# LARES Mission: Separation and Retention Subsystem

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## Abstract

As part of the Lares (LAser RElativity Satellite) mission, an all-Italian scientific mission launched with the Vega maiden flight in February 2012, a mechanical separation and retention subsystem (SSEP) has been developed to retain the LARES satellite during launch and release it in the final orbit. The design flow was based on the identification of the driving requirements and critical areas to guide the trade-off, design, analysis and test activities. In particular, the SSEP had to face very high environmental loads and to minimize the contact areas with the satellite that had a spherical shape. The test activity overview is provided.

## Introduction

The scope of this paper is to describe the activities done for the design of the SSEP (Separation Subsystem) developed for the LARES program, give an overview of the test campaign performed, and show the relevant main results underlining the acquired experience.

## LARES Mission Main Objectives

LARES (LAser RElativity Satellite) is an all-Italian scientific mission, developed for the Italian Space Agency and successfully deployed in orbit by the European launch vehicle Vega on its maiden flight on February 13, 2012. The main goal of the LARES mission is to take high accuracy measurements of the Lense-Thirring effect, i.e., the dragging of inertial frame due to additional space-time curvature produced by the Earth's angular momentum. Two secondary objectives were assigned to the mission: to provide a separation platform for additional payloads and to support the launcher qualification. In order to support Vega qualification, the system included a stand-alone avionics system devoted to measure the launcher payload area environmental conditions during flight and to provide video of launcher lift-off, stage separations (by using an external camera), and payload separation in the target orbit.

## LARES System Architecture and Subsystems

The LARES system is composed of the following main elements:

- The LARES satellite, a tungsten sphere of ~400 kg with 92 Corner Cube Reflectors embedded;
- The Separation and Retention Subsystem (SSEP) to retain the LARES satellite during the launch flight and release it in the final orbit;
- The Support Subsystem, the main structural interface with the launch vehicle upper stage and to support all the subsystems of LARES system;
- Avionics and Harness Subsystem, the subsystem to provide separation of the payloads, to assist the launch vehicle in acquisition, to monitor key parameters inside the launcher fairing and the separations of the launch stages during ascent by means of video cameras, and to download data to ground stations.
- Eight secondary payloads.

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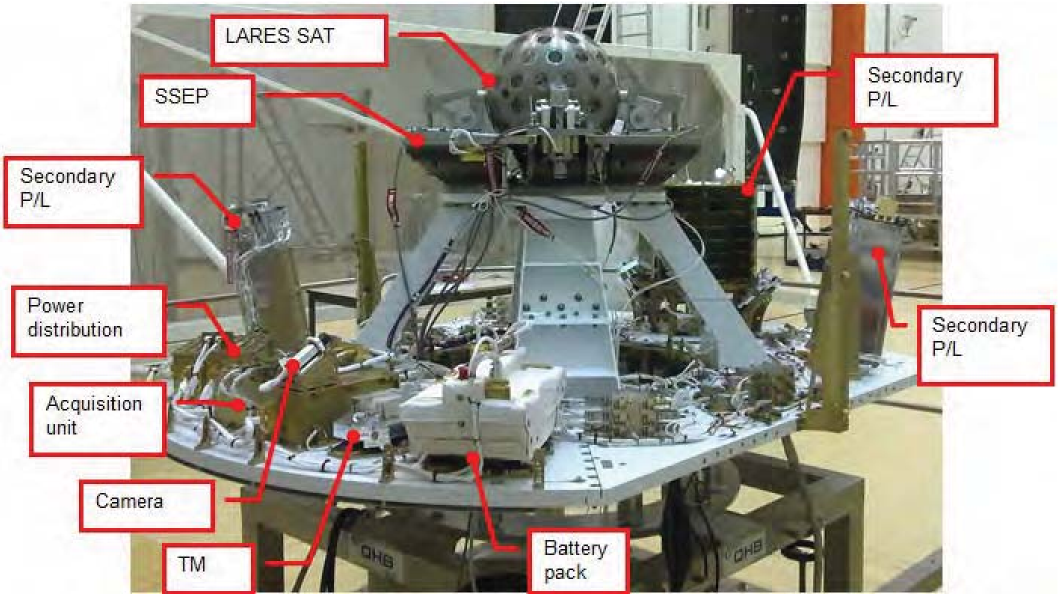


Figure 1. LARES system before launch

The industrial contract for LARES development was given to the Compagnia Generale dello Spazio as prime contractor, and a structure of industrial and universities subcontractors for the different subsystems. In particular, Rheinmetall S.p.A. satellite line of business (the line of business later merged with CGS), designed, manufactured and tested the Separation Subsystem.

## SSEP Design Driving Requirements and Critical Areas Identification

The main goal of this kind of Subsystem was meeting the following challenging, severe and contradicting requirements:

1. To be stiff with the LARES satellite installed (lateral first frequencies higher than 70 Hz, while vertical frequency higher than 140 Hz);
2. To withstand high environmental loads (i.e., quasi static load of 15 g in each orthogonal directions applied to the 400-kg payload);
3. To lock a spherical body tungsten made by minimizing the contact areas;
4. To be single point failure tolerant in terms of release function (degraded kinematical separation conditions were acceptable);
5. To transmit negligible shock to the LARES during the separation

The structural/stiffness requirements (number 1 ,2, 4 and 5) were specified by the launcher in order to be as much conservative as possible as this was the VEGA launcher's maiden flight. The third one was a scientific requirement aimed not to alter the spherical shape of the satellite that for scientific purposes shall be as perfect as possible so as to be modeled as a spherical body. To fulfill the above requirements, the following critical areas have been identified:

1. Reliable, simple and failure tolerant design concept identification;
2. Suitable separation device identification → only non-explosive initiators have been considered;
3. Separable surface design optimization in terms of material selection (with the satellite side fixed), geometry and preload;
4. Robust and repeatable alignment and integration process identification.

