EntrySat Satellite Mechanics

Álvaro Fernández Galiana, ISAE

Daniel Gagneux, ISAE

Raphaël Garcia, ISAE

1 Scientific Context

Over the last decades, the number of satellites orbiting the Earth has been constantly increasing. Nowadays, the consequence of this increasing number is that some orbits, e.g. the Geostationary Earth Orbit (GEO), are beginning to become full. The reaction of the international community has been the development of a regulation whose objective is to force the different agencies to provide a de-orbiting plan for every orbited satellite. The space agencies are conceiving different options for this voluntary de-orbiting process, especially considering that the conditions are not the same for the Low Earth Orbit (LEO), the Medium Earth Orbit (MEO) or the GEO. However, for the LEO it seems that the best option is to force a re-entry of the engine into the Earth's atmosphere to disintegrate it. Actually, there is a huge number of small objects that impact our atmosphere every day and, even if there are not all coming from human space engines, the truth is that the debris coming from launches are a significant part of them. Thus, as it is presumable that the number of debris impacting our atmosphere will heighten, there is a rising interest on defining the conditions (pressure, temperature, degradation, etc.) supported during the re-entrance phase of this debris.

In this context, the EntrySat mission is developed via a wider cooperation involving academic partners (ISAE and University Paul Sabatier) and research partners (CNES, ONERA, IRAP) with the aim of define the mentioned conditions using a CubeSat satellite. This kind of satellite, much less expensive than a conventional one, will use its small dimensions to simulate the re-entry of debris and collect valuable data of the trajectory and the degradation suffered by these debris. Thus, the EntrySat mission is designed to fulfill three principal scientific objectives that are to determine the kinematics, the aerodynamic pressure variations and the evolution of the integrity of the space debris during the re-entry. Indeed, as the estimated orbiting time around the Earth is about a year before the re-entrance, an important number of LEO condition information will also be collected as a secondary target.

At the same time, as the number of space projects including CubeSat satellites has boomed lately, especially in University projects, EntrySat mission is also an opportunity for the academic partners to develop their capabilities and the facilities for future similar projects, i.e. Jumpsat [1]. These future projects will be an important component in the education of future space engineers as it represents a first contact with a special project but with a relatively low cost for the institution as they can be partially funded by external partners, e.g. the EntrySat mission.

2 State of the Art

One of the most important parts of any space mission including satellites is to find the way to send it in orbit. For the EntrySat mission, this transfer into orbit will be done by including the satellite in the Von Karman Institute's (VKI) project QB-50. This mission, as shown in [2], aspires to demonstrate the possibility of launching a network of 50 CubeSats as a primary payload on a low-cost launch vehicle to perform first-class science in the largely unexplored lower thermosphere. Nevertheless, the QB-50 mission is dimensioned to only use 40 2U CubeSats with a common payload to provide multi-point measurements of the Earth's low atmosphere. Thus, 10 other In-Orbit Demonstration CubeSats, carrying their own payload, will be selected by the VKI to be launched. The first launching option for EntrySat mission is to be selected between these 10 satellites, what will guarantee being launched in January 2016. However, for this selection the QB50 mission managers impose several constraints to candidate

CubeSats. These constraints are classified depending on the design area and can be consulted in [3].

Before detailing the different tasks that have been performed by the mechanical team, it is important to keep in mind that, as the nanosatellites are seen as a low-cost option to carry out different tests and measurements, the interest of the scientific community in CubeSats has increased over the last years and there are nowadays a significant number of firms that provide satellite components adapted to the CubeSats dimensions. Thus, the structure of the EntrySat has not been developed by the mechanical subsystem but bought to an external supplier. In particular, this external supplier is Innovative Solutions In Space (ISIS), which provides an already qualified and tested 3-unit structure [4]. Obviously, using qualified components is not enough to guarantee the structural integrity during the flight and will never replace the tests that have to be done, but it is a good way to increase the state of the EntrySat. Actually, many other components of the EntrySat, e.g. the EPS [5] or the UHF/VHF antenna [6], will also be supplied by ISIS and they have all already been individually tested. Moreover, the way of assembling these components with the structure is already provided. Thus, the critical part of the assembly and where there is a potential risk of failure during the launch phase is at the payload of the satellite. For the EntrySat this payload is essentially composed of the sensor board and the pressure [7] and the heat flux and temperature sensors [8]. One of the main problems with the assembly is that the sensors, even if they are small enough, are not designed for CubeSats so the recommended mounting ports, e.g. those shown in [7], are not adaptable to the constrained dimensions of those nanosatellites.

