IMPROVING SYSTEM-LEVEL MECHANICAL QUALIFICATION OF CUBESATS

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ABSTRACT

The typical approach for mechanical qualification of CubeSats is to test the spacecraft directly integrated into a test dispenser, which is in turn installed on an electrodynamic shaker system. The test adapter should be representative, in terms of interface with the CubeSat itself, of the dispenser that will be used to deploy the spacecraft into space. However, it is often the case for CubeSats that the exact flight dispenser type is not known until late in the project, sometimes after the (proto-) flight qualification campaign. This, coupled with the advent of dispensers with different interfaces available off the shelf, such as, for example, clamping dispensers, requires that special considerations should be undertaken upon test preparation and before, at analysis stage.

The fundamental issue is that the transmissibility of the dispenser alters the loads that are specified by the launch vehicle user manual, affecting the qualification requirements and the representativeness of any tests. Previous investigations [1] have shown that clamping deployers provide a more predictable loading environment but with amplification of some loads at the CubeSat interface. Non-clamping deployers, on the contrary, seem to dampen the loads but other drawbacks may occur, such as a non-linearity of the test setup, which renders testing more complicated, and fretting corrosion on the CubeSat rails. Furthermore, if the actual dispenser transmissibility was not accounted for during system-level verification by analysis (i.e., structural finite-element analysis), unexpected loading conditions may occur within the satellite structure during testing and/or during launch. Consequently, structures may be oversized to account for conservative factors of safety or, without sufficient margins, undesired effects may occur.

This paper discusses the issues of system-level mechanical qualification of CubeSats and proposes new approaches to test campaigns for CubeSat projects where the flight dispenser is not known in advance. Also discussed are the implications that this has upon system verification by analysis. Lessons learned from (proto)flight qualification campaigns performed are addressed, as well as the outcome of specific investigations conducted to support the above conclusions. Finally, some technical solutions to improve the effectiveness of system-level mechanical testing on CubeSat are proposed.

LIST OF ACRONYMS

CDR	Critical Design Review
ESEC	European Space Security and Education Centre
FD	Flight Dispenser
FEM	Finite Element Method
FLL	Flight Limit Loads
GEVS	General Environmental Verification Standard
IUT	Item Under Test
MPE	Maximum Predicted Environment
NRCSD	Nanoracks CubeSat Deployer
P-POD	Poly-Picosatellite Orbital Deployer
PSD	Power Spectral Density
PSL	Picosatellite Launcher
RMS	Root Mean Square
SSMS	Small Spacecraft Mission Service
TD	Test Dispenser
VEGA	Vettore Europeo di Generazione Avanzata

1 INTRODUCTION

The concept of CubeSats has evolved from a framework where it was exploited mostly by amateurs and students, to a stage where the simplicity of use paired with the large availability of ready-made products and knowledge is appealing to professional and governmental entities. The CubeSat mission is, in fact, not necessarily seen as a high-risk project anymore, and increasingly more effort and resources are being invested on such. In other words, the quality of CubeSat projects is overall increasing and can be compared to the levels sought or achieved in micro- or mini-satellite projects. The risk of under- or over-qualification is therefore less acceptable than in the past and more care is dedicated to ensuring that a product is adequately verified and qualified.

2 QUALIFICATION ENVIRONMENT

The qualification requirements are usually specified at the satellite interface by the launcher user manual. The specification is in terms of random, acoustic, shock, sinusoidal, and quasi-static loads. Generally, the most critical mechanical environment for a CubeSat is the random vibrations (20-2000 Hz range), therefore for the sake of the discussion we will refer to this type of environment from now on.

The topic of qualification of CubeSat hardware is often a reason for discussion. An element of confusion appears when selecting the approach for design verification at system and subsystem level. A typical approach is to adopt the GEVS levels [1] for random vibration, as this specification envelopes most of the random vibration profiles defined by currently available launch vehicles. Some prefer to take a conservative approach and specify the GEVS as required for system-level qualification, and design accordingly. Taking this approach, however, may mean that the specifications for qualification of equipment and units become very strict, as generally the loads increase when moving to lower levels, and the GEVS may be considered already a conservative specification. A different approach is, instead, to consider the GEVS as a specification that is well suited for equipment qualification and to define a less conservative specification at system level, but the determination of that system-level specification can be challenging unless there is good confidence on what launcher will be used for the mission (cf. Figure 1). This can be problematic as in CubeSat projects the launcher is typically only determined at a late stage of the development lifecycle.

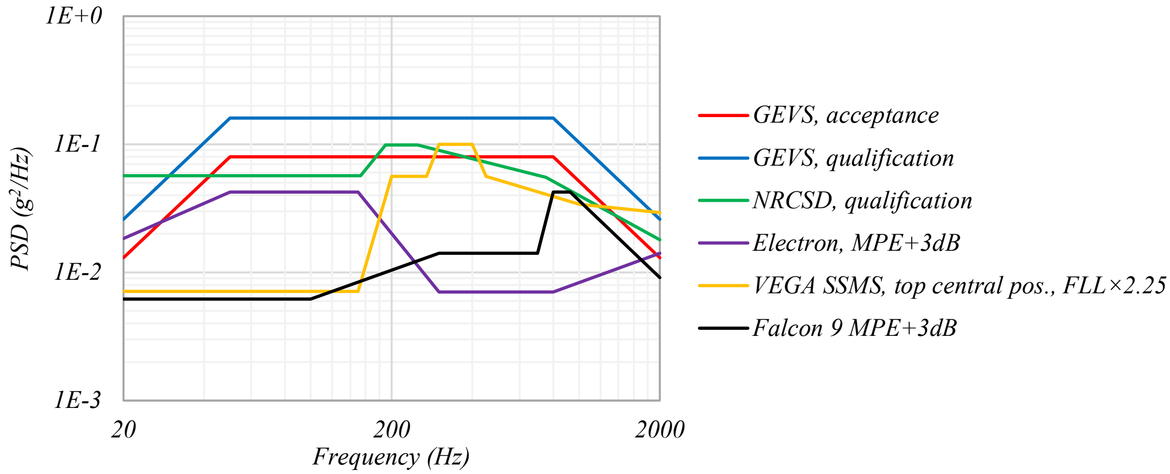

Figure 1: Exemplary random vibrations environment specification for different launch authorities [3][4][5][6].