### Trade studies

The first trade analysis for the concept selection was performed by taking into account the above listed critical areas. Existing or similar applications have been used as starting point. Several configurations have been analyzed considering applicable requirements in terms mainly of mechanical environment, available room and taking into account technological, manufacturing and functional aspects. In particular, four basic concepts have been studied:

- Tropical solution: to apply the preload using three pullers hardly engaged in the satellite body.
- Clamp Solution: to apply the preload using four arms on the upper surface of the satellite to push down the satellite against a preloaded pad.
- Equatorial Solution: to apply the preload using four pin-pushers inserted in the equatorial holes and by using a lower supporting circular pad engaging the sphere bottom part providing a vertical support and preload.
- Hinge Solution: the same as solution 3 without using sliding pins but using equatorial hinged pins.

Solution n. 1 (Tropical Solution)
The satellite is fastened to the SSEP structure by using three fixation points positioned at 120°. These three points could be threaded bars screwed in the satellite for one side and fixed to the separation device on the other side. After the release, three protruding elements remain attached to the spherical satellite. The benefits of this solution are simplicity and stiffness; simplicity means high reliability and shorter development, manufacturing and testing time. On the other hand several disadvantages exist that lead to discard this solution: the protrusions modify the satellite configuration by adding a small uncertainty source in the Lense-Thirring measure, the preload application to these bars is complicated, and finally the failure tolerance implementation is not easy (if a threated bar remains engaged no possibility to release the satellite exists).

Solution n. 2 (Clamp Solution)
The Clamp Solution was designed to provide the preload using a combination of locked arms in the upper part of the satellite and a pushing cap on the south polar region of the satellite. The clamps are used to obtain a reaction to the preload applied by the pushing cap. The clamps are blocked during the flight until the separation devices receive the separation signal. To provide enough satellite clearance, the clamps have to move when the constraint is unlocked; they are pulled back by a rotational spring inserted inside a hinge.

The contact surface between the clamp and the sphere needs to have an area > 23 cm$^2$; which means the clamp has the same curvature of the sphere. In order to avoid damage on the satellite surface due to vibration effects, the same surface finish has to be on the clamp interface area and the satellite. Micro welding is prevented using a suitable material for the clamp. The most important part of this configuration is the clamp that has to hold the satellite. In Figure 2, the main components of this solution are shown; furthermore, the mechanism in open and closed configuration is shown. The conical insert, where the separation device is positioned, is designed in order to withstand shear loads.

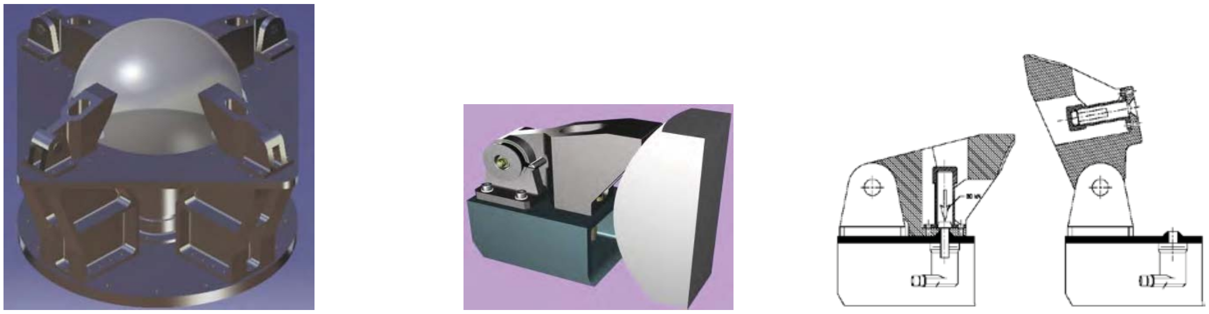


**Figure 2. Clamp Solution assembly on left. Clamp detail in the center. Clamp section in open and closed configuration on right**

The benefits of this solution were simplicity and stiffness; the main drawback is that it is not possible to implement the failure tolerance functionality (if a clamp remains in closed configuration, the vertical force component blocks the satellite on SSEP).
Solution n. 3 (Equatorial Solution)

The Equatorial Solution has four equatorial pin-pushers blocking the sphere. Each pin pusher provides a preload by means of non-explosive actuators. During the flight phase, the pins are hardly pressed in the cavities by the devices; once the satellite has reached the separation altitude, the separation devices are activated by removing the preload on the pin-pushers and allowing the pin retraction via springs in order to disengage the satellite. In Figure 3 and Figure 4, the preliminary design of this solution and the two pin working positions are shown.

