CubeSat Spatial Expedition: An Overview From Design To Experimental Verification

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Abstract. Over the past two decades, government space organizations have provided university-level inexpensive access to space that has prompted the design of miniaturized versions satellites for research scope: the "CubeSats". If on one hand, the standard specifications of this pico-satellite are widely defined to provide easy access to space for educational and research institutions, on the other hand, the design phases of the mechanical and electronic structures are however a very complex and delicate moment of fundamental importance for the success of the launch. The purpose of this document is to provide an exhaustive and critical picture, derived from a broad and in-depth literary analysis of all the critical phases to be faced in order to structurally verify a CubeSat 1U. Starting from the design phase, passing through the simulation and construction of the nano-satellite up to the effective execution of the experimental tests. The aim is to define a linear and efficient path underlining the possible errors and critical moments of the structural verification of a CubeSat.

1. Introduction
For a long while, the national space agencies were the only holders of the possibility of launching a satellite for a research scope and technology demonstration. This was mainly due to the huge funding requirements inhibited the initiation of such projects at the university level. During the last twenty years, the government space organizations had the idea of providing, at the university level, cheap access to space that prompted the design of miniaturized versions of satellites for research purposes: the "CubeSat". The reference design of CubeSat born in 1999 \cite{1} in a university environment by Professors Jordi Puig-Suari of California Polytechnic State University and Bob Twiggs of Stanford University. The goal was to use as a reference the first spacecraft, Sputnik to permit students to design, build and testing a real spacecraft. At first, CubeSat did not set out to become a standard, as it is today, it became standardized spacecraft over time. Today the aim of the CubeSats layout is to provide a standard for the design of nano-satellites to reduce development time, cost, risk and to intensify accessibility to space, increasing launches number. The young history of CubeSat, therefore, arises in a university context which, as we can see from figure 1 (whose data is taken from \cite{2}), is difficult to abandon. In fact, universities are still today the main launching institutions. The CubeSat Project counts a collaboration of more than 100 universities over the world.

CubeSat born as a little cubic shaped small satellite 10x10x10cm dimensions for 1.33kg, which is usually called 1-UNIT CubeSat. The design optimization study of these nanosatellites started
in 2011 immediately after their standardization. After 2013, by now the term "CubeSat" was coined to denote nanosatellites that adhere to the standards described in the CubeSat design specification and the multi-units CubeSat were used, or better, units that are geometrically multiples of the 1-U reference. As we can see in figure 2 the 3-U became early the most commonly used nanosat structure, principally because it represents the balance between cost and payload. Today, this multi-unit arrives at more than 700 units launched. The most of CubeSats are intended to use in low Earth orbit (LEO, about 400km from the sea level) to perform scientific research and explore new space technologies.

2. Launch Statistics ans Reference Standards

Albeit to Date, as shown in figure 3, more than 1210 Nanosats have been launched [3], however, anyone who decides to tackle in planning, building, and launching a CubeSat, have to take into consideration that the mission still requires considerable planning and many man-hours of work. Despite the initial emphasis on simplicity and low costs, who faces a CubeSat design and creation procedure have to address all the critical issues required for a spatial successful mission, from the external and internal mechanical design of the nanosatellite to the experimental test procedures.

Even if the upcoming launches demonstrate the growing interest of universities, companies, and government organizations to develop CubeSats to perform valuable scientific experiments and missions; we have to take into consideration that only 52% of the CubeSat launches (manufactured at University level) have success [4-5]. Definitely an increasing standardization helped maximize the chances for success. As for all space missions, including the CubeSat, the reference standards that guide the designers are mainly four:

- GSFC-STD-7000A (22/4/2019) [6]; The General Environmental verification standard for GSFC Flight Programs and Projects; written by NASA;
- ECSS-E-ST-32C Rev.1 (2008) [7]; Structural General Requirements, Publication Division ESTEC, The Netherlands;
Figure 2: Launches of the nanosatellites divided between the typologies [2]

Figure 3: Histogram representing the launches of the nanosatellites

- CDS-REV13 (6/04/15) [8]: The CubeSat Design Specification Rev.13 developed by California Polytechnic State University;
- BSI ISO 17770:2017 (31/6/2017) [9]: The Space systems- Cube satellites (CubeSat) published by the British Standard Institution.

