DELAYED RELEASES ON ORBIT – ONE SOLVED, ONE NOT SOLVED

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1.0 ABSTRACT

As mechanism engineers, we design with significant margins such that we will not be surprised by unknowns on orbit. However, this time we did design to large margins, tested extensively, and yet on this satellite two mechanisms had several delayed deployments, some for months. After investigations of the issues, while both were mitigated for future flights, only one of the likely root causes the delayed deployments was determined.

2.0 OVERALL DESIGN DESCRIPTION

The solar array wing consists of five panels that are held to spacecraft via cables through the panels at 8 locations to a pyrotechnic release mechanism. It is deployed by independently damped, spring-driven hingelines. The panels are approximately 1.9 m x 3.7 m. There are two solar array wings per spacecraft – one on the north side and one on the south. This constellation of satellites added a couple attachments to the wings. The wing has fixed Thermal Shields attached to three panels, and Trim Tabs for momentum control on each panel (Fig. 1).

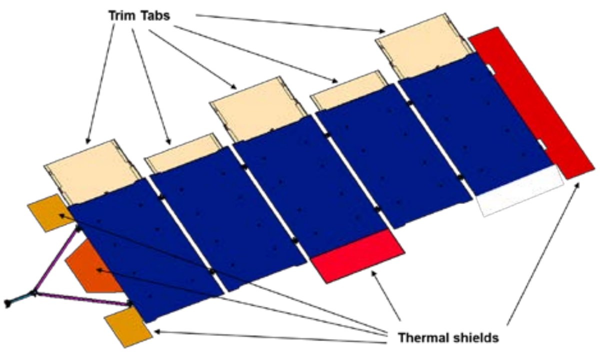

Figure 1. Solar Array Wing Design Schematic

Three Trim Tabs deploy and two are fixed. These are thin sails, folded in half held for launch with a Frangibolt® release mechanism, and deployed with a simple strut hinge [1]. The Kapton® sail membrane is held between two tubes with a crossbeam to connect them to each other and to the release mechanism (Fig. 2). Satellites sometimes incorporate Trim Tabs to use solar radiation pressure to generate torque to balance other disturbances in order to minimize the need for active momentum management from thrusters or magnetic dipoles [2].

Figure 2. Trim Tab in Stowed Position

3.0 TEST PROGRAMS

The primary deployment mechanism for the solar array wing are the hinges, and thus the hinges are tested most extensively. Resistive torques from the wire harnesses are measured in qualification testing and torque margins (>200%) are confirmed in each hinge acceptance test by measuring torque vs angle. Each flight hinge is tested to confirm acceptable spring torque, friction, and performance following vibration and thermal vacuum testing. Since the hinges are tested at component level, and the true flight deployment envelope is proven by a Monte Carlo deployment analysis, the deployment test at the solar array wing level (without Trim Tabs) and at initial and final vehicle installation (with Trim Tabs) is a demonstration that there are no unknown interactions or major issues with the deployment – at ambient conditions. After completion of spacecraft dynamics testing, the wings are offloaded to simulate micro-gravity environments, are commanded to release its shear tie hold downs and allowed to deploy to verify release will occur on orbit – however, again at ambient conditions and focused on the motion of the first panel away from the vehicle which as we will see are key factors in this investigation.

The Trim Tab mechanism is also fully analyzed and tested. Each strut hinge has a torque test (hysteresis loop for torque and friction), the assembled Deployable Trim Tabs are tested at ambient conditions for timed deployment, sine vibration, thermal vacuum timed deployment at -60°C and +85°C (Fig. 3), and a final ambient manual release timed deployment.

Figure 3. Trim Tab Thermal Vacuum Deployment

Once the Trim Tab is mounted on the solar array wing, there is an ambient first motion demonstration, and then on the vehicle a full deployment after the vehicle acoustic test. These deployments are not as insightful as gravity is assisting deployment on one wing and retarding deployment on the other. Post vehicle acoustic test there is yet another timed deployment of the Trim Tab offloaded with the hingeline vertical in the Thermal Vacuum Deployment fixture.

