

## GPM Solar Array Gravity Negated Deployment Testing

Jonathan Penn\*, Chris Johnson\*, Jesse Lewis\*\*, Trevin Dear\*\* and Alphonso Stewart\*\*

### Abstract

NASA Goddard Space Flight Center (GSFC) successfully developed a g-negation support system for use on the solar arrays of the Global Precipitation Measurement (GPM) Satellite. This system provides full deployment capability at the subsystem and observatory levels. In addition, the system provides capability for deployed configuration first mode frequency verification testing. The system consists of air pads, a support structure, an air supply, and support tables. The g-negation support system was used to support all deployment activities for flight solar array deployment testing.

### Introduction

Global Precipitation Measurement (GPM) is a satellite developed in partnership between NASA and the Japanese Aerospace Exploration Agency (JAXA) to advance scientific understanding of the Earth's water cycles and help forecast extreme climate events.

GPM is the successor to the Tropical Rainfall Measuring Mission (TRMM) that was launched in 1997. Just as for TRMM, GPM depends on solar arrays to deploy once in orbit to provide power. GPM requires a significantly larger amount of power than its predecessor and was designed with a Solar Array Deployment and Drive System (SADDS) that provides approximately 1.75 times more energy. This larger and more efficient array consists of two wings each with four panels per side.



Figure 1. Rendering of GPM in Orbit



Figure 2. Walk Out of Flight GPM Solar Array

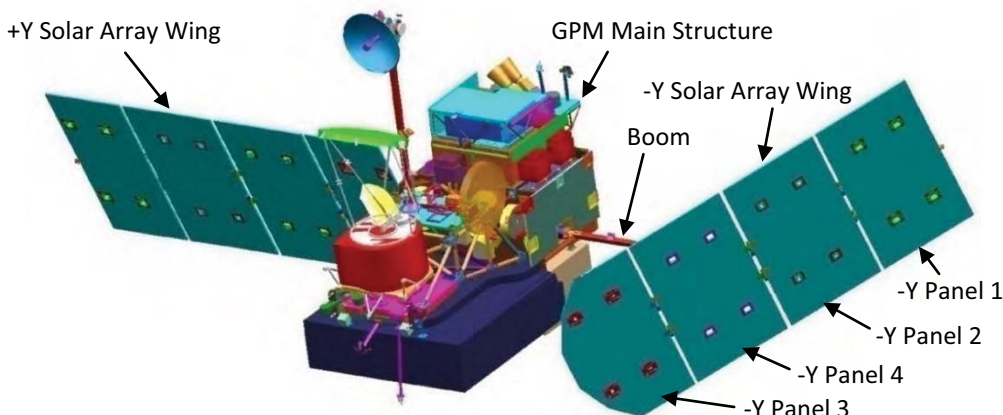
One of the challenges at NASA GSFC has been to negate the effects of gravity during deployment testing of the SADDS since it cannot support its own weight in a 1-g environment. The ability to “g-negate” allows the engineers to verify the SADDS deployment capability before and after environmental tests and again prior to launch when fully integrated to the spacecraft. The solar arrays are required to deploy in less than 300 seconds. A consistent time within 10% of baseline performance is required to evaluate performance changes. At full deployment, all hinge hardstops must be contacting and all hinge latches engaged. The

\* Stinger Ghaffarian Technologies, Greenbelt, MD

\*\* NASA Goddard Space Flight Center, Greenbelt, MD

g-negation support system must not compromise the electrostatic sensitivity or contamination requirements of the spacecraft and must be compliant with use on the GPM spacecraft.

The GPM Solar Arrays consist of two Solar Array Wings with one installed to each of the +Y and -Y sides of the GPM Spacecraft. Each Solar Array has a boom that extends approximately 3 m (10 ft) and attaches to the center of four panels. Each panel is approximately 1.5 m (5 ft) by 2.75 m (9 ft) aluminum honeycomb with carbon fiber face sheets. Separately, each Solar Array wing weighs about 177 kg (390 lb). Compared to its predecessor satellite TRMM, GPM's Solar Arrays have about two times the mass.



At the time of publication the SADDs has been shipped to Japan on the GPM Spacecraft for a 2014 launch. Prior to shipment, each wing underwent environmental testing, multiple walk outs, and four official deployment tests. Through the process of developing the g-negation system and working through issues as they arose during deployment testing valuable lessons learned were discovered which are described herein.

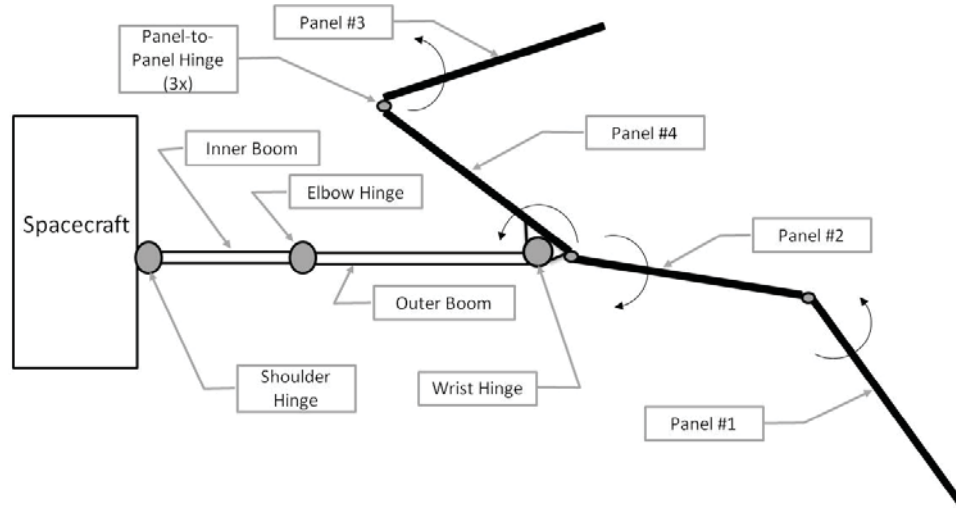
## Background

Each of the GPM solar array wing assemblies deploys in the same relative sequence. As such, and because only one wing would be deployed at any given time for testing, only one g-negation system needed to be developed. Initial concepts for the g-negation system included a table system which supported the wing assembly from below and an overhead gantry system which supported the wing assembly from above. Previous GSFC projects TRMM and X-ray Timing Explorer (XTE) had successfully employed table systems that supported the deployable subsystem using air pads. As a result of these prior efforts, air system advantages and disadvantages were fairly well known and additional consideration was given to an overhead gantry system. Gantry research and development was short-lived however, due primarily to the multi-directional deployment sequence and path of the wing assembly panels as shown in Figure 4.

