# NOVEL CONCEPTS FOR ON-GROUND DEPLOYMENT TESTING OF LARGE ANTENNA STRUCTURES

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## ABSTRACT

Large antenna structures reveal novel challenges for on-ground functional and performance testing, concerning notably their gravity compensation, alignment needs and model correlation. Therefore, the need for innovative test approaches, intensive correlated analyses, and tailored ground support equipment to achieve reliable test results is indispensable, as recent examples on the 5-meter Deployable Reflector, deployable booms, and on the ROSE-L antenna have shown.
This paper aims to discuss the relating common challenges as well as the development and solution approaches to overcome these obstacles, while further providing lessons learned and optimization possibilities from the latest large-scale on-ground deployment tests.

## 1 TESTING OF LARGE ANTENNA STRUCTURES

Deployable systems have a longstanding history in space missions, in which various designs have widened the fields of space exploration, earth observation, communication, and navigation by enhancing the operational range, performance, mass reduction and cost-effectiveness of large-scale antenna structures.
In particular, passive deployment mechanisms add the advantages of simplicity to the design and operation, reducing the risk of mission failure while maintaining a high performance. Recent examples for such systems are the ROSE-L SAR antenna, the 5-meter Deployable Reflector, and several antenna and instrument deployable booms.
Despite their advantages in space applications, all of the aforementioned systems are facing similar obstacles during on-ground, gravity-compensated alignment and deployment testing.
Proportionate deployment mechanical ground support equipment (MGSE) are prone to adding a significant degree of friction and momentum, which could interfere with the motion of the instrument, and further disturbing forces may even prevent a successful test.
In addition, geometric boundary conditions of the test assembly may influence the deployment behavior and, therefore, decreasing the gravity compensation or otherwise supporting element of the MGSE.
Equally challenging as the dimensions of the deployable instruments is the corresponding size of the MGSE, requiring sufficient space to perform a full deployment test, significantly minimizing the number of potential facilities, which directly impacts the cost of the test.
Ultimately, deployment MGSE with a passive supporting function offer no monitoring of the instrument's characteristics through external measurement devices during the performance of the test. The following chapters paint a more detailed image of each challenge and general requirements on the test assembly, while providing real-life examples for each case and explaining the respective solution approach created for solving the issue and related lessons learned.

## 2 FUNCTIONAL AND PERFORMANCE TESTING REQUIREMENTS

There is a multitude of requirements for a successfully performed, gravity-compensated integration, alignment, and deployment testing process for large antenna structures. The following list provides an overview and short description of the deciding requirements, which were identified during the latest performed tests.

- **Gravity compensation:** The respective MGSE should provide an effective means of compensating for the effects of gravity for the complete motion profile of the instrument.
- **Disturbing forces**: The test assembly should introduce as little disturbing forces into the dynamic system as possible to best simulate the microgravity conditions of space.
- **Precise control**: The test assembly should allow for precise control over the deployment process. It should enable accurate measurements of relevant forces, displacements, and other applicable parameters to evaluate the performance of the deployed antenna and build an accurate correlation analysis.

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- **Reproducibility**: The test assembly should be capable of reproducing the deployment process consistently and reliably, enabling repeatable tests and validating the performance of the structure regardless of environmental conditions.
- **Simulated space environment**: Certain hardware requirements may necessitate reproducing the conditions the antenna will experience in space as close as possible, e.g., the temperature profile, or vacuum.
- **Modularity and Adaptability**: The test MGSE should be modular and/or adaptable, allowing for swift configuration or facility changes to accommodate various deployment scenarios
- **Structural integrity**: The test assembly should be structurally sound and capable of supporting the weight and forces involved during the deployment process so it withstands mechanical stresses and vibrations without compromising its stability and performance, or introducing excessive disturbing forces to the system.
- **Safety**: The test assembly must ensure the safety of personnel and hardware involved in the deployment test to prevent accidents, minimize risks, and comply with relevant safety standards and regulations.
- **Cost-effectiveness**: The design of the test MGSE should consider cost-effectiveness without compromising the quality and reliability of the testing process to minimize expenses associated with construction, operation, and maintenance.

## 3 CHALLENGES DURING THE TESTING OF LARGE ANTENNA STRUCTURES

### 3.1 Disturbing Forces, Friction

For deployment devices of passive nature, former tests and preceding analyses have shown, that disturbing forces, especially friction, have a major effect on the torque margins of the system to be tested, consequently biasing the test performance and results. Test assemblies for all aforementioned instruments include low friction pulleys, thin ropes, and lubrication in order to reduce this influence, but still a significant share of the torque margin originates from friction. This is especially challenging for the ROSE-L deployable SAR antenna, where the contribution of the MGSE friction can reach 15-20 Nm at certain positions, while the internal friction of bearings, harness, damper, etc. is in the range of 3 Nm.

