A selection of lessons learned from phase C/D of CubeSat projects of the Fly Your Satellite! programme

Alexander Kinnaird[1], Cristina del Castillo[2], Hasse Hansen[3], David Palma[4], Gilberto Grassi [5]

Abstract

Fly Your Satellite!" (FYS) is a recurring programme part of ESA Academy's portfolio of "hands-on" activities. The programme was established to support University student teams in the development of their own CubeSat missions and aims at transferring 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 standards, tailored to fit the scope of university CubeSat projects.

As part of the educational goal of the programme, a systematic effort of capturing, discussing and contextualising difficulties, mistakes, and anomalies in general, is carried out. From this effort, the participating students benefit from a unique framework where lessons learned from one project can be transferred to other ones. This exercise is blended with the "regular" transfer of knowledge from the ESA professionals that support the programme and occurs both concurrently (lessons learned from current cycles) and from previous projects (lessons learned from previous cycles).

This paper reports a revised and updated collection of lessons learned during phase C/D of the FYS CubeSat projects, in particular the projects now participating in the 2nd cycle (FYS2). At the same time potential changes and mitigating approaches are discussed.

Particular focus is given to lessons learned from issues which arose in hardware development activities, as well as from planning and execution of system-level assembly, integration, and verification (AIV) activities.

This approach is taken since first-time developers tend to underestimate the number of issues arising when their design is translated from documentation and models into real hardware. In general, it has been observed that many of these issues typically arise from lack of (space) project management experience of the student teams, or from the lack of resources which prevent the application of standard/established methodologies to small satellite/educational projects.

Keywords

Assembly, Integration, Testing, Verification, CubeSats, Education, Phase D, Phase C,

[1] Education Office, European Space Agency, The Netherlands, Alexander.Kinnaird@esa.int
[2] Aurora Technology B.V. for ESA - European Space Agency, The Netherlands
[3] Education Office, European Space Agency, The Netherlands
[4] Redu Space Services S.A. for ESA - European Space Agency, Belgium
[5] Redu Space Services S.A. for ESA - European Space Agency, Belgium

Abbreviations

AOCS	*Attitude & Orbit Control System*
CDR	*Critical Design Review*
COTS	*Commercial Off-the-Shelf*
ESA	*European Space Agency*
FAR	*Flight Acceptance Review*
FYS	*Fly Your Satellite!*
GEVS	*General Environmental Verification Standard*
LEO	*Low Earth Orbit*
LTAN	*Local Time of Ascending Node*
PFM	*Proto-Flight Model*
RF	*Radio-Frequency*
TVAC	*Thermal-Vacuum*

1. Introduction to Fly Your Satellite! 2

The second edition of the Fly Your Satellite! (FYS) programme started in 2017 with the selection of six teams: [3]Cat4, CELESTA, EIRSAT-1, ISTsat-1, LEDSAT, and UoS[3] .

The teams were supported through Phases C to E of typical satellite missions.

Phase C, known in FYS as "Design Your Satellite", focused on the consolidation of the CubeSat design and was concluded with a Critical Design Review (CDR).

Phase D1, "Build Your Satellite", focused on the production of in-house units and qualification of their engineering models. Different model philosophies and flatsats and "stacksats" were used to carry out various tests. Following subsystem development and qualification, the CubeSat is assembled and a Full-Functional and a Mission Test is performed.

Phase D2 "Test Your Satellite", includes environmental tests. Before being offered a launch opportunity, teams pass ESA's Flight Acceptance Review (FAR) demonstrating that the full system has been successfully verified, and that the legal and regulatory obligations are fulfilled.

At the time of writing, of the six selected teams, one has launched (LEDSAT, Aug. '21), and two have Flight Models Assembled (ISTSAT-1 and [3]Cat4) and one (EIRSAT-1) has completed Engineering Model qualification.

2. Introduction to Lessons Learned

Building upon FYS first edition, which was primarily focused on testing CubeSats at an advanced stage of development, the second edition of the programme has supported teams from the detailed design stage, enabling the identification of fundamental issues earlier when may then be addressed with reduced impact to the project cost or schedule.

This paper focuses on common problems identified in the second edition of FYS during the design, development and testing phases. These elements have informed the definition of subsequent programme cycles and have prompted the preparation of guidelines and webinars to help students in their work.

Team specific technical or managerial issues will not be discussed in this paper.

3. Systems Engineering Lessons Learned

3.1. Orbit compatibility analysis

Student teams often baseline their mission analysis to a specific orbit simplifying simulations and analysis. When launch opportunities present themselves, this can be a limiting factor as compatibility to different orbits is uncertain. This is compounded by the knowledge gap created when team members leave the project or if the project resources are dedicated to other critical issues closer to launch.