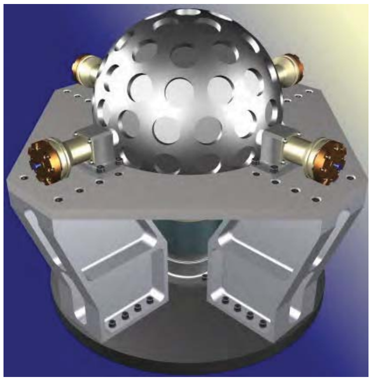


**Figure 3. Equatorial Solution**

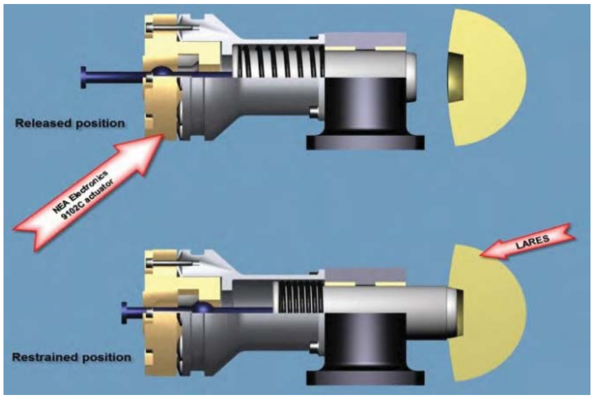


**Figure 4. Pusher working positions**

The benefits of this solution were simplicity, stiffness and the failure tolerance because it is possible to design the interface geometries between pin and satellite to allow the disengagement of the satellite even if a separation device fails; but a problem exists with the loads acting on the pin when the structure is preloaded. The retracting spring on each pin had to be bigger than available space for accommodation.

Solution n. 4 (Hinge Solution)

This solution is an upgrade of the equatorial one, because in it LARES engagement is ensured by four hinges in order to avoid the friction problems in the contact points between LARES and the four pins. The structures must be compacted to improve the stiffness, the vibration behavior, and to reduce the total mass, as shown in Figure 5.

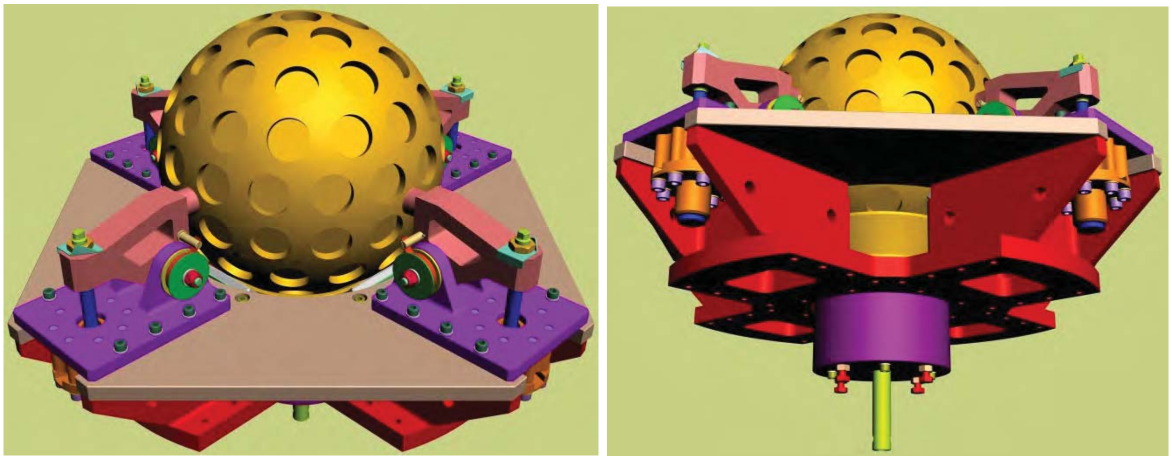


**Figure 5. Hinge Solution**

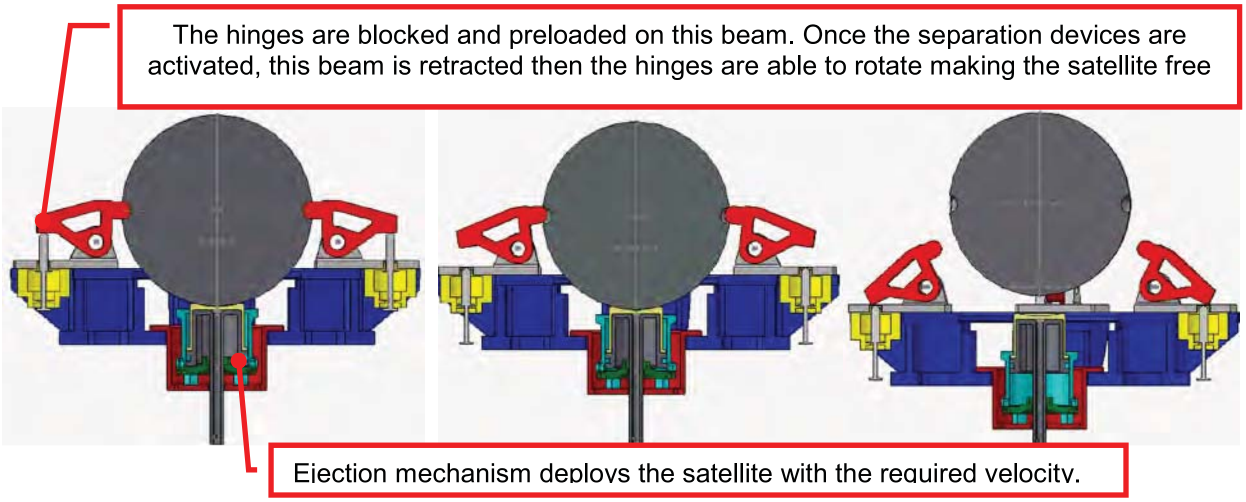
This solution collects all the advantages of the previous solutions by minimizing the disadvantages; for this reason this has been selected as final configuration for LARES SSEP. The separation device geometrical position and number (4 actuators) required a very good simultaneity in the separation. This simultaneity requirement coupled with high strength and power budget boundaries lead to the usage of a NEA Electronics solution to initiate the LARES separation. In particular, the actuator had to withstand a maximum 195000-N static load applied in compression along the pin axis and had to separate properly when subjected to a total compressive load of 148000 N along the pin axis. Then the release mechanism, considering an infinitely rigid interface flange, had to guarantee a minimum axial stiffness (against the load direction) of 219 MN/m. Furthermore, the release mechanism allows an angular misalignment of rod corresponding to a 10° cone under the loads above specified.

