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Lessons Learned from AIV in ESA's Fly Your Satellite! Educational CubeSat Programme

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ABSTRACT

'Fly Your Satellite!' (FYS) is a recurring hands-on programme conducted by the ESA (European Space Agency) Academy Unit of ESA's Education Office. Fly Your Satellite! was established to support university student teams in the development of their own CubeSats by enabling a transfer of knowledge and experience from ESA specialists to students. Selected teams are guided through project reviews and supervised through design consolidation and verification activities, conducted according to ESA professional practice and to standards tailored to fit the scope of university CubeSat projects.

This paper focuses on key lessons learned and issues identified during the ongoing verification activities of the CubeSats in the second cycle of FYS (FYS2), and on how that experience is used to the benefit of participants of future cycles, including the teams in the third cycle (FYS3), who are now in the late stages of their Critical Design Review. Special attention is given to the lessons learned during the manufacturing, assembly, integration and testing phases as experience shows that first-time developers tend to underestimate the number of issues which arise when the design is translated from documentation and models into physical hardware. The lessons learned are categorised into the topics of Development, AIV, Project Management, and Product Assurance.

In the Development category, the lessons learns suggest attention should be focused on emphasizing the importance of development models and FlatSats for early testing, proactive development of aspects which don't appear to be immediately critical or appear to be on the project's critical path (such as software and test GSE), and anticipating the need for compatibility with a range of possible orbit scenarios.

The Assembly, Integration, and Verification category contains a large variety of lessons learned from the preparation for AIV activities, anomalies encountered, and reflection on what was done well in the programme. These lessons cover topics such as dimensional requirement non-conformances, electromagnetic interferences, and recommendations for system level testing preparation.

Lessons learned for the Project Management category mostly arise from the understandable lack of (space) project management experience of the student teams, and the discussion focuses on possible mitigation approaches that can be implemented. Specific topics covered include delayed project schedules, management of student resources, risk management, and experiences with legal and regulatory requirements.

The lessons learned on Product Assurance stem primarily from the difficulties in applying standard methodologies to educational small spacecraft projects. Problems with configuration control, clean room practices, and anomaly investigation methods are discussed, with recommendations for how student teams could solve such issues, primarily through the creation of additional documentation to track modifications and processes implemented

INTRODUCTION TO FLY YOUR SATELLITE!

'Fly Your Satellite!' (FYS) is a programme in the ESA Education Office dedicated to one, two, and three-unit CubeSats developed with educational scopes. The programme is open to university teams from ESA Member and Associate Member States[1].

Within FYS, university students are supported and mentored by ESA specialists with the purpose of ensuring that the satellites undergo thorough verification, increasing the chances for a successful mission. Students become acquainted with standard practices of the professional space sector by applying methodologies to their CubeSat project similar to those applied in larger ESA missions. FYS also offers access to state-of-art ESA test facilities, aiming at reducing the entry barrier for teams with less resources, as well as a launch opportunity for those achieving flight readiness.

The missions undertaken by the university CubeSats are conceived by the students' teams, and the development is funded by the universities and/or by their public or private sponsors. By participating in their CubeSat project, the students gain significant practical experience in the lifecycle of a real satellite project.

As such, while largely addressing the engineering aspects, the programme also focuses on non-engineering topics that are to be covered in the undertaking of an actual space mission, such as frequency registration, space debris mitigation, and third party liability.

FYS Programme Phases

The ongoing second[2] and third[3] editions of 'Fly Your Satellite!' consist of five phases (**Error! Reference source not found.**) that closely resemble the development stages of a professional satellite project. At the end of each phase, the CubeSats are submitted to formal review processes, tailored from ECSS (European Cooperation in Space Standardization) standards. This provides the students with the experience of ESA reviews, thus providing them with valuable knowledge for a future career in the space industry.

University teams that are successful in their application start the programme in the 'Design Your Satellite!' phase, already with a detailed design proposal that is then reviewed by ESA specialists, who identify key issues and assist in solving them in preparation for the Critical Design Review (CDR). During the CDR, the formal review panel and review board study every aspect of the project, including technical design, management (e.g., funding, schedule, project team, facilities), educational return, and legal & regulatory aspects, e.g., frequency notification to ITU (International Telecommunication Union), space debris mitigation. Those teams that are considered to have the detailed design at a mature level, and that have adequately dealt with the actions assigned are then accepted to enter the next phase.

In the 'Build Your Satellite!' phase, the teams engage in procurement and manufacturing activities, followed by the assembly, integration and functional testing of their spacecraft. All the activities are performed following procedures carefully reviewed by ESA specialists.

Following a Functional Test Review to establish that the team has developed a fully functional spacecraft and ground segment, successful teams are allowed to begin the 'Test Your Satellite!' phase, where the satellites are submitted to an environmental test campaign, using facilities and operator support that are provided by ESA. Many tests are conducted at ESA Education's own CubeSat Support Facility (CSF) located at the ESEC, Galaxia site in Belgium. The campaign includes, at least, vibration testing and thermal vacuum/thermal cycling tests, with additional testing being performed where required. If the CubeSats have meet the success criteria in the 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 following a Flight Acceptance Review (FAR).

