SWOT and NISAR Boom Ground Deployment Test Challenges & Resolution

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Abstract

NASA's Jet Propulsion Laboratory is developing two new spacecraft that use radar instruments to characterize temporal changes in the Earth's surface with unprecedented precision (Figure 1). Both the Surface Water Ocean Topography (SWOT) and the NASA-ISRO Synthetic Aperture Radar (NISAR) spacecraft utilize large, precision flight deployable booms to properly position and support their instrument reflectors. The SWOT spacecraft includes two nearly identical reflector booms, each of which have similar flight deployable hinge designs. The NISAR spacecraft has a single reflector boom, with four unique hinge designs. These booms each undergo a multi-staged flight deployment sequence on orbit to transition from the launch stowed configuration to the science configuration within days of launch (Figure 2).

Figure 1. Artist's Renderings of Deployed SWOT (Left) and NISAR (Right) Spacecraft On-Orbit

The SWOT and NISAR projects faced significant challenges relevant to requirement verification as well as hardware safety in their approach to ground testing these large flight deployables. This report summarizes flight deployable system design decisions that contributed to ground testing challenges. The report also summarizes the architecture trade study conducted for ground deployment testing.

A summary of key issues encountered during flight deployable ground testing with the chosen common gravity offload system ensues, with discussion of the issues and mitigation measures implemented by both projects that ultimately enabled successful flight subsystem-level full range of motion ground tests. Recommendations and lessons learned are offered to facilitate ground testability of future analogous large scale flight deployables.

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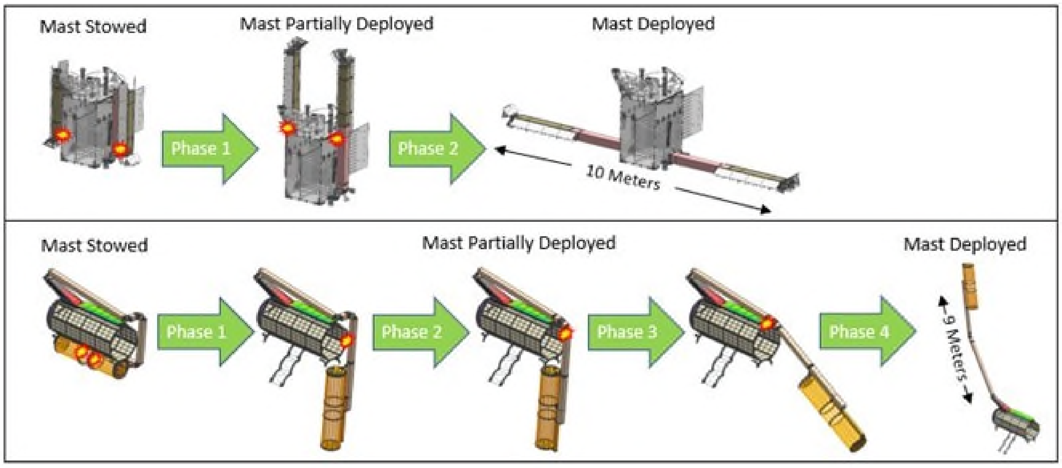


Figure 2. On-Orbit Boom Deployment Sequence for SWOT (Top) and NISAR (Bottom)

Flight Hardware Design for Testability

Deployable Structure Architecture Decisions

Both the SWOT and NISAR deployable boom designs faced significant technical challenges to meet project performance requirements while also stowing to fit within tight launch vehicle constraints and deal with loads from an over-constrained system. Priority was given to overcoming these technical challenges and several decisions were made early on to enable the primary on orbit mission success while sacrificing ease of testability during ground integration and test activities.

The NISAR project had a very complicated configuration to fit within an extremely tight launch vehicle (Figure 3). The radar feed and the stowed reflector were located on opposite sides of the payload structure, requiring the composite boom to wrap around the aluminum structure resulting in additional complexity for the design. The boom required four hinges to meet the stowed launch configuration volumetric constraints while still meeting the deployed optical prescription and with some consideration given for ground testability. Configurations utilizing three hinges all resulted in two hinges deploying in a common plane with the third hinge deploying in a challenging-to-test orientation. The four hinge configuration selected enabled three hinges to deploy in a common plane with the fourth hinge deploying in an orthogonal plane. While this configuration was chosen to improve the deployment test program feasibility, the orthogonal out of plane hinge deployment still proved to be exceedingly challenging to implement. For this hinge, offload weight errors and offloader friction became direct sources of deployment drag in contrast to the other hinges with hinge axes nominally oriented parallel to gravity for testing.

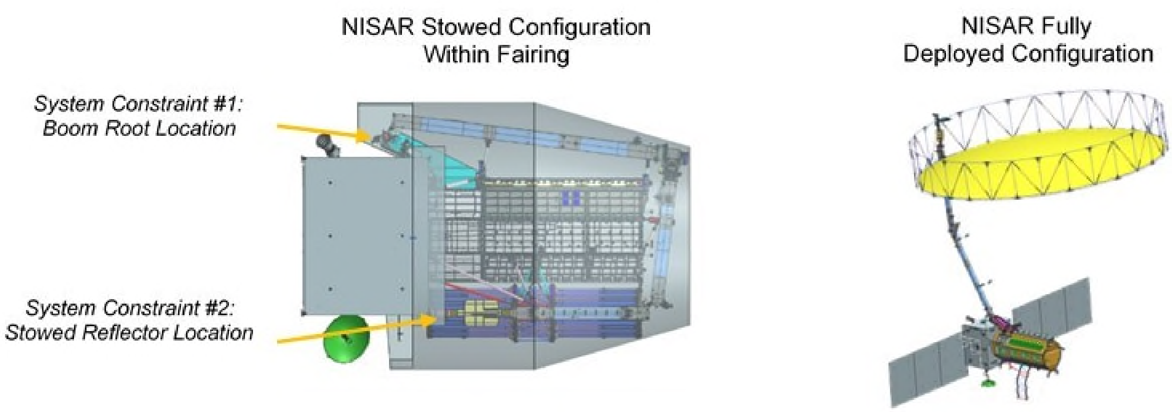


Figure 3. NISAR Boom Stowed Versus Deployed Key and Driving Configurational Constraints

