FRETTING WEAR ANOMALY OF FINAL CUBESAT EJECTION TESTS: EXPERTISE, SOLUTION TESTING, AND LESSONS LEARNT

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ABSTRACT

During the qualification campaign of the satellite (PFM), vibration testing of the ANGELS cubesat in its deployer was performed at PFM levels. A deployement test was then carried on and showed that the satellite was stuck inside the deployer. Investigations quickly focused on a tribological issue because wear marks and particles were found after extraction of the cubesat. Equivalent friction coefficient calculations from sat/deployer ejection tests led to μ>0.9 which suggested sticking or gripping phenomena.

A fretting test campaign carried out at tribometer scale demonstrated that wear resulted in accumulation of debris inside the contact. That resulted in the creation of a very adhesive 3rd body. Gentle cleaning and manual deposition of MAPLub PF100b grease revealed to efficiently lubricate the damaged contact. The PTFE particles embedded in the grease accumulated in the damaged areas to created, in situ, a thick lubricious layer made of PTFE based materials. The solution was successfully applied on the cubstat/deployer.

Tests in representative conditions with representative materials/coatings shall be made as soon as possible during development in order to avoid late and critical anomalies.

1 Context

ANGELS (*Argos-Neo on a Generic Economical and Light Satellite*) is a 12U satellite designed to demonstrate a new and more economical solution for ARGOS systems. ANGELS was launch on the 18th of December 2019 using a soyouz launcher and a cubesat deployer.

During the qualification campaign of the satellite (PFM), vibration testing of the cubesat in its deployer was performed at PFM levels. A deployement test was then carried on and showed that the satellite was stuck inside the deployer. 9 different possible root causes were identified: tribological issue, residual deformations of satellite/deployer, geometric non-conformance of satellite/deployer, etc. Investigations quickly focused on a tribological issue because wear marks and particles were found after extraction of the cubesat. These marks were found on both satellite rails and deployer rails. Both CNES and FEMTO-ST started to investigate right after these observations in July 2019.

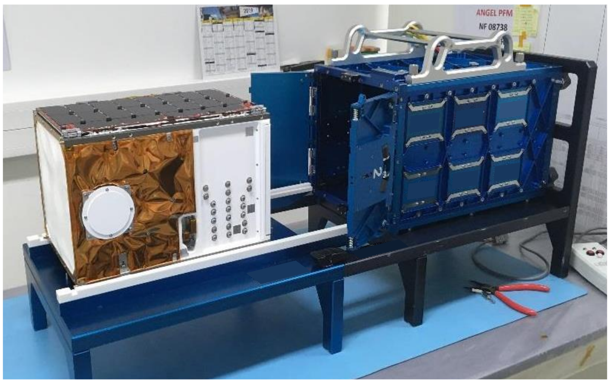


Figure 1: ANGELS and its deployer

2 Characterisation of the wear areas

First of all, one should note that all the tests and investigations were constrained by the time available to find a solution and by the fact that the deployer and the cubesat had to be maintained in a clean room.

2.1 Visual inspection and particle analysis

CNES teams were send to perform visual inspections and particles sampling (see Figure 2).

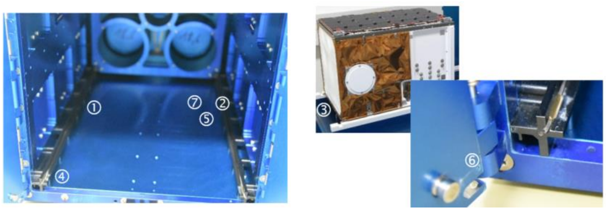


Figure 2: Sampling areas

During visual inspections, we noticed that at least 3 areas were subjected to abnormal wear and a lot of particles were present. Two of these areas are located near switches of the deployer rails. The corresponding areas on the satellites rails exhibits also a lot of wear.

