Boosting knowledge and system reliability: ESA Education's constructive approach to CubeSat environmental test preparation and execution

David Palma[(1)], Loris Franchi [(2)] , Jack Praill [(3)], Joost Vanreusel[(4)]

[(1)] *Redu Space Services for ESA, ESEC, Place de l'ESA 1 Redu Belgium, 6890, +32 (0)61 22 95 30, david.palma@esa.int*

[(2)] *Redu Space Services for ESA,* ESEC, *Place de l'ESA 1 Redu Belgium, +32 (0) 6122 9590, loris.franchi@esa.int*

[(3)] *Airbus Defence and Space, Portsmouth, England, United Kingdom, jack.praill@airbus.com*

[(4)] *European Space Agency, ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, +31(0) 648158937, joost.vanreusel@esa.int*

Abstract

CubeSat missions are typically undertaken in the assumption that a higher risk of failure is more acceptable than with typical space missions, and this is often still the case in student-developed projects. The ESA Education Office, through its educational CubeSat programme, 'Fly Your Satellite!', has identified that participating university students sometimes do not have an extensive prior background of hands-on knowledge pertaining to environmental test preparation and execution. It is hypothesised that this gap in knowledge related to space system testing activities may correlate to a number of general issues surrounding system reliability.

In this paper, the methodology and rationale behind the Fly Your Satellite! approach will be discussed and how this implementation seeks to maximise both educational return to university students whilst serving to enhance system reliability. The iterative approach proposed is currently being applied to a number of educational CubeSat projects, each with their own unique objective and design.

As part of the proposed approach, university students are introduced to a streamlined test campaign implementation, which seeks to break down the differing, complex elements into easily applicable steps that aid to familiarise students with the overall test preparation and execution process. This, in turn, serves as a basis for the development of a rigorous test specification, helping to achieve an adequate system verification.

For now, the implementation of this approach has been reserved to tests performed at the ESA Academy CubeSat Support Facility, an industry-grade training facility furnished with environmental test equipment, dedicated to providing hands-on testing experience to university student teams developing space systems. The use of this controlled laboratory environment is advantageous for students to not only learn the test engineering component of test preparation, but also the facility operator perspective, an aspect which is difficult to obtain in a classroom scenario.

In that context, a case study is presented to demonstrate an application of the process to one of the participating teams in Fly Your Satellite! and its outcome is described and assessed.

Finally, drawing on observations and data obtained from multiple sub-system level test campaigns at the CubeSat Support Facility, it is shown that the employed approach has not only shown a positive educational return on the behalf of the students, but also allows for the identification of several issues with the design and manufacturing of the subsystems.

1 INTRODUCTION: THE ESA EDUCATION FLY YOUR SATELLITE PROGRAMME

‘Fly Your Satellite!’ (FYS) is a programme of the ESA Education Office [1], dedicated to one, two, and three-unit educational CubeSats developed by university teams from ESA Member and Associate Member States. It forms part of the ESA Academy programme, which has the objective to complement academic education and to train the next generation of space professionals.

Through ‘Fly Your Satellite!’, university students have the opportunity to become acquainted with industry standard professional practices, by applying methodologies comparable with those in larger ESA missions, to aid in fostering their own CubeSat developments. The programme achieves this by supporting university teams in the design, development, assembly, integration, verification, testing and, finally, launch and operations of their CubeSat.

The missions undertaken by the university CubeSats are conceived and developed by students, with resources provided by the universities and/or other interested sponsors. Thanks to the participation in their CubeSat project, the students gain significant experience in the full lifecycle of a real satellite programme.

Within FYS, the students are supported and mentored by ESA specialists from several different functional areas by means of reviewing design, supporting verification activities, conducting test campaigns, and providing practical recommendations based on experience and resources. In parallel to creating a channel of knowledge transfer from experienced to junior engineers and scientists, the close contact between specialists and academic teams enhance the learning experience. Furthermore, iterations with ESA experts ensure that satellites undergo thorough proper verification, increasing the chances for a successful mission.

‘Fly Your Satellite!’ consists of five programmatic phases (Figure 1) that closely resemble the standard development stages of a professional satellite project following the classic systems engineering V-Model approach [2,3,4].