The ROSE-L antenna is composed of two independent wings. Each of them consists of two panels, and thus two hinge lines. Once initiated, the passive deployment system deploys the wing completely in one unrestrained motion. Therefore, the gravity compensation and deployment MGSE has to enable the deployment of two 3.6x2.2 meter panels simultaneously, see Fig. 1. The chosen device consists of a stable structure over the antenna with guiding rails in two perpendicular axes. Each panel hangs from its own bridge, which slides in both directions by rolling elements on the rails.

Due to the massive dimensions of the MGSE, the friction forces at the rails can lead to high resistive torques at the hinge line. Extensive breadboard tests of different configurations and designs have reduced the friction to the range of 1-5 N (with a panel mass of 140 kg). However, given the limited amount of motorization torque, an additional friction compensation method is necessary, even with such low forces. This approach has been further supported by multi-body simulations of the deployment with varying parameters.

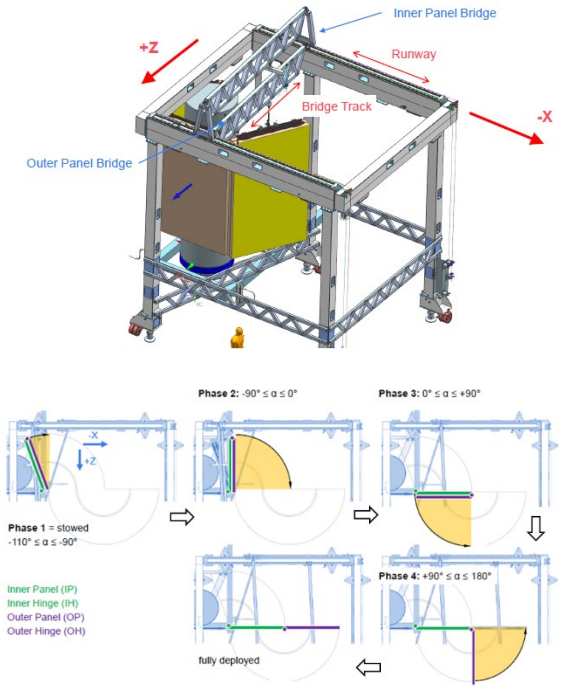


*Figure 1. ROSE-L Antenna deployment MGSE, and deployment sequence of a 2-panel wing*

What in other cases could have been realized straightforwardly with counterweights, becomes challenging in this configuration, given that the panels deploy more than 90 degrees and in changing directions of the rail axes.

An alternative technique under investigation is the use of an active MGSE, in which a small motor can linearly drive the rolling elements with a force strong enough to compensate the friction. Using the existing three-axis force sensor between the panel and the MGSE, the active friction compensation system can feedback the in-plane forces to the motor, minimizing them in a control loop. The control loop is kept “slow” enough to ensure that the MGSE always follows the antenna panels, and thus does not support the deployment (critical point to verify the motorization margin of the deployment mechanism at antenna level). A logging of the force measurement is used as proof that the force introduced by the MGSE, even if low, is never encouraging the deployment.

A similar issue with friction was encountered on the Sentinel-1 SAR antenna. As presented in [1], the complex sequential opening motion of the Sentinel-1 active planar phased-array antenna necessitated a top rope cantilever concept for the deployment MGSE with two hinges for each side of the structure. The concept is shown in Fig. 2.

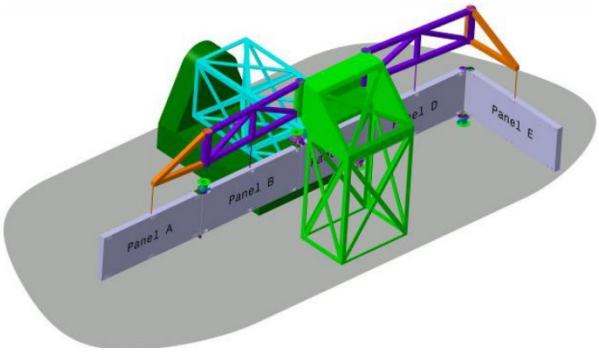


*Figure 2. Top rope cantilever crane concept for the deployment of the Sentinel-1 SAR antenna, image taken from [1].*

The antenna elements where on both sides supported by a complex MGSE, while the panels were attached via cables for support. As described in [1], an Adams model analysis demonstrated that the initial pulley configuration with the compensation wire routed around the hinge line, would directly transfer the wire force, and therefore a friction factor, into the hinge torque, due to a geometrical offset of the lever of the first pulley. As shown in Fig. 3, the configuration was optimized by routing the cable through the hinge line and therefore eliminating the additional torque on the structure. Consequently, in contrast to the possible motorized approach in ROSE-L, the Sentinel-1 antenna deployment test was successfully realized by optimizing solely the structure of the deployment MGSE.

