BIOGRAPHICAL SKETCH

Title of Paper:

Landsat 7 Solar Array Testing Experiences

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Presenter's Background:

1983 BS, Mechanical Engineering, University of Maryland, College Park, MD
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Prior to Landsat 7, provided mechanical engineering support for earth and space science missions at Goddard Space Flight Center, since 1987, including stints on Hubble Space Telescope Servicing Mission 1 and EOS Terra.

On Landsat 7, was the lead Mechanical Systems Engineer from early 1994 through it's launch in April 1999, a little over 5 years.

Led the in-house transportation team through delivery of Landsat 7 via Air Force C5A cargo transport to Vandenberg AFB, California in January 1999.

Following the success of Landsat 7, have been co-located with the EOS-Chemistry project for the last 12 months.

Landsat 7 Solar Array Testing Experiences

Daniel Helfrich*

Abstract

This paper covers the extensive Landsat 7 solar array flight qualification testing effort. Details of the mechanical design of the solar array and its retention/release system are presented. A testing chronology is provided beginning with the onset of problems encountered at the subsystem level and carrying through the third and final powered-spacecraft ground deployment test. Design fixes and other changes are explained in the same order as they became necessary to flight-qualify the array. Some interesting lessons learned are included along with key references.

Introduction

The Landsat 7 Spacecraft

Landsat 7 (L7), depicted below in figure 1, was launched in April of 1999 into a 705 km sun-synchronous orbit. A single, huge, visible/infrared imager called the Enhanced Thematic Mapper Plus (ETM+) is the sole L7 instrument, occupying the entire forward (–Y) end of the spacecraft. ETM+ provides land and near-shore ocean imagery down to 15 meter resolution for a very diverse user community. The spacecraft was built under NASA contract NAS5-32633 by Lockheed Martin Missiles and Space (LMMS), previously a part of the General Electric Corporation, located in Valley Forge, PA. A comprehensive description of the spacecraft and its mission is available on the web at URL: http://landsat.gsfc.nasa.gov.