For both the SWOT and NISAR missions, deployment mechanism architectures were selected to only deploy a single hinge at a time through serial launch restraint releases. This was done to achieve the highest confidence in full deployment success, as each phase could be deployed and telemetry reviewed to confirm success before proceeding with subsequent hinge deployments. Other programs such as Soil Moisture Active Passive (SMAP) have taken alternate approaches where two hinges deploy back-to-back and use a syncronization gear to avoid scenarios where contact or undesired motion could occur. The staged approach of SWOT and NISAR simplified the technical design of the deployment mechanisms and was lower in flight mass, however, it resulted in a significant increase in the number of deployments to set up and test on the ground. While the SMAP deployable boom had two deploying hinges, it only required a single offloaded test set up to fully deploy both hinges. SWOT and NISAR required a unique setup and reconfiguration for each one of their hinges and sometimes even a separate set up for the deploy direction verses the stow direction. This resulted in a significant increase in the complexity of the design of the test program, offload Mechanical Ground Support Equipment (MGSE), and duration of ground test activities. NISAR added further configurational complexity to the design of the GSE with the out-of-plane hinge deployment, a unique motion compared to the other hinges where the center of gravity (cg) changed vertical height by 0.6 m (2 feet) where all other deployments swept in an arc parallel to the ground. The decision to build a one size fits all deployment offload GSE system for both projects resulted in a very challenging design space to be able to accommodate all of the different configurations required.

The ground deployment tests were elected to be carried out on a fixed immovable ground constraint rather than offloading all components in a free-free test condition. This decision stemmed from the complicated over-constrained launch stowed configurations and the need for the launch restraints that reach back to the payload structure to stage the various hinge deployments in a flight-like manner. Ideally, the entire boom would be disconnected from the payload and offloaded in a free-free state. In a free-free configuration, errors in the offload weight would be observable in test as the structure sinks or rises, enabling the offload force to be tuned even with imperfect a priori mass properties knowledge. It was not feasible to offload the entirety of the payloads for either SWOT or NISAR, therefore the fixed root architecture had to be employed. This resulted in much tighter requirements in offload weight accuracy and center of gravity location knowledge as well as increased risk to hardware safety if an incorrect counterweight was applied. This prioritization of the design of the deployable booms for mission performance over ground test simplification enabled the projects to close on technical issues earlier, however, it came with the penalty of a significantly more complicated integration and test program.

Hinge Deploy & Latching Mechanism Handling Constraints

For both SWOT and NISAR, a torsion spring / viscous damper mechanism was used to deploy each boom hinge on orbit (Figure 4). Ground deployment test related requirements were not well-defined prior to completion of the detailed design of these flight mechanisms. Key flight mechanism design decisions were made that created challenges for full range of motion ground deployment testing.

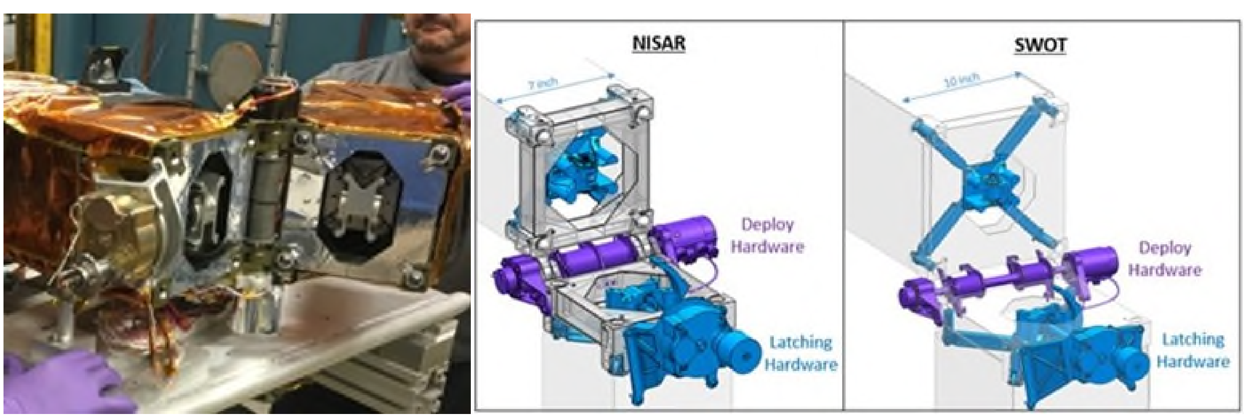


Figure 4. Hinge Deploy and Latch Mechanisms

Both SWOT and NISAR selected a flight deployable hinge architecture in which the deployment mechanisms included hinge pins that doubled as the primary structural load paths. For their function as a mechanism, the hinge pins were coated in a thin, life limited dry film lubrication. The flight configuration of the mechanism made recoating or replacing hinge pins after deployment testing impractical and would engender a hardware safety risk. Similarly, replacing the interfacing press-fit bushings carried non-trivial hardware safety risk and Verification and Validation (V&V) implications. As a result, restrictive allowable loads on the hinge pins for hardware safety during ground deployment testing were levied as requirements on the gravity offload system, which were particularly challenging to meet with the large mechanical advantage present in the flight configuration.

The interfacing bushings for these hinge pins were integral to large bonded composite structures. Large deployable full motion deployment testing was impractical to conduct in the relevant temperature and vacuum environment, and the flight architecture did not include sufficient mechanical field joints to enable lower level subassembly V&V in the flight configuration as these field joints would have necessitated a non-trivial mass increase. Therefore, each matched set of flight deployable mechanisms with flight deployable hinge harness was first installed on a flight-identical test fixture for environmental conditioning and thermal vacuum performance testing and then removed and reinstalled on the flight deployable structure with identical bushings per the same procedure. Part of the verification plan involved demonstrating correlation between the ambient torque performance of each mechanism and deployable harness set between the test fixture and flight installed configurations. Tight requirements relevant to deployment interference torques from the gravity offload system were needed to enable this approach to V&V.

In addition, volume constraints on the flight spring / damper mechanisms responsible for deploying the hinges resulted in low net deployment torque available for deployment. Non-trivial uncertainty in the resistance torque associated with deployable hinge-crossing electrical harness resulted in relatively large bounding allocations, which further limited the torque available to overcome ground deployment system torque losses. Given the small net deployment torque available from the flight mechanisms, modest gravity offload system alignment errors and offload force magnitude errors would result in violation of the bounds of the acceptable deployment torque test profile.