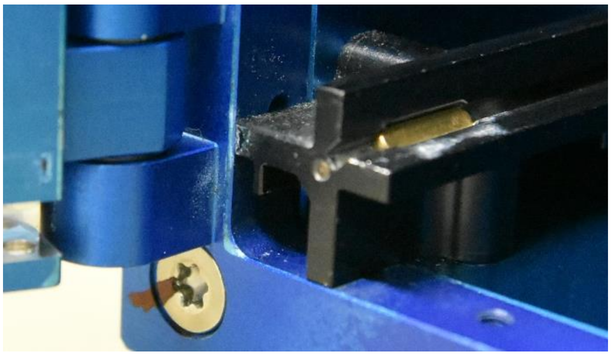


Figure 3: Wear and particles near a switch

Particles were sampled using carbon adhesive on SEM stubs and were analysed using SEM and EDX. The results showed that the particles were mainly composed of alumina. Traces of Ziconium, Titanium and fluor were also found. On satellite side the rails are made of Al7075 treated by hard anodic oxidation and surtec 650. On the deployer side the rails are made of Al7021 treated by Hard anodic oxidation and interflon. The composition of the particles is thus consistent with the materials in contact.

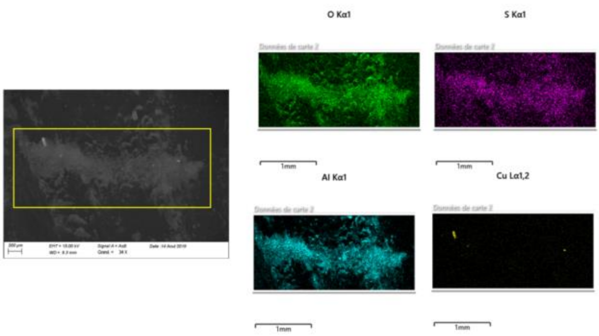


Figure 4: Example of an EDX analysis

At this stage, the hypothesis of an external contamination acting like a third body in the contact and increasing the wear was excluded. All the particles came from the contact itself and the third body is not an external contamination but the product of the wear itself.

2.2 Topological analysis of the wear zones

After the particle sampling, the interest areas were cleaned using isopropyl alcohol. The wear areas were replicated using a silicone resin. In the following pictures, be aware that the analyses were performed on a negative of the surface. A positive step on the measurement corresponds to a negative step on the real surface.

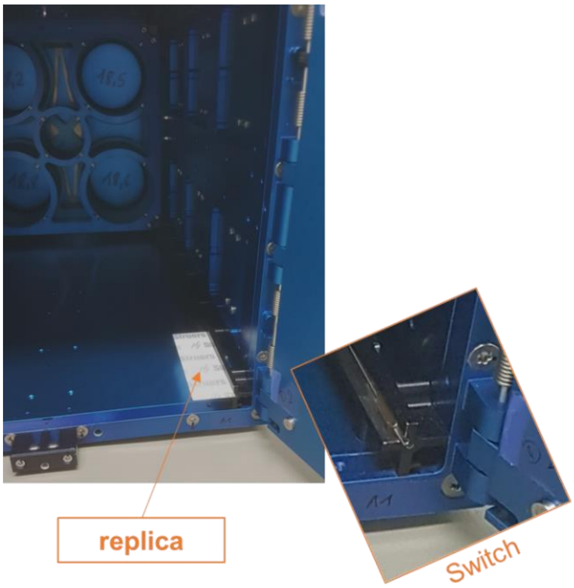
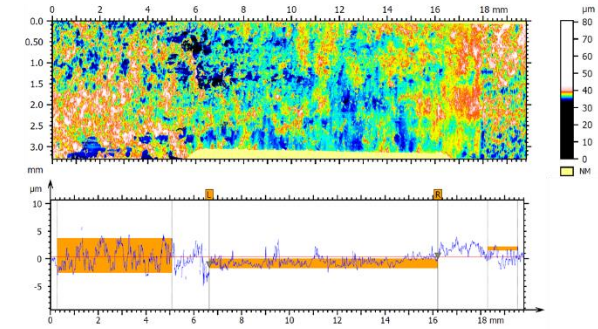


Figure 5: Example of a silicone replica on the deployer rail

The wear area on the Figure 5 shows almost no wear. The mean surface in the area is 800nm above the original mean surface. We also notice that the surface in the wear area is smoother than the original surface.



Paramètres	Marche 1	Unité
Largeur	9.56148	mm
Hauteur maximale	5.22081	µm
Hauteur moyenne	0.820652	µm

Figure 6: Profilometry on the deployer rail

With a closer look on this surface we were able to see that the weared surface could be locally 5 to 6µm above the original surface.