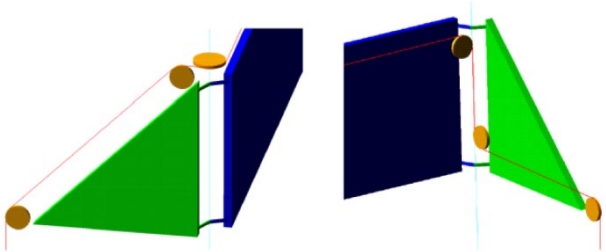

*Figure 3. Pulley test assembly before (left) and after the optimization (right)*

The detrimental effect of friction was also detected during the deployment testing of the proto-flight model (PFM) and flight model (FM) of an x-band antenna boom. During the spring-loaded deployment of the boom, two hold-down and release mechanisms (HRMs) are released in sequential order, first at the tip of the boom and subsequently at the centre bracket as shown in Fig. 4.

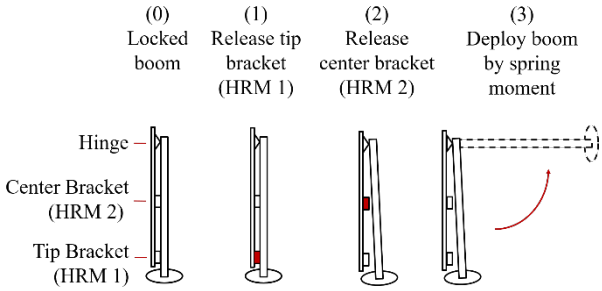


*Figure 4. X-band antenna boom deployment sequence*

For testing, the hinge of the arm was horizontally supported by a solid MGSE, so that the boom would deploy in a perfectly horizontal movement. Due to the geometrically simple setup, a passive counterweight approach was chosen and attached to the centre of gravity (CoG) of the boom, with the counter mass hanging from a pulley directly above the hinge, see Fig. 5.

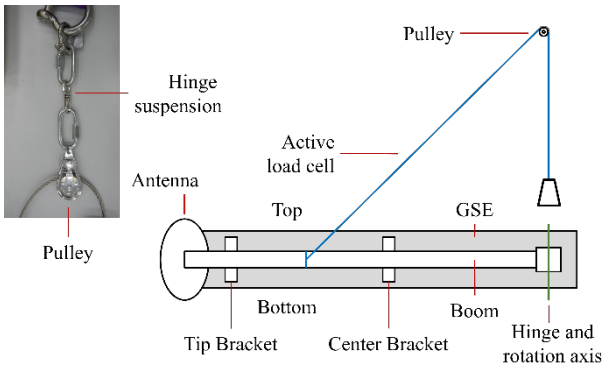


*Figure 5. X-band antenna boom deployment test setup with malfunctioning pulley and hinge suspension*

During the first deployment tests, step (3) of the sequence prematurely stopped after just 15 cm of antenna tip movement. Investigations into the test setup revealed that the pulley showed an increased amount of friction under load and a stick-slip effect on its horizontal hinge. This effect caused the pulley to grind to a halt so that the wire was slipping over the surface of the pulley, significantly introducing friction into the system. The malfunctioning parts of the MGSE are shown in Fig. 5.
Ultimately, it was determined, that the increased friction in the system led to an imperfect load transmission from the counterweight to the free end of the boom, undercompensating the instrument and causing a loss of height at the tip of the boom, which led to a blockage of the center bracket of HRM 2. For the subsequent deployment tests, corrective actions at the MGSE were taken, by reducing the friction at the pulley, but foremost by implementing an active load cell into the compensation system at the boom side of the pulley. The active load cell enabled an online measurement of the compensating load on the free end of the antenna boom and therefore a fine-tuning of the MGSE before each deployment test. The implementation of this monitoring system permitted repeated

successful deployments of both, the PFM and the FM booms.

A more complex issue involving pulleys was identified for the 5-meter Deployable Reflector, where, due to the nature of its design, each of the 36 individual carbon fiber reinforced plastic (CFRP) panels needed to be compensated independently. Reference [2] describes the deployment mechanisms and kinematics in extensive detail. Further, the deploying motion was to be performed simultaneously around the whole system, considering varying panel masses and centers of gravity (CoGs). This was implemented by leading up a thin wire from the ends of the panels over a two-pulley structure and attaching a counterweight to its far end, see Fig. 6.