Similarly, while the hinge latch mechanism design had sufficient capability to withstand all on-orbit deployment and post-deployment load cases, this flight latch mechanism design created highly challenging design constraints on the ground deployment test system. Due to the large mechanical advantage of the gravity offload points on the boom and the relatively low latched hinge preload, small errors in offload force and offload alignment with the center of gravity of the deployable hardware would cause latched hinges to gap, potentially damaging the flexures in the latching mechanism. Hardware safety handling constraints for ground testing were levied restricting maximum allowable moments on latched hinges to approximately half of the minimum gapping threshold loads. This necessitated multiple offload points on each boom segment, tight tolerances on target offload forces at each offload point, and continuous monitoring of these offload forces at each location during deployment for hardware safety. A whippletree system was employed to attempt to achieve the target offload force distribution between the multiple offload interface points.

Ground Deployment Test Architecture Trade Study

To identify the appropriate gravity offload methodology that could be used for all six types of deployable hinges for SWOT and NISAR ground deployment testing, the following heritage JPL approaches were evaluated in a trade study (see Figure 5):

1. Helium Balloon Offload System
2. Overhead Swing Arm Offload System
3. 2-Axis Overhead Trolley Offload System
4. Caster / Air Bearing Support from Below Offload System

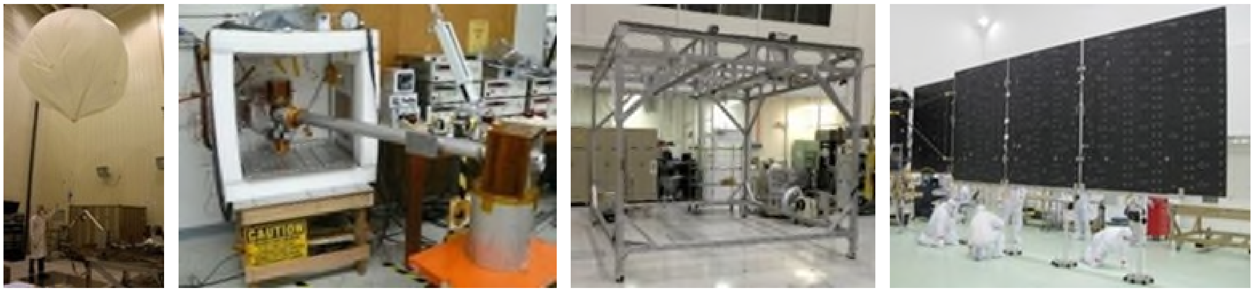


Figure 5. (From Left to Right) Insight Robotic Arm Balloon Offload, Aquarius Boom Deploy Device, SMAP Boom Overhead Trolley, JUNO Solar Array Castered Offload System

The primary metrics used for evaluation included the following:

1. Hardware and Personnel Safety
2. Estimated Cost of Offload System Development
3. Test Facility Needs

Results of the trade study are summarized in Figure 6. Additional metrics including deployment performance impacts and offload system setup / characterization time were considered but not assigned an appropriately high priority, given the fact that dozens of setups were required in the SWOT and NISAR integration flows. The overhead swing arm architecture with whippletree system was selected for both SWOT and NISAR, and an MGSE design implementation team took over the design-through-delivery of the offload system henceforth referred to as the Deploy Fixture (DF).

Category	Criteria	Balloon Offload	Double Swing Arm	2-Axis Overhead Trolley	Support from Below
Hardware Safety	Boom in GCF Testing	• 0.5x to 1.8x of boom inertia during deployment • Relatively constant offload force • Minimal drag effects	• 0.5x to 1.3x of boom inertia during deployment • Constant offload force	• 0.4x to 5.0x of boom inertia during deployment • Constant offload force	• 2.3x to 4.1x of boom inertia during deploy • Each cart will be between 40-170 lbs • Very friction/slope sensitive
	Boom in GCF Failure	• Negligible risk • Balloon catch system • Spreaders above flight hardware	• Negligible risk • Spreaders above flight hardware	• Negligible risk • Spreaders above flight hardware	• Negligible risk • No suspended loads above flight hardware
Cost and Schedule	Total ROM Cost (Eng. Dev + ME + Fab + Assembly + Proof Test)	• $270k • Minimal structure & mechanism count relative to other options	• $300k • More engineering effort for structure and mechanisms than balloon option	• $350k • More engineering effort for structure and mechanisms than other options	• $225k • Floor: ~$120k • Medium structure & mechanism development required
	Schedule Impacts & Cost Risks	• Lowest impact on schedule, most researched option • JPL experience • Vendor quotes ready	• High-level conceptual diagrams complete • No heritage MGSE • No detailed design work complete	• Heritage MGSE but 7-yr ago • No detailed design work complete	• [illegible] & Thompson are in the loop • Large variation in cost estimates due to leveling requirements
Facility Needs	Facility Constraints during Testing	• Floor space: 30' x 30' (42' for NISAR) • SWOT 34' ceiling • NISAR 22' ceiling	• Floor space: arc length of deployment (3' to 12') • Height: ~15'	• Floor space: 21' x 15' • Height: ~15'	• Floor space: 20' x 16' • No ceiling height req. • Highbay 2 floor requires more effort
	Facility Constraints during Storage	• 22 ft³ • Can be folded into box, easy shipping	• Can be designed to fold simply against wall • Arms removable	• Large fixture in cramped highbay • Must be disassembled between tests	• Requires time consuming assembly, alignment, and tear down

Figure 6. Gravity Offload Architecture Trade Study Summary

Gravity Offload System Challenges

An initial set of requirements were communicated to the DF design team to assure boom flight hardware safety as well as acceptable deployment performance to support correlation to analytical model predictions and subassembly-level ambient deployment performance testing. These requirements covered the following topics:

1) Maximum suspended flight hardware mass and center of gravity offset from the DF swing arm hinge axis
2) Interface locations on the flight hardware for offloading
3) Keep out zone for the swept volume of flight hardware
4) Maximum allowable deployment resistance torque from the DF
5) Repeatability tolerance for the DF resistance torque in a given setup
6) No deployment assistance torque from the DF permitted for performance tests
7) Maximum permissible moment loading on latched hinges
8) Maximum permissible inertia of the moving GSE
9) Maximum allowable overshoot force from the moving GSE at the end of deployment
10) The ability to offload all four NISAR hinges and all SWOT hinges multiple boom configurations
11) The ability to be taken apart for shipment

Many of these requirements were fully satisfied in the implemented design of the DF. However, some requirements, such as the total drag torque, were only met under nearly perfect setup conditions. Little was understood at the time of delivery about the alignment and positioning tolerances needed to obtain acceptable drag torques, nor the challenges of the setup process necessary to achieve them. Another example was the lack of understanding of the tolerances on knowledge of mass properties needed during testing to stay within the not-to-exceed hinge moment loads.