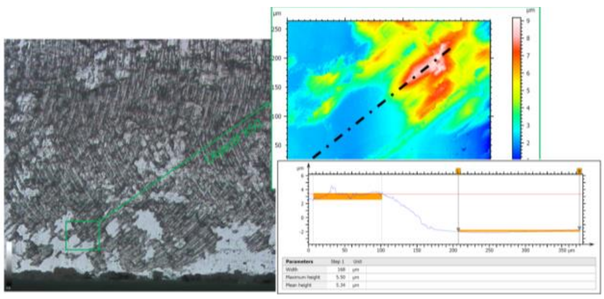


Figure 7: Material trapped in the roughness of the deployer rails

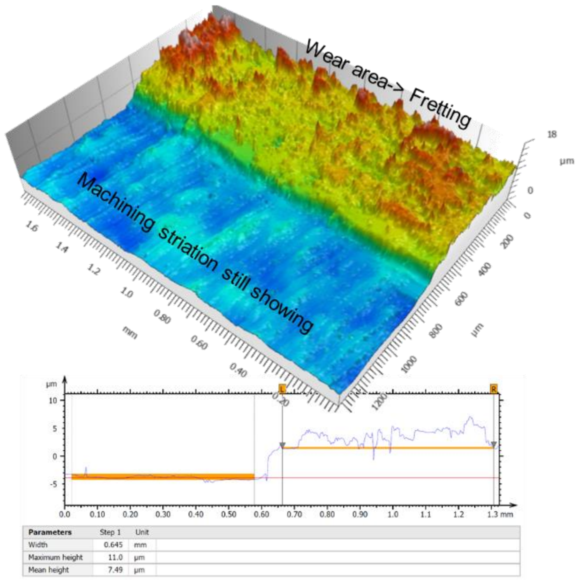


Figure 8: Profilometry on a wear zone of the satellite rail

The same analysis performed on the satellite rails exhibited more than 7µm of wear in average. Wear areas are well defined and it is not hard at all to define a frontier between the wear and the original surface. Moreover the bearing surface at 7µm of the satellite tracks if 100%. Meaning that the bearing surface can no longer increase with wear (locally at least) and that the wear phenomenon is not behaving like a run-in but will continue without any counter-measures.

It is worth mentioning also that the waviness and roughness of the deployer were higher than the ones of the satellite.

3 Tribo elementary tests

3.1 Contact conditions and post-tests analysis

Table 1 - Contact conditions of the fretting tests and comparisons with estimated contact condition from the analysis of the satellite and the deployer.

Fretting tests		Vibration test data
Normal Load	140 N (Contact pressure: 3.6 MPa)	Contact pressure: 1.8 MPa minimum
Amplitude	±300 µm	±100 µm max
Frequency	30 Hz (sliding speed: 36 mm/s)	Eigenmode @60Hz to 100Hz (24 to 40 mm/s)
Duration	3min	2min per axis
Environment	Air (43 ± 4 %HR, 22 ± 1 ◦C)	Clean room (55 ± 10 %HR, 22 ± 3 ◦C)

To understand the origin of the anomaly, a fretting test campaign has been carried out on a TE77 Cameron-Plint tribometer. The objective was to reproduce the wear phenomena (particles and surface morphologies) on elementary scale tests. The tribometer scale study is summarized here. The full study is presented in [1].

Samples emulating both the satellite and deployers are comprised of the exact same materials than the satellite and deployers themselves. The sample emulating the satellite is a cylinder of 8mm in diameter and 20mm in length. Chamfer at both ends reduces the end diameter to 7mm. It is the end disc that is put in contact with the cubic sample emulating the deployer. The cubic sample is 14mm x 14mm x 12mm. Sliding occurs on the 14x14 surface. Contact condition are presented in Table 1. They have been determined after following a first test campaign during which different set of parameters were screened. Note that the difference in humidity compared to the clean room may not affect our results considering literature is not demonstrating any evidence of it [2,3].