Also, the choice of materials has fundamental importance for the design of aerospace structures. This is because the materials must not only have mechanical resistance requirements but, at the same time, specific post-treatments must ensure resistance to phenomena such as "cold welding" that are not present on earth, not all materials can be used in a vacuum. For
Figure 4: Standardized geometric parameters of CubeSat 1U [8]

these reasons further reference standards for materials must be reported:

- ECSS-E-ST-32-08C (2008) [10]: Space Engineering-Materials, Publication Division ESTEC, The Netherlands, published by ESA.

To these we must add the user guides, provided by the reference launcher. An example can be represented by the guide provided by one of the main launchers: ULA, in which all the official load profiles that are generated during the main phases of the mission ATLAS V are present:

- ATLAS V LAUNCHER SERVICES [11] - User’s Guide published by ULA.

3. Geometry, Materials and Cubesat Interface With Launch System

3.1. Geometric Constraints and P-pod Interface
CubeSat standards are tools that facilitate and encourage product engineering. The first fundamental step is to identify a correct geometry of the nanosatellite casing and all the internal supports that regulate the connection of the electronic boards, battery pack, payload, receivers and others; between them and with the external structure. CubeSat Design Specification [8] provides in a simple and standardized way the geometric parameters to be respected comply with the regulations and allow, at the same time, that guarantee the interfacial between the CubeSat and the launch device.

The simple interface between the launch vehicle (LV) and the CubeSat is guaranteed by a rectangular box with a door and a spring mechanism that is called Poly-Picosatellite Orbital Deployer (P-POD) and represent in figure 5. The P-POD is capable of carrying three standard 1-unit CubeSats stacked together and separated from each other by a series of small springs. Once the release mechanism of the P-POD is actuated by a deployment signal sent from the LV, a set of springs at the door hinge force the door open and the CubeSats are deployed by the mainspring gliding on its rails and the P-PODs rails.

The contact between CubeSats and P-POD is guaranteed by four sleds along which the CubeSat’s rails can slip easily during ejection into orbit.

3.2. Materials and Structure Design
Allowed and recommended materials by NASA e ESA [10] for the primary structures are four aluminum alloys: 7075, 6061, 5005, and 5052, whose classic mechanical characteristics are shown in Table 1; with the recommendation that the aluminum used on the structure which contacts the P-POD must be anodized to prevent cold welding. Other materials may be used for the structure if a waiver is obtained from the launch provider. The choice of material is linked to
the type of primary construction to be created. In fact, for the CubeSat 1U spacecraft more structural approaches exist. Most of the primary structures are usually machined from 6061-T6 or 7075-T6 aluminum (which mechanical parameters are summarized in Table 1) using modular structures (shown in figure 6a), where the PCB integration is typically accomplished through a stacked configuration. To maximize internal volume following a monocoque design is a viable way; where loads are carried by the external skin to the internal electrical component. In most cases, the structures monocoque are machined from Al 5052-H32 and that features a machined aluminum modular architecture designed to integrate with the P-pod; see figure 6 b) for their skeletonized 1U construction. To date, new research push to use composite materials such as CFRP (carbon fiber reinforced plastic) can be used in the structural design of CubeSat to reach the goal to have low mass and adequate strength [12-13-14]. The unusual materials must be tested to prove their structural capabilities before being used in a real spacecraft application [15]. However, in general, when new materials are used, the lateral support parts are made with them and never the slide devices, which remain an extremely important interface element. For spacecraft primary structures another new solution is represented by the use of additive manufacturing technique [16]. This solution has been proposed for several years, but only recently has this process is adopted to construct spacecraft secondary structural elements. As an example, the AM technique was used in [17-18] to print the CubeSat propulsion system. Only recently did they begin to see in the literature possible CubeSat prototypes whose primary structure is completely modeled in printed metallic material [13, 19]. It is however necessary very detailed knowledge of the AM materials to improve this practice [20]. Possible new construction solutions could soon be standardized figure 5c). ESA declares: “We’ve been looking into 3D printing using PEEK” [21] In this way, they open new frontiers to printable plastic materials, as a real evolution in terms of weight and resistance towards if compare it to the aluminum. Of these it knows in more detail material proprieties [22], they represent an inexpensive way to construct CubeSat supports for all the Universities.