To make matters worse, several driving requirements on the offload MGSE became substantially tighter as knowledge of flight deployable hardware sensitivities matured; flight hardware development was progressing in parallel with the design of the DF. It was identified in the initial DF requirements set not to apply a moment to an open hinge that violated static proof loads, resulting in a handling constraint of 389.8 N•m (3,450 in•lbf). This was later revised down to 54 N•m (480 in•lbf) based on the need to prevent gapping of latched hinges during deployment testing. A third revision, intended to reduce the risk of damaging the dry lubricant on the flight deployable hinge pins, was identified much later in the DF development, restricting the maximum moment to hinges to only about 11.3 N•m (100 in•lbf). After understanding the implementation challenges associated with compliance with this 11.3 N•m limitation, the requirement was later relaxed to 28.25 N•m (250 in•lbf) through additional qualification model hinge testing that demonstrated no significant hinge pin coating damage occurring at this loading. Nevertheless, it still remained a tight, driving requirement for the test system which, if identified earlier in the gravity offload MGSE development, could have been a driving consideration in the MGSE offload architecture trade study.

Both projects had varying cg distances depending on the hinge being deployed that ranged from 63.5 to 165 cm (25 to 65 in) from the swing arm and varying total offload weights of 46 to 136 kg (101 to 300 lbm). Errors in either the total offload, cg location, or verticality of the hinge line could all produce moments on the moving hinge, and had to be carefully managed (Figure 7). The suballocated test setup tolerances were on the order of ±1.25 kg (±2.75 lbm) for offload error (0.9% of total offload) and ±0.6 cm (±0.25 in) of cg offload location error to stay within the 28.25 N•m (250 in•lbf) not-to-exceed moment requirement. This forced the team to not rely on CAD estimates for mass, and rather to weigh all flight components and GSE components and perform very careful configuration tracking to stay within these bounds. Mass properties testing of the assembled flight components generated very accurate initial mass and cg for each boom tube segment. This was followed on by individual piece part measurement of all additional flight components and GSE added to the moving hardware, including mass and cg location. Procedures were generated to track all configuration changes with quality assurance verifications implemented to ensure the hardware configuration matched the calculations. If it had been feasible, a free-free test configuration (or reduced flight hardware sensitivity) could have eliminated the need for this tedious process and greatly simplified the integration and testing process, not to mention reducing the risk to the flight hardware associated with human error in this extensive analytical tracking effort.

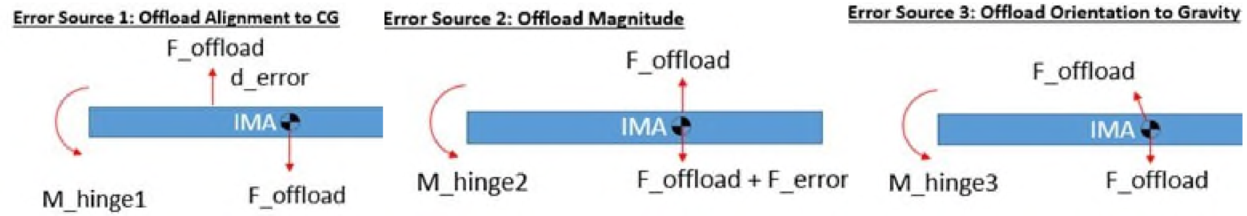


Figure 7. Offload Errors Causing Moments on Moving Hinge Pins & Deployment Resistance Torque

One additional complicating factor for the offload approach selected was the use of a series of four pulleys to route the offload cable from the flight article to the counterweight in order to reduce the inertia of the system. The combined drag force through all four pulleys at the maximum offload weight of 125 kg (275 lbm) was 2.25 kg (5 lbm). If the moving boom did not sweep through a perfectly level arc, its cg would move up or down and the offload weight would similarly need to move with it. With the drag in the system of pulleys alone, this would generate up to 2.25 kg (5 lbm) of error in the offload force on the deploy hardware, which violated the ±2.75 lb requirement. This was managed in several ways. First, the moving hinge pin is intentionally loose fitting, allowing for roughly ±0.1 deg of free angular movement. The verticality of the moving hinge was measured to make sure it was within ±0.2 deg of perfectly vertical prior to each deployment. Therefore the looseness of the hinge pin could correct for some of the initial angular misalignment and allow the boom to deploy through a more level arc with respect to gravity. Second, the pulley diameters were changed from 15.25 cm (6 in) to 50.8 cm (20 in) while keeping the same ball bearing sizes (Figure 8). This allowed for similar load carrying capability through each pulley but drastically reduced the total pulley system drag force from 2.25 kg (5 lbm) to 0.9 kg (2 lbm).

Figure 8: Deployment Fixture with 15.25-cm Diameter Pulleys Upgraded to 50.8-cm Pulleys to Reduce Drag