The solar array panel deployment sequence and path would demand a relatively elaborate overhead tracking system. Additionally, that system could neither introduce significant deployment friction nor influence the wing's deployment path in either an inhibitive or assistive manner. Thus, the need for an uninfluenced deployment path eliminated the early gantry concepts and refocused the development on table systems. Furthermore, minimal system friction was more likely to be achieved on the table surface by using an air pad system. Due to the long moment arm created by each Solar Array's wing span, even the small amount of friction created by a castor-supported system could have overwhelmed the solar array wing hinge springs.

Once the decision was made to pursue an air pad table system, the natural progression was to adapt and refine the table system used by the aforementioned spacecraft's TRMM and XTE. Custom tables and air pads were developed for XTE and these would also be employed by GPM. While the table system

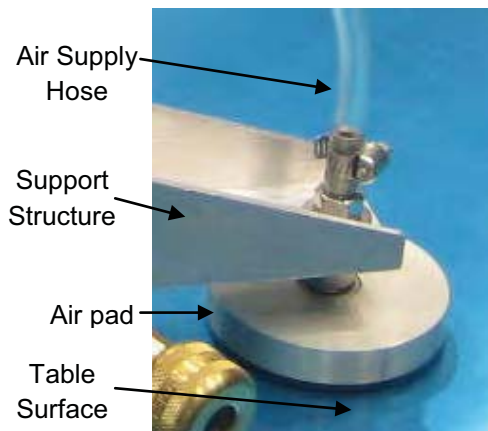
concept was very simply a flat level surface big enough for the deployment area, it was required to be modular to facilitate movement within Goddard and to the launch facility at JAXA. The deployment table was an assembly of several tables. Each table was a 1.22 m (4 ft) by 2.44 m (8 ft) aluminum face sheet honeycomb panel on an aluminum frame and legs. Unfortunately, these tables had warped and worn over time and use. Alternative tables were researched but facility compatible materials and weight limits for mobility restricted selection. Cost was an additional constraint restricting table replacement and refurbishment. It was, in result, determined to be most suitable to proceed with the heritage tables and air pads and tailor both for GPM's needs.



**Figure 4. Solar Array Deployment Path**

### Design and Development

Once the decision was made to use the air pads and deployment tables, the next step was to design additional assemblies that would adapt this hardware to the GPM Solar Array's geometry. This section details how the air pads and deployment tables were optimized and interfaced to the GPM Solar Array to create a working g-negation system.



**Figure 5. Air Pad**



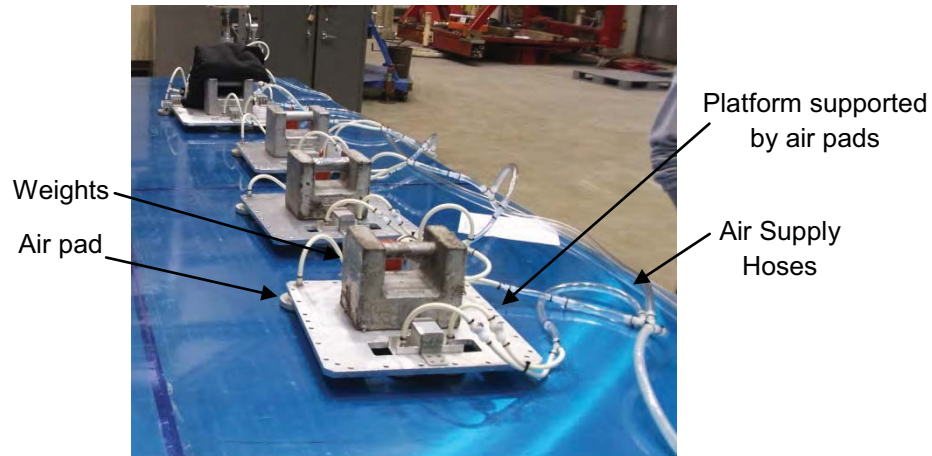
**Figure 6. Set of Four Deployment Tables**

#### Air pad Development

To evaluate air pad capabilities, weights were loaded onto structures supported by the same number of total air pads expected to be used on a flight Solar Array Wing and the air flow was opened fully. The

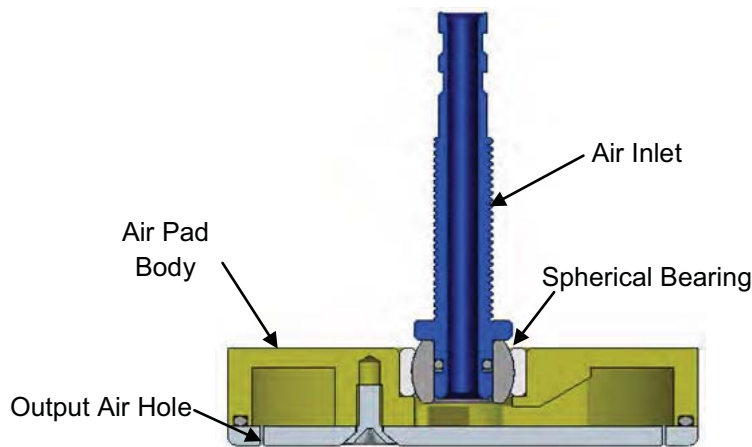
intent of this was to compare the maximum capability of the air supply with the weight of the Solar Array Wing. Unfortunately a problem was encountered as the weight was increased.