4.0 TRIM TAB DEPLOYMENT

The Trim Tabs were envisioned to be a simple deployment – a single release device to set in motion the strut hinges for a 180° motion of the sail. There is little internal friction in the hinge as they are flexures, no harness resistance and only the bending resistance of the membrane, a kickoff spring to ensure first motion, and a resulting torque margin of greater than 1600% (16X worst case resistance). What could possibly go wrong?

4.1 Flight Observations & Initial Fix

On Flight 1, after the wings were deployed and the commands were given to release the Trim Tabs. Nothing. Indications from inertial measurement unit did not occur or were not detectable and over the next several days the expected change in momentum build up did not happen. All the Trim Tabs did deploy, one by one, from 10 days to 298 days from the commanded release. Flight 2 was in final configuration for launch and the same design flew with the same result of deployments from right away to more than 200 days.

The Trim Tab release assembly is shown in Fig. 4, where the sail deploys “into” the page. The notched bolt of the Frangibolt® breaks, allowing the bracket that is attached to the sail crossbeam to slide off and deploy. The kickoff spring initially aids that motion.

Figure 4. Trim Tab Release Mechanism

In studying the high speed video of the Trim Tab tests, it was noticed that the initial motion of the outboard sail is actually “up” and "right" as well as “into” the page as looking at Fig. 4. This is due to the strut hinges being preloaded slightly in the "down" direction and the Frangibolt® fastener providing energy from fracturing in the "right" direction. The strut hinges when stowed are compliant and provide little resistance to this motion. With that motion, the bracket could conceivably strike one of the fasteners holding the kickoff spring (for instance, the ‘top’ one of Fig. 5).

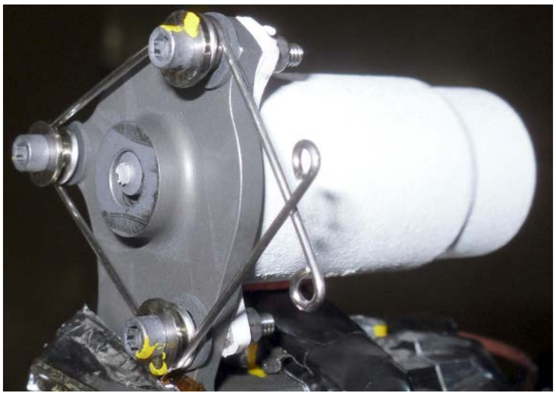

Figure 5. Trim Tab Flight 1 Kickoff Spring

The shock of the bolt fracture to release imparts energy into the bracket and crossbeam. There is little to no force to generate friction between the crossbeam bracket and the Frangibolt® bracket, and the bumpers (Fig. 2) mitigate any sticking of the sail to the panel. So the requirement for the kickoff spring force is little to none. Thus, the design was changed to remove the possible bolt that could cause interference by taking out half of the kickoff spring (Fig. 6). Problem solved – well, until Flight 3 when once again the Trim Tabs were commanded to deploy and nothing happened.

Figure 6. The "Fixed" Kickoff Spring

4.2 Root Cause Investigation

There were several observations that needed to be explained.

- The Trim Tabs are delayed, not permanently stuck
- The deployments appear normal once they release
- The Trim Tabs perform as expected once deployed
- The sails must be stuck nearly stowed or there would be nothing to interact with
- The delayed deployment has occurred on all Trim Tabs regardless of the location on the vehicle.
- Temperature does not seem to be a factor

Why were these releases delayed? The team put together 68 possible explanations and investigated if any were likely cause and could fit the observables. All the Trim Tabs eventually deployed, so there was no structural or release mechanism failure. Because this behavior was consistent with all the units it was not related to something unique like a workmanship defect or contamination. Some deployed almost immediately, some months later so deployments are not correlated with a vehicle motion or a season. Some deployed while vehicle was in eclipse, some while in the sun. Temperatures when they deploy are in the mid-range of acceptance testing. It also must be something that happened on 18 of 18 units! A few of the theories are highlighted below.