In preparation for the launch, the students actively support the safety approval process, assist in the installation of the spacecraft in the deployer and perform the necessary tests to ensure their system is ready to start

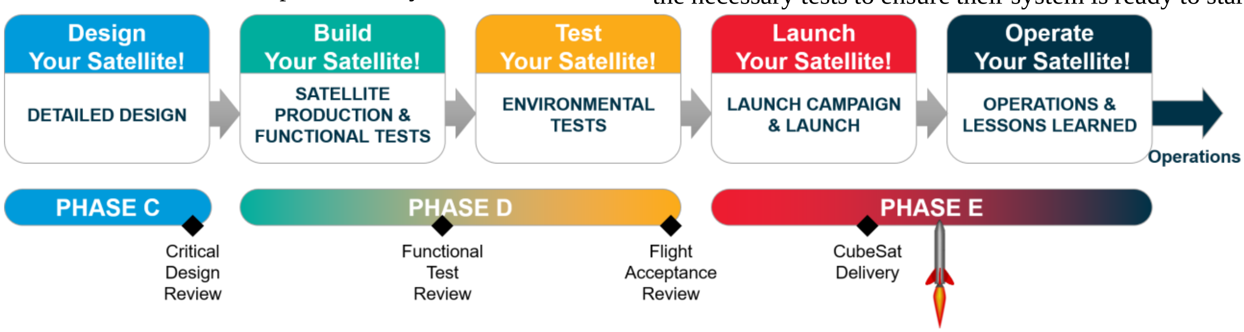

Figure 1: Fly Your Satellite! Programme Phases

the operational mission. Before the launch, the students have the opportunity to participate in the launch readiness review, interfacing with the launch authorities where possible.

The CubeSats are either launched and deployed to orbit directly from the launch vehicle upper stage, or launched as cargo to the International Space Station and deployed from there. The deployment to orbit initiates the last phase of FYS, called 'Operate Your Satellite!'. In this phase, the teams utilise their own ground stations to receive telemetry and to control the spacecraft during the early operations as well as the operational part of the mission, which may last from 3 months up to multiple years. The orbit in which the satellites are deployed is selected to offer a suitable lifetime in compliance to the ESA space debris mitigation requirements.

The participation in '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 CubeSat projects and ESA are drawn.

Phase D and AIV in Fly Your Satellite!

In Fly Your Satellite!, almost all of the AIV activities are conducted in Phase D, during the Build and Test Your Satellite! programme phases. This differs from standard practice, where it is expected that AIV, and particularly qualification or TRL (Technology Readiness level) raising activities begin during Phase C or sooner. This difference stems from the need to ensure students' teams get sufficient expert review of their baseline design in Phase C, before they spend their (often limited) budget on procurement of hardware to begin testing. While this approach is successful, there is also a large benefit to performing development tests early in the project, a topic discussed at length in this paper, and this approach may change during the preparation for future FYS programme cycles.

Phase D encompasses all the manufacturing, assembly, integration, and verification activities needed to build and verify the CubeSat flight model, and concludes with the FAR, where teams are granted a launch opportunity if successful. The following major milestones are in the programme planning for phase D:

1. Subsystem manufacturing and/or procurement from suppliers

2. Subsystems qualification and verification: functional and performance testing, environmental tests

3. CubeSat final assembly & integration

4. Dimensional, physical, and external interfaces verification

5. System functional test campaign: Full Functional, Mission (day-in-the-life) and End-to-end tests in laboratory conditions

6. System environmental test campaign: vibration, thermal vacuum/ thermal cycling / thermal balance tests, and other environmental tests as needed.

INTRODUCTION TO THE LESSONS LEARNED

The concurrent nature of the FYS programme, with teams in different cycles at different stages of their projects, fosters a unique context where lessons learned from one programme cycle can be applied to the others. This results in an overall enhancement of the educational value for the students, and of the quality of the different projects, as common issues are identified and addressed for all teams. Tapping into this experience, the FYS programme phases, milestones and educational opportunities have been reshaped accordingly throughout the various cycles.

It should be noted that while some lessons learned and experiences may unique to student CubeSat or small satellite projects, it may be that many aspects can be seen in other projects with similar attributes e.g. limited budgets, small dynamic / changing teams, limited experience and many lessons learned are not unique to student teams. Furthermore the primary purpose of the FYS programme is the education of the students participating, and therefore it is expected that lessons learned and potential improvements are proactively investigated and discussed.

Lessons learned are presented below, categorised into the topics of Development, AIV, Project Management, and Product Assurance.

DEVELOPMENT

The Need for Development Models and Prototypes

From experience it has been seen that some teams underestimated the need to build and test a prototype or engineering model of their in-house developed units. Inexperience has led to considering that the definition of the design in a document, coupled with the result of extensive analysis was sufficient to close the design and directly manufacture the unit Flight Model (FM).

The result of this approach was that often subsystem flight models were demoted to Development Models (DM) or Engineering Models (EM) following failure of the subsystem verification campaign, for example when detecting out-of-spec performance.

While not manufacturing DM/EM seems to fit well the low-cost profile of student projects, this can result in longer schedules and unforeseen costs:

- The time to conduct complex analysis shall not be underestimated. For the development of certain subsystems it may be simpler to define or verify performances with a test, than to run and validate the analysis. This approach may be applied, for example, in the development of TT&C equipment or deployable mechanisms.

- Not having sufficient budget to manufacture additional models can put the project in a difficult situation as human errors should be expected. This is especially common in an education environment, where the lack of experience of students in working with hardware results in unintentional damages to the units. The same philosophy on extra budget applies in cases of COTS (Commercial Off The Shelf) units' damage or degradation.