2.1 Objective and Constraints

If we focus on the mechanical design of the mission, it can be stated that the main objective of the mechanical subsystem is, on the one side, to guarantee the structural integrity of the satellite during the entire mission. This includes the three principal phases of the mission that present different risks. First of all there is the launch phase, where the satellite will have to face a high rate of vibrations that may be destructive. Then, during the Orbital phase, the nanosatellite will have to deal with a width range of temperature that may lead to the material or the assembly failure. Finally, the extreme pressure and temperature during the re-entry threats the data collection during this phase, compromising the accomplishment of the main objective of the EntrySat mission. The Mechanical team's response to these risks is to perform different vibration and shock test that simulate the launch phase and to find an optimal distribution for the different boards to create, in association with the thermal team, a passive thermal control system for the Orbital phase. Finally, the goal during the re-entry phase is to lengthen the lifetime of the EntrySat, especially of the data collection, via a right external distribution and a correct attachment of the sensors. On the other hand, to integrate all the components of the EntrySat being respectful with the imposed constraints it is also part of the main objective of the Mechanical team. These constraints come essentially from two sources: QB50 System Requirements [3] and the EntrySat subsystems.

As it has been said, the EntrySat has to satisfy an important amount of constraints to be selected for the QB50 mission. Concerning the mechanical design of the nanosatellite, these constraints are basically focused on the total mass and the geometry of the CubeSat, that are restricted due to the design of the deploy system. Bearing in mind that the real deployer will have to host 50 CubeSats, there is also a constraint about the position of the Center of Gravity of the EntrySat. These constraints, which are detailed in [3], determine a maximum mass of 3kg for the 3U CubeSats (QB50-SYS-1.1.5). Regarding the dimensions, the extended volume dimensions may be found on the Figure 1 (QB50-SYS-1.1.3).

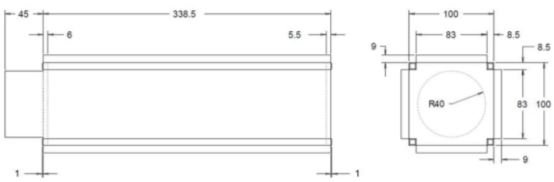


Figure 1: 3U CubeSat extended volume dimensions in mm

Finally, for the Center of Gravity, the QB50 requirements set that *"The CubeSat center of gravity shall be located within a sphere of 20mm diameter, centered on the CubeSat geometric* *center"* (QB50-SYS-1.1.6). According to the reference described in [3] this geometric center is in the coordinates (X, Y, Z) = (50, 50, 170.25) mm.

However, not all the constraints come from the QB50 mission managers. The accommodation of the satellite components is also restricted by the needs of the other EntrySat subsystems. Citing some of these restrictions, the Power subsystem needs to have the maximum number of solar cells available to cover the energetic demand of the CubeSat. This request is also constrained by the team in charge of the fixation of the cells: a CNES intern coming from Cachan [9]. In addition, as the EntrySat does not have an active thermal control system, the Thermal team has been working in a passive control system. This kind of control implies that the boards generating heat flux have to be grouped to create a "hot box" inside the satellite. Another example of other subsystems' constraints is the necessity of position the sensor in the middle of the sides. Actually, as it is shown later, this condition has not been totally fulfilled as long as the area where the sensors have to be attached is really restricted. There is also a constraint coming from the IMU team which is that the IMU, as it contains the accelerometer, has to be as close as possible to the Center of Gravity. Finally, another important constraint that has many implications in the development of the mechanical design is that, to provide stability to the satellite during the re-entry phase, the Center of Gravity has to be as forwarded as possible, considering that the front side is the one that will take all the drag during this phase. So, it can be noticed that this last constraint is at odds with the QB50 requirement that imposes that the center of gravity has to be centered. In fact, the EntrySat team is trying to get the permission from the QB50 to forward the center of gravity. However, while the commission makes a decision, two different models have been developed; the first one being respectful with the QB50 constraints and the second one having the center of gravity as close as possible to the front side.