Frangibolt® - The Frangibolt® bolt was fractured when commanded as we know it did eventually deploy and the thermal environment after the command was not hot enough to cause it to self actuate. There was only one time the current was applied to the Frangibolt®. The bolt fractured at the notch as designed. Any other anomalous failure modes such as a nut thread failure would not allow the Trim Tab to deploy. Because it was evident that the Frangibolt® system worked as intended this eliminated the release device, both mechanically and electrically, as the cause.

Sail – The sail itself is not taut during launch but rather billows and flaps. This allows almost 10 cm (4 in) of 'sag' by design to accommodate thermal expansion mismatch. The sail does become flat and tight if thermal conditions are right (cold). Could the sail snag onto the solar array panel, and then somehow release later, and do this on every unit? Not likely. By design, the area on the panels adjacent to the trim tabs were left bare.

Misalignment or thermal distortion – Maybe by design the Trim Tab is installed misaligned and requires time, thermal cycling or some other phenomena to release. The Trim Tab qualification unit was deployed in "distorted" configurations to evaluate the sensitivity. The mounting feet of the strut hinge were angled "toe in" and "toe-out", and the mounting surfaces were changed "left high" and "right high". The compliance of the Trim Tab frame is different than many mechanisms. While creating more possibility for interaction with the adjacent structures, it also didn't allow any significant load transfer. As a result, even with the induced distortions, the compliance in the hinges and frame accommodated the deflection. No change in the deployment dynamics was detected during testing with induced distortions.

Electrostatic Charge – The Trim Tab sails are two large surfaces in contact with each other that need to separate. Due to on-orbit radiation and potential for charge build-up, a voltage differential may be created between the Trim Tab sail adjacent surfaces, or the Trim Tab sail and the backside of the solar array panel. If the differential is sufficient in magnitude and duration, an attractive force may result which would prevent Trim Tabs from deploying. Simplified calculations show that a voltage differential between surfaces is possible. While the grounding was sufficient to mitigate primary electrostatic events, there is still some resistance and therefore possible voltage differences. Regardless of theoretical differential, actual charging environments exist very infrequently and charging dissipates within minutes. Although it may be possible to have attractive forces between charged surfaces such as between the sail and panel, the environment is fleeting and charges dissipate immediately such that delayed deployments spanning months are not credible. To further test this theory, an on-orbit maneuver was executed to test this hypothesis. The sun was pointed towards the back of the solar array wing, neutralizing any potentially built-up charge. No further Trim Tabs deployed during this maneuver.

Strut Hinge Cold Welding – The strut hinge consists of four laminates of beryllium copper in close contact. If this contact in vacuum and vibration made the materials cold weld temporarily, maybe the deployment would be delayed. While some data exists for copper-copper interaction, none could be found for BeCu. A worst case engineering test was done instead. Strut laminates were cleaned and assembled into a stack using screws to clamp the ends as in flight. The laminate assembly was "stowed" and a vice grips were used to apply clamping force to provide a normal force to generate friction and worst-case cold welding (Fig. 7). The laminate assembly was released and the deployment was normal.

Figure 7. Clamped Strut Hinge Test

Fractured Frangibolt® Snag – The Frangibolt® bolt fractures and of course leaves a rough surface. The actuator expands 0.75 mm (0.030 in) when activated generating a gap at the fracture to preclude interaction. The bolt fracture releases strain energy that drives the two halves apart, but possibly the motion of the sail is not fast enough and the bracket comes back into contact. Nominal dimensional analysis shows that there is an interference fit of 0.1 mm (0.004 in) between the Trim Tab Frangibolt® bracket and the Frangibolt® so it would seemingly want to come back into contact. Forcibly putting the hardware into this configuration is shown in Fig. 8.