3 EFFECTS OF CUBESAT DISPENSER

When addressing the mechanical qualification of CubeSats, the typical implementation is to test the spacecraft directly installed on a CubeSat dispenser, which is in turn installed on an electrodynamic shaker system (cf. Figure 2), as this approach allows to recreate the dispenser-CubeSat flight configuration and follow the "test as you fly" logic.

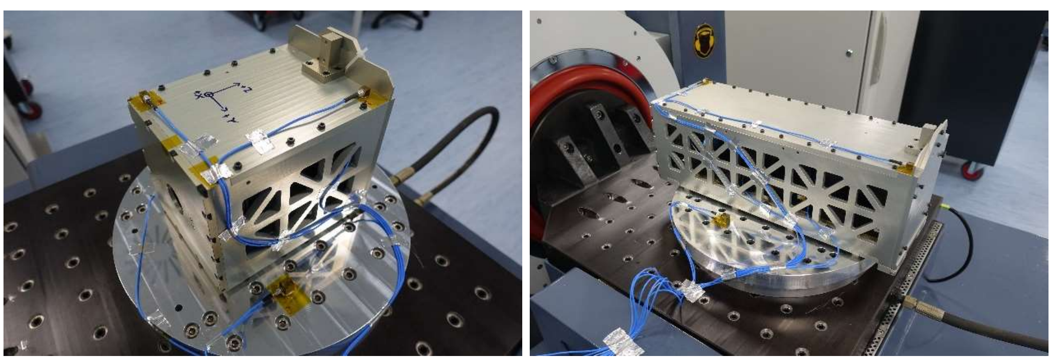

Figure 2: Generic CubeSat vibrations test setup. Above: 1U test. Below: 3U test.

Once the test setup is defined and the most appropriate environmental requirements specification identified, another problem arises. On 'standard' spacecraft project it is a well-consolidated approach to verify the spacecraft directly against the identified environment, this being normally specified directly at the spacecraft-launcher interface. For CubeSats the approach has traditionally been the same, however it is to be noted that the environmental requirements specification often only directly applies to the CubeSat dispenser, and it is not necessarily true that the same levels are transmitted to the CubeSat itself. It is important to understand that the CubeSat dispenser has its own structural characteristics and modes of vibration. As a result, the loads received by the CubeSat installed within the deployer assembly may be different from the original baseline requirement specified by the launch authority. It is therefore clear that, to have a meaningful design verification, the assumptions adopted to inform the structural analysis and later the test activities shall necessarily include information also on the CubeSat dispenser.

It is to be remarked that, while the CubeSat standard specifies the CubeSat physical properties such as mass and dimensions with accuracy, the same does not apply to the CubeSat dispensers. Several alternative solutions, each with different features, are available on the market; each solution works in a different way and thus how the loads are transmitted to the CubeSat differs. Specifically, a large influence on the mechanical behaviour is given by how the dispenser is interfaced with the CubeSat. The two most common solutions available are the following.

1. "Free" constraint (cf. Figure 3, left): the dispenser has a loose housing of the CubeSat, in a way that there is a residual gap between the CubeSat rails and the dispenser. This is the solution adopted for example on the P-POD dispenser from CalPoly (US) [7] and the ISIPOD by ISISpace (NL) [8].
2. Clamped interface (cf. Figure 3, right): the dispenser effectively clamps the CubeSat in a way that there is no residual gap unlike in the previous case. This solution is adopted for example on the PSL dispensers produced by Astrofein (DE) [9] and on the ExoPod by ExoLaunch (DE) [10].

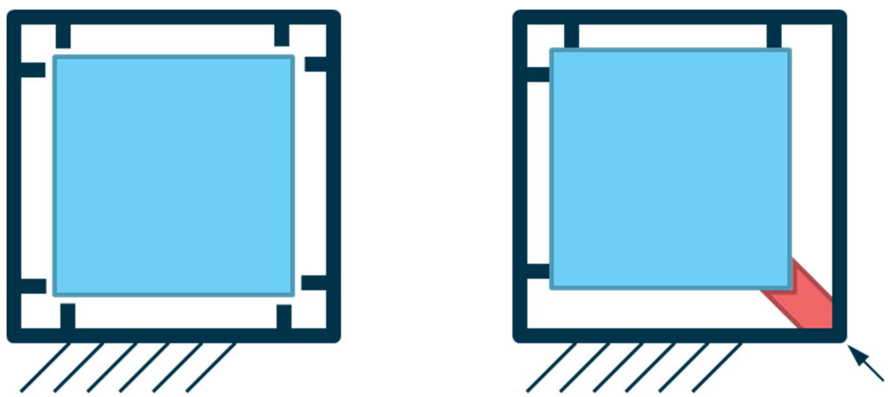

Figure 3: left: "free" constraint; right: clamped interface

Both solutions have different characterises related to mechanical qualification, as outlined below.

With the "free" constraint, deployer-satellite assembly is strongly non-linear, since the CubeSat has some residual mechanical play inside the dispenser. It is therefore difficult to predict the loads that the CubeSat will experience. It also becomes more difficult to characterise the structural behaviour of both CubeSat and dispenser at test stage, and it is not possible to rely on a Low-Level Sine test (also known as resonance search) to evaluate the absence of damage and to evaluate the dynamic behaviour of the CubeSat itself. The repeatability of a test is also questionable, as by not controlling the interface, the setup will behave in slightly different ways depending on how the CubeSat settles within the housing. The gaps will also allow for sliding of the CubeSat during the test, which may result into damage on the surface of the CubeSat rails from fretting and impacts, as shown in Figure 4. This kind of damage may increase the risk of cold welding between the CubeSat rails and the flight dispenser under vacuum conditions [11]. Nevertheless, dispensers with the free constraint may result more attractive for CubeSat developers for providing a milder loading environment, as shown by Pignatelli et al. [1], and for being devices that are cheaper, simpler to operate, and have potentially higher availability.