LARES SSEP Selected Configuration Summary

The selected configuration for the SSEP is composed of the following elements:

- A supporting structure that guarantees lower mechanical interface toward the LARES System support structure (white structure in Figure 1).
- An upper main mechanism that is the mechanical interface to the LARES satellite, including:
  - The interface pins to the satellite
  - The hinge system, which allows the retention of the satellite during the launch phase and its separation on orbit.
  - The initiator device that releases the hinge system
  - The switches indicating the opening of the first mechanism and the activation of the second one.
- A support and preloading system
- An ejection LARES mechanism.
- An electrical interface to the avionics, including:
  - The switches lines
  - The initiators lines

The functionality of the release mechanism is explained in the separation sequence shown in Figure 6, from locked configuration (on left) up to the satellite separation (on right):



The hinges are blocked and preloaded on this beam. Once the separation devices are activated, this beam is retracted then the hinges are able to rotate making the satellite free

Ejection mechanism deploys the satellite with the required velocity.

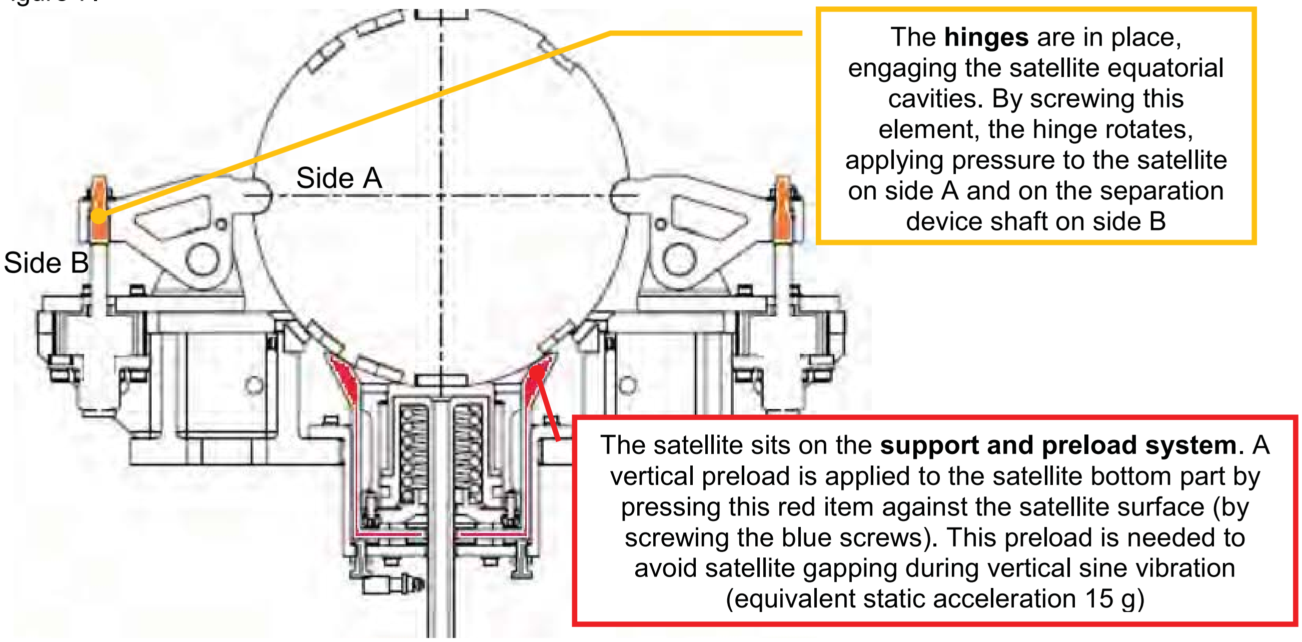
**Figure 6. Separation sequence (from left to right) and functional explanation**

When LARES system reaches its final orbital position and the satellite has to be released, an electrical signal is sent to the actuators that disengage the pin pulled back by means of a retraction spring, thus allowing the hinge to rotate. Hinge rotation is also driven by two spiral springs suitably preloaded.

Once the LARES satellite is set free by the main separation mechanism, the compression spring of the ejection system, in the zero-gravity condition, pushes the LARES satellite along the vertical direction. At the end of compression spring elongation, the LARES satellite will have the nominal vertical speed of 0.75 m/s. The push-out spring has been designed to provide a force of 350 kg for the safety reason to avoid LARES ejection during the operation on ground in case of accidental activation of the SSEP. An electrical device will confirm the release operation.

Support and preloading system

A section of the SSEP with the satellite installed and with the description of the preload path is shown in Figure 7.



The **hinges** are in place, engaging the satellite equatorial cavities. By screwing this element, the hinge rotates, applying pressure to the satellite on side A and on the separation device shaft on side B

The satellite sits on the **support and preload system**. A vertical preload is applied to the satellite bottom part by pressing this red item against the satellite surface (by screwing the blue screws). This preload is needed to avoid satellite gapping during vertical sine vibration (equivalent static acceleration 15 g)

**Figure 7. SSEP Functional Scheme**

The contact surfaces between SSEP and LARES satellite are:

- LARES and support and preload system: Sphere on cone; the SSEP part is covered by Kapton, to avoid LARES surface damage. This contact area is so large that the Hertzian stress is not critical (negligible);
- LARES and hinges: sphere on sphere (cavity on satellite and pin on SSEP). The sphere geometries have been optimized to have an acceptable level of Hertzian stress; in addition, to avoid cold welding issues, Braycote lubricant has been used in between. Both caves on satellite and hinge pins have spherical form.