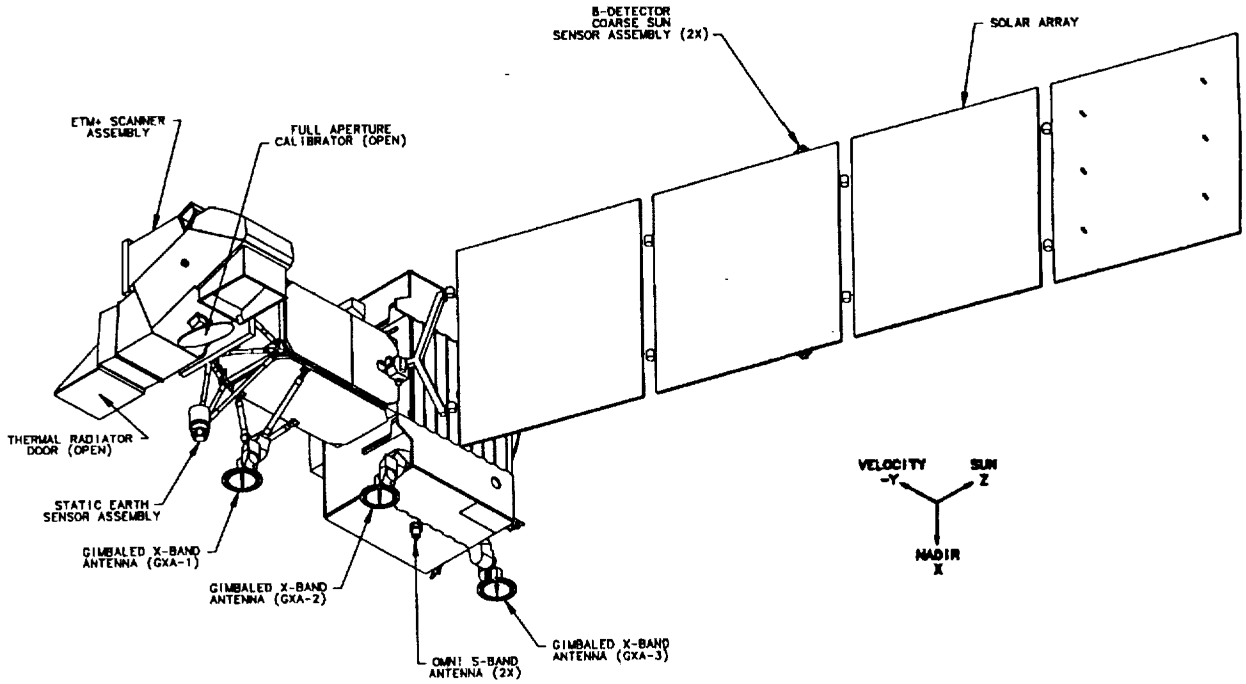

Figure 1. Landsat 7 Spacecraft and Fully Deployed Solar Array

The L7 Solar Array

The L7 solar array (S/A) is an assembly of four rigid aluminum honeycomb panels and an aluminum yoke with a total length of 8.5 m (335 in). Each 25 mm (1 in) thick panel weighs approximately 22 kg (50 lbm) and is 2.27 m (89.3 in) tall and 1.88 m (74 in) wide. At CDR, the end of life power requirement with one

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lost string at the least favorable beta angle was 1658 W. (Shortly after launch, the output was determined to be 2252 W at 32.9 Vdc.) Each hinge line latches into place at full rotation. Analytical models of the array predicted a first resonant mode of 0.232 Hz.

As can be seen in Figure 1, there are two hinge fittings per hinge line. Negator springs integral to the solar array's hinge fittings drive the deployment. The hinges all operate independently. Deployment time was originally specified to take no longer than 120 seconds with one hinge spring failed. The most recent analysis showed that the final design provided a nominal deployment time of 30 seconds and deployment in 67 seconds in the worst case single hinge spring failure. The solar array was fully tested at the factory and shipped in the stowed configuration for final spacecraft processing at Vandenberg Air Force Base, demonstrating one aspect of the "ship and shoot" philosophy.

Solar Array Restraint/Release System

The S/A Restraint/Release System (RRS) held the four solar array panels tightly against the side of the spacecraft for launch. Cables passing through the panels within cup-cone fittings in the four panels squeeze the panels together to prevent gapping of the panels during launch. Once on-orbit, pyrotechnic cable cutters inside the spacecraft are fired in pairs, releasing the four panels all at once after the final pair of cables is cut. Friction is used in the RRS to dissipate the released energy of the cut cables. Getting this friction just right in this shock absorbing device became something of a small research project, the details of which may be found in the referenced LMMS documentation.

Ground Support Equipment for the S/A

The Mechanical Ground Support Equipment (MGSE) of greater interest is the g-negation deployment hardware which included these key items:

1. a deployment surface, which in the beginning, at least, was a poured epoxy floor,
2. four solar array supports stands, each on a set of four air pads, for a total of 16 air pads, and
3. a solar array mounting interface simulator mounted on a three-axis positioner.

The three-axis positioner was to become very useful as the need arose for unexpected test setups. The first two MGSE items are described in greater detail in the following pages.

In the beginning, the deployment of the array was a purely manual operation, requiring no Electrical GSE (EGSE). The EGSE for the solar array deployment testing later on was quite an assemblage consisting of many interconnected spacecraft test control stations. The final solar array deployments were commanded through the spacecraft C&DH system and associated flight harnessing, an important verification test to assure a successful deployment.

Testing Chronology

For the L7 solar array, what originally was a test effort spanning 6-8 months became twice that in duration. Major schedule impacts to the overall program were avoided only because the ETM+ Instrument had suffered its own problems in the power supply that had caused nearly a year-long delay. What follows in this section is just a quick summary of the flight qualification testing efforts. These activities are then more fully described towards the end of this paper.

Assembly of the solar array was accomplished at the LMMS East Windsor plant in New Jersey in the Fall of '97. The deployment MGSE was checked out simultaneously at the LMMS King of Prussia plant near Valley Forge, Pennsylvania. Around that time, operational difficulties with both the unevenness of the deployment floor and the stickiness of the support stand air pads were dismissed by the contractor as negligible. The first full deployment of the array on November 6, 1997--a manual operation before its installation on the spacecraft--suffered as a result. Corrective actions included additional floor smoothing and a changing of the air pads.

On April 28, 1998, the first powered-spacecraft deployment including the firing of live cable cutters was attempted before a large audience. The array released only partially due to RRS problems which had caused insufficient cable pre-load and had resulted in inadequate extraction of some of the cables. The RRS was manually released after a full inspection of the failed hardware, allowing numerous failed manual deployment attempts several days later which demonstrated the epoxy floor was still a problem. Individual hinge lines were tested on a granite table within a week just to show those components were working properly and wouldn't need to be reworked. More corrective actions on the RRS and the deployment MGSE were also implemented as part of a multi-facetted failure recovery effort.

