Design and Qualification of a Restrain-Release Mechanism for a 600-kg Deployable Panel Array

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Abstract

The SAOCOM satellites have a Synthetic Aperture Radar (SAR) instrument with a distributed electronic architecture. This concept resulted in two arrays of deployable panels for the antenna with a mass of approximately 600 kg each. To support the deployable panels of the antenna during launch, each assembly has six restrain-release mechanisms. Both satellites deployed the SAR antenna panels in orbit succesfully. This paper presents the design constraints for these restrain-release mechanisms, the characteristics of the adopted solutions for the design, and the steps and results of the qualification campaign.

Introduction

The SAOCOM Mission (Satélite Argentino de Observación Con Microondas) is a program defined, managed and operated by CONAE (Comisión Nacional de Actividades Espaciales), Argentina's Space Agency. It is composed of a twin satellite constellation, SAOCOM 1A and SAOCOM 1B, each carrying a polarimetric L-band SAR instrument operating at 1.275 GHz with a spatial resolution between 10 and 100 meters as regards to the acquisition mode and the observation angle. The main driver of the mission is to generate soil moisture maps and both satellites are in orbit and operative. The satellites were launched in 2018 and 2020 respectively, and now are in full operating mode in a polar sun synchronous frozen orbit at 619 km with a 98° mean inclination. Figure 1 shows the SAOCOM satellite in flight configuration with the solar panels and SAR antenna deployed.

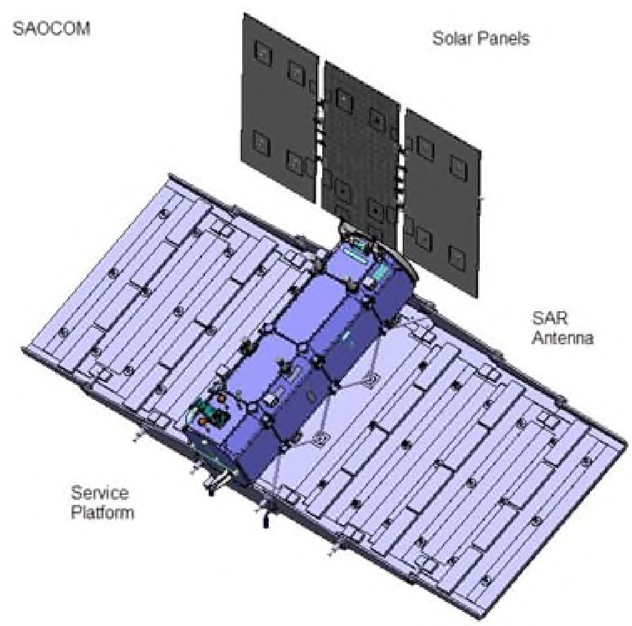

Figure 1. Flight configuration of the SAOCOM satellite.

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The SAR antenna structure and deployment mechanisms were designed and manufactured by the Comisión Nacional de Energía Atómica (CNEA), while the assembly, integration and tests were conducted together with CONAE.

The SAR antenna has a distributed electronic architecture, so the front-end electronics of the instrument are mounted on the antenna. The SAR antenna consists of seven panels whose structure is made of an aluminum honeycomb core sandwiched between high-modulus carbon fiber laminated facings. The electronic boxes and radiofrequency front-end electronics are mounted on the backside of this structure, and the radiating modules are mounted on the frontside. With all hardware mounted, each panel weighs approximately 200 kg and the smaller panels are 1.5-meters long and 4.0-meters wide. The total radiant surface is 35 m^2 at 10-meters long by 3.5-meters high. The SAR antenna has a structural configuration with one central panel fixed to the Service Platform of the satellite by means of a dedicated interface structure, and two symmetrical wings with three deployable panels each. Each wing has a mass of approximately 600 kilograms. During launch, each wing is folded and retained with an array of dedicated mechanisms. Once in space, each wing is released and then deployed by stepper motors via ground commands, reaching its final position after six deployment stages.

To support the panels of the antenna wings during launch, each assembly of three panels has six restrain-release mechanisms, which were designed not only to meet their mechanical and functional requirements, but also those of the integration. They are able to absorb misalignments between panels to guarantee the flatness of the antenna once deployed.

The restrain-release mechanism also prevents the folded panels from hitting each other during launch and transfers all structural loads supported by the antenna during launch to the satellite Service Platform (SP). The location and available space for the mechanisms in each folded panel has to comply with certain requirements imposed by the electromagnetic design of the radiating elements of the antenna.

Mechanism Design

The design of the restrain-release mechanisms for the SAR antenna had constraints related to the required electromagnetic characteristics and design of the antenna. The location and available space for the holes required in each structural panel to fix the mechanism must comply with certain requirements imposed by the radiating elements in the electromagnetic design.

The holes in the radiating surfaces could have a maximum diameter of 75 mm and any two holes should be made between successive rows of eight radiating slots and, in each panel, between the second and third circular slots and between the sixth and seventh circular slot of the row. The resulting position of a hole for the restrain-release mechanims, according to these requirements is shown schematically in Figure 2.

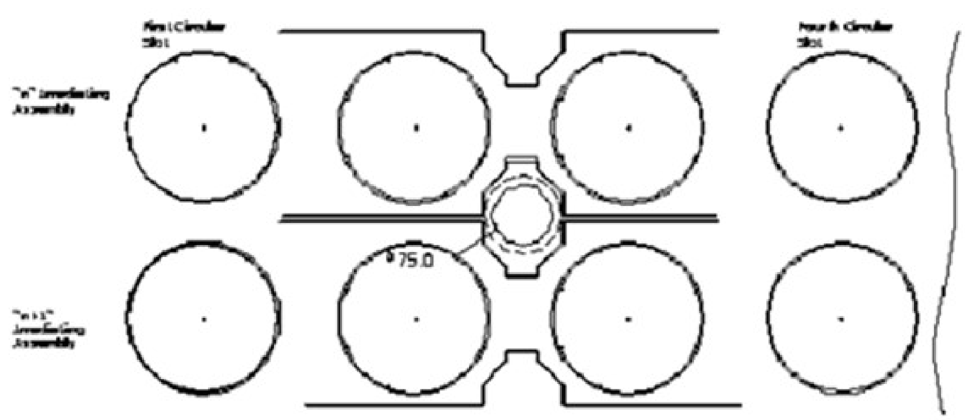

Figure 2. Available space and location for the restrain-release mechanisms holes in the radiating surface.

The restrain release structure must have a smaller diameter (less than 75 mm) to avoid mechanical contact with the radiating elements to accommodate mounting tolerances and to allow the alignment of the mechanisms with the folded panels. These requirements limit the maximum diameter of the restrain-release structure to 67 mm in the area where it crosses the radiating elements of the antenna.

Also, in order not to affect the emission and reception characteristics of the antenna, it is required that no metallic element protrudes from the radiating plane of the panels in their unfolded configuration. Therefore, the separation surface of the restrain release parts shall be below the radiating surface in each panel.