Integration approach

In order to implement the theoretical preload philosophy that has a uniform vertical preload applied by the support system and the hinge preloads acting symmetrically and balanced in the equatorial plane (the preload of two hinges on the same axis null the force contribution in this direction if the forces are the same), an excellent alignment has to be reached during the integration. The SSEP by design was suitable to reach this theoretical condition, but the integration procedure had to be carefully tuned. In particular, the support and preload system has been instrumented with 4 strain gauges placed at 90° in order to evaluate the preload distribution and uniformity on the whole bottom circumference, and each separation device rod has been instrumented too by using strain gauges to measure the force applied to the separation device itself. Additional strain gauges were placed on the structure of the Qualification Model to verify the sensitivity of the preload distribution with respect to the integration approach. Figure 8 shows three integration steps.

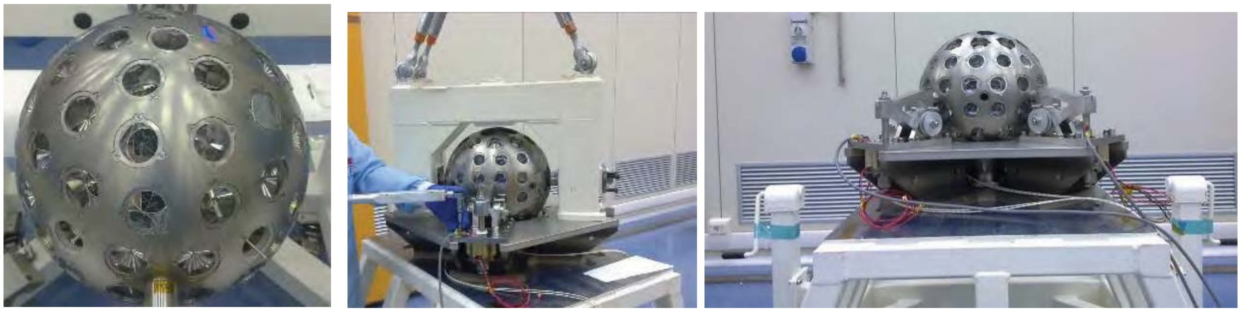


**Figure 8. SSEP Flight Model integration with LARES Flight Model**

The detailed definition of the integration procedure and the decision to perform the shear pin holes execution in an assembled configuration guaranteed the capability to reach a final integration fully compliant to the requirements and with an extremely high repeatability.

## Model philosophy and tests

Taking into account the criticality of the subsystem and the requirements to satisfy, the following model philosophy was adopted:

- Two (2) Breadboards models
- One (1) Qualification Model
- One (1) Flight Model

In particular, the Breadboards were to be representative of the two most critical elements - an arm of the bond and the spring of separation / boost system. These models were used for the characterization of the hinges from both the structural point of view (stiffness) and from the functional point of view (torque margin, deployment main parameters). The Qualification Model (QM) was representative of the flight model but the satellite was the LARES Demonstration Model (DM) that was identical to the flight for interfaces but it was the 6% heavier than the flight model to be conservative.

<u>Philosophy verification</u>

*Breadboards*: On these models, characterization tests were performed at the extremes of temperature in a climatic chamber (operative range 10°C - 40°C). A cycle in thermal vacuum (non-functional) to verify the compatibility of materials (lubricants) with the space environment was performed too.

*Qualification Model*: On this model the following tests were carried out:

- dimensional test
- mass measurement
- vibration
- separation test at the critical temperature (highlighted by the tests on the breadboard )
- thermal vacuum test exclusively for the electrical part

*Flight model*: On this model the following tests were carried out

- dimensional test
- mass measurement
- functional acceptance tests at room temperature (postponing system-level environmental testing).

<u>Breadboard #1 tests</u>

*Objectives*

- To demonstrate the functionality of the pin and cave interface (separable surfaces) under operative load (the critical separable surface);
- To demonstrate the functionality of the pin and cave interface under operative load with a load factor of 1.5.

*Pass criteria*

- No plastic deformation on the cave or pin under operative load (measured both via optical method and Coordinate Measurement Machine (CMM));
- No plastic deformation on pin or cave under operative load time 1.5 measured both via optical method and CMM);

*Test article identification*

- 15-5PH H1025 Steel Pin;
- THA-18N Tungsten Cave;

**Figure 9. Steel Pin on left and Tungsten cave on right**

*Tests sequence*

1. Visual inspection with electronic microscope (magnifcation: 7.5x; 10x; 20x; 40x);
2. Dimensional check with Leitz machine;
3. B/B mounting under compression machine;
4. Visual inspection with photos;
5. Greasing pin and cave with Braycote 600;
6. Slowly applying compression load (26612 N), compression speed equal to 0.0003 mm/s;
7. B/B demounting under compression machine;
8. Visual inspection with electronic microscope (magnification: 7.5x; 10x; 20x; 40x)
9. Dimensional check with Leitz machine;
10. B/B mounting under compression machine;
11. Visual inspection with photos following grease removal;
12. Greasing pin and cave with Braycote 600;
13. Slowly applying compression load times 1.5 (39918 N), compression speed equal to 0.0003 mm/s;
14. Visual inspection with photos following grease removal;
15. B/B demounting from compression machine;
16. Dimensional check with Leitz machine;
17. Visual inspection with electronic microscope (magnification: 7.5x; 10x; 20x; 40x).