Mission analysis should reflect the full compatibility or flexibility to different orbital altitudes, LTANs and inclinations. This includes eclipse, power generation and energy budget, thermal analysis, AOCS simulations, Earth coverage, payload performance, ground station contact, link budget, orbital lifetime (in compliance with Space Debris Mitigation Rules), radiation, etc.

3.2. System Budgets

The preparation and maintenance of system budgets is a standard systems engineering tool used by most teams in the definition and detailed design of their system. However, students struggled to prepare detailed system budgets, resulting in undetected issues at the design stage. Points of attention were the misapplication of margin policies and the derivation of unnecessary requirements from the subsystem budgets.

Teams were thus requested to prepare budgets (power, data, link, pointing, etc.) for each CubeSat operational mode, to consider duty cycles, and to apply different margins depending on the maturity of the subsystem.

Having margin in the system budgets is beneficial to cope with changes in the design, remaining flexible to several orbits and to mitigate discrepancies between "as-designed" or datasheet values, and the "as-built" or "as-measured" characteristics and performances.

3.3. Requirement's definition

Defining good requirements for the mission is always a daunting task for students on a CubeSat mission, as this might be the first time, they convey the needs of the mission into a formal specification. Some patterns have been observed when students have prepared their technical requirements, such as reliance on external advisors' or project stakeholder's knowledge or derivation of requirements from COTS (Commercial Off-the-Shelf) datasheets. It is also typical that requirements are poorly formatted resulting into tricky situations when preparing the verification plan or if a specific COTS product is replaced.

The FYS programme tries to mitigate this issue by performing requirements reviews and explaining the importance of requirements as means of system design and verification. Teams are invited to conduct requirements workshops and to often revisit their technical specifications.

3.4. Operational Modes

The importance of a well-structured operational mode philosophy is found to be regularly underestimated or overcomplicated by CubeSat teams. A clear definition of all operational modes, their boundary conditions and the transition logic should be clearly defined at the design stage, to facilitate the identification of possible risks and flaws (e.g., loops).

The number of modes should be limited to avoid unnecessary complexity, and the difference between each mode should be evident: a parameter change, or subsystem status change should not necessarily be regarded as a different mode. Additionally, all possible modes and mode transitions should be tested, under mission conditions, in simulated scenarios and during environmental testing. This will limit any unexpected transitions and will aid in the characterisation of the performance of each mode and transition (e.g., temperature dependability of voltage-driven transitions).

3.5. Flexibility to launch requirements

CubeSats are most often launched as piggyback or secondary payloads and may be subject to late launch configurations changes. Teams should prepare to accept any change in requirements from the launch authority or the main passenger, including changes in the environmental levels, for example due to a configuration change.

A general recommendation for teams is to design according to the most demanding environment possible e.g., GEVS (General Environmental Verification Standard) [1] to envelope all the possible cases.

Additional needs from developers such as late access for battery charge or to replace short shelf-life items on-board are typically not included in the launch service, and reduce the possible launch vectors.

Furthermore, when considering a deployment from the ISS, teams need to be aware of the additional requirements imposed by the human spaceflight safety requirements, such as the safety certification of batteries which may affect budget and schedule

4. AIV Lessons Learned

4.1. "This is our flight model but not the model that will fly"

Many CubeSat teams adopt the proto-flight model (PFM) philosophy for its simplicity and theoretically lower cost.

For COTS subsystems, a single unit is procured in line with the reduced cost budget. In some cases, these units are either expensive or subject to long-lead times, creating risk. In these cases, additional protection and handling measures shall be taken to prevent unintentional damage during development and testing work.

For in-house developments, it was observed that soon after the (first) proto-flight unit was manufactured, a need for design iterations was identified due to insufficient performance or mistakes. In fact, development and engineering models were often not included in the AIV planning, with a belief that the first build would be correct. Therefore, it is recommended to plan from the beginning the use of prototypes, development, engineering and/or qualification models. This approach also allows early prototyping, testing and interface verification activities as a de-risking activity. Furthermore, it can sometimes be simpler to verify functionalities and performances by testing development or engineering models than by analysis.

4.2. Design for testing

As part of the FYS programme, teams are required to conduct the following tests at CubeSat level: Full Functional, Mission, Vibration and Thermal Vacuum-Thermal Cycling Tests. For these campaigns to be successful, the following considerations shall be made early in the design stage:

- Access to internal buses is possible via the umbilical connector with sufficient parameters to observe all the components and elements of the system including lines to charge the batteries.