2.2 3D CAD Model

With the idea of finding the optimal accommodation for all the components included in the satellite a 3D CAD model has been performed. Actually, to provide a workable 3D CAD model is also one of the tasks that have to be carried out by the mechanical team as long as other components of the EntrySat team needed this model, e.g. the ONERA aerodynamics specialists are using this model to establish the stability of the nanosatellite during the re-entry. Indeed, this model is almost the only way to know the exact situation of the center of gravity.

This model was developed using the Dassault Systems software CATIA V5 with the Supaero (ISAE) license and different phases were followed before getting the final model. First of all, each component had to be modeled individually, which was not an easy task as long as they have been (and they still are) many uncertainties about the components that will be used. In fact, these uncertainties have been focused essentially on the sensors, the solar cells and the GPS/IRIDIUM antenna. Finally, at this moment, the selected sensors are the EPRB-2 [7] and the HT-50 [8] for the pressure sensors and the heat flux transducers respectively. However the sensor team is working to find a new kind of heat flux transducer as it seems that the operating temperature range of the HT-50 makes it unlikely for the orbital phase. Anyway, the list of the components to be integrated that it is available at this moment with the corresponding mass of each one (the mass of the elements marked with * has been approximated) is shown in Figure 2.

COMPONENT	Number	Mass (g)
STRUCTURE	1	328,588
BATTERY x4	1	240
BATTERY x2	1	105
GPS_BOARD	1	60,9
IMU_BOARD	1	76,7
IRIDIUM_BOARD	1	62,7
MAINBOARD	1	55
SENSORBOARD	1	100
UHF_BOARD	1	85
MAGNETO	1	195
UHF-VHF Antena	1	100
EPRB-2	5	24,7
HT-50	5	23,1

Figure 2: EntrySat list of components and mass

Once these components were already modeled the first step was to define the external distribution to face the fixation of the sensors. The main idea was to attach the sensors on the external sides of the satellite trying to place them as centered as possible. For the HT-50 the fixation was not difficult to establish as long as these sensors already have a slot to be screwed on a surface and the idea of using glue in the attachment was rejected because of the huge amount of risks that carries. Nevertheless, two different attachment options were considered, as presented on Figure 3, and had to be validated during the tests. The difference between these options is if the sensor is attached directly on the external side or it is placed through this side. For the EPRB-2 the choice was not as easy because, as shown in [7], there are different sensor sizes available and with their recommended mounting port. The chosen model, keeping in mind that the limited dimensions of the EntrySat turn most of the mounting options into impossible, was the N. The reason is that M5 was the only one that holds an auto blocking nut fixation without overstep the settled dimensions. This final attachment can also be observer in the Figure 4.

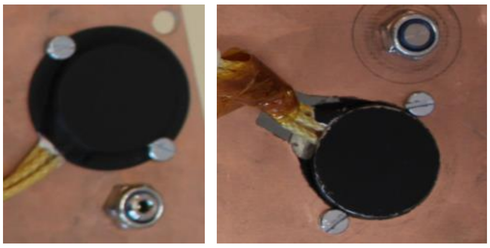


Figure 3: HT50 proposed attachments

Figure 4: EPRB-2 proposed attachment

Once decided the attachment of the sensors, and after selecting the printed circuit board (PCB) that will be used on the external sides (which is the glass-reinforced epoxy PCB FR-4), the external distribution was developed. Taking into account the restrictions imposed by [9] concerning the solar cells arrangement, the external distribution includes 25 solar cells besides the EPRB-2 sensors, the HT-50 transducers and the GPS/IRIDIUM transceiver.