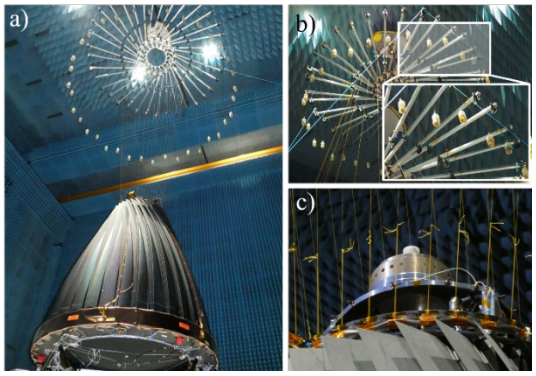


*Figure 6. 5-meter Deployable Reflector zero-g deployment device design, with a) complete assembly with instrument below, b) detailed view of the two-pulley assembly on the upper structure, and c) detailed view on the wire fixations on the panel tips.*

A two-pulley setup was implemented because the use of only one pulley would position the counterweight above the deploying reflector contour, leading to a possible collision of the panel with the counterweight during its opening motion. After deployment, the counterweight would be positioned above the open reflector, posing a risk of damaging the hardware, as shown in Fig. 7.

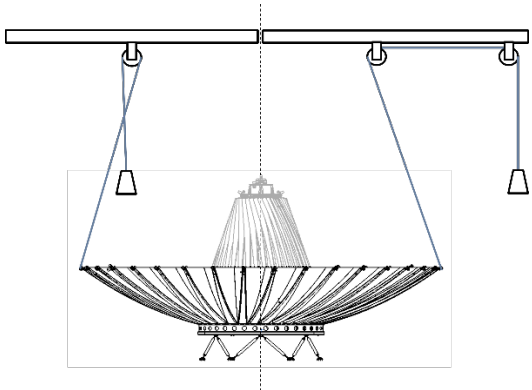

*Figure 7. One-pulley design (top) and two-pulley design (bottom) of the 5-meter Deployable Reflector MGSE*

Breadboard tests had also shown that the smaller distance between the counterweights in the one-pulley design could lead to two counterweights crossing and tangling up their ropes, rendering a successful deployment impossible and potentially harming the hardware.
Friction was critical in this case, since the individual pulleys had variant friction parameters based on their manufacturing, integration and applied load, potentially causing varying panel deployment speeds and therefore hindering the simultaneous deployment of all panels.
A deployment simulation was consulted, as during the Sentinel-1 testing. However, the results for this MGSE led to the decision to stay with the planned two-pulley design without changing their positions or orientations. Instead, a threshold for the maximum allowable friction in a single pulley assembly was defined (5% of the average absolute dynamic panel mass). Accordingly, the pulley pair performance was individually characterized before conducting the deployment test and unsatisfactory hardware was repaired or replaced. Eliminating excessive torque on individual panels caused by the MGSE ensured a reasonable and reproducible deployment test procedure, while also applying a cost-effective and adaptable approach.

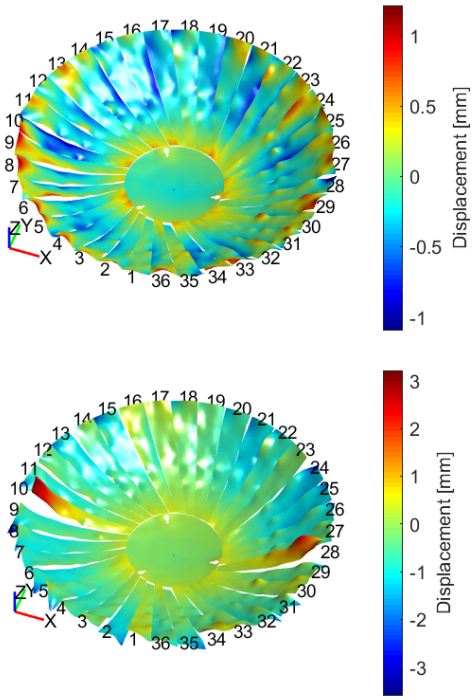


*Figure 8. Contour measurement results for the 5-meter Deployable Reflector FM after the final alignment (top) and after the final deployment test (bottom)*

Still, the minor dissimilarities in friction caused minute variances in the reflector shape in comparison to the previously performed zero-g alignment of the panels. Since the reflector contour was evaluated by photogrammetry [3] via 45 measurement points on each panel and additional reference points on the static central reflector, each panel could be evaluated separately.