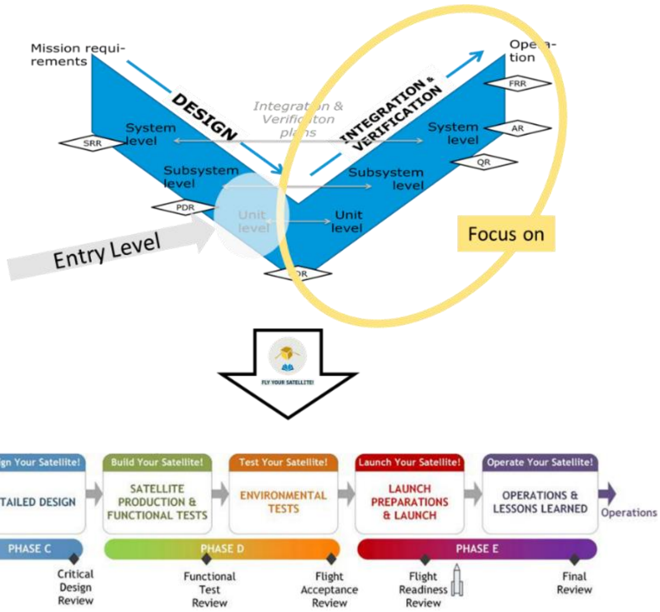

Figure 1 - Programme phases of Fly Your Satellite!

At the end some of the phases, the CubeSats are submitted for formal review processes, tailored from ECSS standards (European Cooperation in Space Standardisation) [5].

University teams start the programme in the 'Design Your Satellite!' phase, already with a detailed design proposal that is then reviewed with the support of the ESA specialists. Those teams that are considered to have a detailed design at a mature level are then accepted to enter the next phase of the programme, termed 'Build Your Satellite!.

Throughout the 'Build Your Satellite!' phase, the teams engage in procurement and manufacturing activities, followed by the assembly, integration and functional testing of their spacecraft in ambient conditions. All the activities are performed following procedures carefully reviewed by the ESA specialists, and successful teams are permitted to enter the 'Test Your Satellite!' phase. In this latter phase, the satellites undergo an environmental test campaign. The campaign includes, as a minimum, vibration testing and thermal vacuum/thermal cycling tests.

If the CubeSats successfully survive all environmental and functional tests, and the teams demonstrate that their ground and space segment meet all applicable requirements, they are awarded the access to the 'Launch Your Satellite!' phase.

In preparation for the launch, the students actively support the safety approval process, assist in the installation of the spacecraft in the deployer and eventually participate in the launch readiness review, interfacing with the launch authorities.

The deployment to orbit initiates the last phase of FYS, called 'Operate Your Satellite!'. In this phase, the teams exploit their own ground stations to receive telemetry and control the spacecraft during the operational phase. The participation to 'Fly Your Satellite!' concludes with an evaluation of the operational phase and a *lessons learned* workshop, where the path of the teams through the programme is put into perspective and improvements for both future CubeSat projects and FYS editions are drawn.

This paper focuses on the 'Test Your Satellite!' phase, presenting the approach adopted in the preparation and execution of environmental test campaigns in the dedicated ESA test facility, known as the CubeSat Support Facility.

2 SUPPORTING CUBESAT TESTING: THE ESA ACADEMY CUBESAT SUPPORT FACILITY

The CubeSat Support Facility (CSF) [6] is located within the ESA Education Training Centre, (ESEC-Galaxia facility, Transinne Belgium).

The CSF serves primarily as an assembly, integration and testing facility for educational CubeSats, offering state-of-the-art training and test facilities for university students, some of which not often found in universities, effectively opening opportunities to student teams with less resources to be able to be involved in a CubeSat project. The facility is therefore used primarily to support the activities of the aforementioned Fly Your Satellite! Programme.

Figure 2 - CubeSat Support Facility

The CSF (see Figure 2) is integrated within an ISO 14644-1 Class 8 (100000) clean room that hosts a number or environmental and ambient testing capabilities. These include:

- A 3-axis, 20 kN Electrodynamic Shaker system for vibration testing (Figure 3);

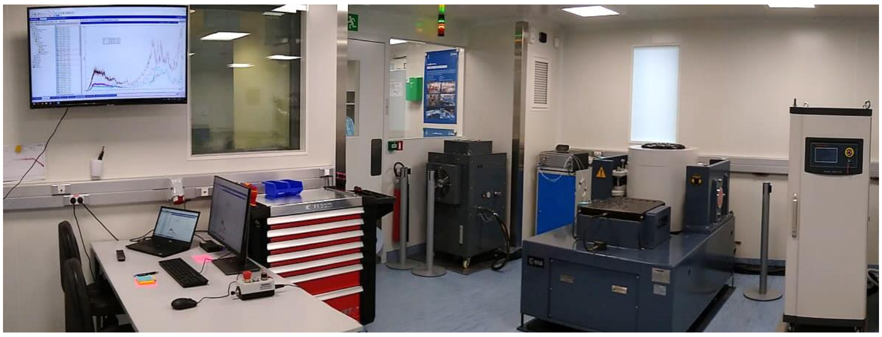

Figure 3 - CSF 20kN Electrodynamic Shaker System

- A Thermal Vacuum Chamber (TVAC), capable of achieving high vacuum ($1x10^{8}$ mbar) and projected CubeSat temperature ranges for thermal cycling and balance tests (Figure 4);