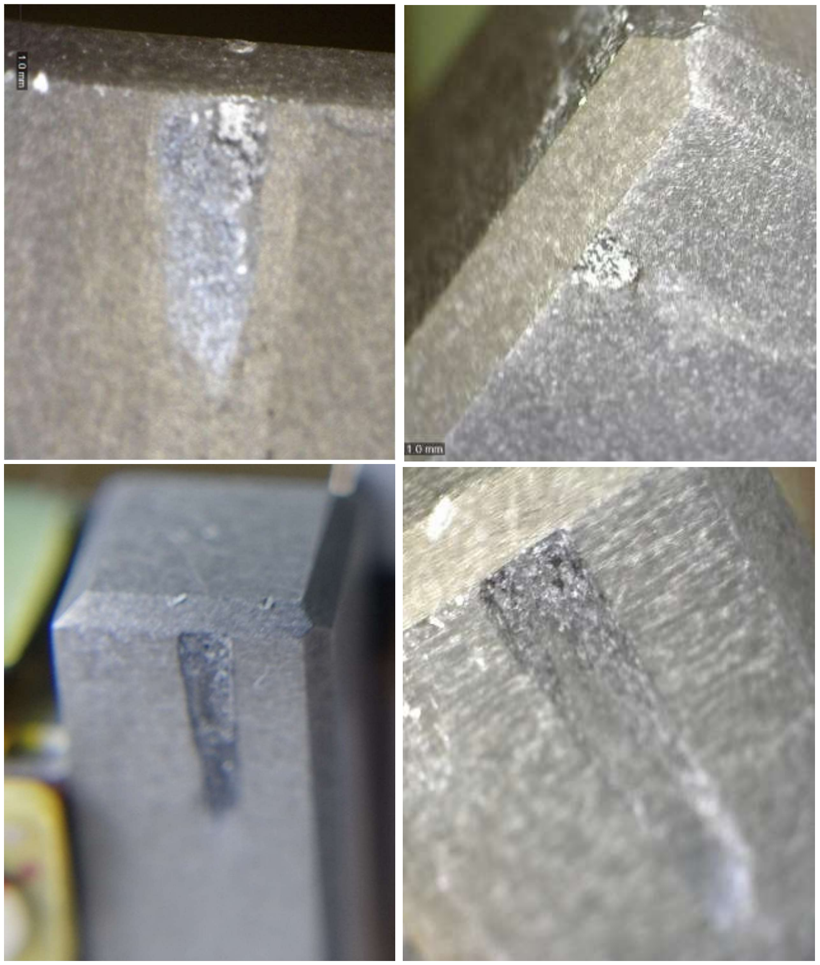

Figure 4: Damage from impacts (top left, top right) and fretting (bottom left, bottom right) observed on LEDSAT upon proto-flight qualification testing on a dispenser with "free" constraint.

Clamping dispensers provide a more linear assembly than in the previous case, but on the other hand, the loading transmitted to the CubeSats in this configuration may be considerably higher than on those with "free" constraint.

Pros and cons of each solution are recapped in Table 1.

Table 1: Pros and cons of "free" and clamped CubeSat dispenser interface.

Type	Pros	Cons
Free	Milder loading environment.	The setup is strongly non-linear.
	Easier to use.	Risk of fretting and impacts on structure.
	Simpler and cheaper device.	Test not necessarily repeatable,
		Difficult to predict the loads on the CubeSat.
Clamped	Test setup is linear.	Higher loading environment.
	Test more repeatable.	More difficult to operate.
	Easier to predict the loads on the CubeSat.	More complex and expensive device.

4 ACCOUNTING FOR DISPENSER TRANSMISSIBILITY

Let us consider a generic CubeSat vibration test setup such as the one displayed in Figure 2 and schematised in Figure 5. Assuming a random vibration solicitation with a Power Spectral Density equal to $S_{\text{in}}(f)$ is injected at the base, an accelerometer installed directly on the CubeSat under test will measure a certain output signal of PSD equal to $S_{\text{out}}(f)$ (cf. Figure 5).

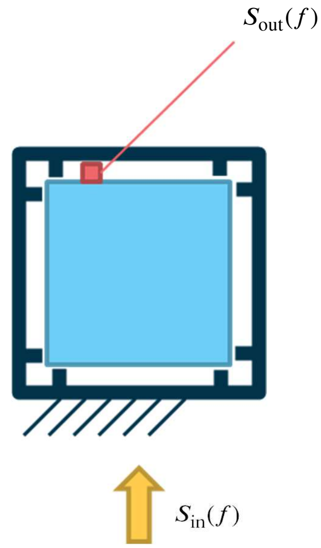

Figure 5: CubeSat vibrations test schematics.

Let us then define the transmissibility function $T(f)$ as indicated in (1).

$$T(f) = \sqrt{\frac{S_{\text{out}}(f)}{S_{\text{in}}(f)}} \tag{1}$$

$T(f)$ is a function of the frequency as at different solicitation frequencies the module of the transmissibility will be different. Furthermore $T(f)$ is a characteristic of the assembly being tested, and it is affected by factors such as mass of the CubeSat, configuration of the IUT (e.g., 1×3U vs. 3×1U), the actual size of the CubeSats and the dispenser model dynamic behaviour (natural frequencies, damping and mode shapes), and the loading direction.

In particular, the common assumption in the CubeSat community, that tests on 'similar' test dispensers may be considered interchangeable, is not correct, as different dispenser models will yield different loading to the CubeSat being tested; it is also not correct a priori that a test dispenser has the same transmissibility of a flight dispenser from the same supplier. This was demonstrated via test conducted at the ESA Education CubeSat Support Facility in ESEC-Galaxia (Transinne, Belgium): different test cases were executed on two different CubeSat dispenser models (cf. Figure 2) as reported in Table 2, employing mass dummies instead of actual CubeSats. Both the dispensers used in this case employed the "free" constraint, therefore a test on a clamping dispenser may yield generally higher levels on the CubeSat, given the same input specification.

Table 2: Test cases.

Case	Dispenser model	Axis	CubeSat
1z	1U ISIS testPOD	Z	1×1U
1y	1U ISIS testPOD	Y	1×1U
2z	3U ISIS testPOD	Z	3×1U
2y	3U ISIS testPOD	Y	3×1U

The measured $S_{\text{out}}(f)$ on the CubeSat mass dummies in the different test configurations is plotted in Figure 6 and Figure 7. It is easy to observe that the CubeSats see different loads in each different case and therefore the transmissibility function is different for each case presented in Table 2.