This requirement, together with the maximum diameter of the mechanism structure in this area, limits the area of the support and separation surfaces of the restrain-release parts in each panel, restricting the loads that each mechanism can transmit and support. This load limitation, together with the one supported by the chosen release device, determine the minimum number of mechanisms required and their distribution in each set of folded panels, which must be placed according to the loads produced by the launch vehicle.

The selection of a six-mechanism configuration for the array of panels resulted from the previous requirements and the need to reduce the bending moments generated on them and, as described in the following paragraphs, to limit the preload of the mechanisms. Considering this arrangement of mechanisms distributed on the surface of the folding panels, the load cases foreseen for the launch indicate that each of the mechanisms must withstand a minimum of 55 kN (12,365 lb) of compression load to avoid loss of preload and panel separation.

To comply with these requirements and constraints, the adopted design of the restrain-release mechanism is an assembly of tube sections located on each folded structural panel and on the primary structure of the Service Platform (SP). These tubes are joined by male and female cup and cone type sections to transfer the forces, bending moments and torques that the antenna supports during launch to the SP structure. Inside this tube a preload rod maintains the contact between tube sections and assure the load transfer.

A release device located on the outer panel supports the preload of the rod and, when operated, releases the rod and allows the latter wing deployment. A redundant assembly of helical springs retracts the rod into the SP to avoid interferences during the deployment operation. To stop the movement, the rod has a shock absorber located just beside the release end. A scheme of the restrain-release mechanism is shown in Figure 3 in both configurations, i.e., with restrained and released panels.

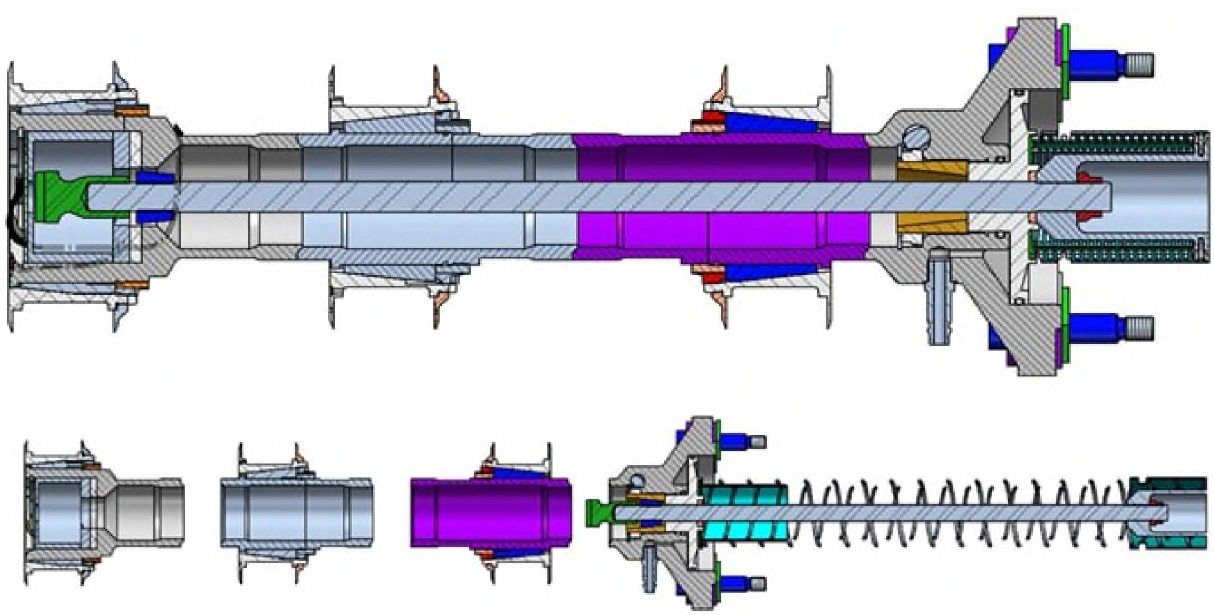

Figure 3. Restrain-Release Mechanism.

All the tubular parts, the flange mounted on the SP, and the preload rod of the restrain-release mechanism are manufactured from a titanium alloy (Ti5Al4V) due to its high strength and low mass. This alloy's low coefficient of thermal expansion also avoids the generation of high tensions between the carbon fiber structural panels and the fixed part of the mechanisms due to thermal stresses produced by differential expansion between components.

The pullback springs are made of stainless steel, the pneumatic piston is made of a titanium alloy and the shock absorber is made of Delrin®. The cup and cone type contact surfaces of the tube sections incorporated a surface coating to avoid cold welding that could be produced by the preload and vacuum conditions that the mechanism must withstand in orbit before activation. The coating used on these surfaces is a multi-layer chrome nitride coating with a few microns of thickness applied by means of a PVD (Plasma Vapor Deposition) process developed and qualified in-house.

The selected release device is an electromechanical separation nut based upon patented split-spool and fuse wire technologies from NEA Electronics Inc. (USA, model 9106B-3, shown in Figure 4, with a load carrying capability of up to 148 kN).

In addition to a lightweight design, the release device provides extremely low shock – orders of magnitude below pyrotechnic devices, is fast acting, releasing in milliseconds, can operate over a wide temperature range, and provides misalignment capability of up to 15 degrees. The design is a fully redundant configuration, both mechanically and electrically.

It should be noted that the manufacturer of the release device recommends using a preload rod made of Custom 465® stainless steel in order to use the entire preload allowed by the device. During development, a requirement was generated indicating that the use of magnetic materials inside the satellite SP should be avoided and therefore, as the preload rods of these mechanisms are housed inside the SP after the mechanisms are activated; it was necessary to change their material to a non-magnetic titanium alloy that could withstand preloads of up to 75 kN.

Figure 4. NEA Release Device.

To reach the preload on the internal rod of the mechanism during the integration process, a disc or piston operated pneumatically (using compressed dry nitrogen, vented at the end of the maneuver) produces the load and then a nut is pressed close against the disc of the piston to maintain the preload. The use of the pneumatic device to preload the rod reduces the required size of the nut and the volume and mass required for the mechanism. Figure 5 shows a cross-section of the described mechanism mounted into the tube section located on the SP.

The dimensions of the structural panels of the antenna and the distribution of the six restrain-release mechanisms therein require their precise alignment during the integration of the array of folded panels. To facilitate the integration tasks, both the tubular sections of the mechanisms and the parts located on the satellite SP have mechanical devices that allow the precise alignment of the parts, thus ensuring the proper transfer of both the preloads of the mechanism as well as the loads that are generated during the launch.