The absolute reflector shape was quantified based on the single measurement target deviations with the root mean square method (RMS). The success requirement for the contour was an RMS < 500 µm, which was achieved during the alignment process. However, after the deployment test, the contour was not exactly reproducible, varying by as much as 71%. See Fig. 8 for a comparison of the reflector contour after the final flight model (FM) alignment and the final deployment test.

These differences, especially at the heavier launch lock panels at positions 10 and 28 illustrate the non-compensable effect of a passive deployment MGSE on the hardware during test. The matter was solved by reintroducing the stationary gravity compensation device, which was used for the prior alignment of the panels.

After the successful deployment test, the deployment MGSE was removed from the instrument and the previously used stationary compensation was attached. This stationary device was based on the straightforward principle of a counterbalance rocker, completely eliminating friction by supporting the free-hanging rocker with a thin wire to a rigid support structure, see Fig. 9.

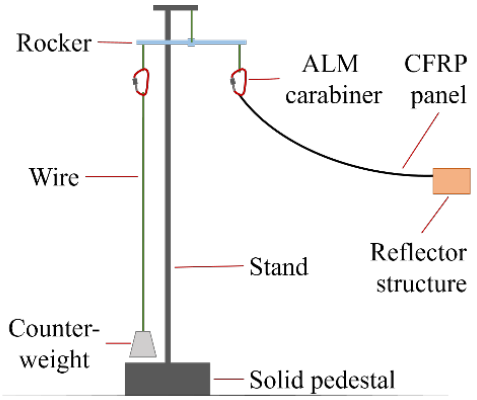


*Figure 9. Zero-g panel alignment device*

One end of the rocker was attached to the panel tip, with a panel-specific counterweight attached to the far end. The device was placed outside of the reflector instrument with the load bearing wires all being arranged perfectly vertically to eliminate transverse forces. The device was constructed of only RF transparent plastic parts with the panel attachment realized by an additive layer manufactured (ALM) carabiner hook, which guaranteed the removability and safety of the device. The metal counterweights were placed just a few millimetres above the ground to ensure additional safety in case of MGSE failure and to remove RF critical mass from the measurement range. Consequently, the RF transparent design enabled a third use of the device by supporting the reflector shape during the near-field RF performance measurement.

### 3.2 Dynamic Loads

The forces introduced by MGSE and gravity compensation not only affect the motorisation margin of the mechanisms, but also the dynamic behaviour of the deployment. In the case of ROSE-L, a stick-slip effect was identified during breadboard testing and further checked under simulation. The root cause of the issue is that the bridges, which support the panels, have a breakaway friction higher than the nominal running friction. This leads to a coupled dynamic of the antenna panel with the MGSE bridge, as the following Fig. 10 and sequence illustrate:

1. Panel and bridge are stationary. Deployment starts and thus the panel starts moving
2. The link between panel and bridge (by means of a spring element) deflects, creating a force that pulls from the bridge towards the panel. However, the bridge remains stationary.
3. Once the force is higher than the bridge breakaway friction, the bridge starts moving. This stops the panel deployment.
4. As the bridge moves towards the panel, the force at the spring is reduced, so the bridge slows down until the friction makes it stop completely.
5. The panel then continues to deploy, and the process is repeated with a swinging of the panel and bridge.

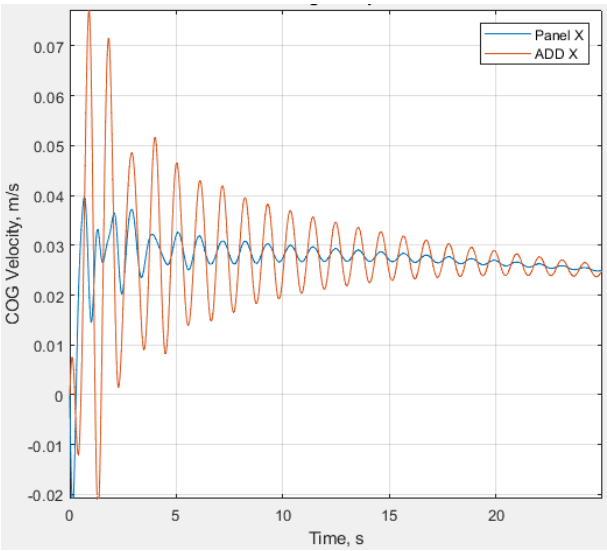


*Figure 10. Simulation of the stick-slip effect between ROSE-L antenna panel and bridge MGSE. Plot shows the velocity of the Panel CoG in the X direction (blue) and the bridge velocity in X direction, following the CoG (red)*

The dynamics of this deployment are affected by the friction values. The current model simulates a Stribeck friction function, with an initial breakaway friction, a running friction and a further dependence with velocity. Currently, Monte-carlo simulations with varying friction parameters are carried out to test the robustness of the deployment test.