Software / Firmware Development Oversights

A common theme seen in the FYS CubeSat projects is the issue of delayed software / firmware development for in-house subsystems and the main on-board software. This generally occurs because in early phases the student teams will have a heavy focus on the physical architecture of the system and the supporting analysis. It is often the case that the software development stays in a theoretical state until well into Phase D, and is even delayed to the last possible moment before it is required. The software development time is often underestimated and finds itself on the critical path of the project schedule.

Beyond the issue of schedule revisions, if software becomes the limiting factor before the team can move to the testing that they would like to perform in Phase D, shortcuts in the development become a temptation. Initial software builds are rushed to completion and are unfinished, only providing the most basic functionality which allows the test results to be obtained, but only be conclusive at a hardware level.

This approach can lead to more issues down the line. First, the rushed development process presents an increased risk of software bugs, some of which put test campaign results into question or delay the project further during the troubleshooting. Beyond this, however, is the fact that these initial software builds are created with the idea in mind that they will be changed, fixed, or expanded on when the time is available to do so. This means changes in the software configuration, which puts the validity of the tests performed using this software in question.

FlatSats for Compatibility Checks and Software Development

While AIV plans issued in Phase C allocate a short period in Phase D for verification using FlatSat models, it has been seen that teams often end-up relying heavily on this configuration for design and verification activities. A FlatSat serves the threefold purpose of confirming compatibility of interfaces, accelerating software development, and facilitating the definition of operational procedures.

In particular, the FlatSat model turned out to be of special value for systems with a mix of in-house and COTS units to verify the data and power buses, and the software/firmware compatibility. This configuration also facilitates access to debug and programming connectors and the resolution of hardware issues on specific PCBs, before the CubeSat internal stack is integrated.

Based on this experience, the programme recommendation to future participants will be to start FlatSat activities in earlier design phases and to plan them for longer durations. It should be noted that in this configuration, special protections shall be implemented to avoid the damage of expensive or difficult to replace flight/qualification models and sometimes the risk of damaging the unit outweighs the benefits of its integration in the FlatSat.

Missing Analysis of Acceptable Orbit Ranges for CubeSat Missions

Many student CubeSat projects do not have a consolidated mission analysis or understanding of which orbit ranges their mission can be compatible with. The approach of most teams is to assume a "baseline orbit" during the design stage. This often causes a problem as CubeSat missions often rely on rideshare or piggyback opportunities for launch. The possible orbit scenarios within the typical Sun Synchronous Orbits (SSO) or ISS-related orbits still have enough variance that considering one "baseline orbit" is not enough to ensure compatibility with all scenarios. Factors such as altitude, eclipse fraction, and radiation doses can be significantly different between the ISS and SSO orbit options available.

Changes in the launch opportunities are not uncommon, and can happen well into Phase D. If a comprehensive understanding of compatibility with orbits is not prepared for the project, the team will need to repeat their analysis during Phase D to understand if they are compatible with new orbit options. There are two major risks here. The first risk is that students who performed previous analyses may have left the team, so there may be delays in repeating this analysis. The second risk is that due to lack of orbit compatibility assessment in the early stages, it may be that the baseline design is only viable for an unrealistically narrow range of orbits. This inevitably leads to design changes during Phase D, which can impact the schedule or cost budget, and can invalidate previous test results.

Development of Melt Line retained Deployable Mechanisms

Many student CubeSat teams elect to develop their own deployable antenna mechanisms, as it is a valuable educational experience to develop an in-house subsystem and it can reduce costs. A recurring lesson learned in the FYS programme is that the effort to move from a design concept to a prototype and then to a flight model is much larger than most student teams expect. The deployable mechanisms are typically spring loaded and retained using a tensioned melt line and deployed by means of a heating element to burn the line. This approach is used because of its heritage on past CubeSat missions, the fact that it uses cheap and easy to procure components, and that it is a simple mechanism, implying reliability. Because the deployment of the antennas is a mission critical functionality, the mechanism must be proven to be reliable through intensive testing. This is where teams in the FYS programme have encountered issues, but also where the experience and expertise of the FYS programme can add significant value to the projects.

The setup of the melt line and heating element must be carefully implemented to ensure reliability. The tensioning of the melt line and the dissipation of heat from the heating elements are factors which must be well defined in the prototype stage. If the prototype does not implement these factors exactly as they will be implemented on the flight model, there can be significantly different performance of the mechanism. At high levels of tension in the melt lines, there can be some slip of the knots / crimps or stretch of the lines over time which reduces the tension, so some teams choose to pretension the lines to reduce this effect and increase reliability. The use of a melt line and heating element also proves to be sensitive to the environment it is placed in. During thermal vacuum testing, many teams discover that at cold temperatures they are unable to burn their melt lines and perform a successful deployment.

The solution to these issues is to move the development of these deployment mechanisms to early stages of the project, allowing time for extensive testing and design iterations. Careful attention should be paid to having low variance in the burn times, as any variance will be amplified during TVAC testing. Characterisation of the heating element performance is crucial during anomaly investigations related to the deployment.

Design for Testing

In a perfect world, the entire development cycle of a project should be considered at the design stage, where performing modifications is still relatively easy and cheap, when compared to later stages of the project.