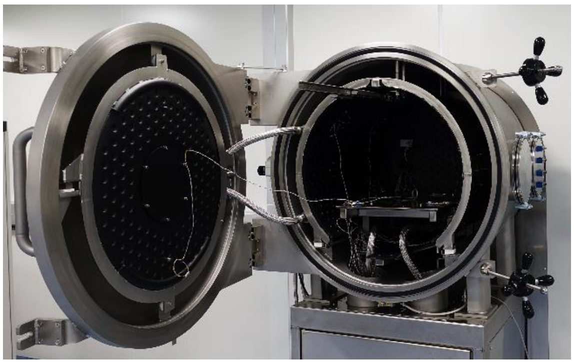

Figure 4 - CSF Thermal Vacuum Chamber

- A host of equipment for electrical and communication functional testing;
- Work benches and tools for assembly and integration activities;
- Standardized interfaces to test equipment such as CubeSat deployers and Shaker adapter flanges ready to be used.

3 ROAD TO TESTING: FYS EDUCATIONAL APPROACH TO ENVIRONMENTAL TEST PREPARATION and EXECUTION

The approach to testing implemented in the 'Fly Your Satellite!' programme is intended to mirror closely the practices that are assumed as standard in the context of the European space industry, such as those defined by the ECSS standards [7].

The focus on those normalized practices serves to provide the participating university students with a solid basis of knowledge regarding testing processes that can be immediately relevant in their future professional careers.

The learning experience starts with the theory, which is in part provided by the resources created by ESA, in the form of Document Requirements Definition (DRDs), Memos, lessons learned and other formats.

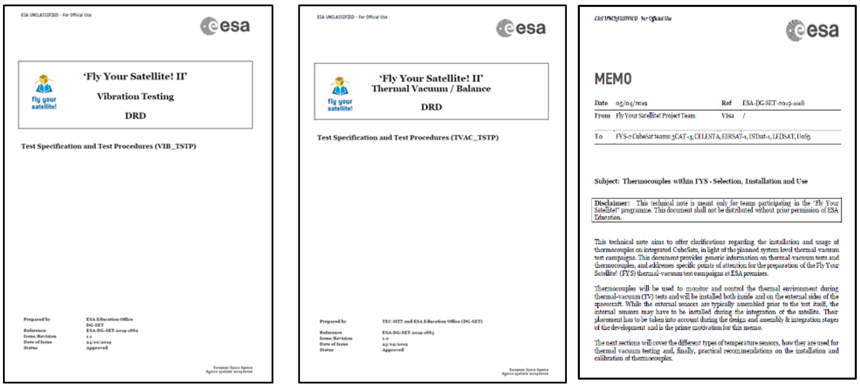

Figure 5 - Test preparation: Environmental test DRDs and Memos

These resources, complemented with the support from ESA engineers, allow the CubeSat teams to create their Test Specifications and Test Procedures (TSTPs). Through several feedback sessions, the documentation and test set-up concepts evolve until the stage in which the team is ready to start the hands-on part of the test exercise.

This iterative process allows the ESA team to put the spotlight on the highest priority aspects first (e.g. test objectives, setup concept) and then move on to other details such as test organization, logistics and finally the step-by-step procedures; allowing the students to become acquainted with the typical flow of a test campaign preparation.

As the topic of testing is one that inherently combines theory with hands-on expertise, the theoretical resources are only useful to a certain point and the transition from the classroom to the real world application is sometimes challenging.

In the practical part of the exercise, the students get hands-on by preparing themselves the test setup, with help from ESA operators, and learn how to analyze results and to deal with problems and anomalies on the spot. Furthermore, by being immersed in a cleanroom environment, students also learn good practices in cleanliness, Electro-Static Discharge (ESD) control, amongst others.

The approach can be summarized as shown in Figure 6 and is aimed at transferring to the students some understanding of how to:

- Identify or define test objectives;
- Prepare a test that satisfies the identified objectives;

- Establish proper success criteria;
- Envision an adequate test set-up, with logically selected and placed instrumentation;
- Write good test documentation, in accordance to industry standards;
- Manage a test campaign;
- React adequately and thoroughly in the face of unexpected issues and anomalies during test;
- Manage lessons learned in preparation for future test campaigns.

After going through the aforementioned process at least once, in a test of lower complexity (e.g. subsystem level), the CubeSat teams in 'Fly Your Satellite!' are better equipped for the preparation and execution of more complex campaigns, such as system-level tests, allowing in principle for a reduction in the preparation time and number of issues related to poor preparation.