Simply increasing the airflow was not sufficient to increase the load capability because the air pads would start to chatter at high frequency once the weight reached a certain threshold. The air pads were acting as air motors, storing and releasing energy from their plenums causing them to rise and fall. The time delay in filling and emptying the plenums caused a time lag between the air flow into the plenums and the resulting pressure buildup below the air outlets. This pressure buildup inside the plenum increased the flow rate through the air outlets, which in turn increased the air pressure below the outlets, increasing the upward force on the load, raising the load, which lowered the pressure below the pad.



**Figure 7. Air Pad Capability Test**

This chatter was unacceptable as it would introduce friction preventing ground deployment of the Solar Array Wing. The solution was counterintuitive: the team blocked half of the air outlet holes on the bottom of the airpads and eliminated the chatter. This moved the major pressure drop to the air outlets. With the absolute pressure ratio at these outlets now above the critical ratio (0.528 for air), the air velocity through the air outlets rises to Mach 1, and no downstream air pressure changes below the air pads can affect the flow rate. With the pneumatic feedback loop broken, no instability is possible. Once this design fix was implemented it was determined that our facilities could supply enough air to lift the weight of a Solar Array Wing with a 40% margin.



**Figure 8. Air Pad Cross-Section**

### Panel and Boom Supports

A support structure was designed to ensure that the Solar Array Wing had sufficient support to prevent tipping but did not become over-constrained and bind up during deployment. Four panel supports were built that each captured the lower Ground Support Equipment (GSE) attachment inserts of its respective mating panel, shown in Figure 9. Two of the panel supports also had a strut extending to an upper GSE attachment location to stabilize the array against tipping, shown in Figure 10. An additional support was also designed for the boom. The supports were optimized for an even load distribution among 19 air pads, shown in Figure 12. In some cases two or three airpads were placed directly next to one another to support a higher load and were coupled with a universal joint to avoid over constraint. Mockup panels were used to evaluate system performance prior to installing to the ETU assembly.

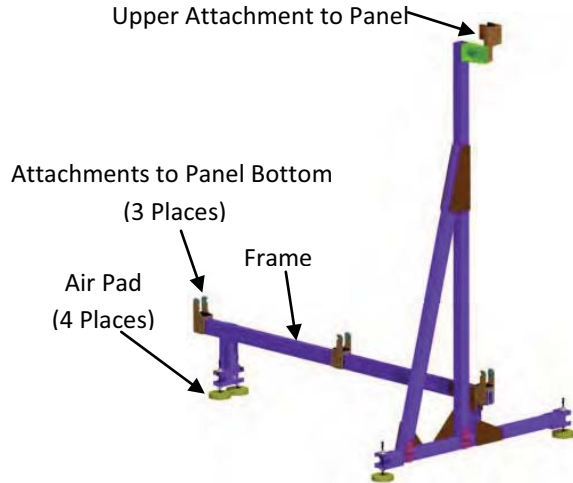


Figure 9. Panel 1 Support

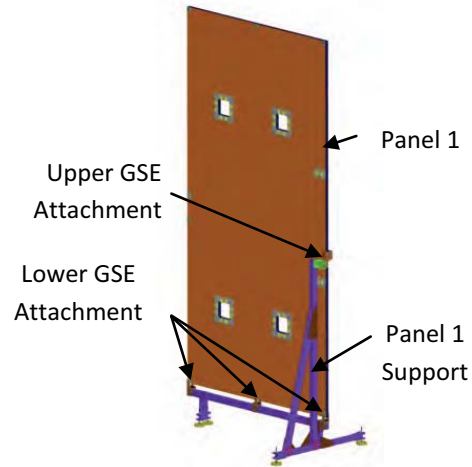


Figure 10. Panel 1 Mounted to Support

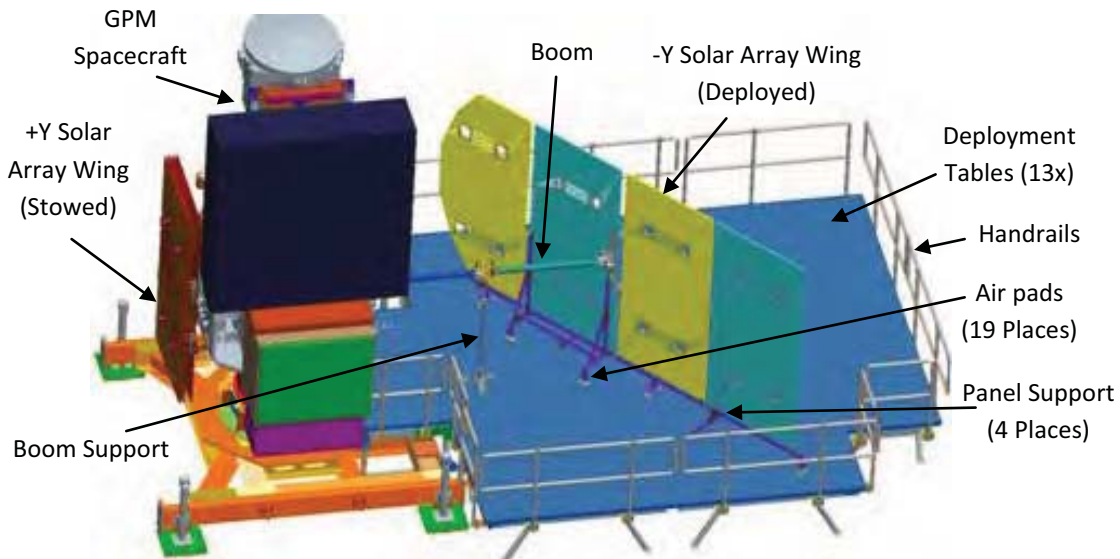
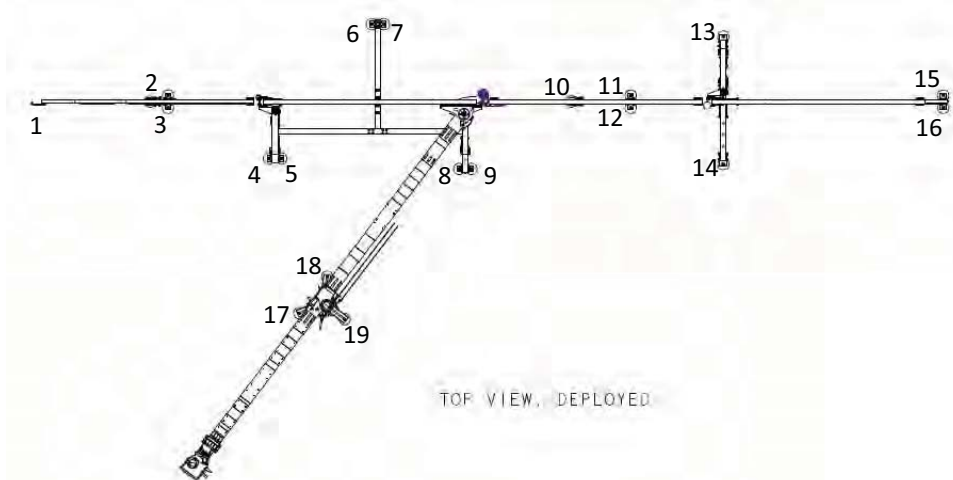


