SMOS PLM MIRAS Hold-down Release and Deployment Mechanisms

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ABSTRACT

The hold-down, release and deployment mechanisms designed for SMOS PLM MIRAS have been a challenging activity in terms of design compromise, schedule and cost effectiveness. The existing design coming from previous phase was totally reanalysed to be adapted to a specific mission with extra requirements, making the previous design not totally valid as it was conceptually conceived.

Novel concepts were implemented to maintain the feasibility of the design, providing compliance to new and more restrictive requirements. Exhaustive testing proved those concepts and provided the necessary maturity to be valid for flight. This paper is focused on all those new concepts and novelties implemented in phase C/D for the SMOS PLM Instrument Mechanisms as to reach the compliance to the applicable specification.

1. INTRODUCTION

MIRAS (Microwave Imaging Radiometer with Aperture Synthesis) instrument is the only payload contained in SMOS (Soil Moisture and Oceans Salinity) PLM (Payload Module). Its mission is to measure Soil Moisture and Oceans Salinity to get better knowledge of seasonal-climate variations and to make better weather forecasting. MIRAS instrument is a radiometer that requires three radial arms of about four meters length each to comply with the requested quality of the measures.

Each arm of SMOS-MIRAS instrument is composed by three segments that are piled during launch but that must be deployed and perfectly aligned once in orbit. A deployment mechanism makes those three multi-panel arms reach their in orbit deployed configuration in a controlled and safe way. Those three arms are installed laterally on the SMOS PLM (Payload module) structure. SMOS PLM is a hexagonal prism with two main platforms (upper and bottom) joined with a set of struts. Mechanisms are rigidly attached to those main platforms during launch.

The SMOS PLM is installed on top of a PROTEUS platform that acts as a service module, making the

SMOS satellite. SMOS project was selected by ESA as Earth Observation Mission to be launched on year 2007 in polar orbit.

Fig. 1. Artist's impression of SMOS in orbit (ESA)

Fig. 2. SMOS in launch configuration (ESA)

SENER designed, manufactured, integrated and qualified the mechanisms necessary to hold during
launch the three arms of the SMOS PLM radiometer, to release them once in orbit, and to deploy them in a synchronized and controlled way, under a SMOS phase C/D ESA contract for EADS-CASA Espacio.

To do so SENER has taken, not only the experience transferred by EADS-CASA Espacio from its breadboard and phase B (SMOS-MIRAS), but also the experience gained in previous programs, in which SENER has been involved, using similar hold-down and deployment mechanisms concepts. Also some novelties have been necessary. The tight schedule and the limited budget advice to concentrate efforts just in the unsolved aspects of the inherited works in front of the current SMOS scenario.

In that sense, SENER performed an important design upgrade, adapting the previous existing design to the mission requirements. The mission imposed a new configuration, higher payload mass, higher launch loads, and all of that fulfilling the operation limits of a mandatory interface with EADS-CASA Espacio deployment regulator.

As dynamic torque induced in the specified speed regulator during the beginning of the deployment (from hold-down release up to almost steady operation of speed regulator) were predicted higher than the speed regulator peak input torque resistive capability, SENER had to develop a novel, light and compact torque limiter to avoid the overloading of the speed regulator and the corresponding potential damage. The torque limiter concept is based on a spring compressing some rollers against a cogged wheel.

Also a novel hold-down concept for the panels pile was implemented to avoid the use of the panels as preloading path (panels overstress), ending in a hard-to-meet full compliance with what was traded as ideal in previous Phase B.

The work was performed under an ESA opportunity program, including a very limited funding and also a very short schedule. Six sets of mechanisms are delivered, two SM (Structural Model), one QM (Qualification Model), and three FM (Flight Model). For SM SMOS satellite, two arms are SM’s, and the other arm is used as QM. The activity was carried out in a very limited time period from kick-off meeting: about 9 months for two SM delivery, about 14 months for QM delivery, and 22 months foreseen for the complete delivery of three FM mechanisms for the flight arms.

The persistent criticality of the mass budget to be within the capacity of PROTEUS platform, made mass one of the most restrictive requirements. Mechanism mass minimization should not endanger the compliance of other critical requirements such as stiffness and load carrying capability. This made necessary the optimization of the mass of every bracket and piece of the designed mechanisms.