With many issues from the April deployment failure closed, on August 24, 1998, the solar array was successfully deployed off the spacecraft and became fully qualified for flight. But that test revealed yet another flaw in the shock absorber mechanism, requiring even more testing on the bench and a third pyrotechnic deployment on December 8, 1998. This final full deployment was completely nominal and laid to rest the remaining concerns about the design of the RRS.

Landsat 7 Solar Array Restraint/Release System

General Characteristics

The S/A used on L7 had six stainless steel wire cables to restrain it to the spacecraft; each cable is chopped into two pieces by pyrotechnically driven cable cutters. Each cable was really a custom assembly, fabricated by Brown & Perkins, Inc., consisting of two different threaded end fittings swaged onto a 7/32" diameter, 7x16 wire rope cable.

The pyrotechnic cable cutter used in the RRS is a Hi-Shear Corporation product specifically built and tested for LMMS. It has been used on numerous programs within the US. An explosive charge drives a chisel into an anvil within a cylindrical housing 19 mm (0.75 in) in diameter. It was also used on the 5/32" diameter restraint cables in L7's three (3) X-band antenna gimbals. In both applications, two cutters are provided for each cable; the second, redundant, outboard cutter is the backup if the first cutter fails to fire.

Figure 2 shows the RRS hardware in cross-section. Unlabeled on the right (outboard) side of the figure are the four solar array panels and the cup-cone fittings through which the cable fits. The assembly on the left of those four panels mounts with four bolts to the inside of the body of the spacecraft, the edge of which is approximated by the heavy dashed line.

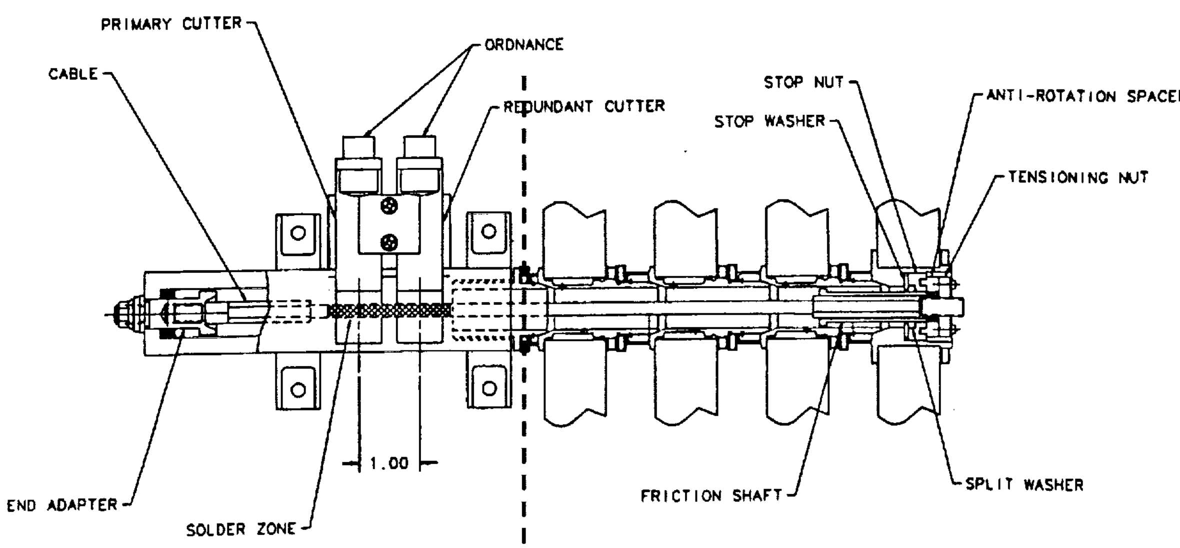


Figure 2. Cross-sectional view of Restraint/Release System

Functional Details

Figure 3 depicts the functional design of the shock absorber mechanism. At the moment of cutting, substantial strain energy is released and the outer portion of the cut cable shoots rapidly outwards. In fact, adequate pre-load in the cable is essential for this self-extraction of the cable. But the cable must remain constrained to the outer panel to prevent the cable from flying away into space and becoming orbital debris. At least 25 mm (1 in) of travel is required.