- In TVAC (Thermal-Vacuum) it should be possible to switch on/off the CubeSat; how this affects the deployment switches logic should be considered.
- Internal thermocouples are needed during TVAC testing. Their installation, compatibility with the facility and routing and post-test passivation should be ensured.
- Effects of activating the transceiver inside the TVAC chamber. Routing of a coax cable through the flange may be needed.
- If possible, solar panels should have probe-points to conduct electro-luminescence tests after environmental testing. This allows the detection of cracks in solar cells not visible with the eye.

4.3. Preparation for testing

The preparatory work required to conduct testing activities is often underestimated by students. Prior to testing teams must:

- ready the item under test (procurement, manufacturing, and inspections),
- develop the firmware and software,
- develop and manufacture the Ground Support Equipment (mechanical and electrical),
- develop and validate the testbed,
- prepare written procedures.

Being aware of this asymmetry in the duration of preparatory activities vs. the actual test, already helps students to prepare more realistic schedules. For tests at external facilities, it is recommended that teams conduct a dry run before travelling to check that they have available all the tools and resources and as a sanity check for the test procedures.

4.4. Interfaces Verification

Frequent verification of the interfaces between different units or subsystems of the CubeSat is recommended. This includes:

- Mechanical fit-checks of parts.
- Incoming inspections and verification of conformance to purchase order or datasheet.
- Dimensions measurement. Especially for external units such as solar panels,
- Early mechanical interference check and with the primary structure and side panels, e.g. using detailed CAD.
- Harnessing design and fit-checks. Mistakes in cable lengths and connector angles have been found after manufacturing.
- Verification of electrical and data interfaces: correct commanding of power and data lines shall be part of the early functional verification activities.

4.5. Software, GSE, Operations and Ground Station

Software, GSE (Ground Support Equipment), Ground Station and Operations are activities typically overlooked during the design phase but are soon in the spotlight in phase D when hardware verification becomes the priority.

Hastily developed software and GSE is likely to result in anomalies during testing, or even later when the CubeSat is in-orbit. To prevent this, teams should assign a taskforce for this early in the project so that the development of software and GSE does not end up on the critical path.

Due to the relatively small size of university CubeSat teams, it may be advantageous to blend elements of software development with operations planning, thus facilitating the implementation of the operational needs and the automation of certain functions. A lean implementation of software may result into simplified and more robust operations: from data generation to on-board storage, RF encoding/ decoding, on-ground storage and data visualization, and back to spacecraft commanding.

4.6. Full Functional testing

The Full Functional test is requirement oriented and demonstrates the integrity of all functions, in all operational modes, redundancy paths and all foreseen transitions. The difficulty for teams has been preparing this test starting from slim and non-exhaustive sets of requirements. The AIV students have had to work hand-in-hand with the systems engineers to develop a comprehensive test procedure starting from the verification of basic and critical functions, modes transition, functional diagrams, software design, etc. Some teams have reported about the benefits of automating parts of the tests, e.g., repeatability.

4.7. Mission testing

The idea of a mission test is to “test as you fly”, following the expected operational plan after deployment in orbit. Defining the mission test procedures should therefore be done in parallel with the operations planning ensuring all necessary telecommands and sequences are verified and validated. Contingency operations should also be tested *in* the mission test, but even experienced student teams might find producing procedures for unpredicted issues in orbit difficult. Failure Detection, Identification, and Recovery should be verified, including testing of watchdog timers.

The temperature and pressure conditions between LEO (Low Earth Orbit) and the lab can cause unpredicted scenarios. While a full mission test may be difficult to carry out during TVAC testing a reduced mission test is still recommended to be carried out during TVAC.

4.8. End-to-End testing

End-to-End tests are recognised a useful tool to verify the full chain of command and downlink, demonstrating, prior to launch, correct functionality of the RF link between the ground segment and the space segment. Because the Ground Segment antennas are located outdoors and the CubeSat shall be kept inside the cleanroom, different test set-ups have been implemented:

- In-lab testing over short distances using attenuators to simulate the loss of signal expected in orbit.
- Long range, requiring specialised approached to keep the CubeSat in a clean environment during the test. Long distances tests also require direct line of sight, which requires careful planning.

4.9. Vibration testing

Vibration test is one of the essential environmental tests, verifying the CubeSat can withstand the mechanical environment levels seen during launch. During the system level test any fasteners may experience loosening if not properly tightened, leading to loose material moving freely within or outside the CubeSat. Use of the correct specified torque levels for each fastener is essential with “hand-tightened” not being sufficient. Secondary locking e.g., thread-locker, acknowledging difficulty in removal if needed.

Large shifts on resonance search (both in frequency and amplitude) are often results of parts dislodging or loosening during the test. Some systems may however experience a natural shift e.g., non-clamping deployers, and may settle during the vibration test. This may result in the test success criteria being violated, despite that the origin of the failure is not directly related to the CubeSat. Nevertheless, any shifts in frequency and amplitude should be investigated further to determine the origin.