In most cases the design phase of the primary and secondary structures of a CubeSat is an iterative process in combination with the secondary structures and with the other subsystems [23]. In these cases, it must be taken into account that the structure and the anchoring elements vary throughout the design phase. An alternative is to use already verified kits. Different companies provide CubeSat-dedicated structure subsystems: Pumpkin Space [24], Clyde Space [25] visible in figure 6a) and 6b) respectively and Enduro Sat [26] are examples. In this case the external structure remains fixed and leaves no room for structural optimization. On the other hand, however, these structures are guaranteed in terms of structural safety and compliance.
3.3. Interface with launch system

As previously mentioned, the nanosatellites are launched through the standardized interface P-POD that is also made up of anodized aluminum. This particular standard device is already space-qualified and guarantees a correct interface between satellite and launcher. The launch of such satellites is usually made as a tertiary payload (piggy-back), thus the P-POD interface is attached at the launcher’s mounting base, but it is possible to launch CubeSat in the space in a number of different ways. It can be a hitchhiker flying to space onboard a rocket whose main purpose is to launch a full-sized satellite we can see an example reported by [28] or it can be put into orbit from the national International Space Station figure 7. Today also air balloons can help to launch small satellites Leo Aerospace developed the first launch system called Regulus [30]. It is ready to start launching CubeSats in 2021. Leo Aerospace’s vehicle is designed for a typical mission of placing a CubeSat to 550 km sun-synchronous orbit [29]. The major kinds of P-POD can carry up to 3 CubeSats 1U or a combination of these. For the entire duration of the launch and in the first flight phase of the launcher, the nanosatellite remains inside the P-POD then is ejected by this with a linear velocity of about 0.3 [m/s]. For this reason, fully integrated P-PODs and CubeSat are tested as a complete integrated system to simulate as real as possible the real launch vehicle interface.

4. Cubesat Testing Philosophy

This paragraph is left with the task of illustrating all the aspects of the purely mechanical experimental qualification campaign (without taking into account the second part of the thermal experimental campaign) that the CubeSat must pass before its launch into orbit. By highlighting
for each step what are the possible modes of action for a correct design by critically comparing different solutions adopted in the literature. The mechanical design phase and the consequent experimental verification have two main objectives:

- ensure that all the elements can be contained in the structure (a common part for all launchers) which translates to: ”compliance with geometric conditions”
- reduction of risks (different part for each launchers) during the launch by the launch vehicle (lv), put in orbit by the dispenser (p-pod), life in spatial conditions

Analysis based on mathematical models that are representative of the structural behaviour helps the designer to assess how the design fulfils structural requirements and gives an insight on how to improve the design [31] and [32]. It shall be demonstrated that the mathematical models are adequate to perform the foreseen analysis and that the finite element mathematical models meet the requirements detailed in ECSS-E-ST-32-03.

4.1. Timing of the Tests
During the space qualification campaign, CubeSats must undergo a high level of functional tests to meet all launch provider requirements as well as any additional testing requirements deemed necessary to ensure the safety of the CubeSats, P-POD, and the primary mission. The module must be tested so that its vibrational values remain within the limit. The General Environmental Verification Standard [6] and MIL-STD-1540 are useful references when defining testing environments and requirements when the LV testing qualification levels are not known. However, the test levels defined in GSFC-STD-7000 and MIL-STD-1540 are not guaranteed to encompass or satisfy all. Table 2 resume this sequence of test. The launch provider testing requirements will supersede testing environments from any other source.