To perform a perfect correlation on dimensions in the various performed tests, a measurement points map was used on the cave and pin such that in all the checks the same points were measured.

*Tests results*

A microscope analysis has been performed after the test to look for eventual problems due to plastic deformation on the steel pin and tungsten cave. Figures 10-12 show the test set-up and the microscope steel pin photos. The microscope analysis and the measurements with the Leitz machine showed that no plastic deformation occurred during the test.

Figure 10. BB1 Test set-up

Figure 11. Pin at 10x after first test

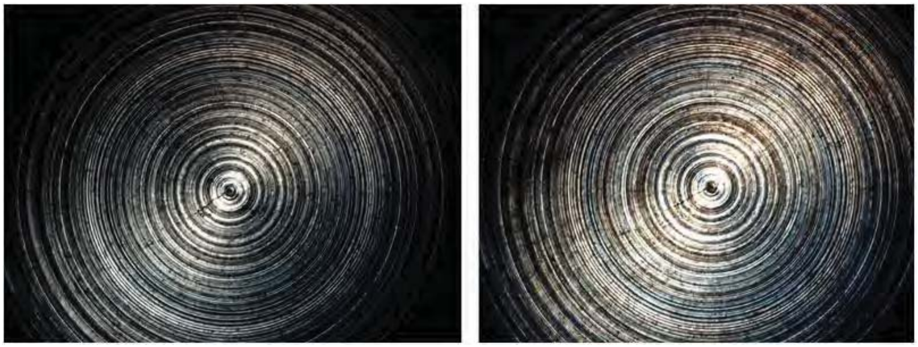


Figure 12. Cave at 20x after the test (left) and before (for comparison)

Breadboard #2 tests

*Objectives:*

- To measure the stiffness along the three principal directions of the restraint mechanism;
- To correlate the FEM analysis previously performed on the restraint mechanism with experimental data;
- To evaluate friction coefficient of the restraint mechanism;
- To demonstrate restraint mechanism strength under operative load;
- To demonstrate restraint mechanism strength under operative load with a load factor of 1.5

*Pass criteria*

- Check of the complete structural integrity of the BB#2 after the tests
- The value of the friction torque, before and after the tests, must be compatible with the ejection of the LARES satellite

*Test article identification*

The test article was composed of the restraint mechanism subdivided in its constituent components:

- Hinge
- Latch
- Pin
- Preload bolt
- Actuator Dummy

All the components were completely representative of flight components, including material, tolerances and dimensions.


**Figure 13. BB2 test set-up**


**Figure 14. Restraint Mechanism**

*Test sequence*

1. Dimensional Check;
2. Visual inspection;
3. Measurement of friction torque;
4. Evaluation of restraint system stiffness;
   a) Measurement of vertical stiffness;
   b) Measurement of transverse stiffness
   c) Measurement of longitudinal stiffness
5. Measurement of strength at nominal max load;
6. Visual Inspection;
7. Measurement of friction torque;
8. Dimensional check;
9. Measurement of friction torque;
10. Measurement of the strength at nominal load times 1.5;
11. Visual Inspection
12. Measurement of friction torque
13. Dimensional check

*Test Results*

- The comparison between the dimensional checks performed with Leitz machine before and after strength tests assures that no plastic deformation occurred on the restraint mechanism during all tests performed up to 1.5 times the qualification load.
- Friction coefficient measured values were acceptable and compatible with the ejection of the LARES satellite, and didn't show variation during the performed tests.
- The obtained results clearly demonstrated the soundness of FE modeling of the entire SSEP subsystem and relevant components (measured stiffness was 20% more than the predicted one in all the 3 directions).

<u>SSEP QM vibration test</u>

*Objectives:*

- To determine the mechanical characteristics of LARES SSEP (in terms of natural frequencies, etc.)
- To demonstrate the validity of the mechanical design with respect to the applicable mechanical environment
- To verify that no degradation or malfunction of LARES SSEP QM components occurs during test.
- To verify that no preload loss occurs before and after testing

*Test article identification*

The LARES SSEP QM Model is shown in Figure 15.

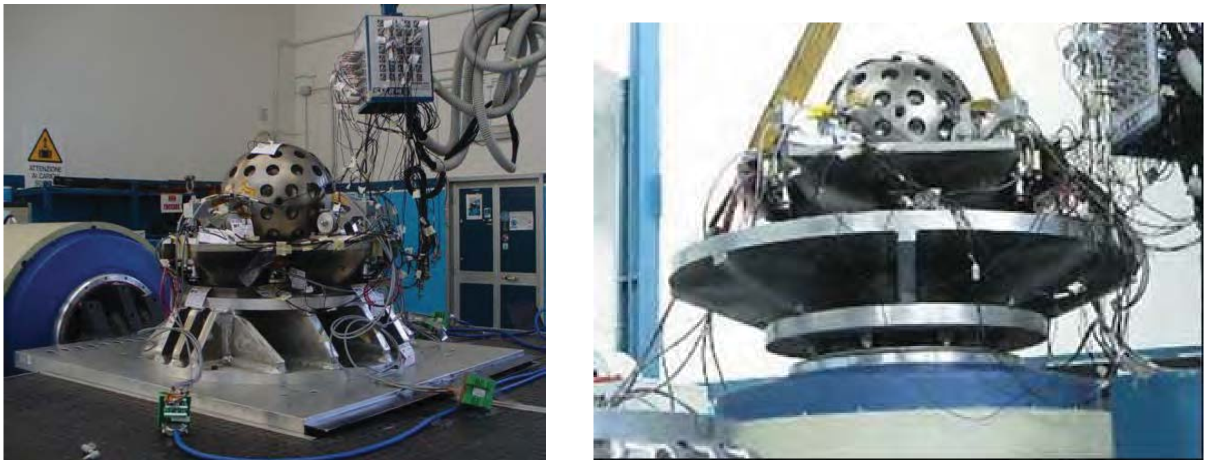


**Figure 15. LARES SSEP Qualification Model on the vibration shaker for lateral test on left and for vertical test on right**