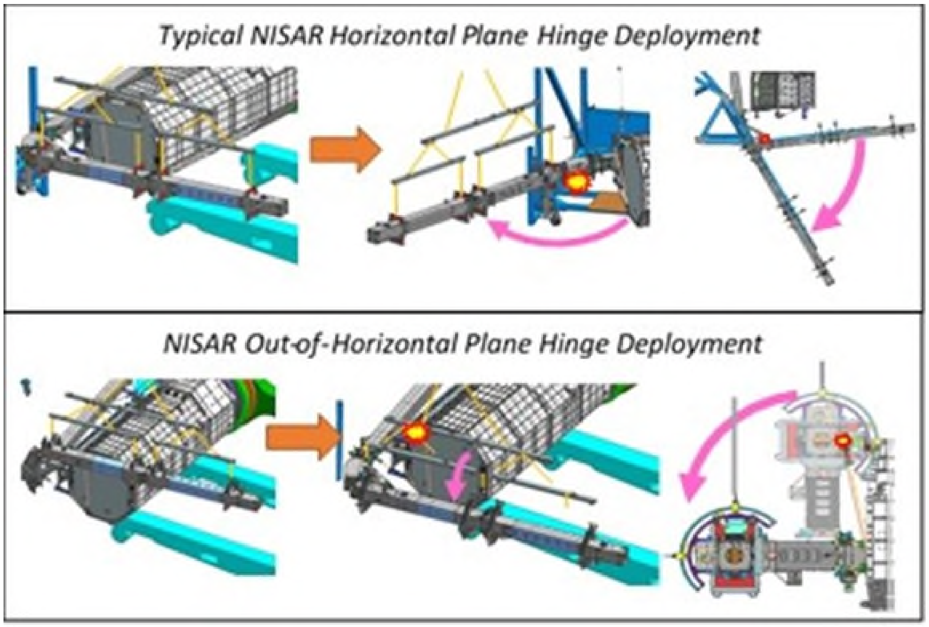


Figure 9: Horizontal-Plane versus Out-of-Horizontal-Plane Hinge Deployments

The offload error due to mass properties uncertainty or friction in the pulleys was especially critical for NISAR's out-of-horizontal-plane hinge deployment as it directly opposed deployment motion (Figure 9). Therefore, the driving constraint was not 28.25 N•m (250 in•lbf) for hardware safety, but only 4.5 N•m (40 in•lbf) to stay within allowable deployment torque performance requirements. At a distance of 63.5 cm (25 in) between the cg and hinge line axis, the maximum offload error could only be zero to 0.7 kg (1.6 lbm). Prior to each out-of-plane NISAR hinge deployment, a dummy weight was attached to the Deploy Fixture and a measurement of the system friction was taken. During the deploy test, the offload mass was intentionally adjusted to account for pulley drag and result in a near nominal offload force.

Even with the care taken to measure all flight hardware and GSE masses, account for frictional effects, and rigorously track the configuration, it was extremely difficult to get consistent deployment results for the NISAR out-of-horizontal-plane hinge deployment. Subtle changes in deployable mass (for example, the routing of test cables or the addition of thermal blankets) significantly effected the measured deployment profiles. Figure 10 shows a spread of deployment profiles taken over a year with multiple reconfigurations in between each data set for both a typical horizontal plane NISAR hinge deployment and the out-of-plane hinge deployment. The deployment profile shapes for each horizontal plane deployment were roughly consistent and deploy times matched ±20% between all tests. The out-of-plane hinge deployment profile data shows very different profiles for each deployment, with total deployment times ranging from 110 seconds on the fastest to 2400 seconds for the slowest. The difference between the fastest deploy time of 110 seconds and the middle deploy time of 740 seconds was determined to potentially be caused by a difference in offload of 0.34 kg (0.75 lbm) and a lateral cg difference of 0.5 cm (0.2 in) between the two runs. This extreme sensitivity of deployment performance due to minor test setup errors led the project to eliminate deployment profile consistency as a metric for test success for this hinge. Instead, the criteria for success was changed to safely deploy the hardware from launch to deployed configurations, with a thorough visual inspection of the mechanisms pre- and post- deployment to confirm their health.

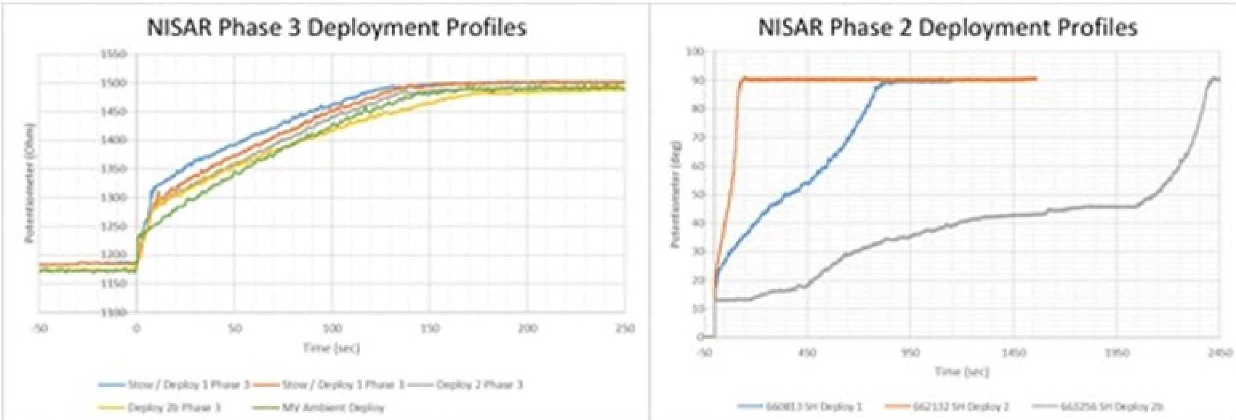


Figure 10: Variation in Hinge Angle Verses Time Telemetry Data for a Typical NISAR Horizontal Plane Hinge Deployment and the NISAR Out-of-Plane Hinge Deployment

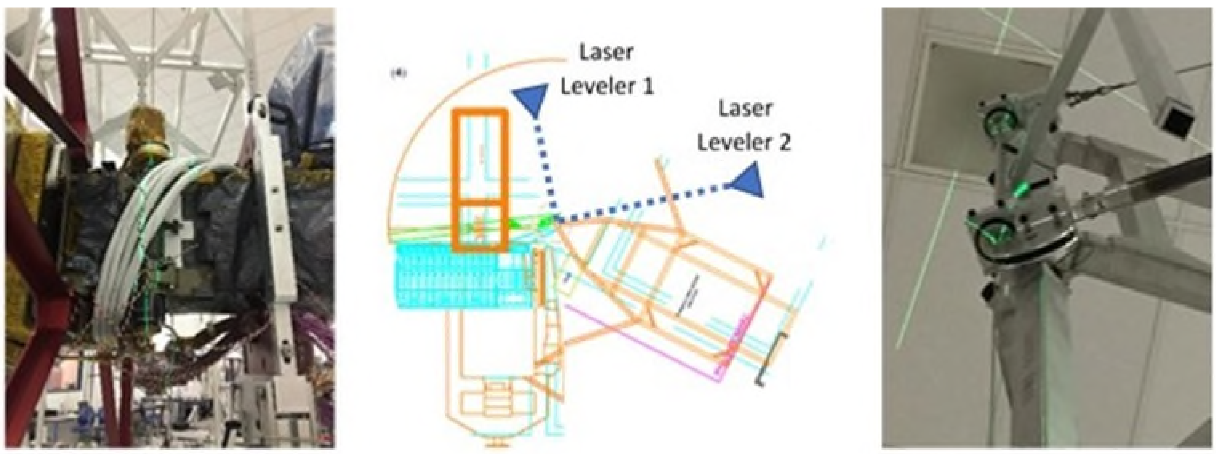
A final set of requirements that was not well understood until after delivery of the deploy fixture pertained to the required stiffnesses for this MGSE. The implemented design had a low-stiffness support structure for the swing arm axis. This meant the DF swing arm rotation axis changed orientation and positioning under load throughout the flight deployable range of motion. Torque error and flight hinge loads associated with this phenomenon needed to be addressed by appropriately pre-biasing the DF orientation during setup to minimize the peak magnitude of these contributions to remain within allowable limits. In addition, the clocking of the DF support structure was carefully selected for each hinge range of motion to minimize the contributions to torque error from swing arm support structure deflection. There was a clear need for pre-characterization of offload fixture performance in each setup prior to usage with the flight deployables.