Figure 2 reflects how in space projects, due to the uniqueness and elevated cost of the hardware, any late design change in the project can have a dramatic effect in terms of cost and schedule impact (e.g. missing the launch!).

In the case of CubeSats, where resources are more limited than in larger projects, the accumulation of changes can quickly grow to become a showstopper.

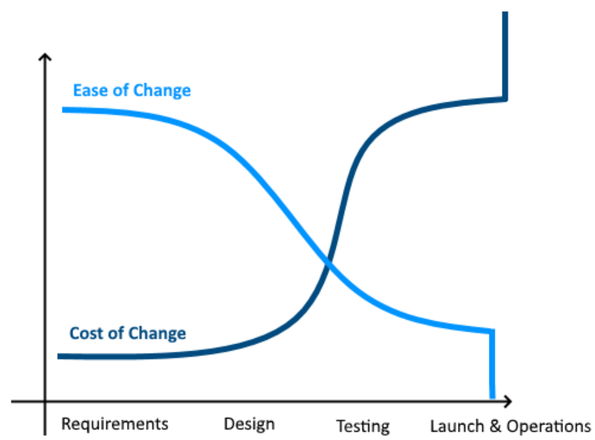

Figure 2 Impact of Late Changes in Space Projects

The inflection point in the curve is the Assembly and Integration (AI) of the spacecraft, after which the spacecraft is placed under tight configuration control and any modification has to be carefully assessed in order to prevent invalidation of previous verification activities. From then on, it is natural that the more verification activities are performed, the lower the ease of change and the higher the cost of performing that change.

The system-level environmental tests take place after Assembly and Integration, but also require a lot of previous preparation to be performed successfully. For instance, the TVAC test is an excellent example for this lesson learned. Test temperature sensors internal to the spacecraft which are essential to the TVAC test must be attached during assembly and integration, and clearances for the cables to exit the spacecraft must be foreseen already at the design stage. The same goes for interfaces with the TVAC chamber or ground support equipment, umbilical connectors, and other capabilities required during thermal vacuum testing.

If the test interfaces are not adequately considered from an early point, by the time of the environmental testing teams will find themselves having to perform last minute modifications to the design, and often partial reassembly of the system. This will be costly in terms of schedule, at a time when the launch opportunity is probably already on the horizon.

ASSEMBLY, INTEGRATION & VERIFICATION

CubeSat Dimensional Non-Compliances

Spacecraft dimensional requirement violations, due to protruding components on the side faces or out-of-spec structures, are often uncovered during verification at the assembly and integration stage. By violating dimensional requirements put into place by standards[4,5], CubeSat teams are reducing compatibility with the CubeSat deployers available on the market and thus limiting potential launch opportunities.

It has been seen in the FYS programme that these non-compliances are not noticed until the procurement of satellite hardware is well underway, and often not until the system stack is assembled and measured. Many violations found were due to parts mounted on the surface of the side panels protruding past the allowable limits. CubeSat width and height variations were also observed depending on the assembly and fastener tightening procedure.

Additionally, interferences between components of the internal PCB stack were common. They do not formally impact acceptance of the CubeSat for integration of the deployer, but they certainly prevent the correct mating of equipment.

There is not just one reason why this problem recurs, in fact there are several potential sources to this problem. The first reason for this is a lack of detail in CAD models of the system, which do not accurately represent the components later found to cause this issue. In some cases, however, it is clear that even when the CAD model included the components, the CAD model was not actually checked against the requirements at all. This is because the teams assumed that their COTS structure would be designed such that there would be space for such components on the surface. Another reason for this issue, however, comes from the assumptions made on the dimensions of components. Student teams often lack expertise in the design of systems with strict dimensional requirements. They overlook the fact that even if they design their system to exactly to meet dimensional requirements, manufacturing tolerances can stop them from doing so in reality. Additionally, it has been observed that product assurance issues on the side of COTS suppliers results in equipment violating the dimensions shown on datasheets, even beyond the tolerances.

The impact of this problem is generally that the student teams need to remanufacture their side panels, internal PCBs, or stack spacers, either to reduce the panel thickness or to change parts and components. In case remanufacturing is not possible, there is a risk that the Request for Waiver for the dimensional requirements is not accepted by the deployer responsible authority. If the teams can select the orbital deployer, this will also limit the choice to only those deployers allowing extra volume.

Student teams are encouraged to monitor their CAD models closely, design with geometrical tolerances in mind, and to perform measurements and inspections on procured parts which could contribute to these violations and interferences.

It is also considered beneficial to include margins in the design, in terms of the dimensional envelope, in a way that in case unforeseen changes are required, the boundaries of the design can be pushed without necessarily resulting in non-compliances.

Uneventful Final Assembly & Integration

The FYS programme has identified some critical steps which can be taken to allow for a successful A&I activity. Following these steps resulted in the FYS CubeSats running into no major anomalies during the A&I activities. In addition, almost no deviations in the CubeSat dimensional and physical requirements were uncovered upon completion of the assembly. Some of the actions taken for this seemingly smooth result are:

- Early inspections and dimensions verification with E(Q)M or (P)FM structures and side panels attached in flight-like configuration, including stowed deployables. This activity uncovered deviations to CubeSat standard requirements: protruding components, out-of-spec structures, problems in rail anodization, etc.

- Early checks of the volume available for harnessing.