2. INHERITED DESIGN FROM PHASE B

Pre-design performed prior to Phase B is shown in [1]. It provides details on defined baseline configuration achieved with a preliminary established specification at a development phase level. Although all aspects were not evaluated in detail (minimum required elementary hinge stiffness, deployment dynamics, hold-down concepts, ...), the performed work demonstrated the feasibility of using exclusively mechanical means to deploy a heavy multi-body appendage in space in an accurate and safe way confirming the validity of selected concepts (motorization, deployment control, synchronization, deployment accuracy, ...), maintaining them for flight units.

A new applicable specification, with new inputs, was established during Phase B to adapt the prototyped equipment to evolved PLM architecture, derived from the specific SMOS mission with ROCKOT launcher and PROTEUS bus. Those new inputs, made necessary an important adaptation of the existing design. The main new inputs were as follows:
- New general configuration (new position in the spacecraft, meaning a new deployment angle, ...)
- Higher payload mass.
- Higher launch loads.
- Highly restrictive interfaces to PLM:
  - search for a reasonable load transfer path from the pilled arm to the PLM structure,
  - limited number of pyrotechnic lines,
  - low shock introduction,
  - highly restrictive volumes and envelopes,
  - no protrusion above deployed antenna plane.
- Mandatory operation limits interface with EADS-CASA Espacio deployment regulator.

Despite prime’s effort, Phase C/D started without having provided solution to main aspects such as hold-down concept, and detail definition of deployment dynamics. Due to the obvious relevance of both aspects in the subsystem design, priority was given to reach a design solution compatible with all performance requirements.

Additionally, a significant amount of complementary analyses and design iteration were necessary to achieve a feasible configuration, looking for a compromise between minimum mass and maximum stiffness, and coping with EADS-CASA selected speed regulator interface.
3. OVERALL DESCRIPTION

As each of the three arms is composed of three segments, that once deployed should provide a very accurate flatness, the design includes a deployment synchronization system as well as adjustable end stops at both sides of every hinge. Additionally, the mechanisms operation is based on a spring driven deployment system including a speed regulator per arm to make negligible the end deployment shock on the spacecraft. As the speed regulator had an operational limit of 10 Nm a torque reduction was necessary from the inner hinge to the speed regulator input maintaining the necessary motorization margin. The optimum reduction according to performed analysis was 3,15 and it was implemented that way.

No latching was considered necessary to guarantee the deployed configuration, maintaining the specified minimum preload in the deployed hinges (3.0, 1.7, and 1.0 Nm). The excess of available motor torque in each hinge guarantees the preload with enough margin.

Four point hold-down release system preloads the three panel stack during launch without inducing internal loads to the panels. The hold-down and release system is designed for 75 kg three panel stack retention during launch and safe release once in orbit.

4. NOVEL TORQUE LIMITER CONCEPT

Deployment dynamic simulation shown that although the steady state of deployment does not induce a torque higher than 10 Nm in the speed regulator shaft, there was a transient at beginning of deployment that could induce, under worst-case analysis, peaks of about 30 Nm. This value was significantly higher than the speed regulator input torque capabilities (< 10 Nm steady input torque; < 12 Nm peak input torque).

The reaction of EADS-CASA delta-qualifying the speed regulator for 20 Nm peak input torque was not enough to provide positive margins of safety. Although the analysis was conservative, it shown the risk of inducing, in a real deployment, torques higher than the maximum peak input torque specified for the mandatory speed regulator (< 20 Nm). As the speed regulator unit to be used was specified, and defined as mandatory, the only way out was to install a torque limiter between the deployment mechanism and the speed regulator. Of course, envelope and mass were major points as there was not additional envelope, and mass estimated in the preliminary design definition was above the requirement due to the robustness implemented to show compliance to the high stiffness required in the specification. In order to solve this problem, a torque limiter was proposed between the transmission pulley and the speed regulator shaft. This space was occupied by the Oldham coupling, therefore the design of the torque limiter was combined with the coupling, maintaining both functions.