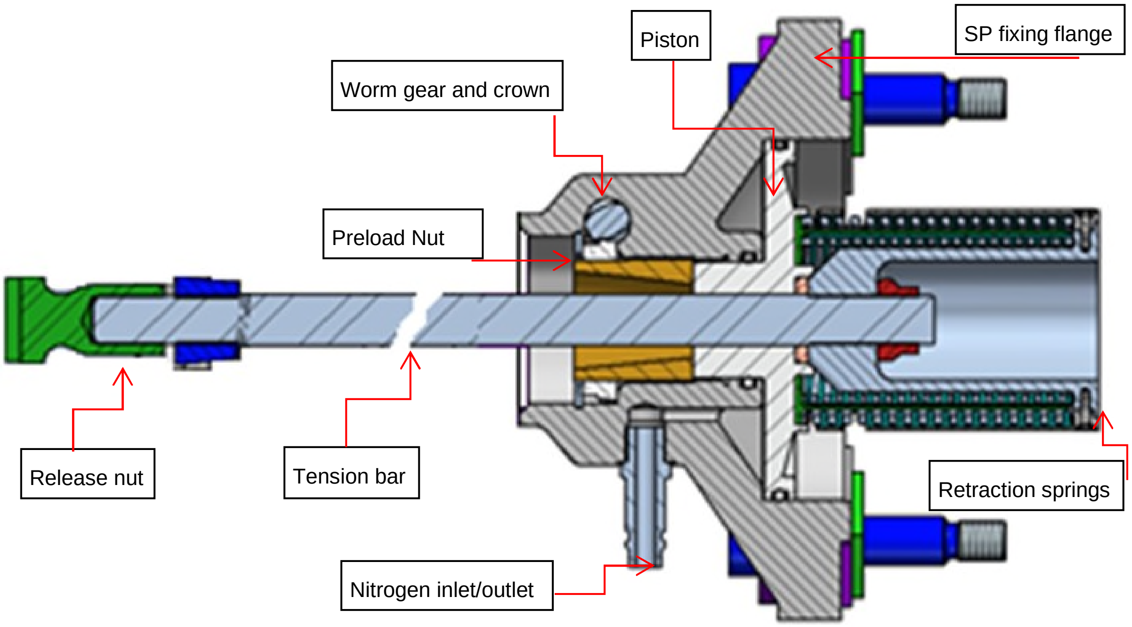

Figure 5. Detail of the pneumatic drive device.

Each mechanism is fixed to the structural panels using large titanium inserts. Inside these inserts, a set of conic elastic eccentrics and nuts are mounted to allow the radial and axial position of the assembly to be adjusted. Also there are eccentric bushings on the fixing points of the flange to align the mechanism in the SP. Figure 6 shows a view of the mechanism assembly which shows the three metal inserts that fix it to the panels and a detail of the alignment mechanism mounted on these inserts can be seen.

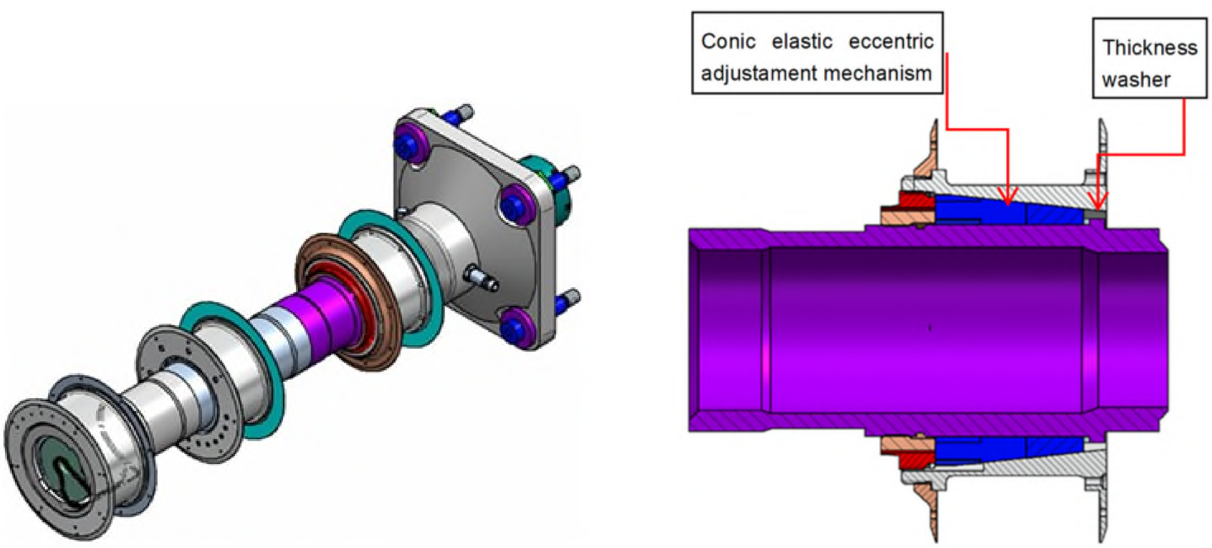

Figure 6. Restrain release assembly and detail of the alignment device.

The total mass of each mechanism, including the inserts that fix it on the panels and the parts mounted on the satellite SP, is approximately 15.6 kg.

Qualification Process

The qualification process of these mechanisms involves environmental and functional tests. Functional tests were performed before and after the sequence of the environmental tests following the guidelines of the NASA document of Reference [1].

The qualification units consisted of the Mechanisms Qualification Model, the SAR Antenna Structural Model (integrated to the Satellite Structural Model), and the Satellite Proto-flight Model (the first flight model).

The Mechanism Qualification Model was prepared to conduct a complete campaign of environmental mechanical and thermal tests with qualification level and functional tests in order to qualify all the mechanisms involved in the deployment of the antenna. This functionality was tested with simulated on-orbit thermal environment conditions using a thermo-vacuum chamber, after a successful first release and deployment of the model carried out before the vibration test.

This model included a structural support assembly for the mechanisms to be tested, consisting of a mock-up of sandwich panels with similar characteristics to those used in the antenna and a fixed aluminum panel to represent the support of the satellite SP. On this mock-up, two prototypes of the latch mechanism (to fix the relative position between succesive deployed panels), two prototypes of the hinge mechanisms (to allow the deployment of the panels using a stepper electrical actuator), a prototype of the restrain-release mechanism and two prototypes of the devices for the passing through of harness between antenna panels were assembled.

The SAR Antenna Structural Qualification Model (SQM) was prepared to be integrated with the satellite's SQM and to carry out a complete mechanical and functional qualification test campaign. This model of the SAR Antenna included the fixed central panel and the Interface Structure, a main assembly of three deployable panels, composed of flight-like strcutures and mechanisms, and a dummy representing the other main assembly of panels with the same inertia and stiffness properties. The deployable panels and the central panel had all the Radiating Modules and the corresponding deployment mechanisms integrated and included a set of six restrain-release mechanisms.