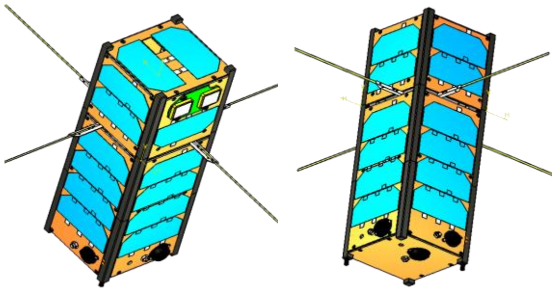


Figure 5: EntrySat external distribution

Regarding the internal distribution, there are many constraints involving the assembly that have to be considered to find the optimal distribution. Just as an example, to place the Sensor board close to the back side, i.e. the one with two solar cells, may be correct regarding the defined constraints but it is obviously not an optimal solution as long as this board has to be connected with the sensors using cables and these sensors are placed close to the front side. These cables, in case of a bad placement of the sensor board, will have to cross all the CubeSat, which is clearly inadequate. So, an additional constraint is defined: the total length of the cables should be minimized, which also entails a reduction in weight. This condition implies, for example, that the sensor board has to be the foremost card or that the two components conforming the Power Supply System [5], i.e. the Battery Pack and the EPS, have to be placed together. In Figure 6 the two options for the external distributions are detailed. The first model is respectful with the QB50 requirement and has the center of gravity in the 20mm sphere and the second one with the gravity center forwarded. The broken line represents the “hot box” where the elements producing heat flux should be placed. In these lines EPS, magnetorque, OBC and UHF/VHF board may be highlighted as powerful heat flux producers.

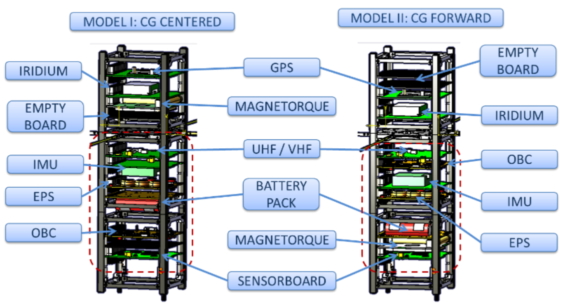


Figure 6: Entrysat internal distribution models

Comparing those models it can be established that one of the strong points of the second model, besides having the center of gravity closer to the front side, is that the magnetorque is in the "hot box". However, in this distribution there is a potential risk of signal dysfunctions due to the fact that the UHF/VHF board and the OBC are placed together. In addition, the magnetorque's lever arm is reduced in 28 mm on the second model. Nevertheless, the decision between those models will be made considering the ONERA's aerodynamics experts advices. These experts are working to determine the goodness of the center of gravity displacement. Actually, as shown in Figures 7 and 8, this displacement is just about 20 mm because it has not been considered the displacement of the VHF/UHF antennas as it will imply the reduction of the number of solar cells available. Anyway, different "extreme" options can be considered to forward the center of gravity beyond the 143.282 mm if the ONERA's experts consider this movement desirable. For example, replace one of the epoxy empty cards by a heavier one or to design a thermal protection for the front side may be two possible options to carry out this movement.

Characteristics		Inertia center	
Volume:	7,093e-004m3	x:	49,376mm
Mass:	2,204kg	y:	47,814mm
Surface:	0,941m2	z:	162,07mm

Inertia matrix					
Ixx:	0,024kgxm2	Ixy:	1,046e-004kgxm2	Ixz:	-1,458e-004kgxm2
Iyx:	1,046e-004kgxm2	Iyy:	0,024kgxm2	Iyz:	5,021e-004kgxm2
Izx:	-1,458e-004kgxm2	Izy:	5,021e-004kgxm2	Izz:	0,005kgxm2

Figure 7: Model I mechanical characteristics

Characteristics		Inertia center	
Volume:	7,093e-004m3	x:	49,5mm
Mass:	2,204kg	y:	48,141mm
Surface:	0,941m2	z:	143,282mm