### 3.3 Geometric and Facility Restrictions

As described in [1], the Sentinel-1 MGSE initially showed elastic deformation during certain phases of the deployment due to the antenna's moving mass. This deformation led to parasitic torques on the panel hinges, which could not be accepted, as shown in an Adams multibody analysis. A three-dimensional framework and additional struts between the tower and the outer hinge axes were implemented.

In contrast to the Sentinel-1 antenna, the 5-meter Deployable Reflector does not pose a significant deforming effect on the deployment or alignment MGSE, due to the light-weight design of the panels and the rigid frame of the deployment device. Further, the instrument is only in contact with the MGSE via the counterweight wires, which have a compensatory function in case of potential rapid movements. Consequently, dynamic geometric restrictions during the test performance could be neglected.

However, the absolute geometric position and orientation of the zero-g deployment device was crucial for the viability of the test, since due to the symmetrical nature of the antenna, a geometrical offset of the device would have led to an asymmetrical load case on the reflector.

This asymmetry would, in turn, lead to an unrepresentative deployment and possibly even damage to the structure. Hence, the zero-g deployment device was to be placed centered above the antenna structure with the extended arms in perfect alignment with the trajectory of the panels during the opening motion, at a right angle to their rotating axes, see Fig. 11.

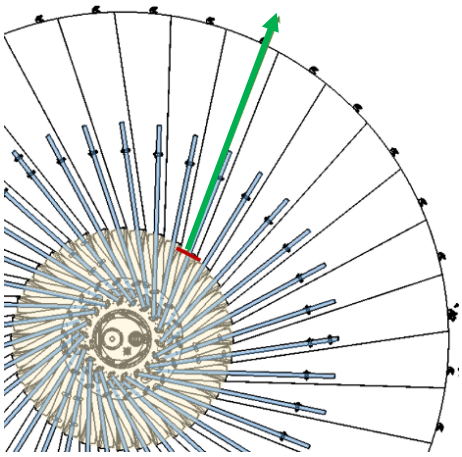

*Figure 11. Alignment of the zero-g device (blue) to the 5-meter Deployable Reflector, with red marking the panel axis, green showing the panel trajectory and yellow indicating the stowed configuration.*

Previous MGSE tests on a breadboard model of the reflector had shown, that the initial impulse of the HRM would cause the upper structure to rotate and shift out of place. Six retaining ropes were introduced to the assembly to create a stable hexapod configuration for keeping the MGSE in place, Fig. 12.

In any case, the height of the zero-g deployment device above the reflector and the radial offset of the first pulley were the most crucial parameters for a successful and representative deployment. The key issue was, that the fixed position of the device with its pulleys resulted in varying angles of attack for the gravity compensation wires, Fig. 13.

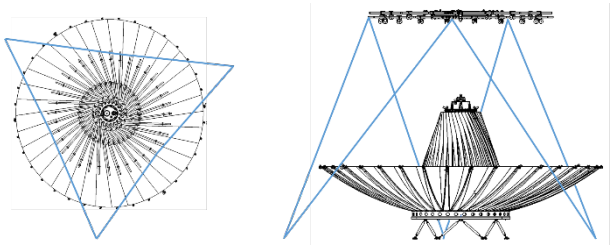

*Figure 12. Hexapod restraints on the deployment device*

The opening motion of the panels is induced by pretensioned springs on the hinge of the panel. These springs are finely tuned to generate enough torque to release the panels from their stowed position, while also leaving just enough torque in their end stop position to not damage the thin CFRP structure and keep the panels in place during orbital manoeuvres.

For an optimal representation of an in-orbit deployment, the spring torque is to be decreased linearly during the deployment. However, the change in the angle of attack led to variations from the optimal torque compensation throughout the opening motion.