The Proto-flight Model (PFM) was the SAOCOM 1A satellite and was subjected to a complete campaign of functional and environmental vibration and acoustic tests with qualification levels. The test campaign included a SAR antenna release and deployment test before and after the environmental tests with the corresponding actuation of the release devices. For these tests two sets of NEA separation nuts were employed.

Qualification Results

The main objective of the thermo-vacuum test on the Mechanisms Qualification Model was to qualify the SAR antenna mechanisms against thermal loads. The different components were analyzed for the most unfavorable temperatures that will be experienced during the release and deployment in flight. Figure 7 shows the model integration to the thermo-vacuum chamber and the deployment performed.

The restrain-release mechanism would be successful if the interruption of the release device circuit is electrically verified, and the retraction of the preload rod inside the thermo-vacuum chamber is observed. If the retraction of the preload rod is successful, the mechanism must allow the correct separation of the set of movable panels with respect to the flange of the mechanism fixed to the SP dummy.

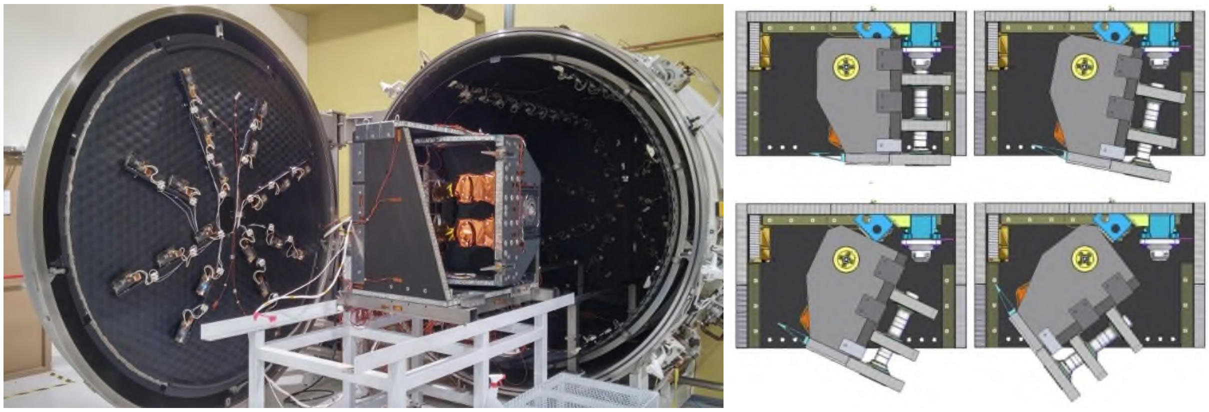

Figure 7. Integration of the Mechanisms Qualification Model to the thermo-vacuum chamber.

The release device circuit had an LED lamp connected to the Electrical Ground Support Equipment in arming mode so, at the moment of release, it would turn off indicating that the circuit was interrupted. This ensures that the drawn current correctly triggers the restrain-release mechanism. The retraction of the preload rod and the panel deployment were visually verified through a window in the chamber.

The actuation of the mechanism and the deployment of the model inside the chamber were performed after the qualification thermal cycling with the release device at a temperature of +45°C. The employed thermal cycling is shown in Figure 8 and it should be noted that, unlike other mechanisms such as deployment actuators or hinges between panels, the restrain-release mechanism did not have active temperature control.

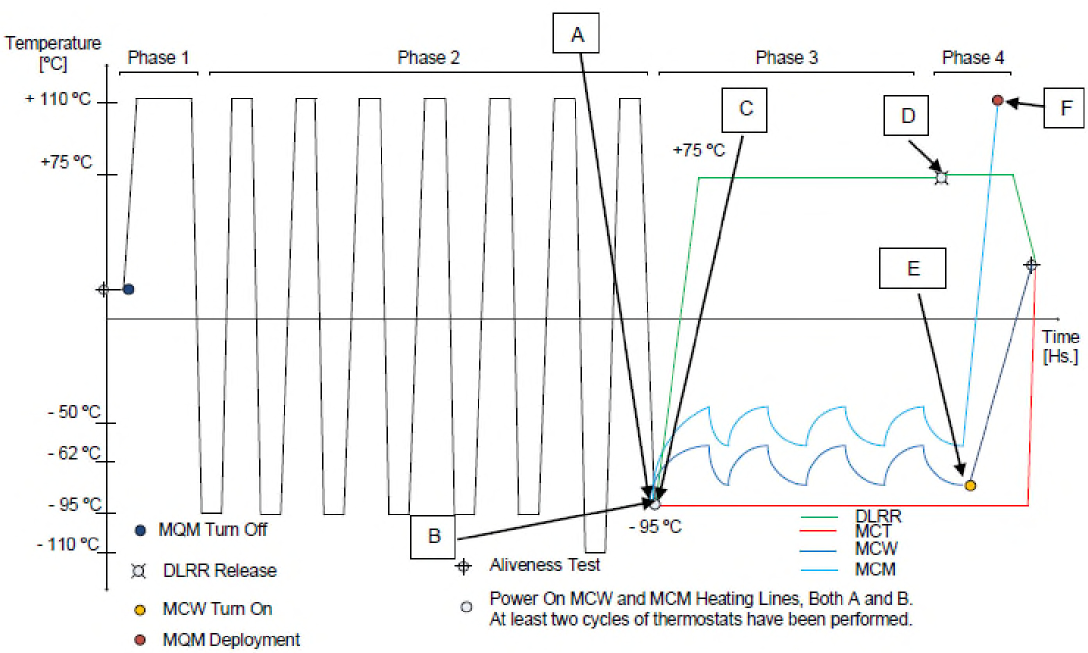

Figure 8. Thermal cycling of the Mechanisms Qualification Model, temperature evolution of the release device (in green) and release of the mechanism (point D).

The next step in the mechanism qualification was the SQM with a complete set of six mechanisms integrated to a complete array of deployable panels. Two actuations of these mechanisms were performed during the test campaign. The first one before the vibration tests and the second one after the acoustic test.

In the SQM, the restrain-release mechanisms' tubes were instrumented with a set of strain gages in order to characterize the preload applied by means of the pneumatic system. The value of preload or minimum axial force required to assure the contact of the cup and cone surfaces was set at 70 kN and is transmitted through the preload rod, which is subjected to traction. The mathematical model results showed that the required preload needed a pneumatic pressure of 8.0 MPa.

The distribution used for the instrumentation was four strain gages placed on the outer surface of the tubes as shown in the development model of Figure 9. This allows bending stress at the junction of the tubes to be ignored and for the minimum compression component to be measured. The compression component of the stress is required by the mechanism to ensure the transfer of loads between the panels of the antenna model during the vibration tests.

Unidirectional grid strain gages were used for these tests, which were fixed to the tubes of the mechanism using an epoxy-type adhesive. For each mechanism, the strain gages were placed on the tube closest to the flange located on the SP, which is the location requiring the highest stress according to the analysis carried out on the mathematical models. A total of 24 strain gages were installed, oriented at 90º to each other, each one with its grid aligned in the direction of the longitudinal axis of the mechanism.