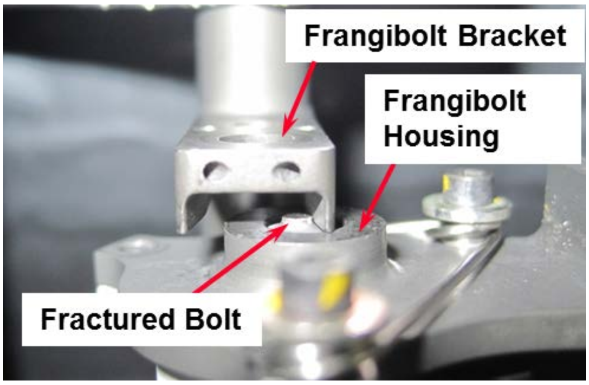

Figure 8. Possible Bolt Snag

Calculating the normal force onto the bolt shows that it is not enough to generate a friction force large enough to stall the hinge. One might imagine that a rough surface could contribute to a higher friction coefficient. Even so, using the measured stiffness with that deflection of 0.1 mm (0.004 inch) results in only 5-mN (0.0012-lb) normal force. With a friction coefficient of 1.0, that is still 100 times less than the deploying force at that point from the strut hinges (0.45 N (0.1 lb)).

Bumpers – Silicone rubber bumpers on the frame prevented the sail from moving relative to the solar array panels when the wing is stowed. Blocking between snubbers and the panels would affect the deployment. However, each bumper has a protective layer of Kapton® film to prevent blocking between silicone rubber and the panels.

Snubbers - The Solar Array Panels have some silicone rubber snubbers on the panel that have Kapton® covers that have edges which could possibly snag against the support scrim on the backside of the sail membrane and delay the deployment. While this may be possible for a single issue, it's not plausible to occur on every unit given that the relative position of the snubber and scrim are random.

4.3 How Addressed

No definitive root cause was able to be identified for the delayed deployments of the Trim Tabs. Four theories were deemed still 'open' in the investigation, but were considered essentially non-credible. While these were possible and could warrant more work, this was a case where the system requirements were re-examined and the deployable Trim Tabs became fixed ones without any significant mission impact.

Two lessons can be taken away from this. While not a strict requirement, it is good design practice to always have the deployable move directly away from the release mechanism – not slide off. Sliding does not use any of the release energy to aid the kickoff, and leaves the release vulnerable to snags when the clearances do not immediately increase upon release. In this case we felt forced to do so due to volume constraints. Another good practice that was not a strict requirement was for the kickoff spring to be actively engaged until the deployable was completely clear of all other hardware. A strong kickoff spring with a stroke long enough to push the compliant sail completely away from the release mechanism certainly may have helped in this case. A further lesson is that in the case where the kickoff spring is pushing against a compliant piece, the stroke must be even longer to ensure clearance.

5.0 SOLAR ARRAY PANEL DEPLOYMENT

The rigid solar array panel design including the release and deployment mechanisms is the standard design (with a couple attachments along for the ride) that had been used on more than 30 satellites. What could possibly go wrong?

5.1 Flight Observations & Initial Fix

After the deployment command for the solar array wings on Flight 1, the north solar array wing was producing 80% of the expected current while the south array wing was performing normally. The wings were then commanded to slew to such that they were in sync, and while doing so the north wing current increased to the expected nominal value.

An investigation ensued, and it was found in pre-flight photos that ground wire for the Thermal Shield had a larger than expected loop. This loop could snag on one of several items on the back of the solar panel in some temporary fashion such that slewing would cause it to free allowing the final deployment to take place.

Flight 2 solar array deployment was nominal so problem was thought to be solved.

On Flight 3, once again the north wing is producing 80% of the current as the other wing. After initial deployment, the arrays were slewed to be in sync, the final panel motion occurred, and current provided was nominal. Power is of course critical to satellites and a delayed solar array deployment is unacceptable, so another investigation commenced. Another wire snag after so much attention was being paid to ensuring wires were secured seemed highly unlikely. Additionally, we certainly thought that maybe we did not actually know the root cause for the Flight 1 behavior.

5.2 Root Cause Investigation

There were several observations that needed to be explained.