The torque limiter was based in a ring spring pressing two rollers against a coge speed wheel, using the excess of transmitted torque to allow the two rollers disposed in opposition at both sides of the shaft, to move in their corresponding ramps up to pass to the following. Those ramps are disposed in a wheel which shaft is coming from the torque transmission pulley (see Fig. 3). The rollers are disposed in the grooves in a way that the torque coming from the pulley is transmitted to the speed regulator shaft through the rollers. The external spring ring maintains the rollers in position, but allows them to move radially due to the radial component of the force caused by the acting torque in the ramps. This ring spring is settled to allow the rollers reach the upper part of the ramps only if the radial force is high enough (due to torque on excess of about 18 Nm). This system prevents from transmitting to the speed regulator torque peaks exceeding a pre-established value. Additionally, the configuration of two rollers in opposition allows misalignment between shafts in the direction of the rollers. In order to complete the compatibility with any misalignment to minimize induce lateral loads to the speed regulator shaft, the designed torque limiter also allows misalignment in a perpendicular direction to the one of the rollers, by adding a groove oriented perpendicularly to the rollers disposition. Therefore the system is a torque limiter and a coupling that allows misalignments between both sides of the transmission (see Fig. 3).

![Torque Limiter Concept](Fig. 3. Torque Limiter Concept)
The torque limiter level can be tuned to the desired torque with a reasonable small dispersion, being its configuration flexible enough as to adapt its design to other torque levels.

5. NOVEL HOLD-DOWN CONCEPT

Usually, hold-down and release systems are considered in preliminary design phases as a minor thing on which it is not worth to loose time. Hold-down and release systems are considered in those preliminary design stages as a mechanism very simple capable of being located in the places that remain after having performed the complete lay-out of the rest of items, and with high potentiality to be adapted to the very changing needs of a program (load levels, stiffness, envelopes, interfaces, etc.).

All that is only partially true, and its necessary adaptation to the specific mission and application is usually underestimated. This is an old “lesson learned” that primes have not yet usually assumed. In SMOS, although the pending aspects were identified in Phase B, no definitive solution were achieved.

A hold-down and release system is designed from loads and from stiffness point of view. Its main function is to transfer the loads coming from the payload to the main platform. But additionally, that mechanism requires:

- Strong interfaces (hard-points in main structure) mainly if the payload is heavy.
- Interface attachments sized to the loads that the hold down should transfer (tension, shear, bending).
- Internal envelope to install the release actuator.
- External envelope as to make feasible the connection of usually redundant activation electrical connectors.
- External envelope as to make feasible the provision of the necessary preloading.
- Envelope to remove the linking element away from the separation surface in the release.

A good rule to take into account when establishing the baseline of a payload hold-down concept is to avoid inducing loads in the payload when providing the necessary preload. The reaction to the preloading is preferable to be established exclusively through the hold-down structure, and not through the payload, in order to avoid inducing excessive stresses to the payload due to the inherent uncertainty of an excessively hyper-static system.
In the design adaptation performed in Phase B the hold down preloading line was located eccentrically respect to the hold-down contacts. Although this layout was compatible with the deployment kinematics and the limited number of pyrotechnic lines, it induced important bending loads to the stacked panels once the hold-down was preloaded.

Decoupling of hold-down was proposed, centring the preloading line in each of the four hold-down point. It means two load paths per hold-down point in order to install the preloading line in its centre. This concept provides higher robustness, liberates the panels from preloading loads reducing the uncertainties, makes each mechanism column be self-standing, does not induce preloading loads in the hinges, etc.

6. MASS REDUCTION EXERCISE

Once preliminary design was compliant with both limiting requirements, positive torque margin and limited torque induced in the speed regulator, design effort was concentrated in getting a compromise between the most critical opposite requirements, maximum stiffness in each hinge and minimum mass.

The first available specification included excessively high stiffness values (lineal and rotational), without making especial mention of the priority values. Indiscriminate reinforcement was not the solution due to its strong impact on mass. Then priorities were given selecting specific reinforcement to increase the most important stiffness values.