- Dimensional verification of each item upon arrival from the manufacturer or supplier.

- Preparation and, most importantly, validation of the procedure for CubeSat Assembly & Integration. Details of the procedure include the order of integration of all components and the application of specific processes (thermocouple installation, torque application to screws, harness routing and fixation, etc.).

Unclear Distinction between Mission and Full-Functional Test

When preparing the test specification for full-functional and mission tests[6], the distinction between the two was not always clear for the teams. In short:

- Full-Functional test is requirements oriented. It is a comprehensive test to demonstrate the integrity of all functions of the item under test, in all operational modes, redundancy paths, including back-up modes and all foreseen transitions. The main objective of this tests is to demonstrate the absence of design, manufacturing, and integration error.

- Mission test is mission and operations oriented. Its definition is driven by the Concept of Operations and the expected mission timeline. It serves to validate the operational procedures for nominal and contingency modes or scenarios.

Ground Segment permitting, during Mission Test it is recommended to operate the satellite from its Mission Control Centre in order to validate the full command and telemetry encoding/decoding chain.

Definition of Verification Testing Goes Beyond Requirements

Upon selection to participate in FYS, CubeSat teams were instructed to apply a requirements engineering methodology to their project lifecycle. In general, the flow-down of requirements from mission, to system, and to the component level was not always well established. Multiple teams had defined only a reduced set of mission and system level requirements, while the design had matured without performing a flow-down to subsystem or lower level requirements. The importance of the requirements to later serve as the baseline of the verification activities was furthermore underestimated.

The lack of a comprehensive set of technical requirements was recognised by teams when defining the testing activities for subsystem and system functional verifications. It was often the case that the activities captured in the test specifications were going beyond the verification of their (sub-)system requirements, like the verification of safety functions, event triggers, etc. This was aggravated by the fact that the test pass/fail criteria did not always cover the additional verifications outside requirements.

The impact of a poor flow of requirements is exacerbated if the group of students participating in the design phase is different from those working on AIV activities. The need for a proper definition and documentation of requirements is key to avoid the loss of knowledge, and to ensure a systematic verification of the functional and operational design.

Electromagnetic Interferences Encountered During System Stack Testing

Electromagnetic interference (EMI), which can cause serious problems in the function of CubeSat projects, is often only encountered when the system is first assembled into a full stack and tested. Many student teams go through extensive FlatSat testing campaigns, only to find that when they assemble their CubeSat they have EMI issues.

These problems arise from the close proximity of EMI sources (e.g. RF transmission) with EMI victims (e.g. microcontroller peripherals), and the effects can be hard to predict. Unfortunately, these issues are rarely solvable with software patches, and usually require a change in the design (e.g. the addition of an RF filter, a change in wire routing, change of PCB grounding plane). This means that the schedule impact of such issues can be severe (in the range of 3 - 5 months); especially considering that this occurs after completing the assembly of the system stack and at least a partial disassembly is required.

The lesson learned in the FYS programme is that it is valuable to assess the electromagnetic compatibility (EMC) of the system from an early stage. By characterising the expected EMI sources and victims at an early stage, the design team can be aware of the possible risks they may face during AIV. EMI mitigations can be implemented, such as shielding or partitioning of high risk components.

The reality of educational CubeSat projects shows that it is often beyond the scope of student teams to fully characterise and mitigate EMI issues on their system, and they must rely on functional tests at system level as a form of EMC testing. Ideally this functional testing would be done as soon as possible, such as on an engineering qualification model. Merely by being aware of the issue and making an attempt to characterise and mitigate EMI effects, the student teams will be in a better position in the event that such an issue does occur. Major milestones (e.g. Full Functional Test at system level) should be accompanied by significant margin in the schedule, to account for issues such as this.

Neglect in GSE Development Leads to Stress During AIV Milestones

Ground support equipment (GSE) required for assembly, integration and testing activities is never the star of the show, taking background priority over the development of the space or ground segments.

It has been observed at test campaigns taking place at the CSF that GSE is often the weak link in many of the test setups put together by the teams, resulting in delays to test activities and, in extreme cases, making it impossible to draw any valuable conclusion from tests due to doubt on whether the setup was adequate or not.

Examples of poor GSE practices and their consequences are included below.

- Using jumper cables and breadboard style connections instead of proper connectors and harnessing, causing setup unreliability, prone to short circuits or open circuits.
- Not testing the GSE prior to the test activity, leading to the need for modifications on the spot or parts of the setup not working as intended. A dry run is always recommended before any test!
- Damage to spacecraft subsystems due to improper grounding practices.
- Keeping data stored in memory without dumping it to a log file before the test is over can cause the loss of test data due to memory overflow or computer crash. Always ensure that data is recorded in a reliable place.
- GSE software not tested beforehand can create lots of bugs during the test activity and a loss of confidence in the test setup.
- Overreliance on (Kapton) tape, which is prone to losing adhesion during thermal vacuum tests, can result in damage to the item under test or the setup.

It should be noted that such problems are not due to poor design intent on the part of the student teams, but often are the result of short preparation timelines and inexperience with the specific test setups. In almost all cases, the issues that were seen in the first test campaigns for each team were learned from and never repeated in future tests.