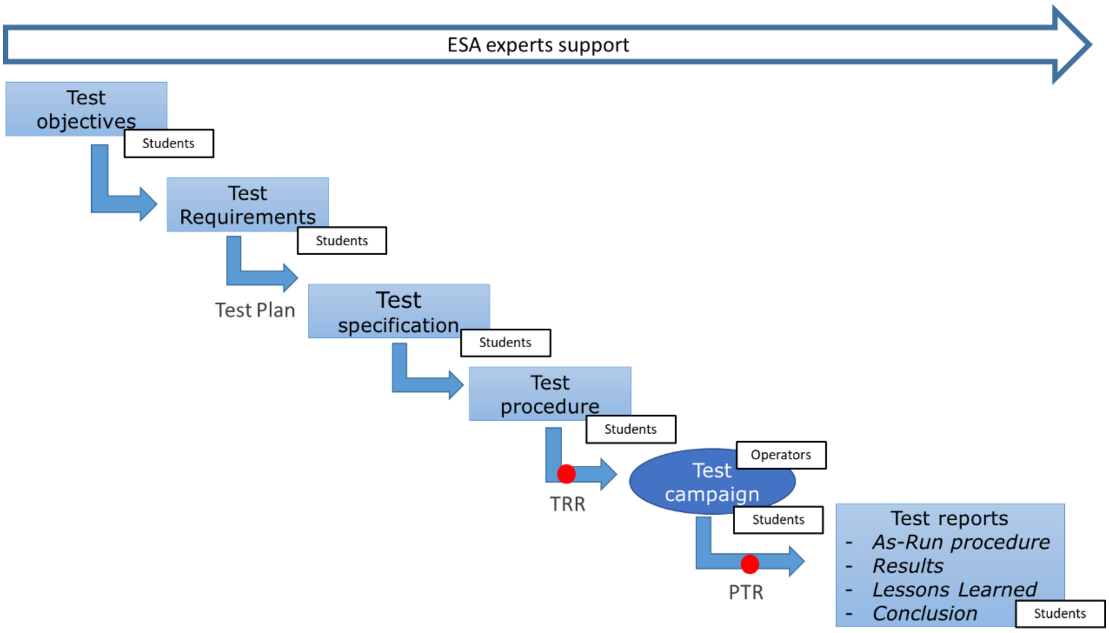

Figure 6 - Overview of test campaign plan at the CSF

3.1 Test preparation

The basis for a solid test campaign is quite naturally the test preparation phase. This phase can be challenging for university students, as environmental testing is not always covered in university courses and, when it is, it may not involve practical aspects. Therefore, the test preparation phase represents the bulk of the student's learning experience whilst also critical in preparing an effective test campaign.

The preparation of each test campaign at the CSF is standardized across participating teams and can be sub-divided into the blocks shown in Figure 7.

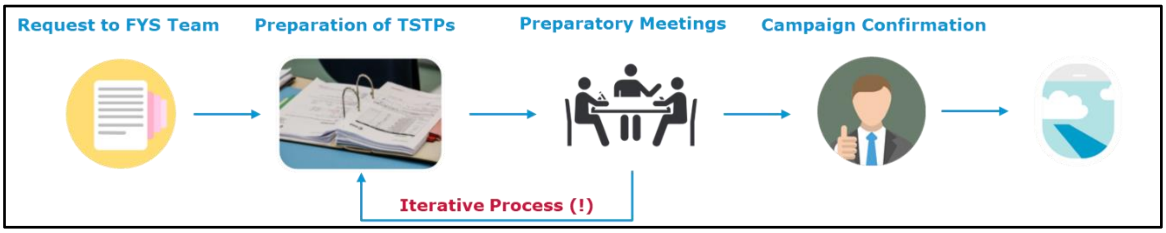

Figure 7 - Environment test campaign preparation overview

The process starts with an identification by the CubeSat team and/or ESA teams of a need for an environmental test at system, subsystem or part level. This need is often already foreseen in an AIV plan that is defined a priori by the CubeSat team, but unforeseen tests are also accommodated. When requesting a test, the team is asked to identify clearly the test objectives and to explain how the proposed test fits in the verification plan, which motivates students to test with a clear goal in mind. This is typically done via the delivery of a short test plan or a brief presentation to the ESA team.

Once the test campaign is validated for its preparation, students can start working on the test specification and, later, on the test procedures. It is in this phase where the involvement of ESA experts is more frequent and when the students require the highest level of input.

The approach adopted by the FYS team is based on a set of subsequent iterations aimed at increasing the maturity of the test campaign preparation, as shown in Figure 8.