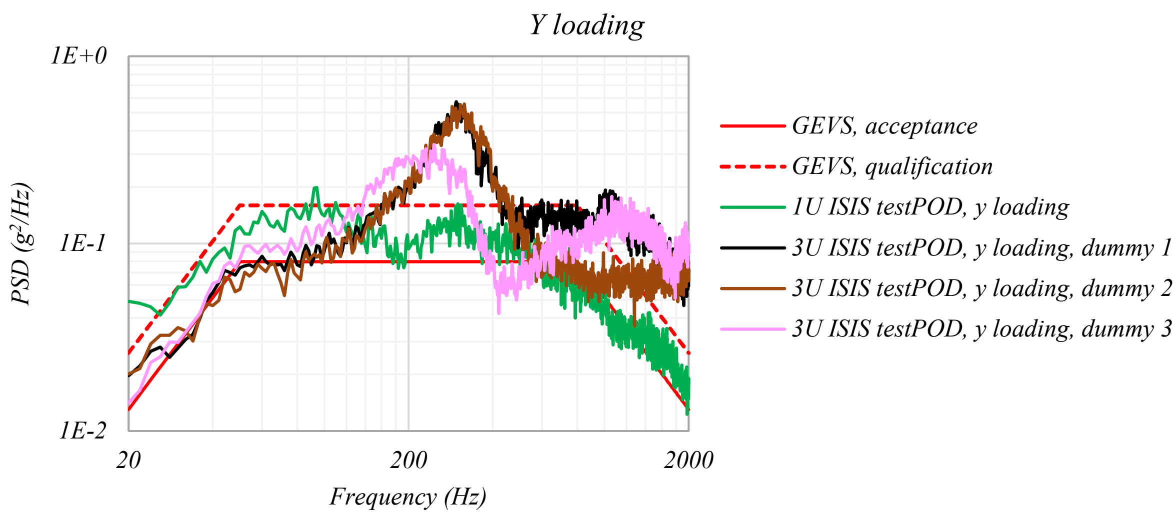

Figure 6: Measured $S_{\text{out}}(f)$ on CubeSat mass dummies in different test configurations. Excitation axis: y (dispenser's lateral direction). Measurement done on the same loading direction. Input $S_{\text{in}}(f)$: GEVS, acceptance.

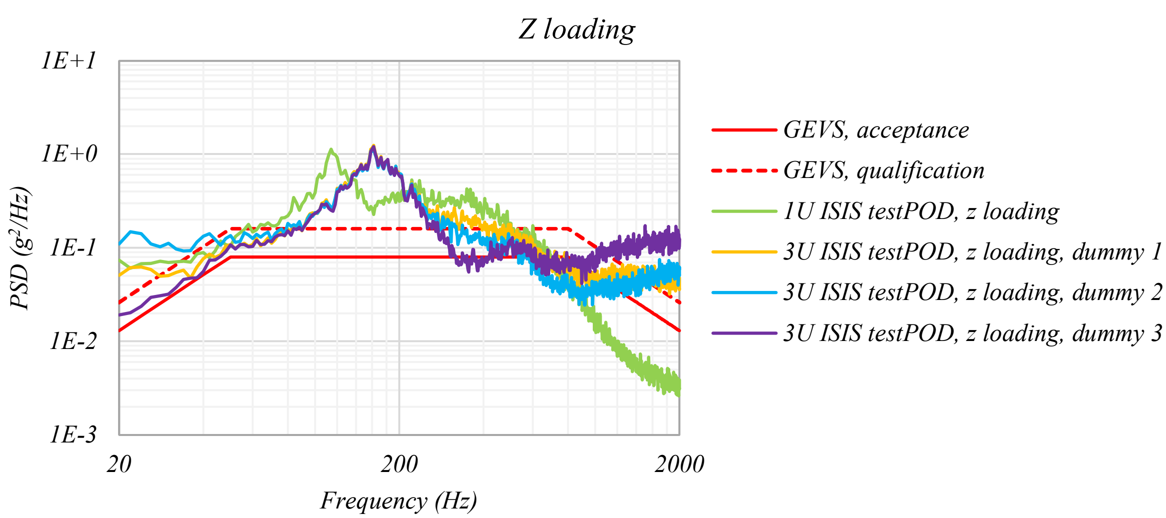

Figure 7: Measured $S_{\text{out}}(f)$ on CubeSat mass dummies in different test configurations. Excitation axis: z (dispenser's longitudinal direction). Measurement done on the same loading direction. Input $S_{\text{in}}(f)$: GEVS, acceptance.

From the tests above, we further observed that the CubeSats being tested generally receive a higher loading than that being injected into the assembly; this loading is furthermore well above the qualification margins and safety factors which should cover the model uncertainties. The overall g_{rms} values associated to the measured signals in each case presented in Table 2 in are reported in Table 3.

Table 3: Computed g_{rms} values for $S_{out}(f)$ curves plotted in Figure 6 and Figure 7.

Case	**Description**	g_{rms}
-	GEVS acceptance	10.0
-	GEVS qualification	14.1
1z	1U ISIS testPOD, z	13.8
1y	1U ISIS testPOD, y	10.7
2z	3U ISIS testPOD, z, dummy 1	14.9
	3U ISIS testPOD, z, dummy 2	14.0
	3U ISIS testPOD, z, dummy 3	16.1
2y	3U ISIS testPOD, y, dummy 1	16.6
	3U ISIS testPOD, y, dummy 2	14.6
	3U ISIS testPOD, y, dummy 3	15.1

In terms of output PSD, the CubeSats see at certain frequencies, amplification peaks that can be up to 10 times the input loading. These peaks may be explained by a coupling of a mode of vibration of the dispenser with an actual translational mode of the CubeSat inside the dispenser, as depicted in Figure 8. It is to be remarked that the frequency at which peaks occur is not necessarily coinciding with the first mode of the CubeSat dispenser, but it is instead at slightly lower frequencies. Detailed FEM analyses are needed to fully explain these amplification peaks and what factors affect their characteristics.