Even with this selected reinforcement the mass increased to inadmissible values due to PROTEUS limited capabilities during launch. Then a systematic mass optimisation analysis was performed piece by piece, establishing as limits, the manufacturability, the positive margins of safety against worst load case combination, and the really minimum stiffness needed by customer to achieve the global stiffness values (> 1,5 Hz deployed, and > 35 Hz stowed).

7. PERFORMANCES

The following performances were extracted from tests:
Mass with harness (for a 75 kg arm mass): <15,5 kg
Deployment time:
  • With torque limiter operation: about 210 s
  • With no torque limiter operation: about 220 s
Dispersion time (in each case): +/- 5 s
Steady motor torque: <31 Nm
  (<10 Nm at speed regulator)
Peak motor torque (using torque limiter): <54 Nm
  (<17 Nm at speed regulator)
Deployed eigen-frequency: > 1,98 Hz
Deployment angles:
  • Root hinge: 90°
  • Intermediate hinge: 180°
  • Outer hinge: 180°
Accuracy (per hinge): < 0,005°
Repeatability (per hinge): < 0,002°
Arm tip repeatability: < 0,4 mm
Deployed preload (all tested configurations):
  • Root hinge (required >3,0 Nm): > 7,5 Nm
  • Intermediate hinge (required >1,7 Nm): > 3,7 Nm
  • Outer hinge (required > 1,0 Nm): > 1,5 Nm
Operational thermal range (qual.): -52°C < T < 45°C

8. TESTS

A set of tests were performed on the hardware to reach the qualification:

• Elementary tests:
  - Harness loops resistive torque at different temperatures.
  - Bearings resistive torque at different temperatures.
  - Bearings stiffness.
  - Springs characterization.
  - Torque limiter characterization.

• Qualification tests:
  - Critical supports static load testing.
  - Stiffness tests for all kind of existing brackets in stowed configuration.
  - Stiffness test for the representative hinge brackets in deployed configuration.
  - Characterization of the gravity compensation jig.
  - Characterization of the SMOS PLM Instrument mechanisms.
  - Functional performance test (release & deployment).
  - Vibration test.
  - Thermal cycling in vacuum including operation at low and high temperatures.
  - Life cycle test.

9. TEST CONFIGURATIONS

In order to have complete guarantee on the performance of the deployment mechanism, it was established to perform complete deployments in ambient as well as in vacuum under extreme thermal environmental conditions.

Ambient tests were designed to be performed in full scale configuration, monitoring 0-gravity condition, torque induced in speed regulator, remaining preload in all hinges once deployed configuration is achieved, etc.
Nevertheless, for vacuum testing a reduced configuration was used for cost optimization. The swept volume of the full-scale mechanism would have required a huge thermal vacuum chamber. Therefore, for thermal vacuum testing, a fully representative mechanism was used, with segments dummies of reduced length, and without using any off-loading jig. Specific analyses were performed to check that the deployment mechanism were capable of deploying completely the reduced configuration segments, even under gravity conditions.

10. OFF-LOADING JIG

An off-loading jig was designed to perform a representative deployment of one arm. This jig was designed with the same kinematics than the arms mechanism. That is with hinges axis co-aligned with arm hinges axis, and with synchronized system between the different modules of the off-loading jig.

It was designed to withstand the loads coming from the 75 kg arm during the deployment with sufficient
stiffness as to minimize its influence in the performance of the arm deployment.

Each arm segment was hung from each module of the off loading jig by means of slings. Each sling contained an adjusting length device, a strong and long spring, and a monitoring load cell, in order to adjust its load to the corresponding mass of the segment.

In order to know its effect in the deployment and derive the motorization margin of the arm mechanisms, the off-loading jig was characterized in deployment and retraction, being each mass hanging of equivalent value to the real mass of each segment. Motor torque and friction torque of the off-loading jig was then obtained.

11. ELEMENTARY TESTS

Characterization of main sources of resistive torque, and characterization of motor torque sources were necessary to demonstrate sufficient motorization margin. The following main resistive torque sources were identified:

- Hinge harness
  - fiber optic cables
  - radio-frequency cables
  - standard harness
- Hinge bearings.
- Transmission bearings.
- Speed regulator.

A representative harness (including its passive thermal protection) were used to obtain under the worst thermal conditions (highest and lowest temperature) the resistive torque values.