Mechanical Qualification Levels: Flexibility is Key

It is a reality that student CubeSat teams often have to adapt to changes in the launch opportunity as they are never the main customers for the launch. Unexpected changes in the launch vehicle or launch configuration may result in an under-qualification to the new flight levels, as the levels selected in the original AIV approach can be lower than the those finally required by the launch authorities.

To mitigate this risk, teams are advised to not try to optimise levels early on and instead opt for designing their systems towards the strictest possible environmental requirements. A good starting point is the NASA General Environmental Verification Standard, widely acknowledged as a suitable envelope of environmental requirements.

This approach can be challenging to begin with, and may be considered by some as over-testing or over-engineering, but will very likely reduce the need for future delta-testing and will lead to a smoother, and cheaper, execution of the project's AIV plan.

COTS and Subsystem Qualification Status

One of the benefits of procuring a COTS subsystem or unit is that often the environmental qualification of the item in question has already been conducted. Teams are recommended to request reports of the qualification status in which the test specification and the test results are captured. While this may seem trivial at the time of procurement, this information is key when assessing the qualification against the launch environment levels.

Application of Proper Torque to Fasteners

The number one cause of vibration test anomalies is the lack of properly specified torque values for the fasteners. Higher than adequate torque leads to screw heads stripping or damage to the item under test, while lower than adequate torque leads to screws loosening during the test, potentially causing serious damage to the item under test.

"Hand tight" is not a scientific way to measure torque.

Safety and Reliability Requirements Impact on AIV Plan

Safety requirements can add a considerable overhead to the design and, especially, to the verification plan of a project. This happens not only in terms of the required number of tests to be performed, but also the level of detail required to demonstrate compliance to those requirements. This can be translated either in additional project time (in-house) and/or in additional cost (both in-house and COTS). Two examples of this are ISS safety certifications, and in-house development of an EPS (Electrical Power Subsystem).

Furthermore, reliability requirements imposed by manufacturers can also add constraints to the verification plan, so teams are advised to carefully discuss the implication of the manufacturer's reliability requirements before purchasing a COTS part or subsystem. A clear example of this is with the operation of antenna deployment. These mechanisms are sometimes sold with only a limited number of guaranteed deployments or, in extreme cases, the manufacturer requires the antenna to be shipped back to their facilities for refurbishment, which causes disruption at system level, when the spacecraft should remain under configuration control.

Lack of Access to Test Facilities

Student CubeSat teams are generally reliant on their university facilities and facilities provided by their sponsoring partners to perform tests for their project. In the FYS programme, the student teams are also given limited access to a range of test facilities operated by or associated with ESA.

A challenge that is faced by many CubeSat teams is the ability to identify and book test facilities which meet the requirements of their mission. A clear example of this is in the performance testing of VHF antennas, which are commonly used in CubeSat TT&C subsystems. A test facility with the capabilities to properly measure the performance of a VHF antenna is hard to find, as the frequency is relatively low (compared to UHF or S-band, the other common CubeSat communication frequencies) which means that a large anechoic chamber is required to provide acceptable results. A facility with the capability to test VHF antennas is unlikely to be available on university premises, and the student teams need to look elsewhere for this option, often joining long waiting lists for a test slot.

The lesson learned here is that planning for testing in Phase D should include a thorough review of test facilities available, making sure that their capabilities are adequate. Alternative test approaches, like performance testing of antennas outdoors using a development model, can also be considered.

Remote Access to Test Setups in the Clean Room

The ability to operate satellite hardware through a remote access connection from outside of the university premises was seen as a very valuable capability for teams in the FYS programme. During subsystem software development, FlatSat testing, and system level testing, the ability to interact with the hardware through the EGSE and a remote access connection allows student CubeSat teams many advantages. In the best case, this involves being able to fully operate the satellite while it is in the clean room and the students are at home.

This capability allowed team members to participate in hardware testing and development in a spontaneous and convenient way. Team members could begin or join ongoing work on the hardware without the need for a physical presence in the facility. The advantage of this was even more apparent during the COVID-19 pandemic, when access to many university facilities was limited. Student teams which were able to set up such a remote connection were able to continue making progress throughout the many months of restricted access to facilities. When only one team member could access the facility due to COVID restrictions, they could have another team member join remotely to serve in the produce assurance role during testing.

Remote access to the hardware setups also benefits long duration tests, such as mission testing, where operations on the hardware are occurring outside of normal working hours. Student teams were able to easily monitor their test results at any hour, without a requirement for physical presence in the clean room.

PROJECT MANAGEMENT

Rolling Schedules

Many student teams struggle to predict the duration of development and AIV activities. This is not an uncommon situation in long-term projects with many new developments, but in the case of student projects it is compounded by their lack of previous experience. This schedule slip is even more exaggerated in cases where there is not a fixed launch opportunity (in particular a launch date) defined for the project.

Throughout the programme, it was noticed that teams were frequently struggling to predict their schedules beyond a 2-4 month window into the future, often iterating over designs and tests multiple times, sometimes with the hope of improving results i.e. not accepting 'good enough'. In addition, major anomalies occurring during tests of flight or qualification models resulted in delays between one and five months in the schedule.

In the absence of other constraints, especially when there is not a launch in sight, the recommendation is to maintain granular schedules in the short-term and high-level work-packages with generous margins in the long-term. It is also recommended to keep open communications with regards to launch opportunities, test facility availability etc.