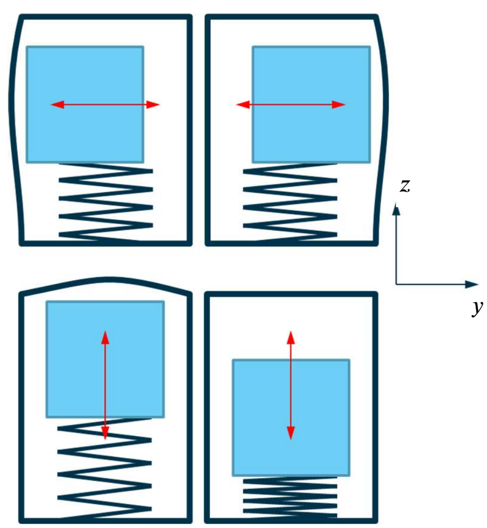

Figure 8: Translational modes of the CubeSat within the dispenser.

It is therefore clear that designing a CubeSat system by simply assuming the launch loads as specified by the launcher user manual is not sufficient, and any dimensioning effort should address conservatively the transmissibility of the dispenser.

5 DESIGN VERIFICATION BY ANALYSIS

Early verification of design requirements is typically conducted with the support of a structural analysis via the Finite Element Method (FEM). The conditions considered for the analysis should be conservative enough to meet the requirements with sufficient margin.

Considering a random vibration specification $S_{\mathrm{sp}}(f)$ assumed applicable for a certain CubeSat, and assuming that the flight dispenser to be used has a known transmissibility function $T_{\mathrm{FD}}(f)$, the loads that the CubeSat will experience during flight are $S_{\mathrm{f}}(f)$ computed simply as indicated in (2).

$$S_{\mathrm{f}}(f) = T_{\mathrm{FD}}^2(f)\, S_{\mathrm{sp}}(f) \tag{2}$$

It is therefore sufficient to analyse the system by applying the new $S_{\mathrm{f}}(f)$ specification directly on the CubeSat structure to account correctly of the effect of the dispenser. We remark that $T_{\mathrm{FD}}(f)$ should *not* replace a qualification margin, which should be included on top of this specification together with uncertainty factors as applicable.

Unfortunately, in most of the cases, the $T_{\mathrm{FD}}(f)$ function characteristic of the flight dispenser is not known in advance. It is of course recommended, in case the flight dispenser is available, to conduct characterisation tests to determine empirically $T_{\mathrm{FD}}(f)$, as suggested also by Pignatelli et al. [12]. This is however not possible in most cases, as the flight dispenser model is typically identified and procured only at late stages of the projects, in any case well beyond CDR stage.

It is therefore necessary to make some conservative assumptions to ensure that the design requirements are met with margins. An approach could be to assume $T_{\mathrm{FD}}(f) = \hat{T}(f)$ as defined for example in Table 4 and plotted in Figure 9.

Table 4: Values for $\hat{T}(f)$. The values hereby assigned are resulting from the test results outlined in Figure 6 and Figure 7. Of course, they may be customised on a case-by-case basis depending on the margin that one may want to assume.

Frequency (Hz)	$\hat{T}(f)$
20	1
100	1
130	$\sqrt{5}$
2000	$\sqrt{5}$

The reason for such definition of $\hat{T}(f)$ is that for low frequencies, and until the first natural frequency, the assembly behaves as a rigid body, therefore the loads are in practice identically transmitted to the CubeSat. Furthermore, in CubeSat and CubeSat dispensers, the minimum fundamental frequency is typically required by several launch authorities may be as high as 130 Hz; it is therefore reasonable to assume that amplification of the loads occurs from 130 Hz and above.

The application of $\hat{T}(f)$ or similar allows to account the resonance peaks of the dispenser-CubeSat assembly as discussed in the previous section. It is nevertheless clear that such an approach may be conservative. As an example, Figure 10 reports the GEVS levels (acceptance) modified by $\hat{T}(f)$.

The overall RMS value of the acceleration becomes, in this case, 21.7 g_{rms}. This number should be compared with the RMS values reported in Table 3. We remark nevertheless that the values hereby assigned to $\hat{T}(f)$ may be customised on a case-by-case basis depending on the margin that one may want to assume.

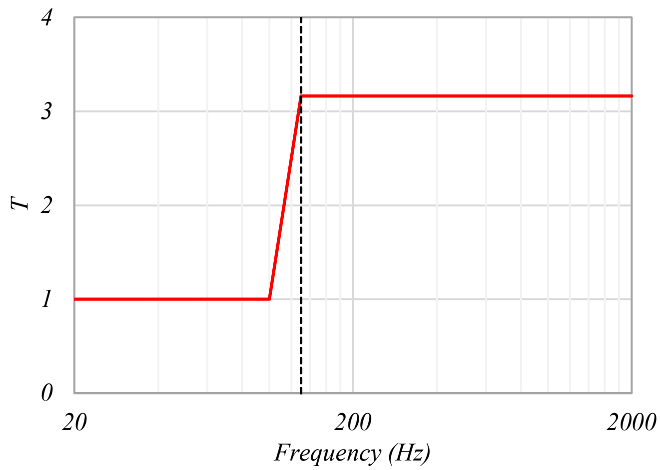

Figure 9: $\hat{T}(f)$. The 130 Hz abscissa is marked with a dashed vertical line.

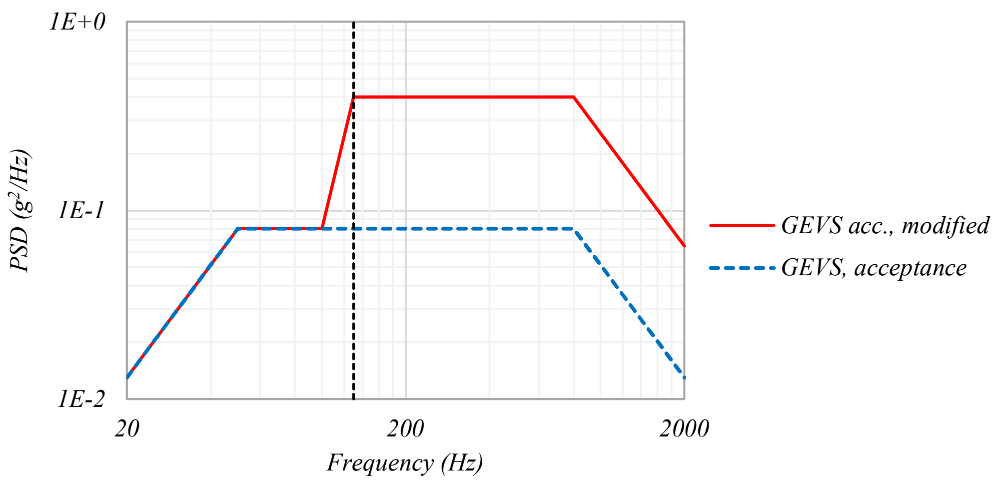

Figure 10: $\hat{T}(f)$ applied to GEVS levels (acceptance). Overall levels, 21.7 g_{rms} against 10.0 g_{rms} of the GEVS (acceptance). The 130 Hz abscissa is marked with a dashed vertical line.