To reproduce at best the vibration test sequence and the anomaly, we started with dry contact configuration. Once the test is over, the contact is opened, samples are cleaned off particles and debris, lubricant is applied, the contact is closed, and the test sequence is run again. In order to have a detailed look at the wear mechanisms, 3 samples were submitted to the dry conditions only, 3 we submitted to both sequence (dry + lubricated). Two lubricants were tested:

- MAPLbub PF100b because it can be applied manually on parts. At contact closing the exess of grease is ejected at the periphery of the contact, which forms a bulged hallo around the cylinder on the surface of the cubic sample
- Lubricants based on alkyl-phosphonic acids molecules because they are dispersed in ethanol-based solvent, and applied by spraying the solution on parts. Within few minutes the solvent evaporated, leaving the molecules organizing themselves on the surface. Such lubrication is considered as dry lubrication

After the tests, samples are analyzed using optical profilometry to analyzed the wear scares and determine wear depth and thicknesses of the 3rd body materials accumulating inside the contact area. Then follows more detailed study of the morphology and the elemental composition of the worn surfaces (including debris) with SEM/EDS analysis. Regarding grease lubricated samples, grease is removed for the analysis and the remaining 3rd body is analyzed. Infrared analysis is also performed to determine the nature of 3rd body created during lubricated tests.

3.2 Results

Figure 9 allows to compared the aspects of the worn surfaces on the satellite and on the tribometer scale samples, after tests in dry conditions. Features, morphology (surfaces and debris) are successfully reproduced. Contact effectively occurs over few large spots. Over the 3 unlubricated test samples, the damaged area remains quite constant and varies little from one test to another.

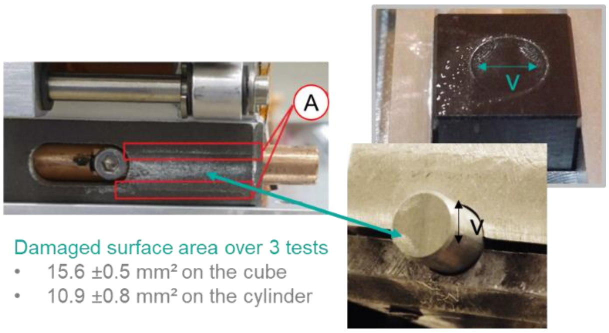


Figure 9 - Comparison of damaged areas from satellite and from tribometer tests samples. The arrow v displays the sliding direction during the friction tests

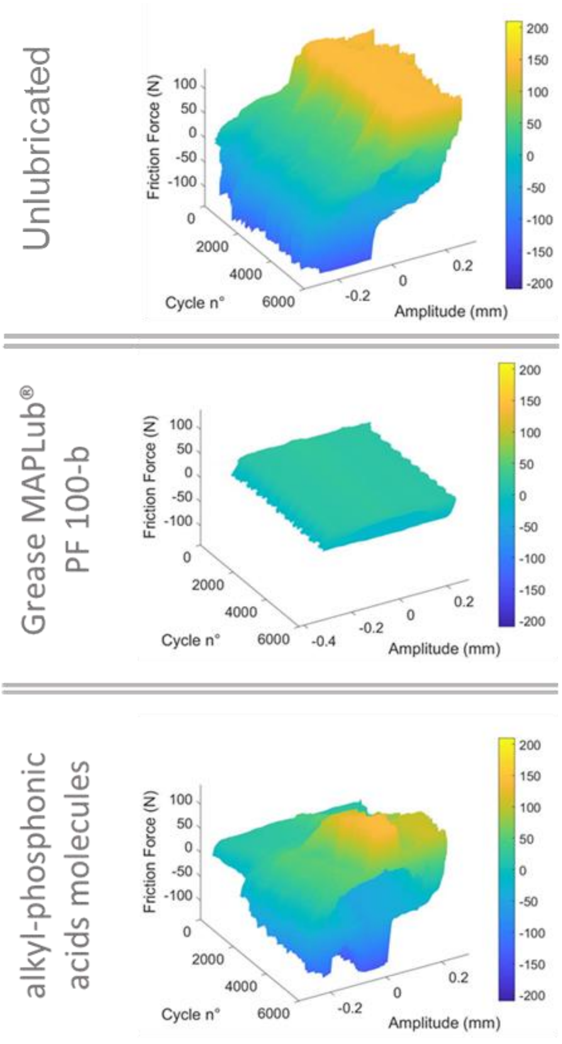


Figure 10 - Fretting loops of the fretting unlubricated and lubricated tests. The loop shape, with curvy sides, is typical of high adhesion fretting in sinusoidal displacement

Figure 10 is showing the fretting loop obtained during the fretting test in unlubricated condition, and in lubricated conditions after lubricant is applied on the damaged surfaces. It can be seen that in the unlubricated case, the friction demonstrates partial slip and very high amplitude of friction force, up to 100N in average (0.7 friction coefficient), pic at 140N (1 friction coefficient). During the test, particles are rapidly created and ejected continuously outside the contact, as evidenced on the cubic sample in Figure 9. White debris are indeed observed in the left side of the contact area. White 3rd body patches, are observed inside the friction tracks, in the mostly loaded areas. amount may have not been sufficient to sustain lubrication over the full test.