Characterizing Gravity Offload System Performance

Shortly after delivery of the DF to the Integration and Test team, it was recognized that the DF would be a challenging system to use to meet the precision and consistency of offload needed for SWOT and NISAR boom ground deployment testing. The teams operating the DF in conjunction with the flight hardware needed to develop and utilize consistent procedures for the set-up, characterization, and pre-test analysis of DF performance to ensure each setup was safe for the flight hardware and would enable successful verification of performance requirements. A tedious but workable process was developed, but the methodology evolved significantly as the teams learned the nuances of large-scale gravity offload operations throughout the test campaigns.

Before any setup and characterization of the DF took place, the flight hardware was secured to a stable fixture with its deployable hinge axis sufficiently well aligned to the gravity vector. The maximum permissible angular error between the flight hinge axis and the gravity vector was 0.2 degree to limit cg vertical translation (and associated deploy torque impacts) throughout the deployment range of motion.

In regard to DF setup challenges, the DF consisted of a massive support structure with very limited and coupled degrees of freedom. The available degrees of freedom proved insufficient to allow for efficient setup for testing. The DF swing arm hinge axis had to be sufficiently aligned to the flight hardware hinge axis. To achieve this, two self-leveling lasers were projected, perpendicular to each other, onto the flight hinge axis (Figure 11). The DF was rolled into position such that the DF hinge axis coincided with the flight hardware hinge axis (defined by projected lasers) to within 5 cm (2 in) in plane projected distance. Because the DF swing arm was about 6 m (20 ft) above the flight hardware, the lasers had to be moved and projected onto to the DF axis in order to measure the offset to the flight hinge axis on the ground. Projecting lasers between two axes separated by a height of two stories, and then measuring the offset to the visually estimated centerline of the flight hinge axis had non-trivial measurement uncertainty. When accounting for the stackup of measurement uncertainties, the remaining allowable offset from nominal concentricity was determined to be 1.9 cm (0.75 in). In other words, the 1360 kg (3000 lbm) DF structure had to be rolled across an uneven floor on its four casters, and its swing arm hinge had to be aligned to the flight hinge axis 6 m (20 ft) below it, to within 1.9 cm (0.75 in). Once the two axes were aligned, the levelness of the DF swing arm axis with respect to gravity had to be characterized to ensure it did not impart any deployment assistance torques or unacceptably large resistance torques onto the flight hinge. Four jacks positioned at the four corners of the base structure provided only coarse adjustment capability to the levelness of the swing arm. Due to the large distance between the jacks and the swing arm, small adjustments at the base mapped to large changes in swing arm rotation axis levelness and position. Oftentimes, the levelness adjustments would put the hinge axes alignment out of the allowable 1.9 cm (0.75 in) positioning tolerance. As a result, the huge structure would need to be lowered back onto the casters to make small adjustments to the concentricity. And then the leveling process would need to be repeated. Many time-consuming iterations were typically needed to achieve an acceptable levelness in conjunction with an acceptable hinge axes co-alignment.



Laser Lines on Flight Hinge *Laser Lines on DF Swing Arm Axis*

Figure 11: Laser Levelers Positioned Orthogonally for Alignment of Deploy Fixture Swing Arm Hinge Line to Flight Hinge Line

To characterize DF induced deployment interference torques in each setup, a test mass representative of the moving hardware was suspended from the DF offload cable while an operator manually rotated the swing arm at a constant rate using a T-handle wrench with extension. To record this characterization data, a torque transducer with angle encoder were placed in series with the load path of the T-Handle wrench and the adapter on the DF swing arm, capturing data while the operator rotated the swing arm and hanging mass. The transducer and encoder data were recorded on a nearby laptop. It was assumed this method of monitoring the drag torque would be sufficient in verifying that the DF was not assisting the rotation of the swing arm with hanging mass, and also not exceeding the resistance torque requirement. This characterization method was also used prior to stowing the flight hardware hinges pre-deployment test; however, the resistance/assistance torque requirements were significantly looser as only hardware safety requirements had to be met, rather than the more strict deployment performance correlation requirements.

For the NISAR project, this manual characterization method proved to be sufficient to meet their hardware safety and deployment performance requirements. This stemmed primarily from the fact that the flight deployment mechanism minimum net torque available at the end of the deployment sweep was significantly higher for NISAR than for the SWOT booms, and hence the deployment resistance torque requirements were higher for the NISAR deployment fixture. But inconsistent results from this manual characterization scheme from different operators (and even from different characterization runs done by the same operator) resulted in more torque characterization variability than could be used to demonstrate requirements compliance for SWOT booms. The SWOT project's booms also had a higher mass and rotational inertia than the NISAR boom segments during ground testing (given the stowed reflector needed to be included at the end of the SWOT booms, but not on NISAR's). The increased inertia of the hanging mass on the swing arm made it more difficult for an operator to maintain consistency through manual characterization. One of the major difficulties that became hard to avoid in manual characterizations were inconsistent human interference loads in the torque data. These were caused by the operator accidentally rotating the swing arm too fast and then attempting to correct by slowing down (not necessarily rotating in the opposite direction, but just reducing the speed of rotation). When combined with small pendulous swinging motion of the test weight under the swing arm, this would sometimes show up as assistance torque in the data. Operator manual interference torques proved very challenging to decouple from DF torques in the measured data, resulting in high uncertainty in characterization runs and preventing deployment performance requirements from being able to be verified conclusively for SWOT.