Activities Not Predicted Well in Schedules

While most of the teams prepared a reasonable AIV sequence for their system, the following activities turned out to be drivers of the schedule in the short term, causing overall delays in the schedule:

- Procurement activities and lead times
- Software and Firmware development, both in the flight and ground segment.
- Preparation of subsystem environmental testing (additional analysis, manufacturing of GSE) and subsequent redesigns triggered by anomalies.
- FlatSat configuration was extensively used for software debugging and validation, beyond what was predicted.
- The development and validation of AIT tools and facilities, such as
    - Test benches: FlatSat motherboards, Helmholtz coils, sun simulators, optical test benches, etc.
    - Ground Support Equipment (GSE): jigs, stands, power supplies, harness, hand tools, etc.
    - Cleanroom preparation to host the flight hardware
- Ground Station installation and setup for operation. Development of Mission Control software.
- Newcomers' on-boarding period, exams, and holiday slowdown.

Scheduling of CDR

The Critical Design Review (CDR) is the first formal review within the programme for which the teams document in detail the allocation of AIV activities for the system, subsystems, and units. The student projects are typically constrained by their own funding schemes, such that they choose to wait for the CDR to be passed before they begin the procurement of hardware. It is extremely common for anomalies to be discovered during testing once the hardware is eventually procured, which results in changes to the designs presented at the CDR. The changes to baselined designs result in delays to the project, and the lesson learned is to not push for an early CDR until prototypes of critical in-house developments have been demonstrated.

In future editions of the programme, an informal review will be organised upon acceptance to the programme to review the AIV plans for phase C and D. Teams will be encouraged to allocate funding to the development of prototypes for testing before the formal CDR starts, with the goal of significantly reducing the need for design changes after CDR.

Procurement Considerations

When planning procurement activities, there are four aspects that should be paid special attention to:

1. Third-party developments: At earlier stages of the project, teams may have decided to procure a product "in development". This puts the team at the mercy of someone else's delays, and this can result in schedule problems which teams have no control over. Developers should consider looking for qualified components, and flight heritage if possible; there should be a very good rationale to rely on third party developments.
2. Good communication with suppliers: Detailed information like lead time (from purchase order to delivery), option sheets, product qualification status / test reports, availability of datasheets and extensive user manuals, engineering support hours, etc. should be clear to the party procuring the product. It should be also understood if the documentation can be available before receiving the actual item so that the customer may familiarise themselves with all manuals and datasheets.
3. Funding administration rules: Universities and other public entities follow their own rules and approval loops before a purchase order can be sent to a supplier. Enrolling the support of experienced staff can help developers understand the administration cycles and avoid foreseeable issues.
4. Always when receiving an item, teams should carry out incoming inspections. As a minimum, visual inspection (for soldering quality, contamination) and verification of conformance to datasheet or purchase order (component placement, pinout connectors,

dimensions, mass, serial numbers, etc.) should be conducted. For more complex systems, additional acceptance tests shall be planned to verify the functions, electrical configuration, interfaces, etc.

The importance of the incoming inspection procedures was confirmed as teams uncovered quality issues in the COTS products received, e.g. poor-quality crimps, conformal coating application issues, damaged screws, incorrect connector size, incorrect machining of thread holes, etc..

Furthermore, teams also make mistakes in their purchase orders (incorrect components selected, specific instructions missing) and review of the design files/ option sheets are needed before the updated part is ordered. Conducting incoming inspection procedures enables the systematic checking of all arrived products and avoids delays. Having a second person review the order in the first place could help prevent the issues in advance.

One common practice is to procure three copies of inexpensive items: one to release for flight, one for testing/qualification and one spare. Once items are accepted, the cleaning and storage recommendations from the manufacturer shall be followed.

Loss of Expertise and Continuity due to Graduating Students

The reality of long-term projects run by student teams is that students will come and go from the project. This happens when students graduate, get internships, or other commitments interfere with their ability to contribute. The loss of student resources can create immediate and long-term problems for the project. In the short-term, it can mean that the project has lost expertise on a particular subject matter, or that ongoing developments are delayed while another student takes over the tasks of the departing team member. In the long-term, it might mean that there are difficulties re-running analyses which were done by departed team members, for example if there is a design update which changes the assumptions made in the initial analysis.

One of the leading causes of this issue is that optimistic project schedules may imply that the student will have enough time to complete and document their work before their planned departure from the team. If this schedule eventually is not met, a proper handover of responsibilities and expertise may not be completed to the standard that the team would hope for.

This problem is nearly unavoidable in educational CubeSat projects, but the impact of it can be mitigated. The important lesson learned here is that the project manager must make an active effort to manage the student resources and transfer of knowledge. There are many ways to approach this task.

An effort must be made to compare the project schedules with the academic plans of the students. It is valuable to anticipate the departure of students and be ready to recruit more students when needed. It is also common for teams to hire/provide a research grant for graduating students on a temporary basis so that they can complete a critical task.

One simple way to promote transfer of knowledge is to ensure that students are working in groups and communicating with each other. Ideally this involves overlapping the tasks of incoming students with experienced/departing students to allow for direct knowledge transfer. If students are working in isolation, it is inevitable that when they depart the team there will be a loss of expertise.

In parallel to the management of student resources, the CubeSat team should encourage the creation of documentation which can be used to trace what was done by past team members. This involves documenting more than just results from tests/analysis, but also established procedures, thought processes, research references, and meeting minutes.