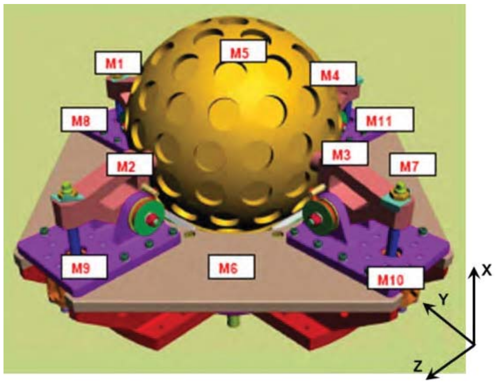


**Figure 16. Accelerometer position and vibration test reference system**

*Test sequence*

On this model, the following tests have been done:

1. Dimensional controls
2. Mass measurement
3. Vibrations
4. Functional tests at the most critical temperature (found during the tests performed on the breadboards) in climatic chamber
5. TVAC test on electrical components only
6. Separation test

*Tests Results*

In the following figures, the results of low sine excitation before and after full-level sine for the accelerometers positioned on the four hinges (M1-M4, see Figure 16) and on LARES satellite (M5, see Figure 16) have been reported for the X direction (that is the vertical one directed as the launcher thrust axis).

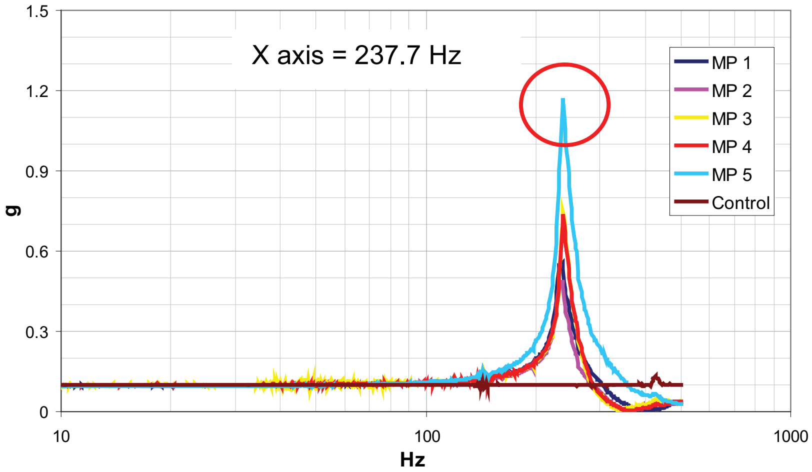


Figure 17. Low sine pre, X direction

In Figure 18, the results of low sine excitation for the same accelerometers after full-level sine are reported.

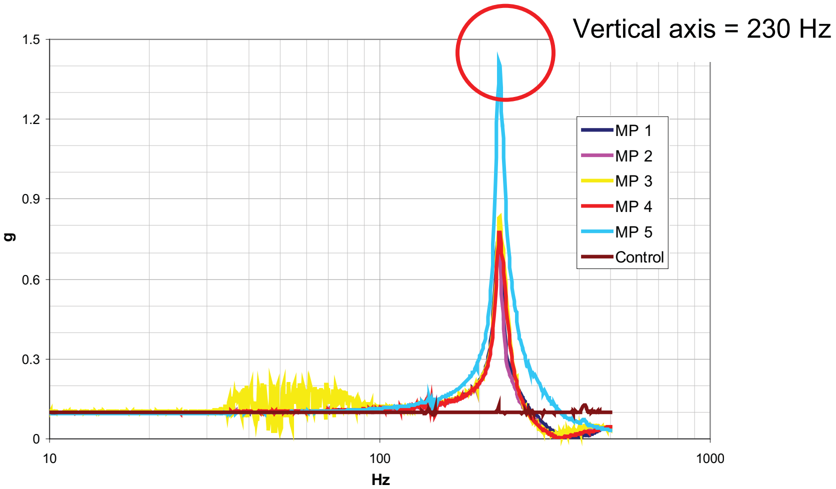


Figure 18. Low sine post, X direction

The previous data show that after a full-level sine a little structure stabilization is present, as revealed by the slight difference between the resonance frequency before and after full level sine test (about 3%). Final value of the first natural frequency on X direction is 230 Hz, greater than the 140 Hz (requirement).

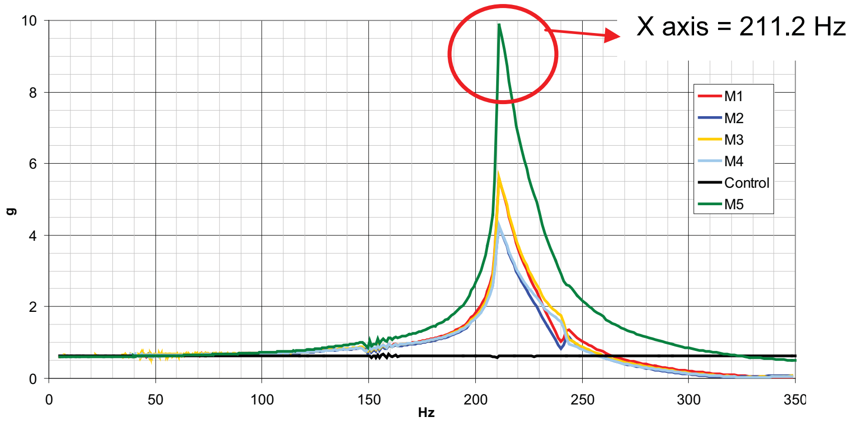


Figure 19. Full sine test, X direction

The full sine test showed a lower value of the first frequency, demonstrating a certain dependence of this parameter with sine amplitude. The low sine test performed after this full sine confirmed that no damage occurred in the mechanism.