As we can see from figure 8, after the determination of the physical proprieties of the CubeSat, the pure mechanical qualification sequence consists of 3 basic steps: Qualification tests - Proto Flight tests - Acceptance tests. Each of which consists of a determined series of experimental tests at different levels of load intensity illustrate in Table 2. The flow diagram illustrated in figure 8 helps the reader to understand the correct timing of the tests to be carried out to arrive at the CubeSat unit ready to flight.
Table 2: Most used aluminum mechanical characteristics.

| Tests          | Qualification | Protoflight | Acceptance |
|----------------|---------------|-------------|------------|
| Sinusoidal     | +6dB Level    | +3dB Level  | Real Level |
| Random         | +6dB Level    | +3dB Level  | Real Level |
| Shock          | +6dB Level    | +3dB Level  | Real Level |

| Hardware Configuration | Qualification Unit | Flight Unit |
|------------------------|---------------------|-------------|
| Dispenser + CubeSat    |                    |             |

4.2. Verification of physical propriety

The mass properties report identifies the CubeSat’s total mass, the centre of gravity (CG), moments of inertia (MOIs), and products of inertia (POI) relative to each axis. Mass requirements for the 1U-CubeSat unit, should not exceed 1.33 kg. The centre of gravity should be located within 2 cm measured from the XY plane of the geometric centre in the Z direction see figure 4. The standard requirements declare that the CubeSat must have an access area on a side face to manipulate the inner parts of the satellite. Other geometrical limitations are well illustrated in figure 4. The rails must have a surface roughness of fewer than 1.6 \( \mu m \) and at least 75% of the rail contact the surface should be in contact with the rail P-POD [6-7-8].

4.3. Verification and validation Detail

If we go into more detail, both the Qualification tests and the Proto Flight tests have, in general, the same sequence of progress. figure 9 illustrates this sequential approach in more detail.

Figure 8: CubeSat General Testing Flow Diagram

Figure 9: Detail of sequence approach
4.3.1. Mechanical Functional Test (mFT) Usually, mechanical functional tests (also called resonance survey test) are performed before and after every major macro-area test (like Vibrational test), in order to check the evolution of the satellite mechanical and electrical behaviour during all the test campaign. If we are testing the CubeSat Qual Unit and an anomaly is found during a functional test, the information can be used to figure out the cause, fix the problem, and corrected the CubeSat to arrive at the Flight Unit. Then, in this case, it possible to be necessary to modify the CubeSat Qual unit and repeat tests to check for full functionality. The flight CubeSat unit not be disassembly or modify after the Proto-Flight testing. Resonance search is the best way to find the mechanical integrity of the system, for this reason, this test is used not only to find the lowest resonance frequency (which must be greater than a value dictated by the VL, typically between 50 and 100 HZ) but also to verify the integrity of the system [33]. In fact, the natural frequencies for the different run should not shift more than 5% [34] (in other restrictive cases 1% [12]), otherwise it may indicate a failure during one of the major mechanical tests, this technique, is normally used to predict the cracks start propagation. As we can see from figure 10 a modal analysis represents the best way to simulate this type of test. From Author’s literature study in most cases, the modal analysis is performed under free-free boundary conditions using shell and beam elements but simulated empty CubeSat structure [35]. In a few cases, the study is conducted on the entire structure including the electronic part[36]. In others, the latter is simplified by concentrated amasses capable of giving a truthful behaviour to the entire structure [12].