Friction is used to dissipate the kinetic energy of the cable so it won't deliver a large shock pulse to the outer panel at the end of the cable's travel through the panel fitting. Enough shock in the outer panel could cause the silicon solar cells mounted out there to crack and thereby degrade the power output of the solar array. Friction between the cable fitting's *friction shaft* and a *split washer* captured in the outer panel dissipates the energy released when the *cable* is chopped by the *primary cutter* and the preload is suddenly released.

Full travel is important to the overall reliability of the RRS. Without full travel, the splayed end of the cut cable will remain in the path of the *redundant cable cutter*. In such a situation, firing the redundant cutter can entrap the cable and prevent the array from releasing. This very problem arose during the failed powered spacecraft deployment attempted in April 1998. Firing some of the redundant cable cutters before all the primary cutters had been fired entrapped several already cut cables and prevented the deployment from proceeding normally. This firing sequence was subsequently revised for flight.

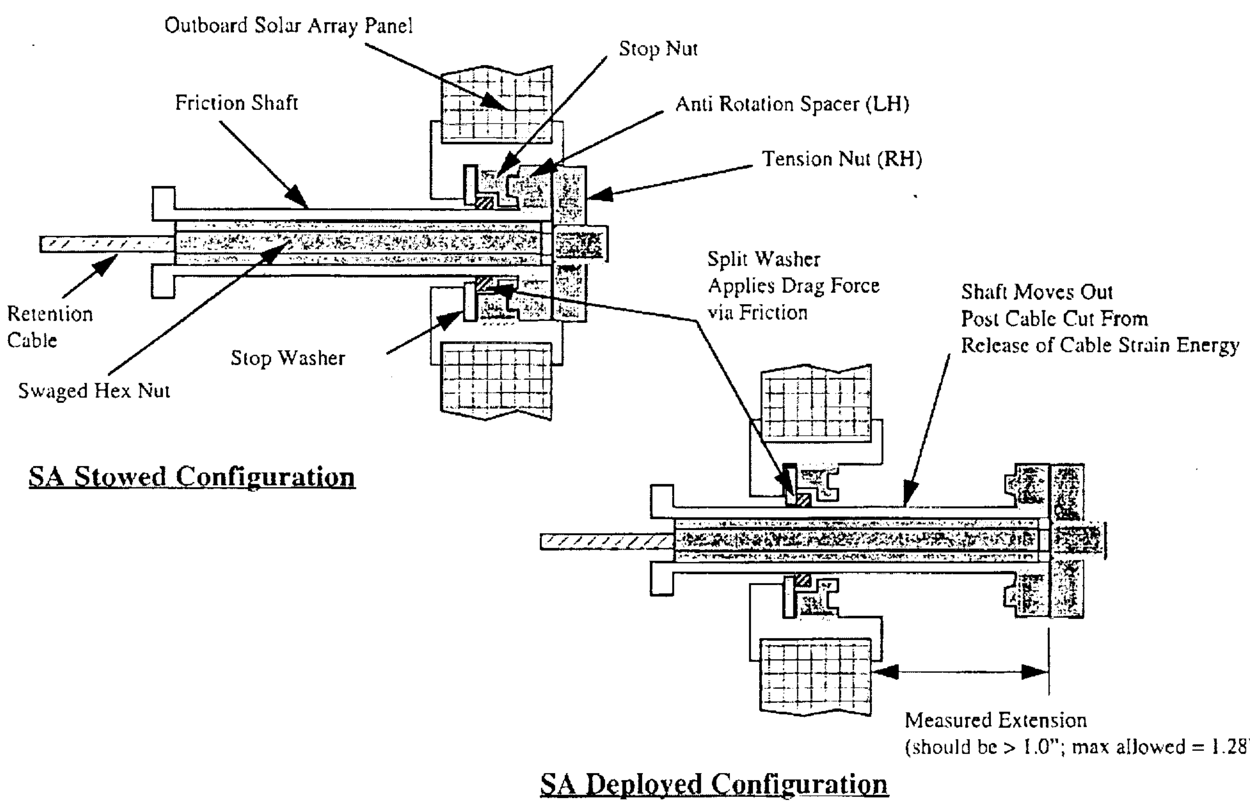


Figure 3. Shock Absorber Functional Diagram

Design Heritage and Intentional Adjustments

The RRS used on L7 has been used in a variety of configurations for GPS, Landsat 6, A2100, and other LMMS-built spacecraft with rigid panel solar arrays. Parameters which are intentionally adjusted include the restraint cable tension and diameter, the orientation and firing sequence of the pyro-cutters, and the material and dimensions of the split washer and sleeve. For Landsat 7, launch vehicle design loads drove the RRS cable tension high enough to require a cable diameter of 7/32 inches. To compensate for the additional strain energy stored in the system, the end fitting was designed with tighter clearances--and a resulting higher friction--to dissipate the greater kinetic energy.