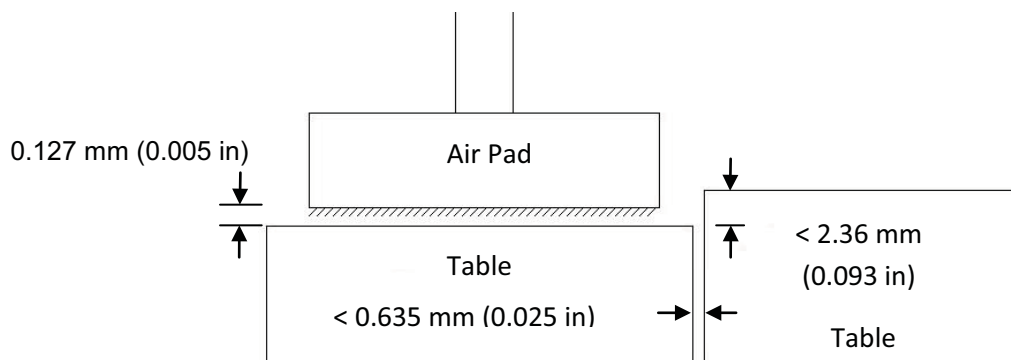
Figure 11. G-Negation System installed to -Y Solar Array Wing



**Figure 12. G-Negation System Air Pad Locations**

Deployment Tables

Problems were experienced immediately on the first tests performed with mockup Solar Array Panels attached to panel supports even though the air pad capability testing proved that the air flow was sufficient to carry a much higher mass. The deployment tables, being over 20 years old, had spent considerable time in storage and warping had occurred on their 1.22 m (4 ft) by 2.44 m (8 ft) honeycomb panel top surfaces. Getting the seams of two tables aligned well was in some cases difficult, and getting all the seams aligned with the full array of 16 tables was not possible. The resulting height differences along the seams of adjacent tables resulted in increased friction or even blocked Air Pad travel. The problem was compounded when multiple air pads attempted to traverse seams at the same time. This table misalignment is illustrated in Figure 13.

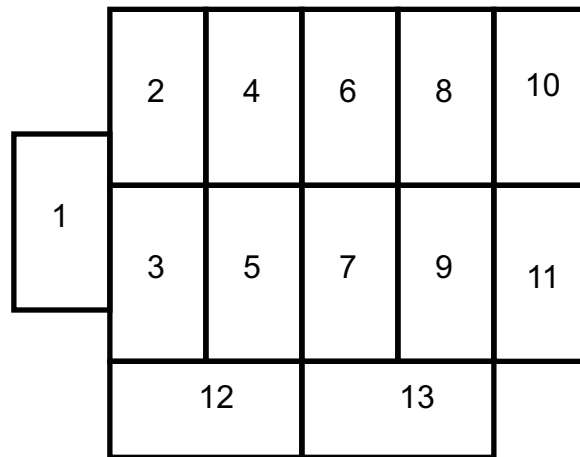


**Figure 13. Table Misalignment (Height Differential)**

Much time and effort was spent optimizing the alignment between tables, however, the team reached a point where any improvement achieved at one location was at the expense of another. It was decided at this point to experiment with laying various materials across the tables to bridge the seams and reduce the effect of the misalignments. It was found that one particular vinyl flooring material vastly improved performance. The reason this particular vinyl material helped so much was not yet fully understood and this topic is discussed in greater depth later in this paper.