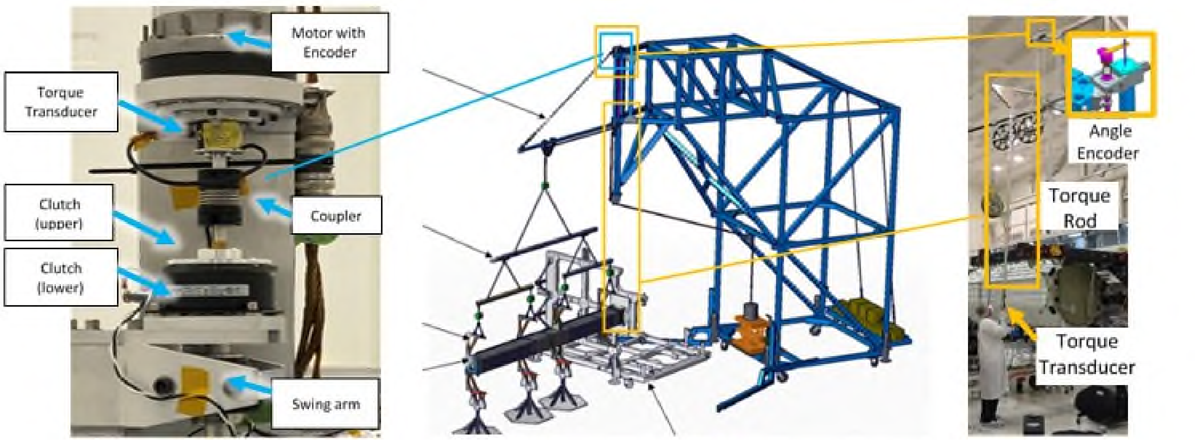


Figure 12: SWOT Motorized Torque Characterization Tool (Left), Full Swing Arm Offload System (Center), NISAR Manual Torque Characterization Tool (Right)

In the pursuit of sufficiently repeatable and accurate characterization runs, the SWOT project reworked the DF after initial testing. A motor with torque transducer and encoder was used to rotate the swing arm at a constant rate (selected to match the predicted average deployment speed) while recording the resistance torque / angle characterization data over the applicable deployment range of motion during characterization runs, with a clutch to disengage the system for flight deployment testing (Figure 12). The integration of this system to the top of the DF was a difficult undertaking, requiring weeks of iterations to align, test, and verify that the rotational axes of the motor and swing arm were sufficiently aligned as to not impart an additional drag torque into the characterization data that would not have existed during flight hinge deployments. While the time spent integrating this device caused a brief testing schedule delay, it resulted in higher characterization accuracy and consistency, which ultimately reduced the frequency of performance requirement violations in test. Despite the increased characterization fidelity, some performance requirement violations still occurred and more characterization challenges remained to be addressed.

In the course of investigation of one performance requirement violation, a concern was identified that DF deployment interference torques may be changing between pre-test characterization and actual deployment testing (or during deployment testing). A system had not been developed to directly measure DF deployment interference torques during flight deployment tests. To investigate this concern area, DF characterization runs were completed both pre-deployment and post-deployment. For some deployment tests, both the average torque value and even the shape of the measured DF torque curve were observed to change significantly between the pre- and post-characterizations (Figure 13). The exact root cause of the change was not conclusively determined, but there are two prevailing theories.

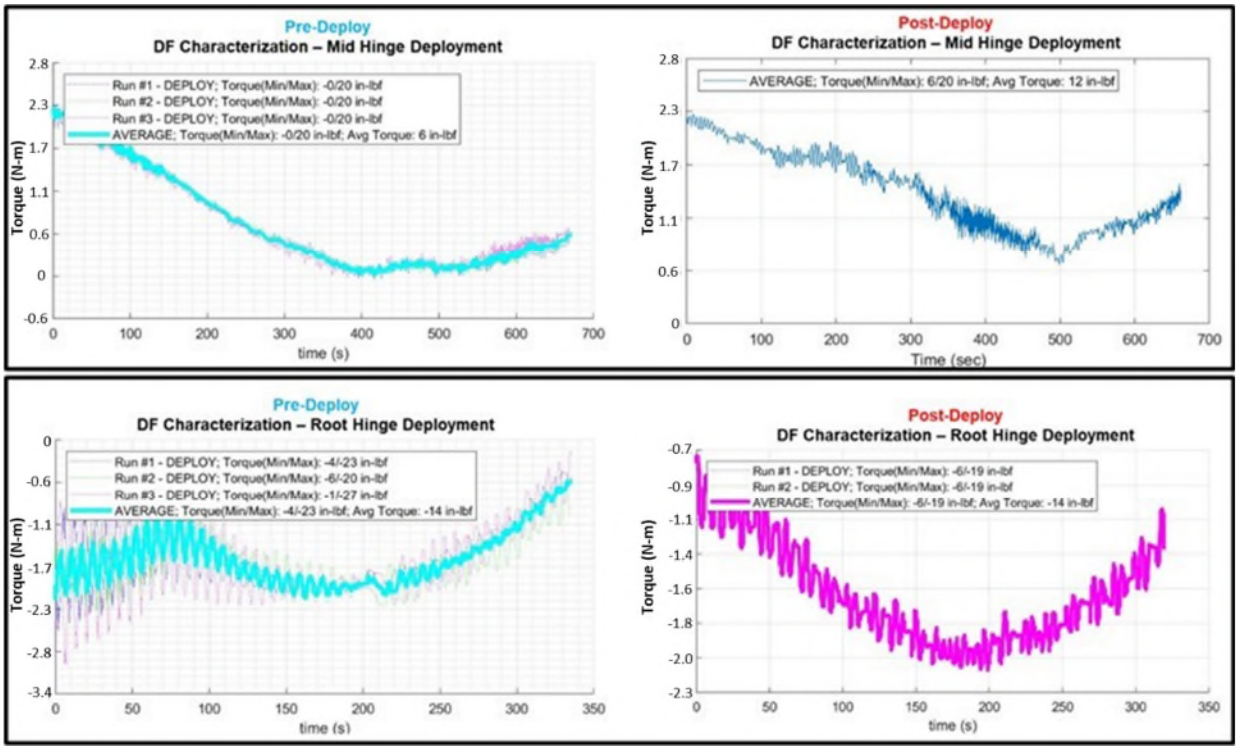


Figure 13: Top Row - Pre-vs-Post DF Characterization Data for SWOT 180 Degree Sweep Angle Hinge. Bottom Row – Pre-vs-Post DF Characterization Data for SWOT 90 Degree Sweep Angle Hinge