- The panel is delayed, not permanently stuck
- The deployment appears normal once it releases
- There is no permanent damage perceivable from the ground
- The panel seems to be stuck at a shallow angle (<30 degrees from stowed)
- This has only happened on wings with Trim Tabs and large Thermal Shields
- Cold temperatures at deployment seem to be a factor
- The release seems to be related to a rise in temperature
- It is possibly only on the mid-outboard to outboard panels

That last point was the first item that we examined to determine what exactly was stuck. Given only the data that 80% current was generated, the array could be in several configurations. No position sensors are on the hinges. On orbit vehicle and solar panel temperature data, solar cell string data, as well as inertial clues indicated that the first three panels were deployed nominally. The last two panels could be in any of the three configurations shown in Fig. 9. An analysis was done on the deployment dynamics for each of these configurations if they were to release from that point – only Configuration A, the outboard panel not deployed at all, matched the data.

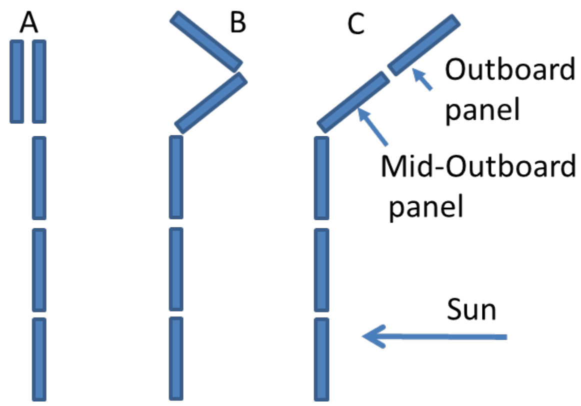

Figure 9. Three Possible Wing Configurations

The team brainstormed 74 possible explanations as to how the last panel could be stuck. None of them provided a credible, likely scenario. It was several weeks later that we thought of the 75th theory which is the likely cause. A few of the failed theories are highlighted below.

Hinges – All hinges on the satellites passed the acceptance testing described in Section 3. No hinge deployment non-conformances during qualification and any acceptance test over hundreds of hinges has ever been a stall mode. Non-conforming hinges, either damaged or mis-assembled, have always deployed without stalling. Even hinges that we once intentionally dropped debris into (to simulate what fell from an overhead crane) deployed nominally!

The resistance due to harnesses was re-examined. The initial harness torque testing had certain configurations and torque is calculated (interpolated/extrapolated) from that data. In order to be sure the correct value was being used, the unique configuration of this satellite's harness was tested and proven to be within family.

All theories for hinges were deemed not credible and did not fit several of the key observations.

Snubbers – Silicone rubber snubbers are bonded to solar array panels such that snubbers from adjacent panels can touch when the wing is stowed. Blocking between snubbers on adjacent panels would affect the deployment. However, each snubber has a protective layer of Kapton® film to prevent blocking between silicone rubber cubes. This satellite has more snubbers between mid-outboard to outboard panels than standard configuration (15 snubbers vs typical 6) to protect against parts that could contact during launch.

The snubbers are constructed with the Kapton® overhanging the edge of the snubber and the adhesive well back from the edge to prevent contamination of the mating surface. Snubbers are inspected regularly for contamination or damage. North and South array snubbers are the same, so difficult to explain why there was no delay with any of the south wings nor a delay on Flight 2. A stuck snubber is likely not to ever release.

Bumper to Bracket – In these types of investigations, the focus is rightfully on items that are different than past successful hardware. In this case, one of those differences is the existence of the Trim Tabs. Multiple Trim Tab theories were deemed non-credible until the bumper to bracket interference was discovered.

In speaking with the responsible engineers, it was realized that the solar array group only felt responsible for the solar panels and their deployment; items added on later like Thermal Shields and Trim Tabs were treated like outside furnished equipment – someone installed them later in the assembly flow and not their problem. One result of this is that the Thermal Shields and Trim Tabs were not in the overall computer solid model nor on the solar array wing assembly drawing. So maybe something we overlooked was interfering.