Each strain gage was connected to the data acquisition system in a ¼ bridge configuration and without compensation for temperature variations. Data acquisition is performed using three Vishay amplifiers (strain indicator) and three switch & balance units.

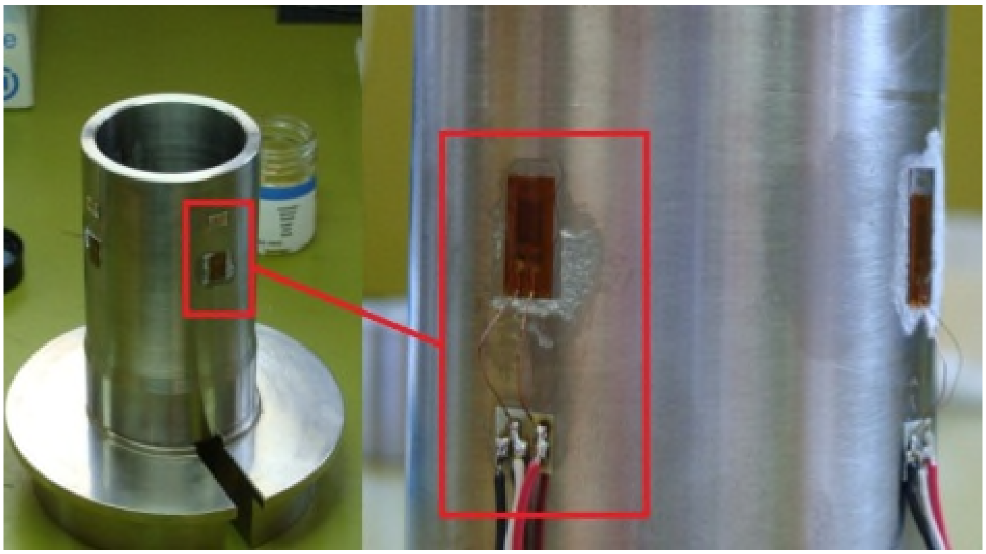

Figure 9. Strain gages for preload characterization located on the development model.

Once the deformation in each strain gage has been obtained, the determination of the bending moments in each axis and the axial force that the tube supports were estimated, being the latter the one that is transmitted to the preload rod. Table 1 shows an example of the strain measurements and preload obtained using a pneumatic pressure of 8.0 MPa in the mechanisms. The results were similar in all the preload operations performed on the SQM and showed that the required preload was obtained with a maximum 2.2% variation respect to the nominal value.

This procedure made it possible to qualify the preload process of the restrain release mechanisms by applying a pneumatic pressure of 8.0 MPa to them. In this way, it was established that it would not be necessary to repeat the instrumentation on the tubes of these mechanisms in the flight models of the antenna.

Table 1. Strain measures and preload obtained applying 8.0 MPa.

Mechanism ID	*SG1 [µs]*	*SG2 [µs]*	*SG3 [µs]*	*SG4 [µs]*	*Preload [N]*
4	*-617*	*-710*	*-668*	*-610*	*-70585*
3	*-622*	*-1089*	*-521*	*-318*	*-69095*
6	*-512*	*-453*	*-904*	*-767*	*-71425*
2	*-845*	*-519*	*-459*	*-736*	*-69339*
5	*-866*	*-553*	*-527*	*-683*	*-71236*
1	*-644*	*-601*	*-715*	*-684*	*-71642*

During the qualification campaign, the restrain-release mechanisms had to comply with two specific requirements. The first one required a complete retraction of the preload rods after the release in order to avoid mechanical interferences during panel deployment. The second one specified that the shock due to antenna release should not introduce shock spectrum in excess of Figure 10 in the most loaded leg of antenna mounted electronic equipment in order to not affect their functionality.

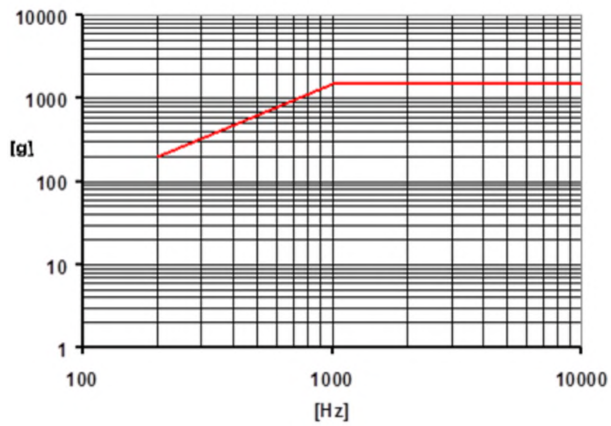

Figure 10. Maximum shock spectrum requirement during the antenna release.

To evaluate the shock due to the panels' release, an array of accelerometers distributed on the structural panel that has the assembly of the mechanism with the release device were employed. The time signals of these accelerometers during the activation of the restrain release mechanism were recorded and processed using the recursive algorithm introduced in Reference [2] to obtain the shock response spectrum (SRS) showed in Eq. 1:

$$SRS_{(f_s)} = \max\left(\left|Real\left[\frac{1}{N}\sum_{k=1}^{N}\left\{H_{(f_s,f_k)}\cdot\sum_{j=1}^{N}y(j)e^{-\frac{2\pi i(j-1)(k-1)}{N}}\right\}e^{-\frac{2\pi i}{N}}\right]\right|\right) \qquad \text{(Eq. 1)}$$

with $H_{(f_s,f_k)} = \left(\frac{f_s^{\,2}+i\frac{f_s f_k}{Q}}{f_s^{\,2}-f_k^{\,2}+i\frac{f_s f_k}{Q}}\right)$ as the transfer function

f_x, are the frequency values, Q is the quality factor and *y(j)* are the acceleration values measured along the test.

Figure 11 shows the accelerometers distributed on the panel near the release devices and also near some electronic front-end boxes and other mechanisms as the latch devices. Figure 12 shows the time signals obtained during the 50-second sequence of release device activation with peak values around 6000 g, and Figure 13 shows the SRS obtained from the accelerometers located near the position of the release devices. The shock waves are attenuated by the structure of the panel, and near the electronic boxes the obtained SRS complied with the requirement. It is shown in the SRS of Figure 14 that measurements near two of the transmision-reception assemblies with values one order of magnitude below the requirement.

The test also allowed for activation time verification of the release devices within the operating parameters indicated by the manufacturer. The activation time was 25 milliseconds and the frequency spectra obtained presented amplifications around 5 kHz, which also matches with the response spectrum of the release devices provided by their manufacturer.