6 DESIGN VERIFICATION BY TESTING

Having discussed the analysis, the approach for qualification and acceptance testing in case a representative dispenser is physically not available, comes as direct consequence. Considering a random vibration specification $S_{\mathrm{sp}}(f)$ assumed applicable, assuming that the flight dispenser has a known transmissibility function $T_{\mathrm{FD}}(f)$, and that the test dispenser has known transmissibility function $T_{\mathrm{TD}}(f)$, the test levels $S_{\mathrm{t}}(f)$ should be derived from the specification $S_{\mathrm{sp}}(f)$, corrected to account for both the flight dispenser and test dispenser transmissibility, as indicated in (3).

$$S_{\mathrm{t}}(f) = \left(\frac{T_{\mathrm{FD}}(f)}{T_{\mathrm{TD}}(f)}\right)^2 S_{\mathrm{sp}}(f) \qquad (3)$$

In this way the transmissibility of the test dispenser is decoupled from the verification activity and the CubeSat is subjected to the correct power spectral density to be experienced during flight. Also in this case, applicable qualification margins should be included on top of $S_t(f)$ to correctly account for the worst-case scenario.

In case $T_{TD}(f)$ and/or $T_{FD}(f)$ are not known, they may be requested from the test dispenser supplier, or determined via a dry run or characterisation test before confirming the test specification.

As an example, by assuming $T_{FD}(f)$ and $T_{TD}(f)$ as reported in Figure 11, $S_t(f)$ and $S_f(f)$ are computed from the GEVS, acceptance as plotted in Figure 12.

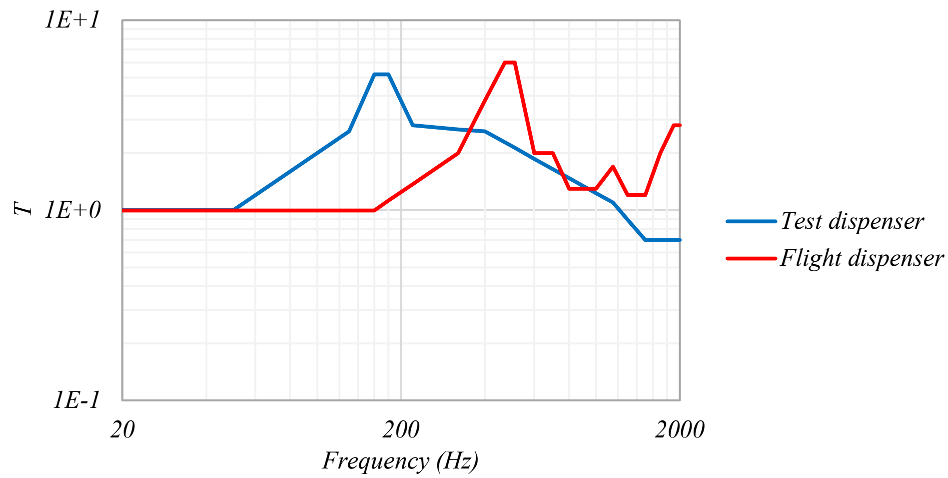

Figure 11: Example of $T_{TD}(f)$ and $T_{FD}(f)$.

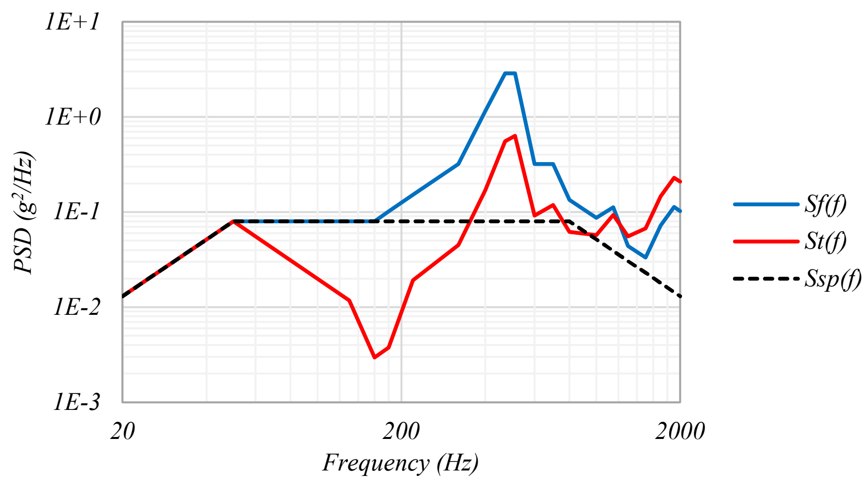

Figure 12: Example calculation of $S_t(f)$ and $S_f(f)$ by assuming $S_{sp}(f)$ equal to the GEVS levels (acceptance) and $T_{TD}(f)$ and $T_{FD}(f)$ as per Figure 11.

It is remarked that, of course, in case the flight dispenser is available for testing, its use should be preferred; in such case, there is no need to adjust the input levels as $T_{FD}(f) = T_{TD}(f)$ and (3) simplifies to $S_t(f) = S_{sp}(f)$.

7 IMPROVING TESTING

This section proposes solutions to improve the verification approach in case the flight dispenser is not available for testing.

7.1 Removing the test dispenser transmissibility

From the observations made above and the example in Figure 12, one may consider removing the test dispenser from the loop completely and replacing it by installing the CubeSat directly on a rigid test fixture that prevents coupling and amplification of the loads on the CubeSat (cf. Figure 8). In this way, defining the test specification is easier as the transmissibility of the test dispenser in the relevant frequency range is equal to 1, and therefore (3) simplifies to $\hat{S}_{\mathrm{t}}(f) = S_{\mathrm{f}}(f)$, with $S_{\mathrm{f}}(f)$ defined by (2). The uncertainties associated with the test dispenser are therefore removed and it becomes easier to define and control the levels injected on the CubeSat structure.