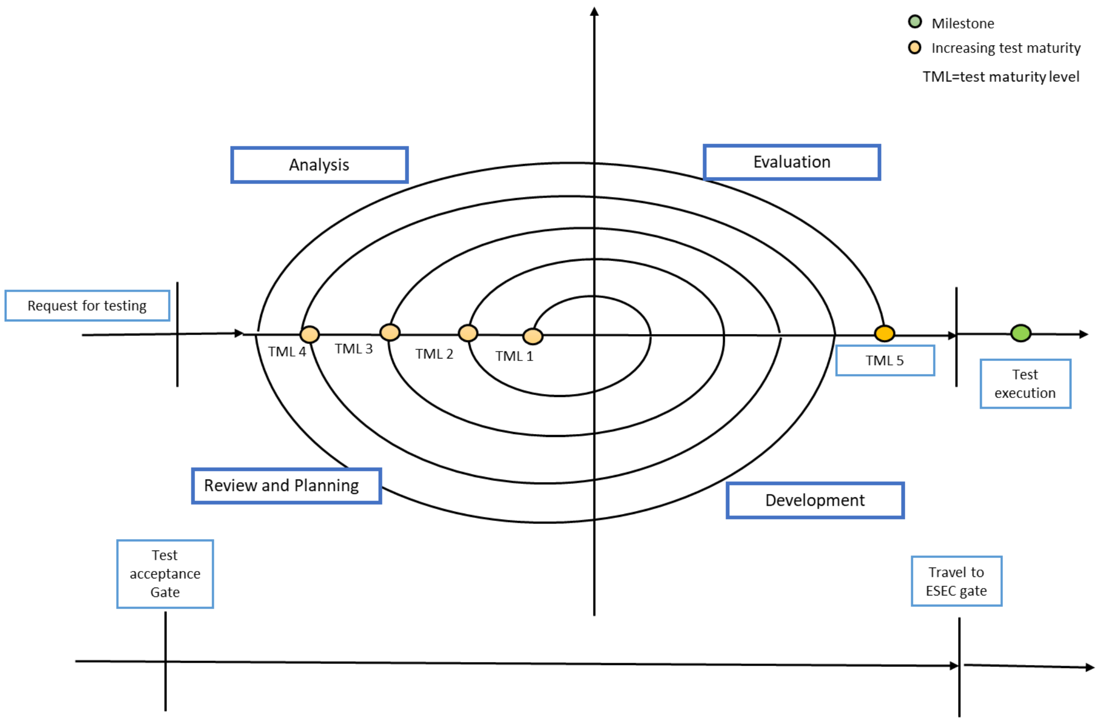

Figure 8 - Iterative test preparation: each iteration is represented by a turn of the spiral

As mentioned above, the process starts with an understanding of rationale and logic behind the test campaign. Once that the objectives are well understood, each one of the follow-up iterations is knowledge centered, as it is scoped at increasing students' comprehension of the environmental test campaign whilst enhancing the understanding and preparation of the test itself.
This is achieved through ad-hoc preparatory meetings between students and ESA engineers, in which the objective is to increase the campaign maturity, following the scale summarized in Table 1.

Students are invited to proceed with the development of test preparation with the goal of answering to the input questions (Table 1), in order to push the campaign maturity to its next level. The outcome of each development session is then delivered to the ESA team for review, who provides feedback and thus a new iteration starts.

Table 1 - Test Maturity Level (TML)

Test maturity level	Objective	Input questions
TML 1	Definition of test objectives, requirement verification, pre-requisites	What is the main scope of the test campaign? Which requirements need be verified? What are the prerequisites to be met in order to execute the test campaign?
TML 2	Definition of test sequence, test levels, pass fail criteria, test requirements.	What is the test concept? What is the breakdown of activities for the test? How is the item going to be tested? How can the success of the test campaign be measured?
TML 3	Test set-up, GSE identification, instrumentation requirements, ad-hoc functional test	How is the item going to be mounted in the test equipment? How will test item functionality be assessed post-test? What type of tools, equipment, or other GSE will be required?
TML 4= Test acceptance	Schedule, organization, health and safety requirements Check of test set-up readiness	How long will the test facility be booked? How long does each activity take? Are there particular safety risks to address? Who is required to execute the test campaign? Has the test set-up been built and has there been a dry run at the university?
TML 5	Derivation and finalization of test procedure	Which steps need to be followed to fulfill the test specifications?

Once the preparation level reaches the so-called TML4, the campaign is given the go-ahead, which also means that the campaign is frozen in the facility schedule and that the travel arrangements can be made. This ideally occurs at least 1 month prior to the campaign execution. During that month, the test procedures are finalized and approved, any issue with the test set-up is ironed out and the CubeSat team is ready to travel to the CSF.

3.2 Test execution and reviews

Environmental tests are performed over a period ranging from between a few days up to a couple of weeks, depending on the scope of the test, and follow a standardized sequence as seen in Figure 9.