The Flight 4 north solar array wings was available for inspection. It was examined while deployed, while stowed, and no way to delay deployment was apparent. Then, the deployable Trim Tab from the outboard panel (but without the panel itself so we could see the hardware better) was manually held up against mid-outboard panel to highlight interference locations. These locations were blind when the wing was stowed.

The Trim Tab bumper from the outboard panel lined up the edge of the Trim Tab bracket on the mid-outboard panel (Fig. 10). The bumper is shown in Fig. 2 stowed against the panel. It is a stack of silicone rubber snubber blocks held together with Kapton® tape with a hole such that the sail tube can pass through. These bumpers are not dimensionally measured after the tape was applied; measuring the existing flight hardware still on the ground showed them to average 0.9 mm (0.025) in larger than the drawing requirement.

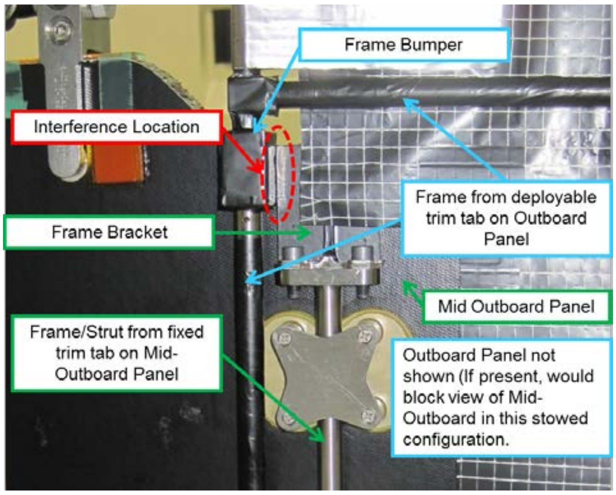

Figure 10. Bumper to Bracket Interference Location

The theory for how these bumpers could cause the delayed deployment and then release is as follows. The Trim Tab crossbeam (Fig. 2) contracts at cold and causes the bumper to conform around the bracket edge that is 1.5-mm (0.060-in) thick. The bumper becomes more rigid at cold, locking around the bracket edge. As the panels warm, the crossbeam expands and the bumper becomes less rigid, and the panel releases.

Due to the very cold temperatures of the crossbeam at the time of commanded deployment (Fig. 11) (note the north wing is colder than the south wing on Flights 1 and 3 due to the season they were launched in and the position on the vehicle), the contraction of the titanium crossbeam is 0.94 mm (0.037 in). The result is a 0.23-mm (0.009-in) interference.

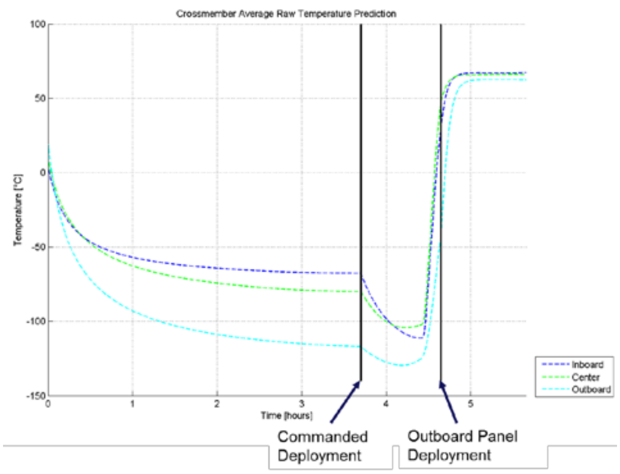

Figure 11. Crossbeam at -120°C when Trying to Deploy

Two sets of tests conducted to determine if that amount of interference could actually hold the panel from deploying. One varied the interference at ambient to measure the resisting force and the next varied the temperature.