Inertia matrix					
Ixx:	0,023kgxm2	Ixy:	9,981e-005kgxm2	Ixz:	-2,915e-005kgxm2
Iyx:	9,981e-005kgxm2	Iyy:	0,023kgxm2	Iyz:	7,551e-005kgxm2
Izx:	-2,915e-005kgxm2	Izy:	7,551e-005kgxm2	Izz:	0,005kgxm2

Figure 8: Model II mechanical characteristics

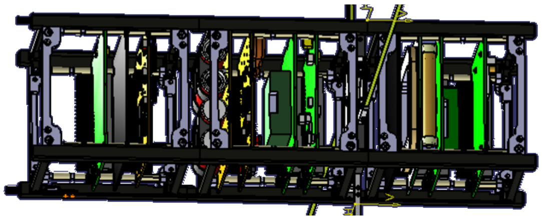
Finally, regarding the maximum mass constraint it can be noticed that, in absence of the mass of the cables, the margin is about 800g, width enough to enable the "extreme" options to forward the center of gravity.

2.3 STM Development

Once the optimal distribution was found, many different tests had to be performed. For the CDR these tests are not performed on the real satellite but in an STM, i.e. Structural and Thermal Model. Regarding the mechanical design, this STM has to have the same mass and volume, which implies the same inertia, that the real satellite. To fulfill the thermal necessities, this model should have also the same reflectivity, absorptivity and conductivity that the real one. However, in this case it was impossible to find the right materials to comply with both necessities so two different models were made. The only real components that were used to develop this STM were the structure (including the external PCBs that had been manufactured by the mechanical team, shown in Figure 9), 5 HT-50, 2 EPRB and the GPS/IRIDIUM transducer. So, an important number of elements had to be designed and manufactured to have the same mechanical properties that the real components. These components have been produced in the ISAE facilities with the assistance of a mechanical design expert, M. Gagneux. In the end, the difference of weight between the EntrySat and the designed STM is 30g, and it is essentially due to the difference of mass between the real and the reproduced Battery Pack.

Figure 9: Manufactured external PCBs

In the end, the STM was successfully assembled on the ISAE facilities using all the reproductions of the boards and was ready to be tested. The assembly procedure can be consulted on the reference [10]. As it can be observed in Figure 10, the distribution chosen to develop the STM was according to the Model I, i.e. respectful with QB50, as long as there is not a definitive resolution to the center of gravity issue.



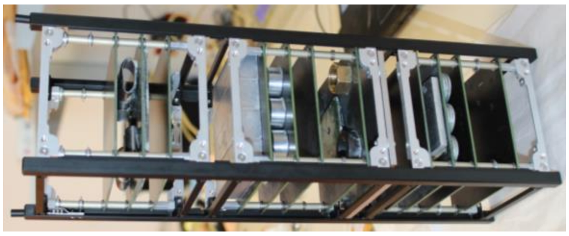


Figure 10: STM compared to 3D CAD model

2.4 Mechanical Tests

The STM objective is to validate the accommodation of the components as well as the fixation of all the sensors. For that reason, four different tests were planned for the STM as part of the mechanical design qualification: three vibration tests and a shock test. First of all, for the vibration tests, a preliminary test was performed using just the external PCBs to have a primary validation of the sensors fixation as well as to become familiar with the test equipment. Then, a second test involving the complete STM was planned during which test important data was going to be collected and subsequently used for the third test. This third test is a specific test for all the "sensitive" boards, i.e. those that have not been directly bough and that are not already validated: GPS, IRIDIUM, IMU and sensor board.

The conditions for these tests are defined in [3] by the QB50 mission managers. For the vibration test, three different spectrums have to be performed: a quasi-static test with 12g amplitude, a sinusoidal vibration and a random vibration. This random vibration is supposed to simulate the three different launch phases that the nanosatellite will have to face and is the most restrictive one. Besides these test, a Resonance survey test has to be also performed to determine the resonance frequency of the elements as well as to check the integrity of the satellite. Actually, for all the tests that have been carried out the order of the vibration test has been, for each one of the three axes, the one shown in Figure 11. The aim of this procedure is to compare the spectrum of the resonance survey before and after the tests to try to found out any anomaly that may report to a mechanical failure of the element.