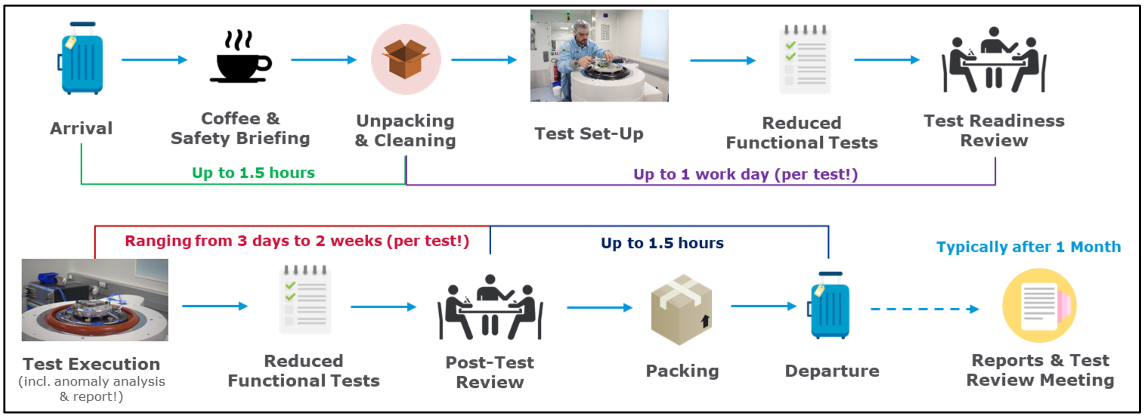

Figure 9 - Environmental Test Standardised Sequence

Upon arrival to the facility, students unpack and prepare their test item as per their detailed procedure.Students are always invited to follow a strict product assurance (PA) plan amid the preparation and execution of the test campaign.

The identification of a PA engineer amongst the visiting students is always recommended whilst in the test preparation phase. The identified PA engineer is stimulated to manually fill-in the procedure during the conduction of the test (Figure 10), along with his/her signature as a proof of quality control. Students are also always asked to inspect carefully the test item and to take pictures to be subsequently attached to their “as-run “procedure.

Figure 10 – PA student overseeing the test set-up

During set-up, students are encouraged to attach the item under test (IUT), to the test equipment themselves, with ESA operators offering support and guidance should any issues or queries occur, maximizing the hands-on participation afforded to the teams.

Test sensors themselves are installed by ESA operators, with the processes and logic behind each action explained to the observing students. Since the liability of the IUT lies with the test facility, teams are motivated to voice concerns with any aspect of the test preparation or conduction performed by ESA staff, an experience often unfamiliar to student teams.

During testing itself, ESA operators follow the student-designed test procedures, verifying each step with the team members before commencing the next. Screens situated by the TVAC and Shaker systems display real-time test data. The responses of the IUT to testing is then discussed with the students (Figure 11). This activity in particular forms an important cornerstone of the educational return provided by the test, and feeds directly into the post-test report.

Figure 11 - Students and CSF operators analyzing test data in real-time

In addition, it is often the case during test campaigns that anomalies are encountered. It is important in this scenario to teach students not to underestimate the identified anomaly and proceed according to a well thought out PA plan. Particular attention is offered in the management of anomalies and the subsequent NCR to be raised. When an anomaly is detected, the test is interrupted to proceed with a first assessment of the possible root causes and ways forward. The ESA team offers constant support to students, overseeing the process while trying to foster engineering-focused critical thinking and thoroughness in the documentation processes (Figure 12).

Figure 12 - Students working on anomaly investigation and follow-up NCR

Before and after the a test, a test readiness review (TRR) and post-test review (PTR) are performed, in which any aforementioned anomalies, deviations from procedure, clarifications or updates to the TSTP can be made whilst still fresh in the mind of students. In the case of the PTR, an array of 'lessons learned' are collected, to be distributed amongst team members unable to attend the test, and future participating teams, allowing the educational return of such campaigns to be shared with a wider audience.

4 CASE STUDY

4.1 Introduction

Since the inauguration of the CSF in late 2018, around 10 test campaigns have been carried out in accordance to the approach presented herein. This case study selects the outcome of the campaigns of a specific CubeSat team in order to underline their progress in the learning curve (Figure 13), starting from the first campaign in December 2018 up until the latest in February 2020.

The learning curve depicted in Figure 13 can be considered unique for each type of environmental test. After a preliminary understanding phase in which the meaning of the test is understood, the iterative approach presented in this paper is represented by the increasing of the expertise in the first phase, characterized by hard work in building the foundation of testing expertise. It is after the delivery of a sufficiently good test specification (TSTP) that the students are then invited to the CSF to run their test campaign (the so-called TML 4). Moving from theory into practice entails a changing in the learning curve slope. The knowledge is then consolidated by experiencing the test campaign. Students maturity of expertise is eventually reached via a retrospective of the test campaign in which reviews are conducted and lessons learned are processed.