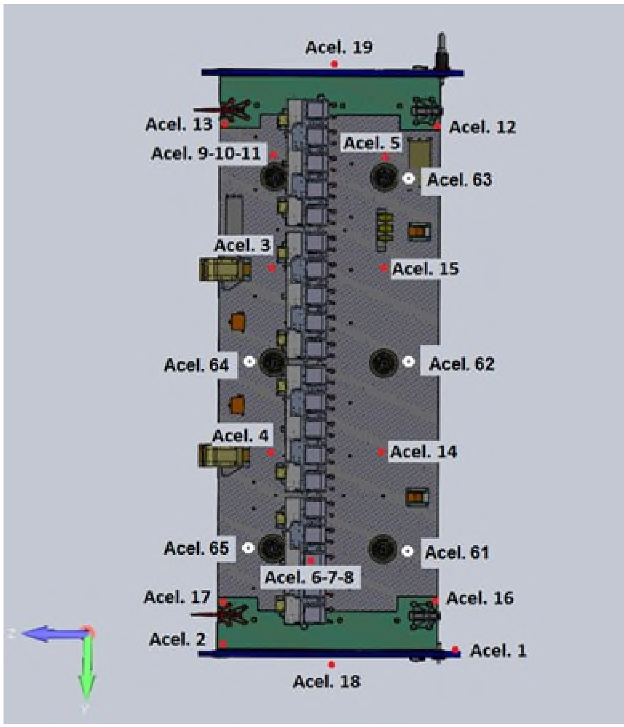

Figure 11. Accelerometers installed on the antenna panel for the qualification campaign.

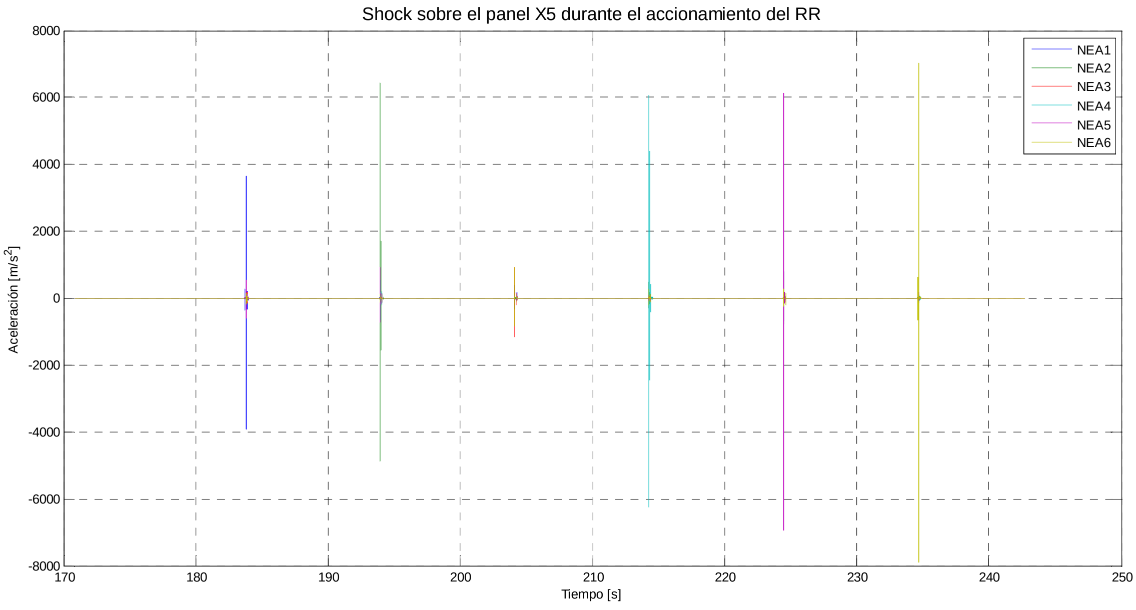

Figure 12. Time signals of the accelerometers located near the release devices during the activation of the mechanisms.

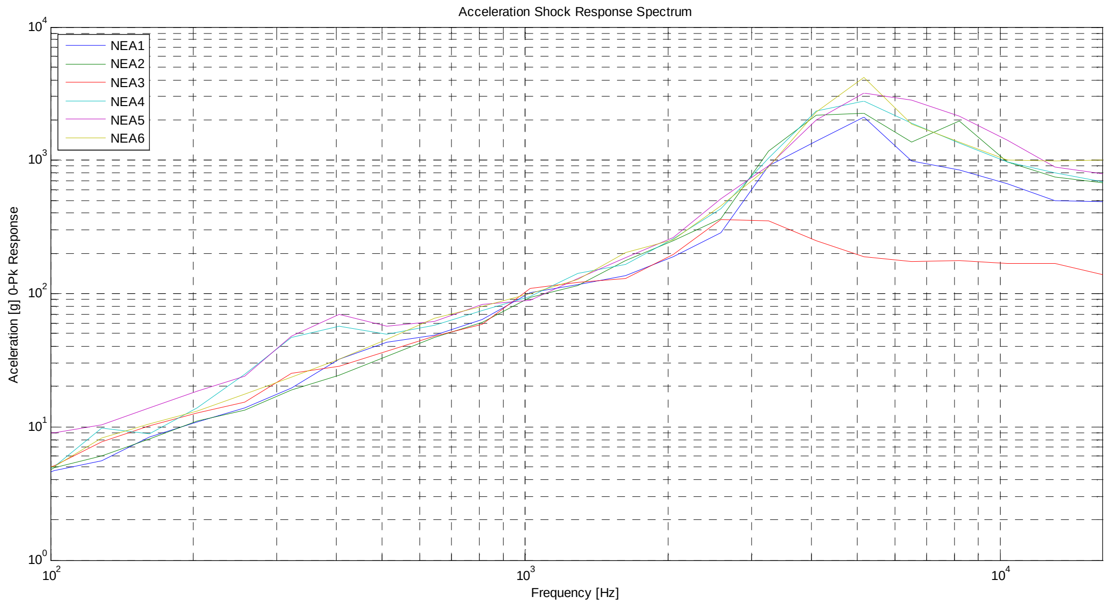

Figure 13. SRS of the accelerometers located near the release devices during the activation of the mechanisms.