A representative configuration (representative loading ranges) of the hinge bearings was tested under the worst thermal conditions, obtaining its friction at different conditions.

Detailed data of speed regulator resistive torques (static and dynamic) at different thermal conditions were available.

The spring used was also characterized to define clearly the desired motor torque in each hinge of the arm, and tune them accordingly.

Also the most critical elements from stiffness point of view were verified. It was performed in the same operational range as in orbit, for both stowed and deployed configuration.

The most critical element identified to reach the required deployed stiffness was the hinge bearings. Specific testing was performed on them to be used in the modeling and analysis of the global system.

12. QUALIFICATION TEST CAMPAIGN

12.1 Stiffness Tests

The output of stiffness tests provided stiffness measures of the hinges in both configurations, stowed and deployed. Obtained values were in line with values obtained from analyses, guaranteeing the achievement of the required stiffness for deployed and for stowed configuration.

12.2 Static Load Tests

The static load tests verified the capability of the hinges to withstand the worst load environment. Tests were carried out on the most loaded structural pieces. Hardware passed the tests successfully without detecting any permanent deformation.

12.3 Functional Performance Tests

The functional performance test demonstrated the capability of the mechanisms to perform the release and deployment according to the specified requirements with sufficient motorization margin.

With this tests the following data is obtained:

- Deployment angle versus time curve.
- Total deployment time.
- Motorization margin.
- Final deployment preload.
- Peak torque at speed regulator
- Deployment accuracy and repeatability.

Before the performance of a totally representative deployment, a quasi-static deployment/retraction was performed to get the characteristic curve and deduct the motor torque and the resistive torque along the deployment.

This measurement reflects the combined contributions of the different elements to the motorization margin (spring motors, bearings, harnesses, synchronization cables, ...).

In order to evaluate the torque margin under 0-gravity environment, the effect of the off-loading jig was also considered making a quasi-static deployment/retraction of the off-loading jig (with equivalent hanging masses).
12.4 Vibration Tests

Random vibration tests were performed to prove the mechanisms capability to withstand the expected dynamic environmental loads. The levels applied for qualification were as follows.

<table>
<thead>
<tr>
<th>AXIS</th>
<th>X, Y, Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>FREQU. RANGE [Hz]</td>
<td>QUALIF. LEVEL</td>
</tr>
<tr>
<td>20 - 100</td>
<td>+3 dB/Oct</td>
</tr>
<tr>
<td>100 - 400</td>
<td>0.58 g^2/Hz</td>
</tr>
<tr>
<td>400 - 700</td>
<td>-5 dB/Oct</td>
</tr>
<tr>
<td>700 - 2000</td>
<td>-9 dB/Oct</td>
</tr>
<tr>
<td>Overall</td>
<td>15.8 g rms</td>
</tr>
</tbody>
</table>

12.5 Thermal Vacuum Cycling Tests

This test verified the capability of the mechanism to release and perform properly the complete deployment of the arm, under extreme climatic conditions. The equipment was subject to four (4) thermal cycles between extreme temperatures, and successful releases and deployments at high (+54 °C) and low temperatures (-52 °C) were performed.

12.6 Life Test

This test demonstrated the capability of the mechanisms to withstand the expected number of operations. Thirty (30) additional releases and complete deployment were performed successfully in ambient conditions, without detecting any sign of performance degradation.

13. CONCLUSION

After intense activities against time with a highly collaborative way of work between EADS-CASA and SENER, the existing design was adapted to the new mission scenario through the compliance to the new applicable specification. In order to reach a feasible baseline, special effort was allocated on a novel torque limiter and on a novel hold-down and release concept. All pieces of the design were subject to a mass optimization exercise, reaching an acceptable compromise between mass and stiffness. Extensive analyses were performed to get the design mature enough as to demonstrate its validity.

Exhaustive testing was performed at element level as well as at subsystem level in order to demonstrate the proper behavior of the subsystem. Successful testing at satellite level such as vibration, acoustic and deployment tests, confirmed the adequacy of the design to the assigned function. Delivered models behaved as expected and according to the agreed requirement specification.

14. REFERENCES