During characterizations and deployments, the DF would sometimes make a creaking / popping sound that generally occurred in the same regions within the angular range. The DF support structure with all of its welds were thoroughly inspected and ruled out as a potential source of the audibles. It is expected that the swing arm radial bearings and thrust bearing may have shifted within their bores during deployment tests, causing an audible sound during the slip events. This bearing position change would result in swing arm rotation axis changes, with corresponding changes in parasitic torque. Another potential root cause identified was that the DF was supported by 4 points of contact to the floor via manually cranked jacks. It was observed during characterizations, where the jacks were used as the mechanisms for leveling, that the DF would sometimes rock about 2 opposing jacks—similar to an imbalanced 4-legged stool. Depending on which combination of three jacks supported the DF, the resulting torque curve / average would change. It is believed this phenomenon could have occurred across characterization tests, as well as during deployment tests, resulting in resistance torques that varied by a non-trivial amount, even in the "same setup" of the DF. The free hanging mass during characterization runs did not perfectly represent the loads on the DF when offloading a partially constrained boom as well as kickoff dynamics in deployment testing; hence the potential for rocking in deploy testing but not in pre-characterization. In response to these findings, both pre- and post-test characterizations were conducted for each deployment test and additional quality assurance verifications were implemented after this investigation to ensure all four jacks were well seated on the floor prior to the pre-test characterization runs.

Another late breaking realization was that the speed at which the swing arm rotated during characterization had an effect on the torque curve. Generally, the slower the swing arm was rotated, the higher the average measured parasitic torque. Once this effect was identified, the new process for characterization included pre-characterization of DF performance to ensure sufficient setup for hardware safety, and post-test re-characterization at the average measured speed of the flight hardware during deployment for performance requirement verification. While this methodology also helped improve the correlation of test results to predictions, more performance requirement violations and associated investigations ensued--further improvement in the process was still needed.

One of the major features the DF lacked was the ability to record real-time resistance torque contributions from the DF with the Flight Hardware rigged to the deployment cable. There was a fundamental difference between articulating the swing arm with a free hanging mass and articulating the swing arm with a partially constrained boom suspended. DF pre-characterization measurements with a free suspended mass simulator did not fully account for any of the error sources referenced in Figure 7.

A detailed ground support equipment deployment performance modeling effort was undertaken to analytically bound additional error sources based on additional alignment and weight measurements taken in each setup; this enabled analytical post-processing of test data to demonstrate compliance with hardware safety limits and adequate correlation of flight deployable performance with lower level ambient test results.

Through this additional deployment modeling, it became apparent that the simplistic approach of specifying a maximum average resistance torque requirement across the range of motion did not ensure compliance with the deployment performance duration requirement. DF interference torque near the end of the deployment range of motion had a far more significant, non-linear impact on total deploy duration than interference torque near the start of the range of motion. Therefore, the maximum allowable resistance torque imparted by the DF needed to be reduced further towards the end of the boom's deployment sweep, posing even tighter constraints on the already-challenging task of aligning and leveling the DF swing arm axis to the boom hinge axis.

To further reduce discrepancies between deployment duration model predictions and as measured performance in test, actual measured DF test characterization data was also input into the deployment model. When accounting for the as-measured characterization data in the model, this method proved to be quite accurate, predicting durations within 5% of actuals for the final two deployments on SWOT for which it was implemented.

Conclusions, Lessons Learned, and Recommendations for Future Large Deployables Testing

The lessons learned following completion of the SWOT and NISAR boom deployment testing campaigns fall into several broad categories.

The first category is to carefully consider ground test needs for large-scale flight deployables early on in the mission planning phase. Flight design teams can have a tendency to "optimize" flight hardware designs for the flight system with little to no consideration for ground testing. A more balanced approach would likely be of best value to the project. Several costly issues encountered during the SWOT and NISAR ground deployment test campaigns stemmed from flight hardware design decisions made very early in the planning, and it was too late to reverse these decisions once the impacts to the MGSE and testing teams were better understood. Involving integration and test and MSGE engineers at the earliest stages to work through the ground test program even at a conceptual level could have uncovered many of the issues that were discovered only after the DF was delivered*.* Generating flight mechanism designs that were outside of the main structural load paths and flight configurations that are able to be tested in free-free offloaded states also would have greatly reduced the risk to the hardware and simplified the overall test setups. Separable field joints should be included for all deployable hinges to allow flight acceptance testing at the lowest levels of assembly and simplify higher level system tests except under the most mass constrained programs. Where possible, self-supporting deployable structures or structures with less sensitivity to reasonable parasitic loads can greatly simplify testing operations and requirements verifications**.**

The second category of lessons learned applies during the concept generation and down selection of MGSE gravity offload architectures. Invest effort to achieve an adequate understanding of flight hardware sensitivities and requirements early in the development, and identify and push back on overly challenging / constraining requirements from the flight system as early as possible. In generating concepts, a good understanding of the architecture's sensitivity to misalignments and how it effects deployment performance as well as the degree of difficulty to achieve the required alignments needs to be a key metric for down selection. For flight designs requiring a very high level of offload precision, self-aligning deployment systems such as balloons or balance beams should be utilized to reduce complexity (and cost and schedule implications) during I&T. GSE architectures should be evaluated with preference toward minimizing setup, reconfiguration, and characterization time needed on the project critical path—for example, a single configuration of GSE applied at the start of the test campaign for all phases of deployment. The overall I&T plan and flow should also give consideration to minimizing the amount of reconfigurations and repeat setups / recharacterizations of GSE and gravity offload systems, including facility considerations to enable offload systems to remain in place.

The final category of lessons learned revolves around items specifically relevant to swing arm gravity offload systems. While these systems can function well for a variety of applications, care must be taken during the initial design phases to understand the detailed requirements and needs of the specific mechanism being tested. Swing arms are sensitive to the alignment of the swing arm with respect to gravity. Direct alignment features / degrees of freedom for the swing arm should be incorporated into the design to allow for any necessary tuning of the swing arm alignment and positioning independent of global support structure positioning / leveling capabilities. And the support structure must be designed to be stiff enough and rigidly assembled to prevent unacceptable levels of deflection or shifting of this swing arm axis during usage.

The SWOT and NISAR projects ultimately achieved their needs for safely verifying functionality and performance requirements for the boom deployment systems. However, there was a long and arduous path to figure out how to use the as-delivered MGSE to meet these needs. Application of the above lessons learned throughout the entire lifecycle of a future project will significantly reduce risks and challenges encountered in meeting the needs of large scale deployable test programs.

Acknowledgement

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).