The optical analysis of the unlubricated samples shows that the worn samples is mainly the samples emulating the satellite. It also and that the 3rd body accumulate to form thick 3rd body patches. Figure 11 indeed shows that the cubic sample is not demonstrating significant wear, the surface at the centre of the contact is slightly smoother than the pristine surface. At the mostly loaded areas, 3rd body accumulates to create patches reaching a thickness of 14 µm above the overall sample surface. The cylinder surface (not shown) demonstrate mostly few microns deep worn region. Areas with accumulated 3rd body demonstrate 3rd body whose thickness may locally reach 2 µm. EDS analysis shows that debris and 3rd body are only coming from the cylinder (satellite-based material)[1]. Note that no fluorine is detected on the cubic samples (layer too thin?) but it on the cylinder material. Surtec650 is indeed containing fluorine [4]. The oxygen content is however significantly higher than what it is detected on the pristine materials, which is typical of tribo-oxidation seen during fretting tests in air [2,5].

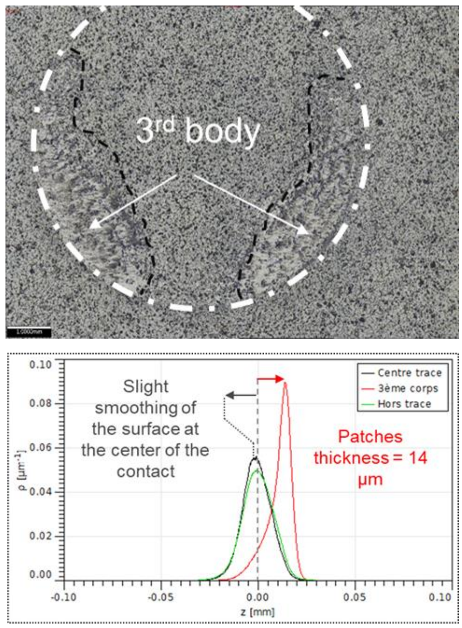


Figure 11 - Optical topography image and height distribution of the 3rd body.

The alkyl-phosphonic acid lubricated case shows that lubrication is sustained over half the test duration, which removed the lubricant from the list. This lubricant may however remain interesting to investigate as it showed to create lubricious graphene oxide base 3rd body [1].

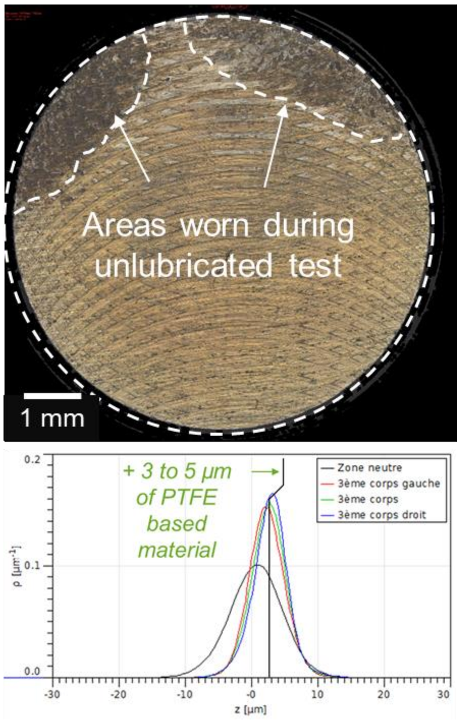


Figure 12 - Optical topography image of the cylinder sample demonstrating large accumulation of PTFE based lubricious material in previously worn areas

The grease lubricated test sequence demonstrates very stable pure sliding friction with a friction force of 15N in average (0.1 friction coefficient). The optical topography shows accumulation of 3rd body from coming from the grease and remaining rigidly bounded to the initially worn areas of the surfaces. This demonstrated on the mostly worn samples, the cylinder (Figure 12). Such PTFE layer formation behaviour has been shown to happen with grease containing PTFE particles [6]. While PTFE appears to bind only on the initially worn areas on the cylinder (i.e. on the satellite material), it is found everywhere in the contact on the cubic samples (i.e. deployer material), with slightly thickest patches in initially worn areas.