With the addition of the table surface cover to the table assembly, table leveling and alignment was revisited. With the table surface cover reducing the misalignment effect at the table-to-table seams, the need for near perfect seam alignment was no longer necessary. Instead, a “best fit” approach to lining up the seams was employed. First, each of the 12 main tables was placed in the appropriate relative

position, shown in Figure 14. Using a laser level and a target block, the first table, table 2 as seen in Figure 14, was leveled by placing the laser on one corner and the target block on the diagonally opposed corner. The target block was then relocated to the opposing corner of table 10 and was leveled relative to table 2. All table leveling was performed at the floor using an adjustable foot at the bottom of each table leg. Following the leveling of table 10 relative to 2, table 11 was leveled relative to 2. Tables 3, 12 and 13 were done similarly. All adjacent tables in between were then leveled and adjusted from level in order to “best fit” their edges and seams to those of the corner tables. Table edge height was assessed by feel across the top surface, from one table to the next. The final step was to bring into position the front table, table 1, and level it to the table assembly. Following leveling and seam adjustment, each table was bolted to the adjacent table(s) to tighten the table seams, stabilize table position, and stabilize the overall table assembly. Once set up was complete, the table assembly was ready for the table surface cover. With the surface cover in place, table set up could be verified with system walk-outs and hand release deployments. Through iterative hand release deployments and adjustments, the table assembly could be optimized for deployment tests. Perhaps the most critical of tables was table 1, seen in Figure 14, which was at the spacecraft interface that supported the entire wing in its stowed state. Deployment time and path were sensitive to the transition of the panels and the elbow support stand across that first seam.

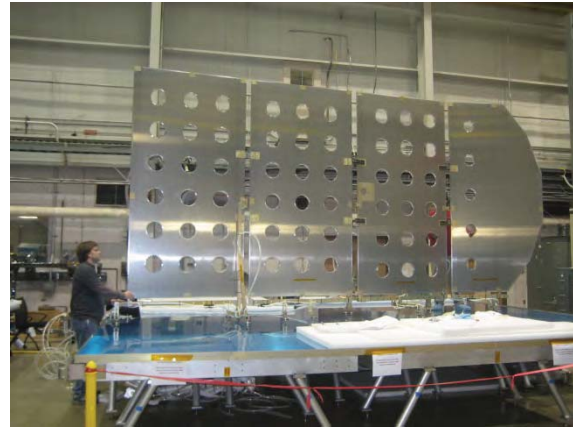


**Figure 14. Table Assembly Layout**

Of equal importance was the adjustment of the g-negation support frames and their respective air pads such that system loads were evenly distributed across all air pads to prevent overloading of any sub-group of air pads. G-negation frames could be adjusted at the interface to the air pads to add or relieve load at pad locations. In this fashion, frame or pad to table interface was optimized at the time of frame installation to the stowed wing assembly. Air pad heights were adjusted so that there was free rotational spin at each pad. Inability to easily rotate any air pad indicated that pad was carrying too much load. Easy rotation and wobble at any air pad indicated that the pad had too much clearance from the table surface and was not loaded enough. Adjustments to the respective frame(s) and pads were made accordingly. Upon release of wing preload and system walk-out, hand release or official deployment, adjustments could be made for further system optimization. This was possible by either adjusting both g-negation frames and air pads, or by adjusting the tables themselves to change table pitch or seam interface issues.

Additionally, the wing itself could be adjusted by modifying the pitch or roll of the spacecraft dolly. This however had to be done with the wing in the stowed position and was only to be done if the dolly was not level in either regard. Spacecraft dolly position and adjustment is covered later in more detail. Of course, proper initial set up would alleviate need for post release adjustments. As such, once the system was refined and understood, initial set up was efficient and all that was required. This was verified through successful post-test deployments which could not be preceded by verification walk outs. Following

successful deployment testing with the mock up panels, the team felt that the development stage was complete. The team was ready to implement the G-Negation System on the Flight Solar Array Wing.



**Figure 15. Testing with Mockup Panels**



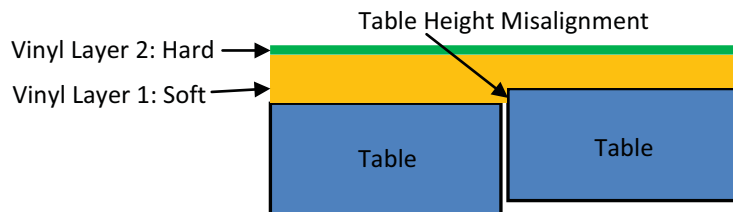
**Figure 16. Tables with Vinyl Covering**



**Figure 17. Qual Solar Array Test**

### Adaptation to the Cleanroom

In order to utilize the g-negation system on the flight Solar Array Wings, it was necessary to replace the vinyl surface cover with a low outgassing substitute. Another requirement was the need to dissipate electrostatic charge created by airflow out of the air pads. The particular vinyl used during development testing had specific properties that made it work successfully. This vinyl had a softer lower layer that conformed to the height difference between two tables and a harder layer on top that provided a good ride surface for the air pads, seen in Figure 18.



**Figure 18. Vinyl Surface Covering**



After extensive research only two alternatives were found with similar properties to the soft layer of vinyl. The first, Viton Foam, was prohibitively expensive; the amount of material needed to cover the table surface would have cost over \$100k. The second, Poron 4701-30, a material made by Roger's Corporation that is commonly used in aerospace applications was adopted, and large rolls were purchased.

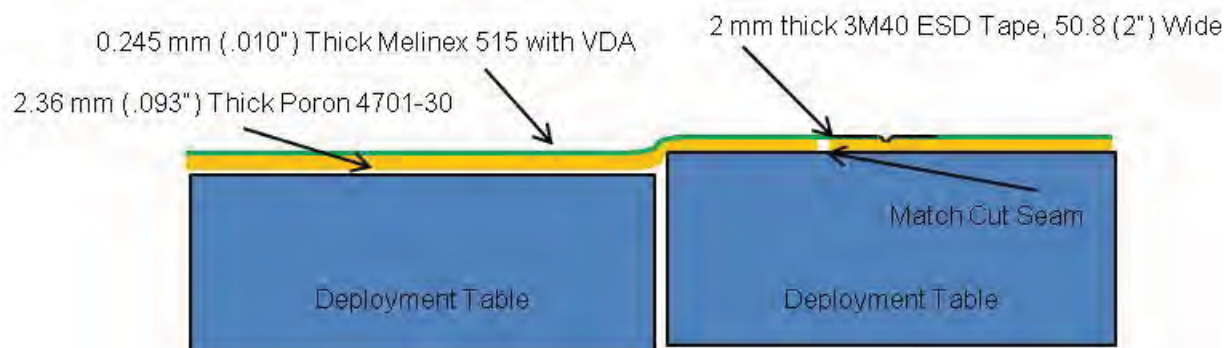
In order to replace the hard layer of vinyl, another material was chosen to place on top of the Poron 4701-30. The material was a 0.254-mm (0.010-in) thick layer of Melinex 515. This material was selected because it could be supplied with a vapor-deposited aluminum (VDA) coating that dissipated the electro-static charge created by the air pads. The combination of these two materials provided a unique solution of soft and hard material properties to properly absorb floor imperfections while simultaneously being able to support the air pads.