4.10. Thermal Vacuum Cycling testing

TVAC tests are arguably one of the most representative test environments that the CubeSat will see before flying. Some teams opted to conduct subsystem thermal qualification as a de-risking strategy for in-house developments. Many anomalies were encountered due to individual components having different performance at temperatures other than laboratory conditions. In addition, the thermal cycles amplify any microcracks caused during vibration testing.

A bake-out at the maximum temperature allowable by the most sensitive component shall be foreseen during TVAC. Preferably, bake-out should be done at subsystem level prior to the system integration, enhancing the outgassing process by going to higher temperatures, and mitigating the risk of contamination to other components and/or the thermal vacuum chamber.

4.11. Shock testing

CubeSats rarely perform shock qualification as shock levels seen at the CubeSat-deployer interface fall typically below a certain threshold [2] and many COTs subsystem are already qualified. However, identifying any shock sensitive items [1] during the design phase to highlight potential risks is *still* highly recommended. While individual units may be shock tested if needed, PFM and FM system level shock testing is not advised.

5. Legal and regulatory Lessons Learned

5.1. Frequency Notification, Mission Authorisation

The administrative work related to the authorisation of a mission and the frequency coordination is often underestimated and delaying addressing them risks being non-compliant to the applicable laws at the time of the launch. Starting the process early was shown to be advantageous for FYS teams.

The use of radio frequency bands is strictly regulated and requires careful planning and coordination. While often wrongly assumed in the past, this also applies to radio-amateur frequencies [3].

National and international law applies and imposes requirements on satellite developers and operators. When a CubeSat is the first space object to be launched by a country, it is vital that team identifies, informs and collaborates with national authorities to identify or sometimes establish the processes to follow.

Some national laws also have insurance requirements for satellite owners/ operators, this must also be understood and addressed.

5.2. Space debris mitigation

International law and guidelines are applicable to CubeSats [4], and following the ESA guidelines is mandatory for participation in FYS. In addition to limiting the orbital lifetime to less than 25 years, space debris mitigations means no parts should intentionally detach from the spacecraft. Other requirements should be considered early in the design, such as the avoidance of fragmentation in case of battery explosion, passivation at end of operational lifetime, and limiting re-entry casualty risk.

6. Project Management Lessons Learned

6.1. Rolling schedules

An optimistic schedule is a common problem, even when margins are considered. Underestimation of development time of in-house hardware and/or software is often seen along with issues during tests. This can impact the schedule of the mission and can also affect the morale of the team. While unforeseen issues are, by nature, difficult to predict, anticipation of these in the schedule in the shape of correct margins is highly encouraged to the student teams.

6.2. Working with COTS

One of the benefits of procuring a COTS subsystem or unit is often the environmental qualification of the item has already been conducted. COTS products can also benefit student teams that might not have the necessary skills or facilities to develop in-house units. While in-house development provides a good educational opportunity, teams may perform a trade-off between the cost of the COTS product vs. development time and skills needed of an in-house product.

Using COTS products does have drawbacks, such as long lead times, especially with the current supply issues of semi-conductors. Moreover, while certain COTS have some degree of flight heritage, this does not mean that the product is flawless. The term flight heritage should be understood with caution as it may provide confidence in a products ability to “work out the box”. While it might have functioned as expected on a previous mission, the same result it not guaranteed for the next. Quality issues may still be present in COTS and inspections of all incoming products is highly recommended.

6.3. Team organisation

With a high rate of student turnover, teams can secure continuity in the project by involving a core team of PhD and Master students, who can support the handovers between students.

Good documentation is also key to a good handover. Sufficient documentation of the design and its justification prevents new students from reverse-engineering designs and facilitates their integration in the team. The predefined FYS data packages have shown to be a good starting point for the teams as they offer clear guidelines on the content and structure.

Involving University employees is also beneficial with crucial tasks such as securing funding, facilities, contacting authorities to deal with regulatory issues and liaising with the university administration.

A limitation that almost all teams suffer at some stage is not having coverage of all relevant areas of the space domain, hindering the development for certain subsystems and delaying the overall progress.

7. Conclusions

The second cycle of Fly Your Satellite! 2 has supported student CubeSat teams through the design, assembly, testing, and even launch of their CubeSats. During this process several lessons have been learned in different domains, but in particular throughout the Assembly, Integration and Testing Phase, primarily in the topics of system engineering, AIV, legal and regulatory issues and project management.

These lessons learned as used to inform further developments of ESA’s CubeSat programmes, and, crucially have demonstrated the participating CubeSat teams the importance of carefully planned and executed verification campaigns, planning and multi-disciplinary system design.

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