4 Pros / Cons between "Use-as-is" and grease lubrication solutions

Due to several ejection anomalies on different tests "dry lubricated" models (PFM and dummy) and to elementary tribological testing showing that fretting on satellite/deployer rails can lead to an adhesive third body, it was decided to apply grease on deployer rails. Indeed, equivalent friction coefficient calculations from sat/deployer ejection tests led to $\mu>0.9$ (compared to $\mu<0.35$ before vibration). Such a high value of friction coefficient is consistent with the high friction measured during the tribometer scale test campaign. That consequently confirm the sticking or gripping phenomena suggested on the cubsat/deployer system.

	Use-as-is	**Grease lubrication**
Pros	Already tested by deployer manufacturer on several configuration	**Surfaces separation (oil + PTFE particles)**
	Insensitive to temperature	**Stable friction coefficient**
		Compliant with "predamaged" surfaces
Cons	**Tribological phenomena not understood**	Not qualified within ANGELS development
	Ejection failure after vibration test on ANGELS'satellite configuration !	Viscosity effects on ejection velocity unknown (including temperature sensitivity)
		Pollution issue ?

MAPLub PF100b grease was selected due to its excellent thermal stability and the presence of PTFE particles within the grease (in case of oil segregation / migration).

5 Grease lubrication validation at satellite/deployer level

5.1 MAPLub PF100B validation on satellite dummy

In order to qualify this configuration on a dedicated and representative model of both satellite and deployer, a structural model of the satellite was manufactured and tested in the deployer spare model (flight configuration).

Both satellite dummy and deployer rails were cleaned meticulously with isopropyl alcohol. MAPLub PF100b grease was applied on deployer side as shown in Figure 13 with a particular attention on the amount of grease: groove of the rail was filled of grease and a dedicated tool was used to spread the rest of the grease (0.2mm film thickness) while removing lubricant excess (cf. Figure 13 C).

Satellite dummy was then inserted into the deployer with a particular care on Sat/deployer alignment in order to avoid removing greases from the lubricated surfaces (cf. Figure 14).

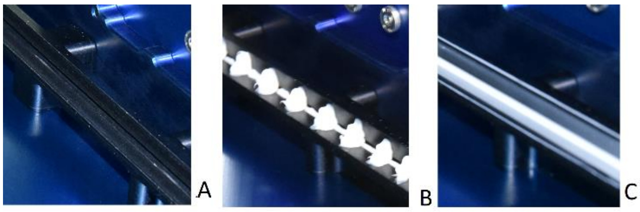


Figure 13 Lubrication procedure: rail cleaning (A), grease application (B), grease spreading and grease excess removing (C)

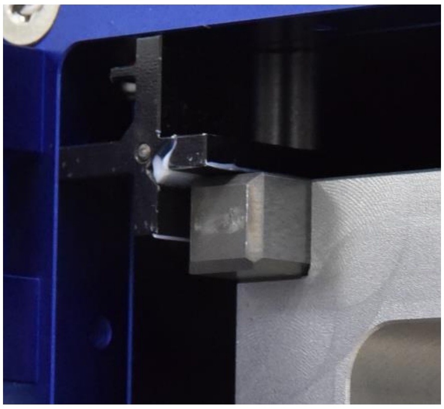


Figure 14 detail view of a rail after satellite dummy installation in deployer (QM)

Both satellite dummy and deployer QM were submitted to a full mechanical vibrations qualification sequence (@qual level for 2 minutes, cf. Figure 15). Grease behaviour was observed during vibrations on bottom rails through an opening in the deployer. A grease bulge was observed and confirmed a satisfying grease circulation in the contact (cf. Figure 16).