Each material was ordered and delivered in factory available sheet sizes. In order to lay out each material on the table, the factory rolls needed to be cut into specific sizes and shapes and placed side by side to fit the table. This was done offline. Once the materials were cleaned and rolled for transport into the cleanroom assembly began.

The cut Poron 4701-30 strips were laid out such that their seams did not overlap the table seams. The Melinex 515 strips were then laid out such that their seams did not overlap the Poron 4701-30 seams. The Melinex 515 seams were then taped using 3M40 tape to prevent air pressure from lifting the strips between the seams. The 3M40 tape was chosen because it has the benefit of dissipating electrostatic build up between any seams of the Melinex 515 or defects in the material. It should be noted that the Poron 4701-30 strips were not taped between the seams to prevent tearing due to the fragility of the material. The layout can be seen in Figure 19.



**Figure 19. Air Pad Gliding on Melinex 515 and Poron 4701-30**



**Figure 20. G-Negation Table Layers**

The finished solar array flooring product is a 20 x 25 foot surface made up of thirteen 8 x 4 foot tables. The tables are first covered by 2.36-mm (0.093-in) thick Poron 4701-30 foam and then topped by 0.254-mm (0.010-in) thick Melinex 515 coated with vapor deposited aluminum and taped together with 2-mm-thick 3M40 ESD tape.



**Figure 21. G-negation Table with Melinex 515 and Poron 4701-30**

Figure 21 shows the completed solar array deployment table surface. The picture portrays the surface such that bubble effects can be seen, however these are an optical illusion due to the reflectivity of the VDA coating on the Melinex 515. Touching the material verifies that there will be no air bubbles in the Poron and Melinex 515 layers once allowed to settle for 24 hours. Minor remaining air bubbles that exist can be pushed out by the test article during testing.

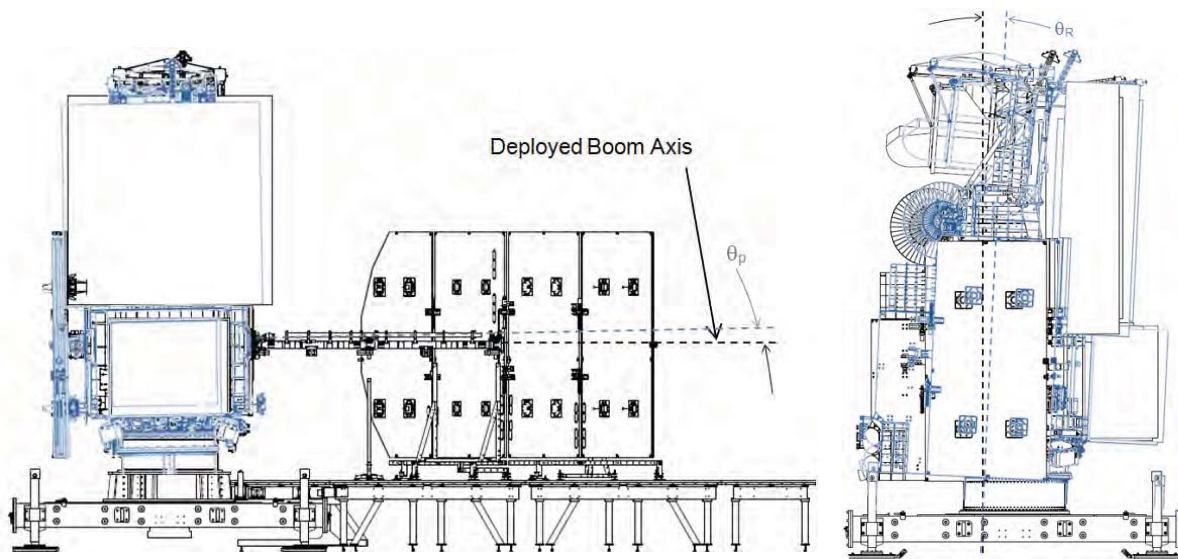
Overall this solution for g-negation worked very well for the largest rigid solar array system built at Goddard Space Flight Center.

### **G-Negation Deployment System Installation Challenges**

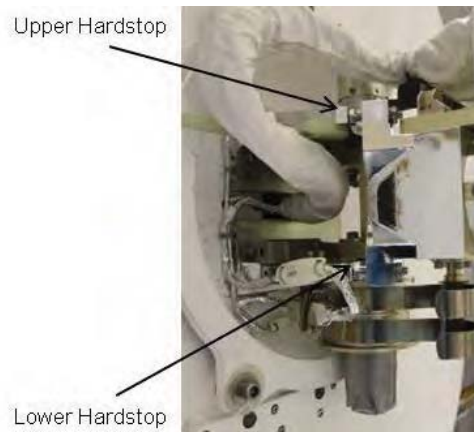
While the initial development testing of the air pad system was successful of supporting a higher mass than required, careful implementation of the system with the Solar Arrays was necessary to achieve required performance. The two characteristics used to assess the performance of the solar array deployment system are the total deployment time and deployment path. The deployment time and path varied with characteristics of the g-negation installation specifically in the areas of hose routing and the dolly alignment to the g-negation tables.