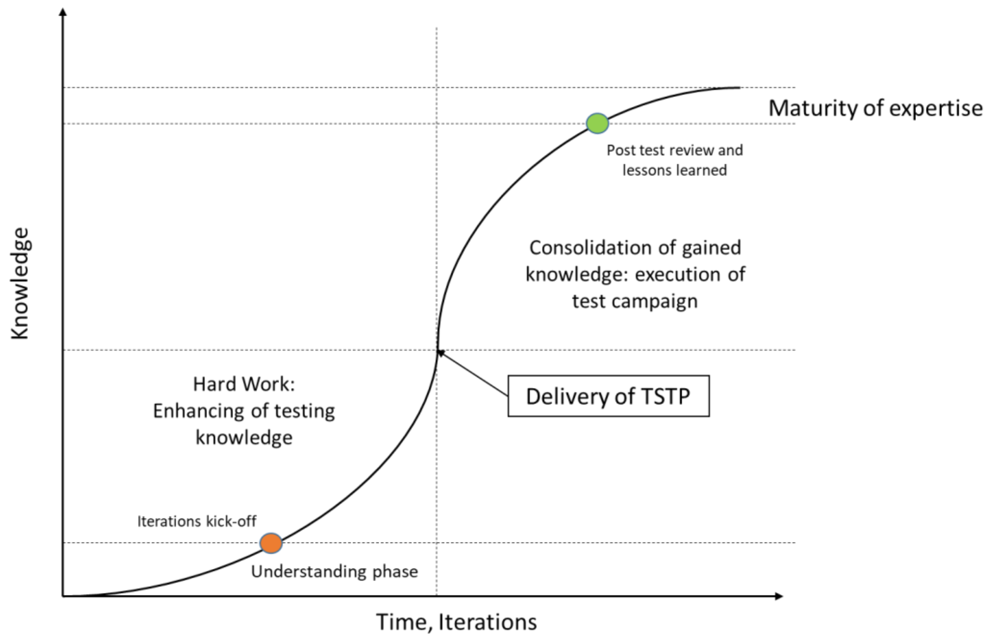

Figure 13 - Students learning curve observed thanks to the applied approach

The most common environmental tests for CubeSat systems and subsystems are thermal-vacuum tests and vibration tests. Naturally, general knowledge about environmental testing and testing practices can be obtained by performing only one of those tests but each type of test requires specific expertise that changes depending on the test typology, thus having a different learning curve.

4.2 Case Study Presentation

The concept mentioned in section 4.1 is illustrated thanks to a sequence of three different subsystem-level test campaigns carried out at the CSF by one of the CubeSat teams participating in the second edition of the Fly Your Satellite! Programme, EIRSAT-1 from Ireland [8][9].

The first test campaign was carried out in December 2018 and was aimed at performing a thermal vacuum cycling test and a vibration test on an antenna deployment mechanism.

- The ADM[10] test in December 2018 was the team's first contact in FYS with the type of information expected in an environmental test specification, on how to interface with the facility to know how to adapt the test to the equipment provided, on how a typical test campaign schedule looks like, amongst others.
- In the first test there were problems related to the schedule, as the thermal vacuum test was slower than expected, due to the setup, which resulted in not being able to complete the vibration test.
- This was one of the first ever tests conducted at the CSF, when the processes were still being constructed and optimized, resulting in a good learning opportunity for the ESA operators as well.

The second test campaign was carried out in November 2019 and was a vibration test on the thermal coupon payload, EMOD.

- For the second campaign, it was clear that the team who performed the test in December 2018 was able to transmit the lessons learned to their teammates, as it took less iterations overall to reach a good test specification. In this sense, the team was able to advance on their learning curve by ensuring that the knowledge was retained and transmitted internally.
- The EMOD test schedule properly envisioned, with adequate margins added, which resolved the main problem faced by the students in the first test. All test objectives were achieved.
- The team was also introduced to bad luck, as a first attempt in August 2019 had to be interrupted due to a facility problem, resulting in a delay.

The two aforementioned campaigns served as an excellent exercise not only in the preparation of the test documentation and test concept for each type of test but also as good lessons in how the logistics of testing have to be carefully considered. A poorly made schedule or unclear roles can easily result in problems related to facility booking which lead to incomplete tests and possible project delays.

Building on the knowledge from the two first campaigns, the team was able to reach maturity in terms of expertise for both types of tests, allowing them to plan for a far more ambitious third test campaign in 2020. The third visit to the CSF consisted in fact of two test campaigns run in parallel, each comprised of a vibration test and a thermal vacuum test. The parallel tests had to fit a period of 5 days and be executed by a group of 4 students.

The test items were the same antenna deployment module tested in December 2018 and a novel gamma-ray detector codenamed GMOD (Gamma-ray Module) (Figure 14).