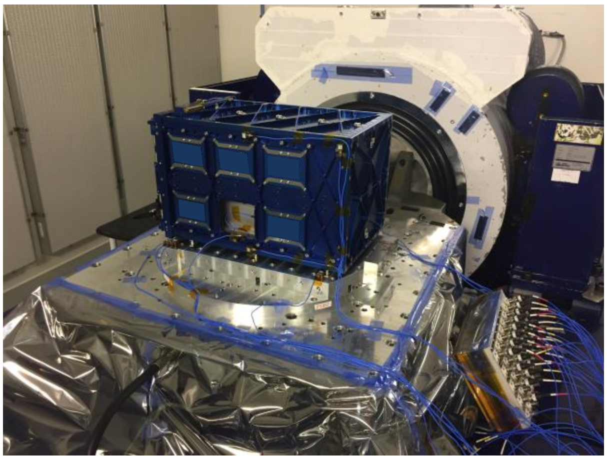


Figure 15 Deployer QM with satellite dummy on MID shaker

An ejection test was then performed at 75° (cf. Figure 17) in order to limit gravity effect on friction (with 1g compensation). A particular care has been paid in transporting the deployer on the ejection test GSE to avoid "unsticking" the satellite from the rails. Satellite dummy was successfully ejected from the deployer with satisfying margin. In addition, no wear or fretting marks were observed on both the satellite dummy and the deployer rails (cf. Figure 18). Grease was indeed observed on all sliding surfaces as expected. This successful test confirmed the choice of the corrective actions to solve ejection anomaly.

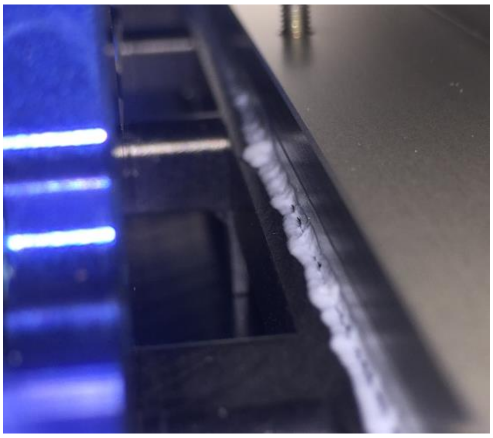


Figure 16 Grease bulge showing grease circulation on bottom rails

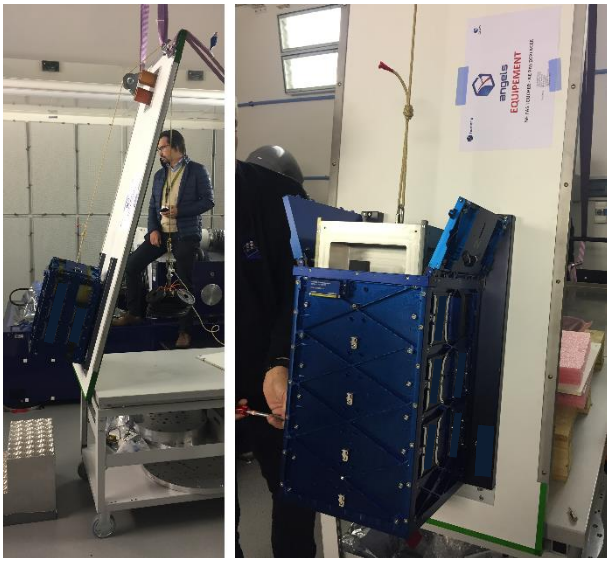


Figure 17 ejection test configuration


Figure 18 Satellite dummy rail after ejection test : no fretting marks were observed

5.2 Satellite PFM ejection

Exactly the same procedure was applied on satellite PFM and deployer FM. ANGELS satellite was successfully launched and ejected from it deployer in December 2019.

6 Lessons learnt

A particular care shall be paid to any system function that depends on tribology because it is often a single point of failure. This is particularly important when motorisation margins are low because they are directly related to critical performances (in this case, ejection velocity shall be controlled and it was not possible to tune/increase ejection springs stiffness). Moreover, tribology issue is not only a matter of friction coefficient and some degradations of coating in contact might lead to adhesive third body.

Tribometer scale test demonstrated that the MAPLub PF100b demonstrated to be an efficient solution to solve the ejection anomaly. The PTFE particles embedded in the grease accumulated in the damaged areas of the surfaces to created, in situ, a lubricious layer made of PTFE based materials. The layer’s thickness is sufficient to separate the bodies in contact and avoid further contact between the satellite and deployer material.

Tests in representative conditions with representative materials/coatings shall be made as soon as possible during development in order to avoid late and critical anomalies. In Sat/deployer ejection case, early tests were performed but surfaces and satellite dummy were not fully representative.

7 Acknowledgement

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8 References

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