TEST ORDER		
1.Resonance Survey I	2. Quasi-static	3. Sinusoidal
4. Resonance Survey II	5. Random vibration	6. Resonance Survey III

Figure 11: Test sequence followed for the vibration test

On the other hand, an important aspect to take into account before doing the test is how the interface between the satellite and the testing engine will be implemented. As the aim of the test is to ensure the integrity of the satellite during the launch phase, when it will be inside the deployer [11], the best way to obtain a representative solution is to use its own deployer as part of the interface to obtain an attachment similar to those presented in [11] and [12]. Thus, a POD especially designed for the tests was bought to guarantee the representation of the results.

The preparation and the execution of the vibration tests has been performed at the Clement Ader Institute facilities and supported by a local expert, Jean Benoit Alibert. The test equipment consists of an electrodynamics shaker [14], 7 accelerometers [15] and the data acquisition system [16]. That means that for each one of the three vibration test a special interface plate has to be designed to make possible the attachment between the testing model and the shaker. The design of these interfaces is also a task to be developed by the mechanical subsystem.

2.4.1 Preliminary Test

The main objective of this test was to validate the attachment of the pressure and heat flux transducers (two different attachments for the heat flux transducers). To this end, three accelerometers were put, respectively, on the EPRB-2, the HT-50 and a third one in the middle of the PCB.

After the execution of the test sequence it may be stated that the preliminary test was complete success. First of all because the mechanical team gained experience about how the vibration tests are performed and second because the results of this test were all positive. These results showed that all the fixations had withstood the vibrations and that none of the sensors had been damaged during the trials. One more useful information resulted of this test which was that with the frequency range given by the QB50 requirement for the Resonance survey

(5 to 100 Hz) important data was being missed as long as the resonance frequency of the elements is over the 100 Hz border. Actually, compare the resonance surveys in this situation has not sense because we are just comparing straight lines. Thus, this experience brought to the determination that for the STM tests this resonance survey was going to be implemented between 5 and 2000 Hz.

2.4.2 STM Test

After the preliminary test, an interface plate was developed to make the STM tests possible. Using this interface and the test POD as shown in Figure 12, the test were developed with the support of the sensor board team, which was in charge of testing the performance of the sensors after each axis test.

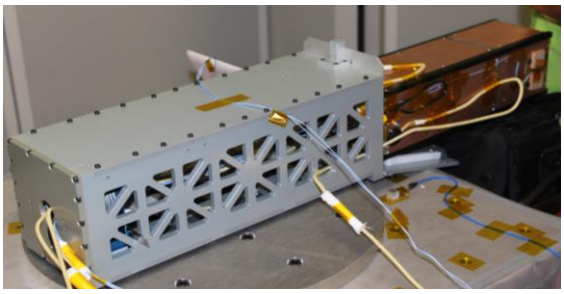


Figure 12: EntrySat STM put into the test POD before the tests

In addition to the objective of qualify the accommodation, this test have also been useful to collect data about the vibration rate supported by the sensor board, the IMU, the GPS and the IRIDIUM boards. However, the truth is that the main objective was to validate the accommodation of the boards and the sensors according to the QB50 specifications. Thus, seven accelerometers were placed in different parts of the satellite to recollect data and compare it to find out any anomaly. Specifically these accelerometers were in the EPRB-2 sensor, the IRIDIUM/GPS antenna, de geometrical center of the side PCB (Figure 13) and the GPS, IRIDIUM, IMU and sensor boards.