4.3.2. Quasi Static test A static test is needed to simulate the static load due to the acceleration of a rocket during all the launch. Typically, these loads are generally encountered at the end of the first-stage burn because of the weaker mass of the launcher for the same amount of thrust
Figure 11: NASA-provided Short Radius Centrifuge; Some VL acceleration load; preformation of quasi static test together with the sine vibration test with an electrodynamic shaker [34].

For this reason, it is important to remain in line with the LV specification in order to use an appropriate load. We want to underline that this study must consider the positioning of the satellite into the LV. The longitudinal axes “z” is considered from the ground and aligned with the longitudinal axis of the LV. Polar Satellite Launch Vehicle launch static load is 11g in “z” axis and 6g in both for “x” and “y” axes [38] for the SE01 CubeSat this value was fixed at about 8g for all axes [34], for the QB50 mission [12] the worst loading case was 13g applied at all three axes, for Ariane 5 VL the load does not exceed 4.55g and 1.15g respectively for longitudinal and lateral force; in the absence of data coming from the VL [35] the claims to use a value of 7g longitudinally and 1.5g laterally. Figure 11 resume some other VL acceleration load.

| Launcher | Long. [g] | Lat. [g] |
|----------|-----------|----------|
| Polar    | 11        | 6        |
| Ariane   | 4.55      | 1.15     |
| Atlas 5  | 5         | 0.4      |
| Falcon 9 | 6         | 2        |
| Vega     | 5.5       | 0.9      |

In some Activity to simulate this scenario, during the design phase, static FEM analysis was used in a very simple way, the static load is expressed as an equivalent acceleration applied at the centre of gravity of the system [34]. It is important, for this simulation to consider masses of the cards and the equipment belonging and model these. In many cases [34] they are modeled as point mass assuming that the satellite is fully loaded and they are connected to the related portions of the CubeSat frame via couplings. In other cases [12] hardware and software are modeled to simulate as real as possible the situation. The best solution to perform Quasi-static test is using a Radius Centrifuge (in figure 11 a view of a NASA-provided Short Radius Centrifuge at UTMB in Galveston). Some studies perform the quasi-static test (QAT) together with the sine vibration test [34]. To do a QAT with an electrodynamic shaker, the acceleration profile should briefly increase to the required amplitude, and come down again for frequencies much lower than the frequency corresponding to the dominant mode in longitudinal or lateral vibration. Figure 11 shows a typical input acceleration profile.

4.3.3. Sine vibration

This phenomenon occurs as a result of the interaction between modes of natural frequency of the launch vehicle and loads due to rapid growth in the breakaway pulse and combustion engines, whose loads are transmitted to the satellite through adapters and separation systems [39]. For LV Ariane 5 Sinusoidal vibration levels at the base of the
Table 3: Amplitude of sinusoidal test level [6].

| Sinusoidal vibration    | Frequency Range [Hz] |
|-------------------------|----------------------|
|                         | 5-100                |
|                         | 100-140              |
| Qualification level     | +6dB                 |
|                         | 10g                  |
|                         | 5g                   |
| Proto Flight level      | +3dB                 |
|                         | 3.125g               |
|                         | 1.5g                 |
| Flight level            |                      |
|                         | 2.5g                 |
|                         | 1.25g                |

spacecraft do not exceed the average value of 1 g in a bandwidth of 2 Hz to 100 Hz for both lateral and longitudinal directions [40], but for the Qualification level this value increase of a multiplication factor 4 (=+6dB). According to NASA GEVS: GSFC-STD-7000A standard [6] Table 3 shows the amplitude of sinusoidal vibrational test and the respective frequency range. The speed with which the spectrum must be swept is 2 oct / min, 5Hz - 140Hz; it will be repeated 3 times for each orthogonal axis. It is not sample to simulate the sine sweep procedure to reach the damage of the system [41] but in all the experimental application examined by the Authors no real damage occurs during this test. To perform this sine sweep test, all CubeSat teams used an electrodynamic shaker.