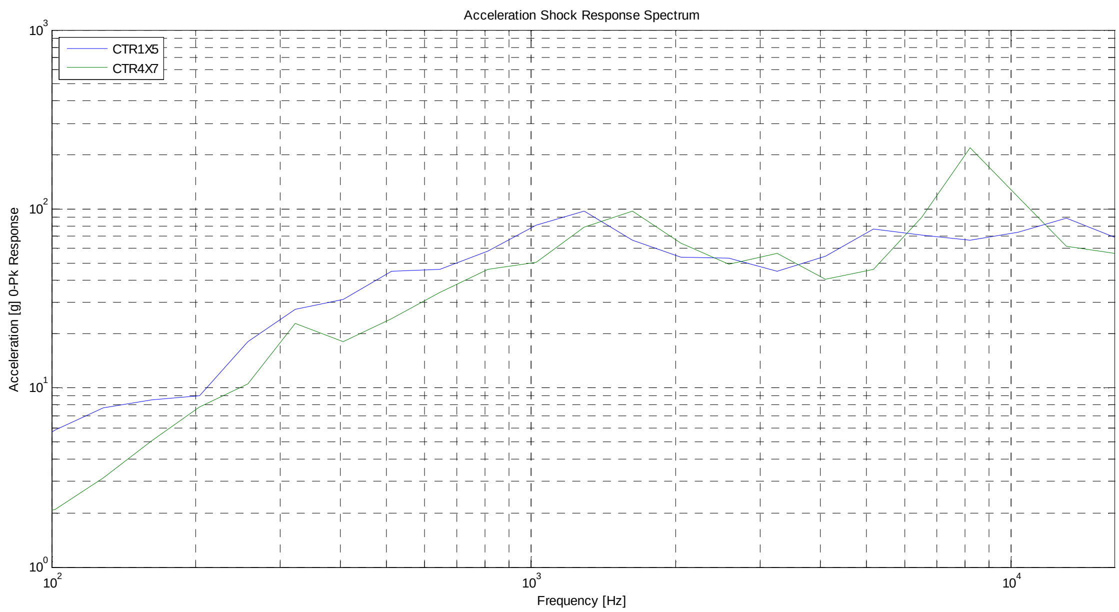

Figure 14. SRS of the accelerometers located near two of the electronic boxes during the activation of the mechanisms.

The mechanisms verification in the SQM also included the analysis of the possible geometric interference in the areas of least clearance that was between two restrain-release mechanisms and the support legs of the hydrazine tank located inside the SP. This possible interference would occur when the preload rods of the mechanisms, once released, retract inside the SP as a result of the action of the springs. If interference occurs, it would lock the mechanism without reaching its expected final position, preventing the deployment of the antenna panels.

In order to evaluate if there are geometric interferences, witness guide surfaces were placed along the path of the mechanism, so that when it was activated it would be possible to assess for any interference beyond the assigned volume.

To fulfill this function, the guide surfaces were painted with an ink for tooling that allows, after the test, to determine if there was contact between the parts during the actuation of the mechanism. Figure 15 shows these painted surface guides installed inside the structural model of the SP in the planned route of the preload rods and the location of the support leg assemblies of the hydrazine tank.

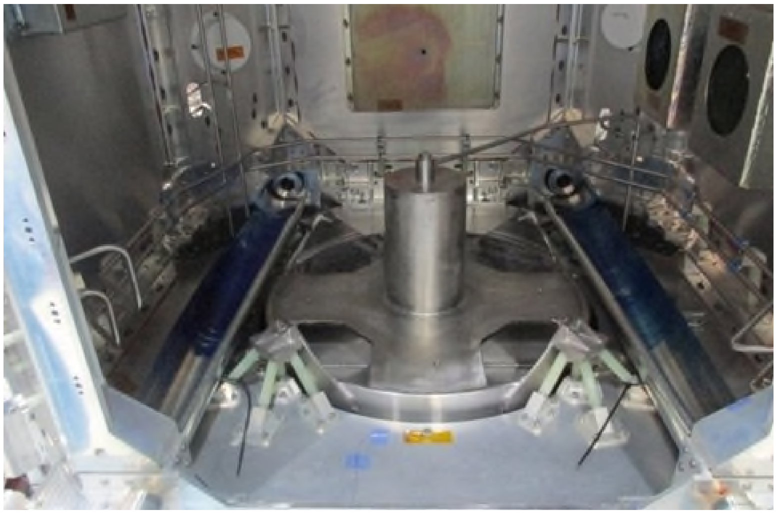

Figure 15. Array of surface guides installed inside the SP model to evaluate geometric interferences between the restrain-release mechanisms and the hydrazine tank supports.

For the test to be conservative, these guide surfaces for the rods were formed by a 0.5-mm thick section of tube and were placed above the possible points of contact (fixing screws and surface of the supports of the hydrazine tank) and the parts that form the end of the preload rod had a diameter of 76 mm compared to the 70 mm for the flight model's mechanisms, which increased the radius of the possible geometric interference by more than 3 mm.

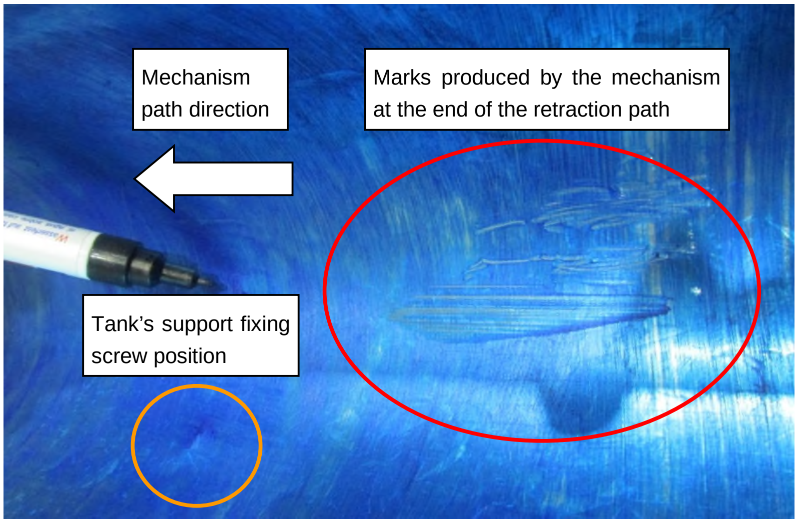

Figure 16. Details of the marks produced by the release of the rods on the guide surfaces.

Figure 16 shows a detail of the marks produced by the release of the rods on the guide surfaces. The inspection showed the areas where the sliding of the end tube of the mechanism occurred. These marks appeared in both cases before where the hydrazine tank supports are located, which indicates that there was no interference or collision between the mechanism and these supports of the fuel tank. Also the contact of the end of the mechanism on the guide surface occurred at the end of the rod's travel. Given that the marks are at the end of the rod's path and that they were found on the lower area of the guide surface, it was concluded that the rod made its entire path centered and without an angle with respect to the bushing located on the flange of the mechanism. And when it stops, it rests on the guide surface due to the effect of gravity.

The release and deployment tests verified the complete retraction of the mechanisms preload rods inside the SP as shown in the example of the visual inspection performed in Figure 17 (left) after the successful panels' deployment of the PFM.

Also, during the PFM qualification test campaign, the visual inspection reveals that 3 of the 12 rods didn't retract completely as shown in Figure 17 (right). In those cases, it was possible to record that the rods with retraction incomplete overhang with respect to the flange of the mechanism by approximately 32 mm, while the design value is 22 mm. However, the maximum admissible limit that geometrically allows the correct deployment of panels is 85 mm. This value was obtained from the most unfavorable condition with respect to the regulation of the panel position by the hinge mechanisms and in the position closest to the panel rotation axis. After the visual inspections and the detection of the rods with incomplete retraction, it was also observed that due to gravity, these rods were in an oblique position with respect to the flange axis, and when aligned, the axis friction forces are minimized and fully retracted it to the design position due to the preload still existing in the springs of the mechanism. Therefore, it was concluded that in the absence of gravity, the rods should retract to their designed position without problems.

