermocouples on the satellite, thermocouples to control the chamber) and consequently the difficulty in installing the satellite itself in the chamber. Indeed, for CubeSats small thermal chambers are used. For TVC tests, e-st@r-II was hanged with nylon wires to two metal hooks: in this case the difficulty was due to the impossibility to test the installation configuration, so the one originally planned was adjusted on site upon installation.

Another lesson-learned concerns the way in which the functional tests are performed. The design of e-st@-r-II allows only the communication via RF to perform a complete set of functional test. The result was the need for a few checks on the communication before installation in the chamber. First it was verified that the unfolded antenna was not in contact with internal surface of the chamber, and then that there was no problem of signal attenuation nor high power at the receiver on-board the satellite due to reflections inside the chamber.

VI. CONCLUSIONS

The environmental test campaign of e-st@r-II demonstrates the possibility to conduct a lean verification test campaign, planned according to a tailoring of the ECSS. Fundamental tests were performed, and thanks to careful planning and the combination of some tests, it was possible to reduce the time and costs, respecting the budget.

The application of lessons learned with previous CubeSats to new projects is one of the way to improve CubeSats design and increase their mission success rate. In this context, the lessons learned gathered during the verification campaign (and its preparation) of e-st@r-II will impact on the new projects of the CubeSat Team at Politecnico di Torino [10]. In fact, a test-oriented design approach shall be adopted, since most of the difficulties faced during e-st@r-II environmental test campaign are avoidable in future projects by taking into account during design phase the following statements:

- internal thermocouples and accelerometers improve the quality of the environmental test campaign and its outcomes
- external interfaces are fundamental to monitor and control subsystem status during tests, without relying only on RF communication
- structure shall allow access to subsystems boards without a complete disassembling of the satellite
- the upload of the software via RF or external interface is fundamental
- a lean reliable GSE shall be used.

In conclusion, lessons learned from past missions are crucial to improve CubeSats design, mainly in university field. This know-how is surely useful to CubeSat Team to improve new CubeSats design, verification procedures and in-orbit activities definition.

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