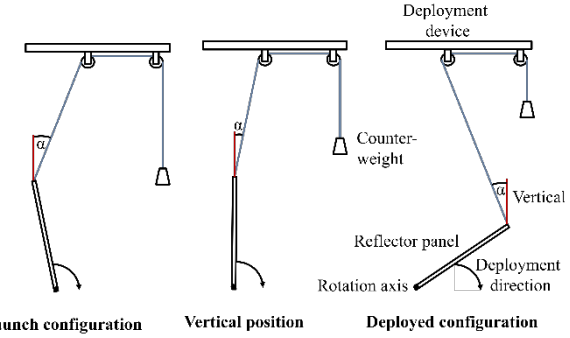


*Figure 13. Schematic visualisation of the gravity compensation during deployment, with α = angle of attack*

Furthermore, during the first 15 degrees of the panel movements, the gravity compensation needs to support the torque of the springs, since the panel tip moves upwards against gravity, as Fig. 13 illustrates. After passing the vertical position, the compensation changes its function by slowing down the panel deployment and counteracting the spring torque. In Fig. 14 the nominal spring torque is shown in comparison to the torque of a lighter standard panel and a heavier release panel, including the additional mass of the deployment mechanism at its tip.

In the case shown in the upper graph, the gravity compensation MGSE was placed at a height of 5.40 m above the panel hinges, which resulted from the maximum

crane height in the functional testing facility. The torque supporting effect of the MGSE during the first 15 degrees is clearly visible on the graph of the release panel, exceeding the nominal torque by 2.47 Nm. During the subsequent opening motion, the spring torque is reduced in comparison to the nominal value, causing a decelerating of the panels. While at this configuration of the MGSE, the standard panels were compensated within the acceptable range for a subsequent correlation analysis, the spring torque of the heavier panels was reduced to zero at about 55 degrees into the deployment, so that their opening motion was only guaranteed by the overlapping geometries of the panels at this stage and not by the performance of the hardware itself. Therefore, this test was deemed satisfactory for a verification of the function, but not the performance of the deployable reflector.

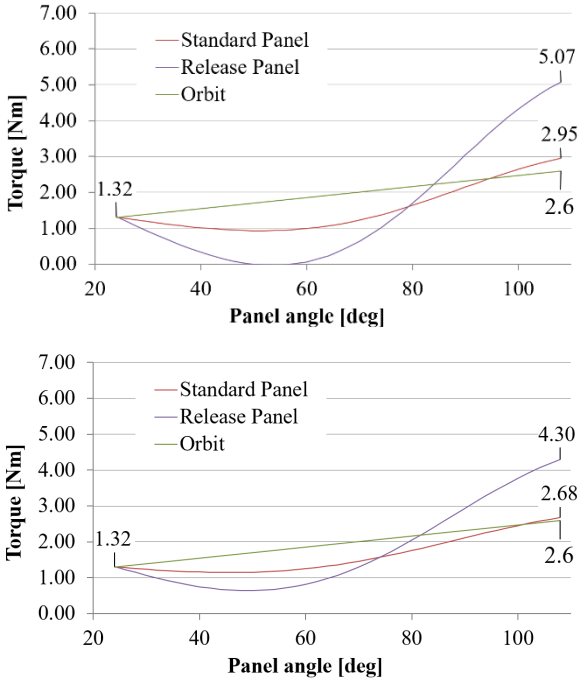


*Figure 14. Torque on the panel hinge during the deployment motion (top: 5.40 m height, bottom: 6.70 m height)*

In contrast, the bottom graph in Fig. 14 illustrates the same case with a height of the MGSE of 6.70 m above the panel hinges. This setup was possible by moving the hardware to testing facilities with a higher maximum crane height, reducing the unbalancing effect of the changing angles of attack during the critical first 15 degrees of the deployment. The result was considered the most realistic approximation of the deployment motion and was used for the following correlation analysis.

The recently performed successful in-orbit deployment of the reflector proved the success and viability of the conducted deployment tests.

However, the in-orbit deployment was ~18% faster than expected. Due to the massive surface area of the panels, the air displacement at ambient conditions could not be exactly verified. This air displacement had a significant effect on the deployment performance, causing a further decelerating effect and slowing down the panels more than expected.

### 3.4 Monitoring

The successful addition of an active monitoring system for the compensation wire forces on the X-band antenna boom test setup illustrated the positive affect of online measurement of critical test parameters. The potential use of the active positional feedback during the deployment in the ROSE-L MGSE to counteract friction further illustrates a practical use case. However, all previously described deployment test assemblies share the common characteristic of lacking an active real-time monitoring of the instrument's performance during the deployment test. Crucial factors to the performance, e.g., the deployment time, acceleration and deceleration rates, stresses, and torques need to be assessed by extensive video and photo analysis, challenging the in Chapter 2 named requirement of *precise control* and revealing the most critical detriment to such deployment systems.

Although the described test results of Sentinel-1 and the 5m-Deployable Reflector mirrored the in-orbit cases exceptionally well and video analyses and reference measurements of the hardware before and after the tests provided a comprehensive resemblance to the real performance, optimization possibilities for passive unmonitored MGSE are present. The resulting lessons learned and improvements, are described in the following Chapter 4.