Mission Authorisation Challenges

CubeSats, like all spacecraft, must obtain mission authorisation from their national government before they can be approved for a launch. The challenges associated with this process vary significantly depending on the national legislation.

Project managers for CubeSat teams should get as much information as possible on the applicable space laws for their mission to obtain the required mission authorisation within a reasonable time frame. Contact should be established with the relevant authorities as early as possible and maintained throughout the project lifetime.

Frequency Allocation and Coordination

Upon acceptance to the programme, teams are reminded of the importance of starting the international and national frequency allocation and coordination. Because of the risk of conflicts or coordination problems, and the risk that the relevant authorities may ask operators to apply changes to the radio system which may also result in additional costs, teams are encouraged to fulfil these obligations as early as possible.

PRODUCT ASSURANCE

Importance of Root Cause Analysis and Data Gathering During Development Model Testing

Anomalies that appear during development testing are prone to being discarded as part of the normal trial and error process that occurs during development, without any further investigation into the root cause of the issue.

This effect is to be (partially) expected in student teams, due to the lack of resources that prevent following up on every single issue. However, when the lack of documentation and root cause analysis surrounding early issues becomes systematic, it is more challenging to fix issues which resurface at a time when the teams are under strict timeline pressure.

When it is not possible to chase down every issue, due to lack of resources or time, it can be of great help to at least record as much data as possible about the early issues in a structured way, including the test parameters, observations, and pictures if relevant. The existence of such a database of early issues will contribute to a more effective prioritisation within the team of what issues should be analysed in detail, since it will make it easier for a team to know which issues have surfaced more than once and thus may warrant a careful look.

In the absence of an independent quality assurance responsible (typical in student projects), anomalies and adverse effects are often only superficially analysed, as students have sometimes not yet recognised the necessity of carrying out these tasks. At the occurrence of an anomaly, comprehensive root-cause analyses should be conducted, as problems might be hidden behind an initial high-level assessment which appears positive. The recommendation is to train oneself in observing anomalies, and to make design choices with a critical attitude.

Configuration control

From the experience of the FYS project team, the concept of configuration control is not fully understood, or not at all known, by university students' projects. It can be seen that teams sometimes have difficulties accepting "good enough" and thus continuing to iterate and optimise a concept, or the definition of a design, whenever there is the opportunity to do so. While this tendency may appear to be beneficial at first glance, the consequences of a never-ending design process is that configuration control becomes extremely difficult, if not impossible, to properly achieve. When the design meets requirements, then it is "good enough", and further changes should be well justified.

Good practice for configuration control is that all updates to a deliverable item (hardware, software, but also a report, a technical document, a plan, a technical requirement, etc.) are tracked and each updated version is assigned a configuration identifier. It is instead often the case that university students need to be reminded of the need to account for any change occurred in a baseline configuration since a previous issue of a certain deliverable. "Change to a baseline configuration" does not necessarily refer only to hardware changes, but also to variation from a previously defined operational concept, update of numerical models based on test result, a software function being updated, or change of plan (e.g., a test activity initially foreseen is not carried out anymore, or vice-versa).

Aside from maintaining a record of changes, configuration-controlled documentation helps newcomers get acquainted with the current status of the project.

The most problematic consequence of any change in the configuration baseline is the fact that any verification activity conducted until that point in time may be impacted or invalidated by the changes. This may in turn trigger delta verification activities. The experience in the FYS programme shows that students are tempted to hastily implement design change without fully considering the consequences, resulting in considerable headaches to solve in often already tight schedules. Furthermore, rushed changes may generate anomalies in other disciplines.

To conclude, it is recommend to never underestimate the value of having a "reviewed and approved" configuration baseline, achieved for example via a Critical Design Review process, and to always assess the consequence of applying a configuration change.

Cleanliness and Contamination Control

Not all the universities have the resources to enable hardware work within a certified cleanroom (e.g. ISO8). This may be a source of issues when the time to discuss a launch opportunity comes, as the main payload or the launch authority may impose strict cleanliness requirements on the CubeSat.

Wherever a cleanroom is not available, alternative solutions should be sought, such as portable cleanrooms, laminar flow test benches or restricted-access rooms with specific cleanliness provisions. The above shall be coupled with cleanliness and contamination control practices and cleaning prior to delivery. Tools that may be useful to conduct cleanliness inspections are a UV flashlight (to detect molecular contamination) and a white flashlight (to detect particulate contamination). To remove contamination, CubeSat developers may start with a single-hair brush to remove particulate contamination and wiping with appropriate chemicals for molecular contamination.

It is also recommended to keep systematic records of the cleanliness status of the hardware, including pictures prior to the assembly of units.

CONCLUSION

The FYS programme has collected in this paper some of the common issues FYS 2 teams faced, as well as suggesting approaches that any student team reading can follow to try to reduce the risks in their approach to CubeSat project development.

It is worth highlighting the fact that many of the lessons learned collected here are not only related to technical aspects but also to programmatic, managerial, and legal issues.

While a prospective CubeSat project team may at first be focused on the engineering challenge, it is essential for the project's success that a solid project management structure is eventually put into place, as many of the hardest obstacles to traverse will come in the form of problems with procurement, student turnover, documentation, legal, safety, and launch requirements.

The lessons identified here will feed back into the improvement of future Fly Your Satellite! cycles, from which many more valuable experiences will surely be gathered.

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