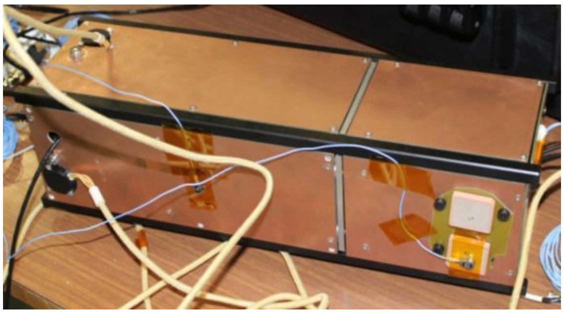


Figure 13: Accelerometers on the external side of the STM

The results of this test were extremely positives since all the sensors worked before and after the test execution and none of the screws get loose. Thus, after an exhaustive observation, no visible damage was found on the structure. However, the outstanding information has been deduced from the data collected by the piezometric accelerometers. Thus, after the data collection, all the resonance survey spectrums have been compared as shown in Figure 14. The analysis of this spectrum shows that, even if there are some slight differences due to the setting of the components, which implies a little redistribution of the energy, none of the studied elements suffered critical damage. Indeed, it is known that in the real deployer system there will be some kind of shock absorber system to reduce this setting as much as possible. Then, it can be stated that if the STM passed these test it will pass the launch phase.

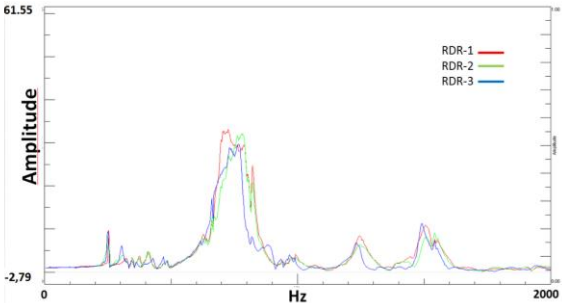


Figure 14: Resonance Survey comparison sensor board axis Z

In relation to the resonance frequency of the EntrySat elements it can be observed on Figure 15 that there is an important part of the energy placed between 300 and 400 Hz, what corresponds to the boards' resonance frequency. On the other hand, the observed acceleration on the elements like the IMU or the GPS has been always below the tolerance rate extracted from their datasheet, e.g. the maximum acceleration suffered by the IMU during the tests was around 30g whereas it tolerates accelerations until 2000g.

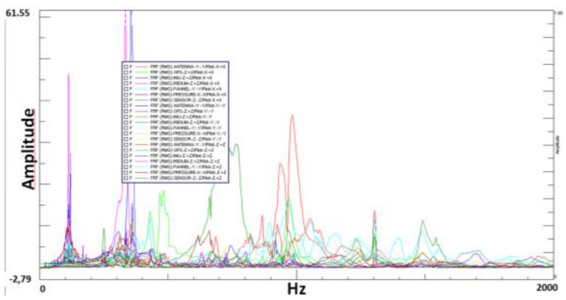


Figure 15: Resonance Survey of all the elements

To sum it up, from the structural point of view this test allows the mechanical team to state that the accommodation and fixation of all the elements is qualified, according to the QB50 requirements, to accomplish the EntrySat mission.

3 Conclusions

The main conclusion that be drawn from this project is that the right accommodation and fixation for all the elements of the EntrySat nanosatellite have been established. Also, the acquired experience will certainly be useful for the continuation of the project. However, there is still a lot of work to be done that will have to be performed in the next months. On the first hand, the production of the external PCB has to be done in the next weeks as the ONERA's intern in charge of the cells assembly finishes his stage on August 4th. At this moment, the only side that has not been already defined is the back side, and the mechanical team is waiting for a reply for the last distribution design. On the other hand, there are still two different tests to do on the STM. The first one is the specific test to be executed on the "sensitive" boards using the vibration data obtained from the STM test. The other one is the shock test, which is an essential test as long as it is stated by the QB50. This test will take place in the Mecano ID facilities but the work of the mechanical team is to prepare all the elements that will be needed in this test. Then, there is also the CDR advice implementation as well as the 3D CAD model update and refinement. Finally, once the STM is validated by the CDR, the Protoflight Mechanical tests will have to be performed for the FFR.

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