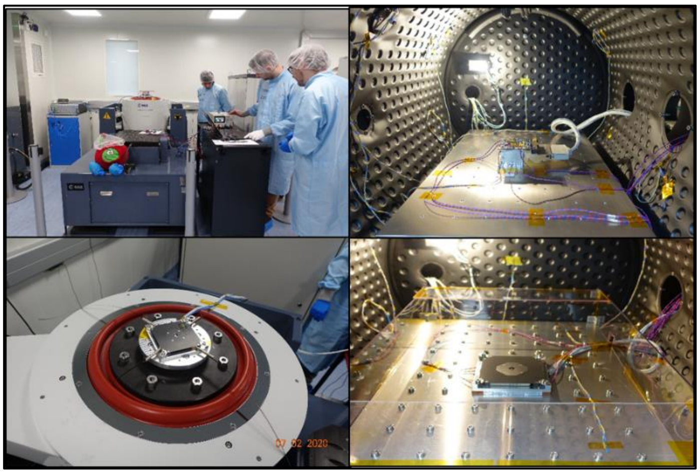

Figure 14 - Students executing in parallel 2 test campaigns at the CSF

The result of the GMOD/ADM test clearly shows that the team was able to consolidate extremely well the lessons learned from the first ADM and EMOD tests, as the campaign was executed without scheduling issues or logistic problems, with the tests having met the objectives defined beforehand.

There were overall fewer iterations in the preparation of the test itself, as less inputs from ESA were necessary than in the previous campaigns.

Throughout the campaign, the team assigned amongst themselves clear roles and responsibilities, showing confidence and professionalism in their actions. The students were also thorough and constructive in their documentation and analysis of any anomalies that appeared, interrupting the test where needed and clearly communicating with ESA operators (Figure 15).

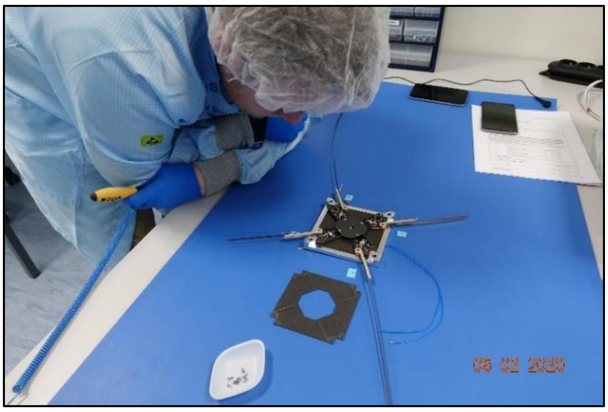

Figure 15 - Team investigating anomalies cause while preparing for NCR submission

After the February 2020 campaign, the team went on to prepare and execute other tests outside the environment of the CSF [10] and is currently preparing the system-level tests of their 2U CubeSat.

All of the above mentioned demonstrates the benefits of giving students an opportunity to train within a safe environment, where critical thinking and taking up responsibilities is encouraged and fostered and where feedback from professionals is constructive. The result of such a positive learning environment is reflected in the ability of the students to progress through their learning curve, from the first steps in the theory to being able to prepare and conduct their own test campaigns independently in accordance to industry standards and practices.

5 CONCLUSIONS AND FUTURE WORKS

The immersive learning experience resulting from the participation in the preparation and execution of test campaigns at the CSF has proven to be valuable for visiting students, who have shown not only the ability to prepare well for those tests but also to retain the knowledge and apply it in their second or third campaign at the CSF.

The integration of the students in the entire process, including all key decisions related to the test, is quoted as one of the aspects that are most valuable in terms of educational return. Another aspect appreciated by students are the lessons learned that are collected and are useful for future test campaigns.

The importance of product assurance is also well regarded by the students, who demonstrate a methodical attitude to the execution of the test and to the documentation & disposition of issues and test anomalies, via the standard NCR processes as established in ECSS. This is evidenced by the quantity of issues that are detected and raised during the tests, which in turn results in an increased system reliability and, hopefully, increased chances for mission success.

Furthermore, the safe space created at the CSF allows students to make mistakes whilst preparing the test, allowing them to progress through their learning curve, driven by the iterative process described in this paper, which serves to increase their confidence and understanding in the preparation and execution of environmental tests.

Even though there are improvements to be made, it is encouraging to see the approach yielding positive results. This is clearly demonstrated in the presented case study, in which over the course of one year, one team went from learning how to prepare a simple vibration test to being able to run two complex vibration & thermal vacuum campaigns in parallel over the course of a week.

Finally, as the process and facility are still in their youth, the ESA team will continue not only making efforts to improve the learning experience for CubeSat teams participating in FYS but also to increase the number of opportunities available for individual students who would like to learn more about environmental tests in general, thus reaching a wider audience within ESA's member states.

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