This approach however comes with the drawback that if fretting and impacts are expected to occur on flight (this may be a risk if the flight dispenser has the "free" constraint, cf. Figure 4), the qualification activity may be not fully representative of the flight conditions.

7.2 Implementation of shimming to improve testing on non-clamping dispensers

A "shimming solution" was tested by the authors as an attempt to mitigate some of the drawbacks that testing CubeSats on non-clamping dispensers have. The idea behind the shimming is that the gaps between the CubeSat and the test dispenser are filled as schematised in Figure 13. The goal of the solution is to:

1. Protect the rails from fretting and impacts.
2. Increase the linearity of the test setup.
3. Improve the repeatability of the test.

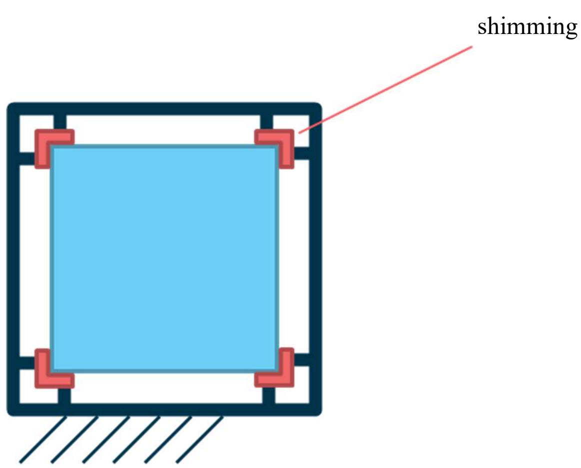

Figure 13: Shimming implementation schematics.

The shims were implemented by means of layers of Kapton and aluminium tape applied in a combination as shown in Figure 14. The exact combination was decided on a case-by-case basis, to fill the gap as accurately as possible. It is to be noted that the test dispensers available for these tests have slight nuances in the dimension of the housing, which vary throughout the length of the dispenser as well, of up to 1-2 tenths of a millimetre.

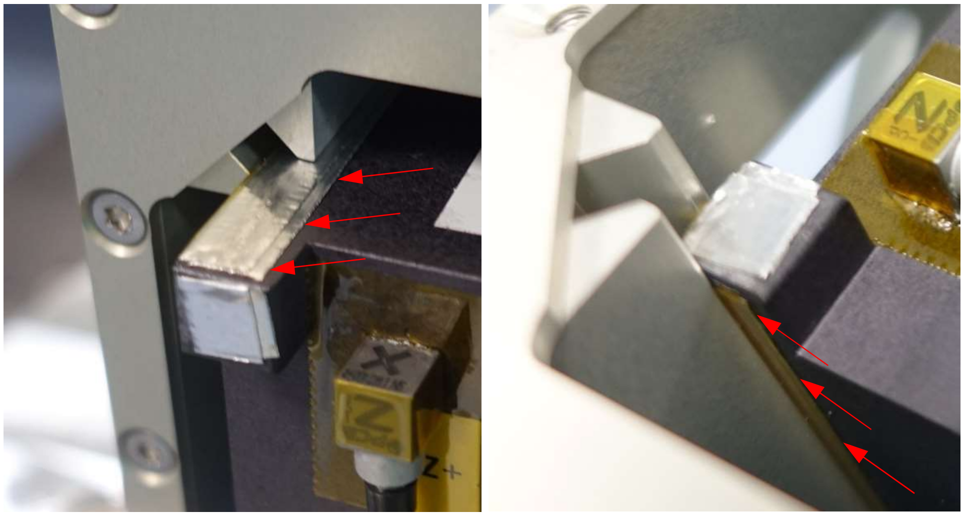

Figure 14: Shimming implementation by means of combination of layers of Kapton tape and aluminium tape.

Excerpts from the test data are reported in Figure 15 (random vibrations), Figure 16 (low-level sine test) and Table 5. As it can be observed in Figure 15 and Figure 16, the effect of the shims is in general to increase the stiffness of the test setup, so that the amplification peaks manifest at higher frequencies. Furthermore, as desired, the linearity of the test setup is improved, therefore the frequency signature (Figure 16) is more coherent before and after the test. Some relatively small shifts in the signature are still observed, which may be explained with an inaccurate implementation of the shimming leaving residual gaps between the CubeSat and the test dispenser.

Generally, the effect of the shimming solution is to bring the test setup close to a clamped configuration. This may be considered a benefit, however it is to be remarked that the levels injected on the CubeSat are as well higher, as can be observed in Figure 15 and Table 5; these levels may be accounted for a priori upon the definition of the test specification, via the methodology presented in section 6. Further work is nevertheless needed to confirm the improved predictability of the loads.

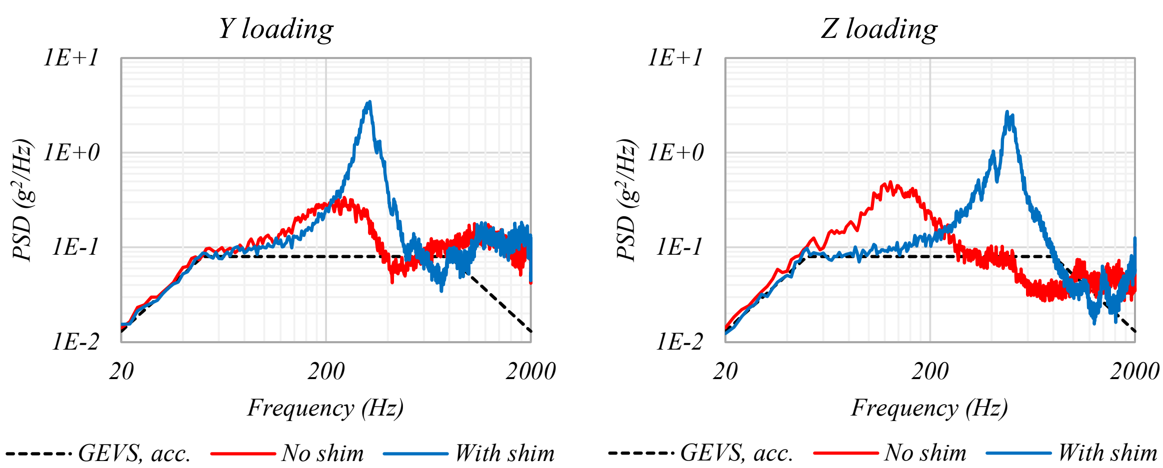

Figure 15: Outcome of random vibrations on a 3U, non-clamping test dispenser, with and without shimming applied to the CubeSats. Test conducted with three 1U CubeSat mass dummies installed in the dispenser. Dummy 3 was installed first, in a way that it is in contact with the deployment spring. Input levels: GEVS, acceptance.