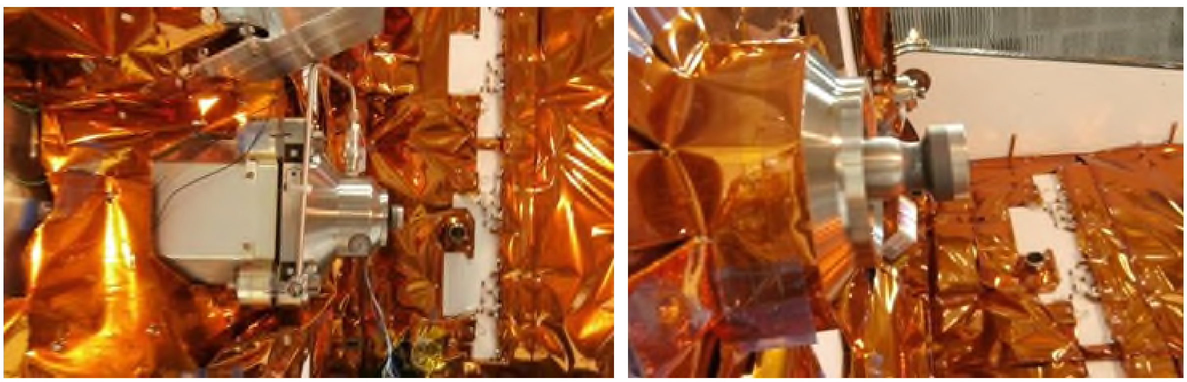

Figure 17. Visual inspection of the preload rod complete retraction (left) and preload rod incomplete retraction after the panels' deployment.

During the Flight Model (FM) SAOCOM 1B acceptance test campaign, a comparison was made between the time signals acceleration recorded during the release tests of the SAR antenna panels, after the environmental vibration tests of the PFM and FM satellites, to analyze the particular case of one of the restrain-release mechanisms in order to identify differences and evaluate their possible causes.

Figure 18 presents a comparison of both time signals synchronized with the firing signal and showing an important difference between the maximum amplitude recorded during the actuation of the corresponding release devices of each model. The maximum amplitude recorded during the FM release test is approximately 82% lower than the amplitude recorded during the same PFM test. The analysis of the signals in Figure 12 also showed that the time of flight of the rods, between release and impact on the shock absorber, was 4 milliseconds longer in the case of the PFM, in addition to not being able to be identified in the latter case, neither the start of the burning of the release device with a duration of 20 milliseconds, nor the pulse that occurs at the moment of panels separation.

These differences can be explained as the result of the absence of preload in the mechanism of the FM, since none of the accelerometers installed in the vicinity of the mechanism registered a significant amplitude pulse immediately after the 20 milliseconds of burning the release device that could indicate the separation of the panels. This analysis concluded that the environmental vibration tests of the FM were performed with one of the restrain release mechanisms without the design preload. The evaluation of the tests showed that there was no gap between panels and the inspection of the mechanisms showed that there was no degradation of the contact surfaces between the parts of the mechanism located in the different panels. This problem, which occurred during the FM tests, showed the important design margins of the restrain release mechanism configuration adopted.

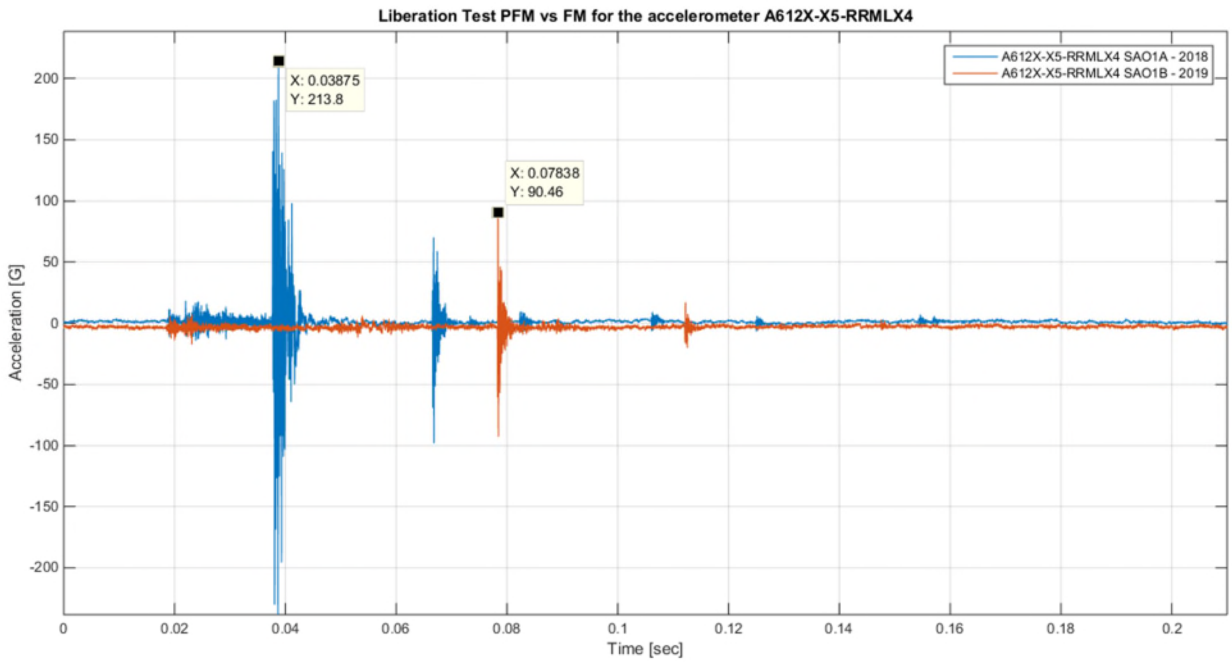

Figure 18. Synchronized time signals for the release of the same mechanism on Proto Flight Model and Flight Model.

Concluding Remarks

The tests performed over the different models during the qualification process of the restrain-release mechanisms for the SAR Antenna of the SAOCOM satellites showed that the adopted concept has design margins to withstand higher loads, originated both in a set of panels of greater mass and in a launcher with a greater acceleration envelope.

In addition to the multiple tests carried out during development and qualification phases of the project, the reliability of the restrain-release mechanisms designed in this case was confirmed by the successful performance on-orbit of a total of 24 units between the two launched satellites.

The qualification campaign of these mechanisms demonstrated the correct choice of a pneumatic preload system, which provided in-family preload values in all the mechanisms of each model and the fast and reliable performance of this task.

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