4.3.4. Random vibration  The structural response to vibro-autistic noise is predicted and measured in terms of random vibration. The first peak occurs at the moment of lift-off, but another important peak level occurs during transonic flight. Generally, this type of loads is expressed by PSD acceleration in a range of 20 to 2000 Hz. The figure 12 show spectral acceleration profile for different launch vehicles [42] compared with the Generalized Random vibration Test Levels defined by NASA [6] that are also summarize in the table. At the experimental simulation level, in most cases, the simulation is entrusted to a finite element code using its spectral response module analysis tool to evaluate the response levels of the system in terms of structural stress. At this level, it is also possible to carry out a fatigue damage analysis. In the articles taken into consideration by the authors, no one takes into consideration multi-axial phenomena that could occur [43]. From a more in-depth analysis, it is possible to deduce that it is very difficult for failure caused by fatigue to occur in the support structures [44] as it is possible to see from figure 13. A more careful analysis could instead be conducted on the internal boards of the system where this phenomenon can more easily cause breakage [35]. The experimental phase involves the use of an electrodynamic shaker for the test which is able to guarantee the determined spectrum of accelerations through a closed control. Each test must follow the amplification factors imposed by Table 2. A typical experimental setting is illustrated in figure 13. At the conclusion of this section a new mechanical functional test must be done to verify the structural integrity.

4.3.5. Shock Test  The shock test emulates the rocket stage separation event and the activation of the release mechanism of CubeSat into the orbit. The payload separation shock (of the spacecraft) is usually higher than other launch vehicle-induced shocks [45]. These instantaneous events can provide extremely high-acceleration levels (up to 100000 m/s²) lasting only a few milliseconds locally (10ms -20ms). Classical waveforms include half-sine pulse (haversine), terminal peak sawtooth, square wave, and triangle. The amplitude and duration of these waveforms are controlled to achieve the desired response. Most CubeSat designers use transient testing to simulate the effects of this short duration - high amplitude phenomena [34]. But
Figure 12: Spectral acceleration profile for different launch vehicles; Typical experimental setting.

Figure 13: NASA-provided Short Radius Centrifuge; Some VL acceleration load; preformation of quasi static test together with the sine vibration test with an electrodynamic shaker[34].

Shaping these transients requires considerable skill on the part of the designers and very often they do not lead to real modelling of the phenomenon, given the extreme complexity and variability of these. No single transient event is statistically representative of the overall field environment. In order to get acceptable data for test criteria, a large number of shocks need to be measured and some statistical averaging done to get a representative test profile. The use of the Shock Response Spectrum (SRS) generally produces a much more realistic simulation of transient events in the operational environment than do classical pulses [46-47]. Once a representative shock spectrum is determined it can be used as the test criteria. A word about
Figure 14: SRS for different CubeSat Launcher compared to the reference of NASA

the shock spectrum. This is undoubtedly the least understood aspect of vibration testing. [48] Shock spectrum plots are usually in Gs vs frequency on a log scale. figure 14 shows some SRS for different CubeSat Launcher compared to the reference of NASA given by [6]. The G levels on these plots do not represent actual acceleration responses. G levels on a shock spectrum plot are the computed responses of a simple mechanical system composed of a bank of idealized damped spring-mass systems that are excited by the waveform being analysed. Shock spectrum data provides a means of measuring the relative damage potential of transient pulses. As discussed for structure analysis, it is possible to perform experimental tests using different ways: most designers it using an electrodynamic shaker with a half-sine profile [34] other reproducing a time history that produces the set shock Response Spectrum [49]. In other case is possible to test CubeSat using a particular and expensive shock machinery that replace the shock test using a sleigh or catapults.

5. Conclusion
At the end of this document, an exhaustive and critical framework was created, derived from a broad and in-depth analysis of the literature of all the critical phases to be faced to structurally verify a CubeSat 1U. In this way it was possible to define a linear and efficient path (also highlighting possible errors and critical milestone of the verification) for the structural study and verification of a CubeSat 1U nanosatellite.

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