During initial testing of the solar array design while working on the protoflight boom assembly, it was found that the deployment time varied greatly with changes in the pitch angle,  $\theta_p$ , between the deployed boom axis and the deployment tables. Initial testing showed any angle outside  $-0.10^\circ$  to  $+0.10^\circ$ , at the shoulder hinge, produced deployments that were longer than expected. Likewise, small changes in the roll angle,  $\theta_R$ , of the shoulder hinge provided variable deployment paths.

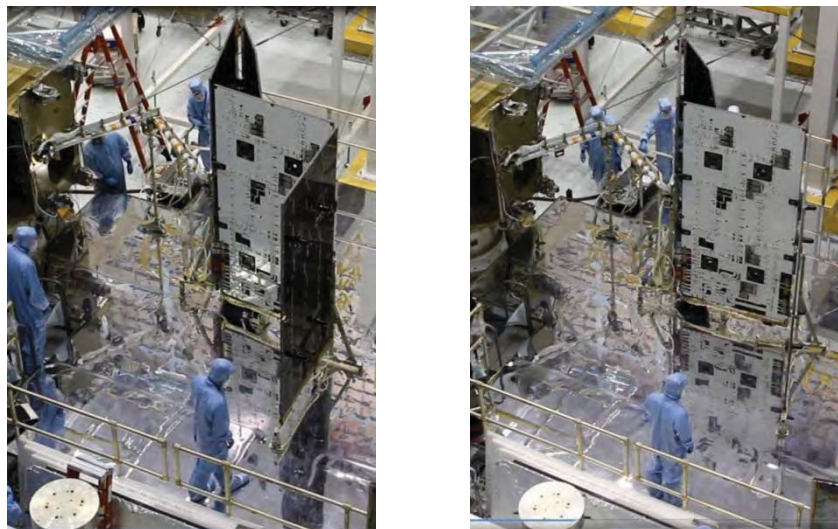
The offset in pitch was evident upon visual inspection of the boom hardstops after the deployment finished. A gap at the upper hardstop and contact at the lower hardstop indicates that the pitch angle is greater than zero and the array is attempting to deploy against gravity. A gap at the lower hardstop and contact at the upper hardstop indicates a pitch angle less than zero and that the array is attempting to deploy into the g-negation tables and binding the air pads. Adjusting the pitch angle within  $\pm 0.10^\circ$ , and as close to zero as possible, closed the gap at the hardstops and provided a significantly faster deployment.



**Figure 22. Definition of Pitch, Left, and Roll, Right.**



**Figure 23. Dual Hardstop Design of Boom Hinges**



**Figure 24. Excessive roll angle (left), No roll angle (right)**

Likewise, small changes in the roll angle,  $\theta_R$ , of the shoulder hinge provided variable deployment paths. This was evident during the -Y Solar Array's post-vibe deployments. The deployment dolly was inadvertently misaligned and the post-vibe deployment took a much different path than the pre-vibe deployment, resulting in a stalled deployment on a highly warped g-negation table that was specifically placed in a spot where we did not expect the deployment to reach based on pre-vibe results. In Figure 24, at the identical time in deployment, the different deployment trajectories can be seen. With  $\theta_R$  being out of spec by approximately  $\pm 0.10^\circ$ , we can see that the wing is not deployed as much as in the case with less or virtually no roll angle. This deployment with excessive roll angle continues on a path uncharacteristic of the expected deployment. To adjust for pitch and roll, the dolly jacks at each corner of the spacecraft dolly were manipulated.



**Figure 25. Roll Angle Measurement at the Shoulder Hinge**

To achieve an optimal setup for a post-vibe deployment, the pitch and roll angles were measured and adjusted closest to the deployment root hinge, the shoulder hinge, while the arrays were stowed. Figure 25 shows the location that we could measure directly on the shoulder hinge to assess roll. Due to the tight packaging of the stowed array, the closest area we could measure pitch was across the two solar array booms between the Shoulder Hinge and the Elbow Hinge, as seen in Figure 26. A Digi-pas brand 2-axis precision digital level with an accuracy of  $0.01^\circ$  was used for these measurements.



**Figure 26. Pitch Angle Measurement on Deployment Boom**

The air hose configuration of the g-negation system, as seen in Figure 27, is nebulous in design and was photographed repeatedly from different vantage points to achieve a repeatable system. Slight changes in the air routing had the same effects as slight changes in the pitch and roll angle with respect to changing the deployment path and deployment time by generating friction at points in the system different from the desired baseline.

By keeping accurate records of the pitch and roll angles as well as the g-negation hose routing, the solar array deployment times and deployment paths were in family. Telemetry graphs from the +Y Solar Array Wing observatory level pre-vibe and pre-ship deployments, illustrated in Figure 28 and Figure 29, show only a 3 second difference in deployment time, a 2.91% difference, and similar angular velocity characteristics between these two different deployment setups performed 3 months apart