Testing of the bumpers at room temperature indicates the load to release the bumper from the bracket increases as the interference increases as one would expect. This load increase, while small, is enough to stall the deployment because the interference occurs at the other end of the panel from the hinge torque, thus a small force at a large moment arm will stall the deployment. The test setup shown in Fig. 12 simulated the bumper-to-bracket interference by constraining a flight-like bumper to a known interference with the bracket and then measuring the force to move the bumper.

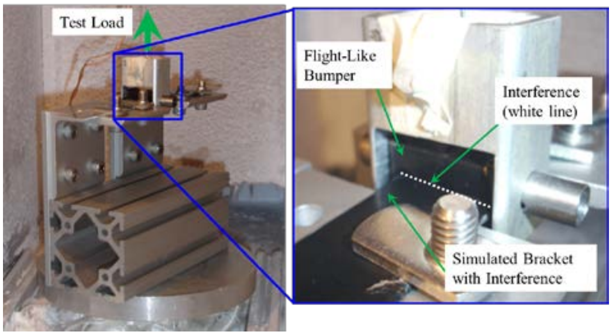

Figure 12. Bumper Interference Test Setup

Testing of the bumpers at a 0.1-mm (0.004-in) interference indicates that the load to release increases with decreasing temperature. At about -70°C the bumper material starts to stiffen. Testing indicates that below -70°C the bumper material at 0.1 mm (0.004-in) interference generates enough force to stall the hingeline. Note on Fig. 11 that the panel released at about -50°C.

Additionally, the Trim Tab frame supporting the bumpers was compliant enough so that the kickoff springs between the panels did not have enough stroke to apply any significant load to this interference. While the compliance in the Trim Tab allowed distortion in the Trim Tab to not impact the Trim Tab deployment, the same compliance did not allow the kickoff springs for the rigid panels to clear the interference.

The interference and cold temperatures on Flight 1 and Flight 3 are sufficient to stall the north outboard panel deployment for a winter launch. The increasing temperatures are enough to release the panel. This fits all key observations:

- The panel is delayed, not permanently stuck – the interference becomes clearance at a certain temperature as the array slews
- The deployment appears normal once it releases – once the bumper releases from the bracket, the hinge provides the usual deployment of the panel
- There is no permanent damage perceivable from the ground - squeezing the bumper does no damage to the solar array panels
- The panel seems to be stuck at a shallow angle (<30 degrees from stowed) – while the hinge would attempt to deploy with the bumper stuck on the bracket, the bending in the system is a small angle consistent with this observation
- This has only happened on wings with Trim Tabs and large Thermal Shields – the Trim Tab bumpers and bracket obviously only exist on these arrays
- Cold temperatures at deployment seem to be a factor – the cold temperature of the crossbeam contracts it to create the interference.
- The release seems to be related to a rise in temperature – as the crossbeam warms (Fig. 11) and lengthens back toward its dimension at ambient, and as the rubber softens, there comes a point where there is enough clearance for deployment
- It is possibly only on the mid-outboard to outboard panels – the outboard panel and crossbeam are colder by more than 40°C than the other panels. These cold temperatures only occurred on the north outboard panel during a winter deployment.

5.3 How Addressed

The fixed Trim Tab does not have this interference as the bumper in question was only used to restrain the deployable portion of the Trim Tab and therefore the likely cause was eliminated from the design. Even so, the critical clearance checklist was updated for more detailed examination of the solar array panels.

6.0 SUMMARY

The root cause of the Trim Tab delayed releases remains a mystery. With re-examination and relaxation of requirements, the problem went away by eliminating the mechanism. Detailed lessons were discussed in previous sections with an overall caution that mechanisms standards have many statements that are “should” that one needs to pay close attention to. They are there for a reason.

The likely root cause of the delayed solar panel deployment was determined and due to the Trim Tab change the fix applied to future spacecraft. Solar array wing deployments on the next flight were nominal. An overall lesson is that many times mechanism designers are assigned the task for individual deployment devices yet they need to pay attention to and apply the same rigor of design to the overall appendage as well.

Figure 13. Satellite Prepped for Successful Launch

7.0 REFERENCES

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