*Test Conclusions*

- The Vibration Test has been performed on the SSEP QM and was successfully completed.
- The satellite was in flight configuration and all the success criteria have been satisfied.
- The test confirmed the FEM prediction (the SSEP behaves like a 1 DoF system)
- Loads acting on SSEP during tests are less than expected.
- In the two lateral directions, the same behavior has been measured, in particular 142 Hz first frequency (70 Hz was the requirement) measured during low level sine, while 130 Hz first frequency measured during the full level.

The frequency shift on full level sine is usual when part of a preload structure. Visual inspection did not identify any damage or physical degradation on the item under test.

<u>SSEP QM Separation tests</u>

*Pass Criteria*

- Test conditions according to specification requirements (worst temperature distribution on mechanism was applied);
- “Clean” separation without any problem;
- Separation with an ejection speed 0.6 < v < 0.9 m/s;
- Correct activation of the end of stroke switch;
- Acquisition of all the test data (temperatures, video recording, NEA activation parameters, ejection mechanism strains).

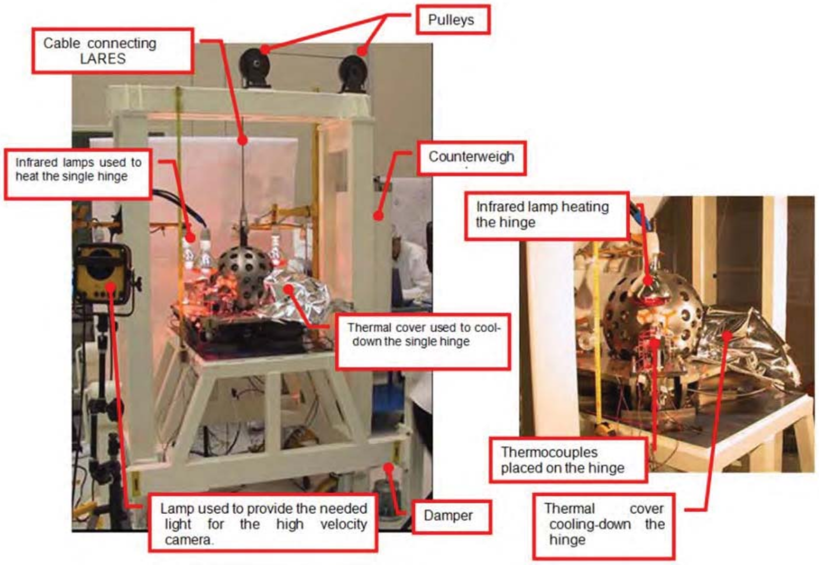


**Figure 20. LARES QM Separation Test configuration**

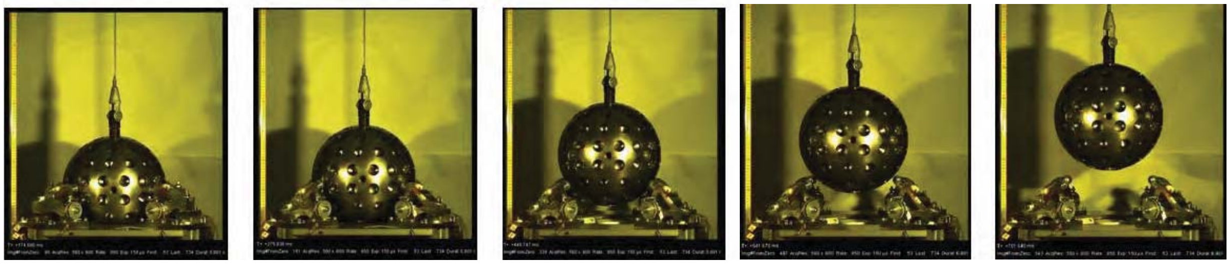


**Figure 21. LARES QM Separation filmed sequence – 527 ms of elapsed time from the first to the last photogram**

*Tests conclusions*

- The Separation Test was performed on the SSEP QM + LARES DM and was successfully completed.
- The SSEP was in flight configuration and all the primary success criteria have been satisfied.
- Visual inspection did not identify any damage or physical degradation on the item under test (no damage occurred after vibration test).
- All the additional controls, measurement and investigations did not show evidence of any degradation or loss of performance of any of the mechanical components.

During the Launch Phase, the on-board camera mounted on the Support Subsystem has shown the nominal performance of the SSEP subsystem.

**Figure 22. Picture of LARES Satellite release on orbit**

## Lessons Learned

The 'lessons learned' from the positive results obtained in the activities performed on LARES Program SSEP is the confirmation of the importance of:

- developing a design oriented to the integration feasibility;
- using an "over-sensorized" model (in this case SSEP QM) to verify the sensitivity of the integration and alignment mismatches vs performance requirement in order to minimize the influence of operator errors;
- adopting a suitable optimized model philosophy that can allow deep investigations of the critical areas;
- focusing strong effort in the testing activity at breadboard level to correlate in advance the mathematical models in order to minimize the technical risk (the BB model testing phase has been included in the timeframe of CDR).

The importance of the above choices becomes more evident in those programs characterized by very stringent and challenging requirements such as LARES.