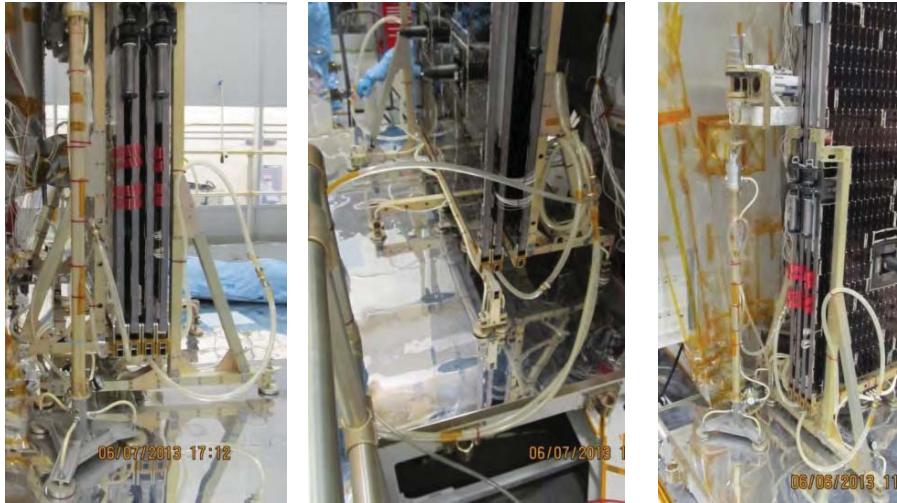


Figure 27. G-negation hose routing documentation

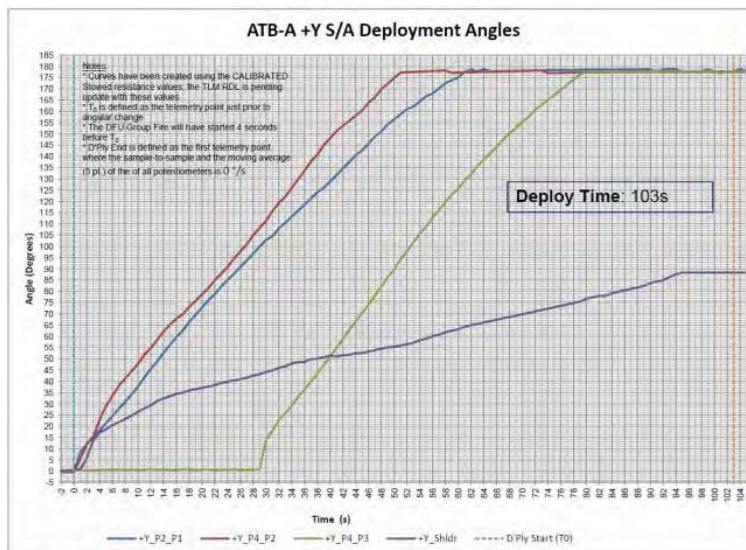


Figure 28. Pre Vibe +Y Wing Deployment Telemetry Comparison, +Y Wing

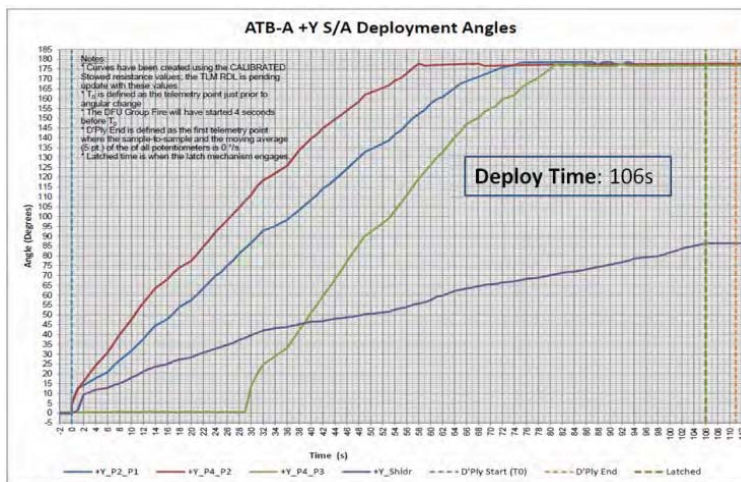


Figure 29. Pre-Ship +Y Wing Deployment Telemetry Comparison

## Ability to Perform First Mode Fundamental Frequency Verification

One of the advantages of the air pad system was that it accommodated first mode frequency verification testing. The Qual -Y Solar Array Wing was configured in the deployed position and a direct measurement of the frequency was able to be performed by placing and releasing side load and examining the oscillating motion of the wing while supported by the airpads. Since the airpads induce almost zero friction and the measured value was found to be close to the predict, the analytical model was verified showing that the Solar Array meets its frequency requirement (Rivera). This test method was found to be more straightforward than others that required suspending the solar array from a cord and performing a twang test as has been used for other projects (Jiang and Gahart).

## Conclusion

In summary, many challenges were overcome developing a system to g-negate the GPM Solar Array Wings so that their ability to deploy once in orbit could be adequately verified. It was decided to implement heritage design air pads even though this type of system had only been used for solar array wings much smaller than those of GPM at NASA GSFC. During this process, it was verified that the facility being used had sufficient air flow and the air pads were optimized to carry the required load. A new support structure was designed in order to capture GSE points on the panels to prevent tipping and allow movement along a flat table surface with the use of air pads. Testing of this design with mass models and full-size mock-ups made it clear that the deployment tables being used, inherited from previous projects, provided an insufficient surface for deployment due to warping of the table top from previous use. Also, difficulties associated with aligning the large array of tables proved inadequate to accommodate the Solar Array's full deployment path. Creative solutions were adopted first to align and provide a surface cover to adequately improve the table surface to allow the Solar Array Wing to deploy. Solutions were also found to modify the table covering to work in the clean room and to dissipating electrostatic charge due to flow from the air pads. Once the table and surface cover solutions were found, additional testing of Solar Array deployments revealed the sensitivity to both the alignment of the wing in pitch and roll and to the air hose routing. Because of these sensitivities, techniques were developed to normalize these parameters. Finally, it was found that this g-negation system was well suited to support first mode fundamental frequency testing. The result of the work involved in developing this system was that the GPM Solar Array Wings were successfully verified through multiple deployment tests while installed to the flight Spacecraft.

## References

1. Rivera, Alejandro, *GPM-SADDS-RPT-0144 - Solar Array Fundamental Frequency Test Results*, <https://gpmmis.nasa.gov/> (accessed 1/8/2014)
2. Jiang and Gahart, *Analysis and Modal Survey Test of Intelsat VIIA Deployed Solar Array*, <http://web.mscsoftware.com/support/library/conf/wuc94/p02794.pdf> (accessed 1/8/2014)

Contributors: Majdi Mukhar, Mike Mutaku, Dick McBirney, Jenny Xu, Robbie Robinson, John Tota, Andrew Scharmann, Chris Matthews, Nick Kwiatkowski, Gary Sheridan, Rodger Farley