Table 5: Computed g_{rms} values for curves plotted in Figure 15.

Case	No shim	With shim
Dummy 3, y axis	15.2 g_{rms}	21.0 g_{rms}
Dummy 3, z axis	11.8 g_{rms}	19.9 g_{rms}

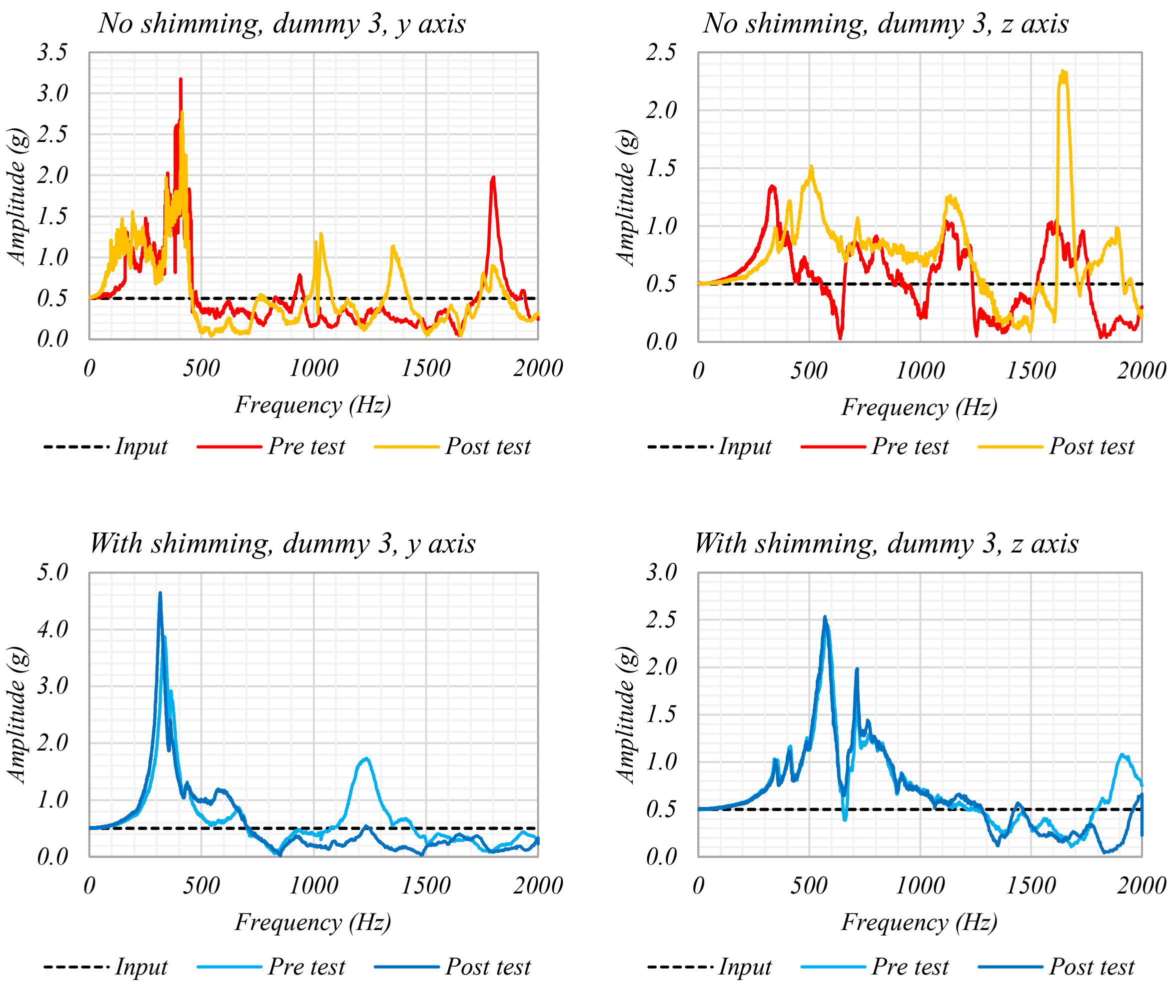

Figure 16: Outcome of low-level sine test before and after random vibrations, on a 3U, non-clamping test dispenser, with and without shimming applied to the CubeSats. Test conducted with three 1U CubeSat mass dummies installed in the dispenser. Dummy 3 was installed first, in a way that it is in contact with the deployment spring. Input levels 0.5 g in the range 5-2000 Hz.

As a final remark, it was also observed during the test that the shimming not only prevents fretting and impacts, but also prevents the deposit of particulate on the CubeSat rails.

8 CONCLUSIONS

As the complexity and ambition of CubeSat missions increases, the consequent invested efforts are more and more important, and therefore the acceptable risks associated with this type of mission is decreasing. It is now the norm, even for amateur developers, to conduct staged verification of a CubeSat design, with a structural analysis at early stages of the projects, and environmental qualification with shaker tests once the spacecraft is integrated. However, it is important to understand the correct conditions that will be experienced on the CubeSat during flight and during testing, to conduct meaningful verification activities, and to avoid over-testing or under-qualification of the flight hardware.

As CubeSats are launched and tested on CubeSat dispensers, the effect of the transmissibility of these should be accounted for when specifying the environmental requirements that a CubeSat shall meet. In general, test and flight dispensers may alter significantly, and in different ways, the levels experienced by the CubeSat. This effect may well exceed the usual qualification margin and safety factors adopted to account for model uncertainties and project maturity, therefore it should not be neglected. An approach to correctly account for the different transmissibility values while defining the environmental requirement specification is proposed in this paper. The verification process may therefore be carried out effectively and with conservative margins by analysis and test.

This paper also presents the benefits of a "shimming solution" that was preliminarily tested with some success by the authors. The goal of this implementation is to protect the CubeSat rails from fretting and impacts, and to increase linearity and repeatability of the test setup.

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