## 4 OPTIMIZATION POSSIBILITIES AND LESSONS LEARNED

### 4.1 Lessons Learned

Considerable knowledge was gained concerning the performance of on-ground deployment testing of large antenna structures. The following list comprises the major lessons learned that resulted from the concept to the practical use of the previously described deployment MGSE:

- **Underestimation of complexity:** Do not underestimate the complexity of the deployment MGSE design. Consider this complexity in the schedule and financial aspects of the project. Timely investing in such systems significantly increases safety and performance during flight hardware testing.
- **Structural and kinematic analysis:** Perform timely structural and kinematic analyses for the deployment MGSE to identify possible safety risks, to optimize the system performance with regards to friction and structural integrity, and achieve more reliable prediction results.

- **Breadboard testing:** Use breadboard testing during early design stages of the MGSE to characterize its test performance, including prove load testing, and identify flaws in the system before using the device on flight hardware.
- **Split function if necessary and possible:** In case of test assembly limitations, consider splitting the functions of one device into two or more devices, should the flight hardware and test requirements allow for this. Reduced functions of a single device lead to simpler designs and increased performance.
- **Adaptability for multiple purposes** When designing a deployment or verification MGSE, consider its adaptability and usability for multiple use cases and test environments to reduce costs, handling errors, and maximize its application during campaigns.
- **Consider and plan for the test environment:** Restrictions in test environment can limit the usability of the deployment device, e.g., the crane height, floor space, ventilation, accessibility, or the use of certain materials. Plan for these possible limitations during the design phase of the MGSE.
- **Consider air displacement:** The successful in-orbit deployment of the 5-meter Deployable Reflector has shown, that air displacement on ground is a significant factor during the testing of large lightweight antenna structures. This aspect must be represented in correlation analyses.
- **Online monitoring + active devices:** Online monitoring of the hardware or test assembly conditions provide considerable knowledge of the test performance and can lead to improved hardware and test MGSE design. In case of failure, monitoring can support the troubleshooting process and risk mitigation.

### 4.2 Optimization Possibilities

Based on the lessons learned during the performed deployment tests, promising optimization possibilities are derived. Experience has shown, that active deployment devices would entail a multitude of advancements over passive devices. For one, an online monitoring of the system itself, as implemented in the X-band antenna boom, would deliver insights into the kinematics and forces affecting the hardware during its motion, leading to a safer test approach, but also to enhanced testing capabilities and adaptability. Driving this approach further leads to the idea of implementing active deployment devices, as prospectively applied in the ROSE-L deployment MGSE. These devices would enable the introduction of a controllable end-to-end deployment with monitoring of the flight hardware kinematics and merging theoretical analysis results and operations cases with the actual performed tests. Two example cases for this approach would be conducting a perfectly tuned on-ground deployment to verify the deployables function and performance under optimal conditions, and second, the emulation of a failure case during the deployment. An enforced disturbance during the deployment, initiated by the active deployment device, would lead to a controllable and safe approach to test redundant deployment mechanisms and fail-safe arrangements. Furthermore, deployments under varying hardware conditions could be tested, e.g., introducing increased internal friction, the impact of temperature loads, or disturbing forces induced by the satellite structure. These exceptional cases would result in a deeper understanding of the deployment system, allowing for more precise and comprehensive prediction analyses. Finally, deployment mechanisms are always going to be subject to friction and induce dynamic loads onto the flight hardware. These influence factors can be optimized by advances in the hardware and test designs, as shown in the previous chapters. However, active deployment devices could react to and offset these disturbing forces, allowing for deployment tests without a measurable influence on the test performance, vastly expending the advantages of low-friction test assemblies.

## 5 CONCLUSION

Requirements for a successful and safe deployment of large antenna structures were defined and the most significant challenges to fulfill these requirements were presented. The deployment testing of the 5-meter Deployable Reflector, the ROSE-L and Sentinel-1 SAR antennas, and the X-band deployable antenna boom was used to illustrate the limitations of the respective deployment and gravity compensation devices and the solution approaches to overcome the described shortcomings. The validity of the performed deployment and verification tests was confirmed by the successful in-orbit deployments of Sentinel-1 and the 5-meter Deployable Reflector, which both provided valuable insights on the influence factors of on-ground deployments. Based on the experiences gained during the deployment tests, lessons learned were defined, which pointed towards the way forward to active deployment mechanisms, enabling increased performance and test scenarios for large antenna structures.

## 6 REFERENCES


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