The functionality of the RRS was actually modified for Landsat 7 in two ways, both of which contributed to the initial deployment failure. First, the frictional drag force in the shock absorber was raised too high by the selection of tighter dimensions. Bench testing early on showed the higher friction prevented end of travel shock, but it was not realized at that time that full travel was a desirable aspect of the design, so that wasn't a bench test pass/fail criteria. Second, the firing sequence was modified for what seemed like a good reason: to address a concern of panel racking in case one of the corner cables was not cut by the primary cutters.

So the firing of the primary cutters on the two central cables was purposefully sequenced AFTER both the primary and redundant cutters were fired on the four corner cables. Ironically, this sequence helped reveal two part fabrication problems in the RRS which otherwise probably would have been overlooked. The firing of the corner redundant cutters entrapped the inadequately extracted cables before they had a chance to pull out of the way, which probably would have happened if only the last pair of primary cutters had been fired first. After these shortcomings were discovered, it was back to the bench for design changes and re-qualification tests at the component level, explained in detail later in this paper.

Deployment MGSE

Deployment Surface

Originally, the L7 deployment surface was a pit in the concrete floor of the LMMS high bay. Self-leveling epoxy was poured into the pit, smoothed out manually, and left to cure. This was put in place several years prior to the actual need date. When the time came to use the deployment floor and difficulties arose, variations over the surface were measured to be as much as +/- 6.4 mm (0.25 in). This may have been in part due to the unwise use of the epoxy floor for temporary storage, but it is not known for certain that an acceptance inspection was performed when the floor was first poured. Subsequent discussions with epoxy vendors revealed the flatness requirements were pushing the limits of the technology.

Support Stands

Each panel moves independently during deployment, so four independent support stands were designed to spread out the weight of the array panels onto four low-friction air pads each. For many years prior to L7, the same square air pad design had been used successfully at LMMS for antenna deployment tests on smooth granite tables. A compressed air leveling system was also designed into the stands to ensure that they worked properly. The stands worked well except that on the epoxy floor, there was enough unevenness in the floor surface to hang up on the corners of the square air pads. Also, small bits of dirt and particulates gathered more easily on the floor, requiring frequent wipedowns to prevent additional air pad hangups.

Air Delivery System

A tricky problem arose later with the air delivery system, consisting of flexible plastic tubing stiff enough to handle compressed air at about 100 psi. It was found that without very careful handling, the tubing could introduce lateral loads into the four floating support stands that were not insignificant. The lateral loads were measured with small force gauges and it was found that only with great care could the effects on the movements of the panels be minimized. In time, it was realized that achieving repeatability was not going to be easy, if not impossible. This problem was never fully resolved.

Solar Array Drive Bearing Protection

Floor flatness and best possible alignments were evaluated by the LMMS stress engineer to determine what loads might be imparted to the duplex bearings in the L7 solar array drive (SAD). It was found that there was a real (worst case) possibility of the bearings being overloaded. To prevent this from happening without making Herculean efforts to level the deployment floor, strain gages were installed on the yoke and calibrated to permit a direct measurement of the forces going into the SAD. (The interpretation of the strain gauge readings became a very difficult task, but eventually the strain data were successfully post-processed and found to be below the limit loads for yielding.)

Initial Solar Array Testing

Initial Bench Testing

Engineering bench tests of the RRS performed in 1997 had two purposes: calibrating the torque required on the cable tensioning nut to achieve proper cable pre-load, and selecting the proper split ring washer for the shock absorber assembly. An Instron machine was used to develop the relationship between nut torque and cable tension. A unique torque was developed for each cable.

A test fixture with a gas actuated separation nut was used repetitively in statistically meaningful tests to determine the proper split washer needed to dissipate the 5.3 kN (1200 lbf) preload that was to be applied with each cable. The test objectives were met, but there were some interesting and important details which were overlooked. No emphasis was placed on demonstrating 1 inch or greater travel of the released cable, and the split washer was not adequately inspected after the test, which would have showed they were yielding due to the excessive interference. In the adaptation of a heritage design to L7, subtle yet critical details were missed that could have easily been documented on the engineering drawings of the heritage design.

Manual Deployments

In October and November of 1997, the solar array was deployed manually prior to installation on the spacecraft. It was soon realized that the slight slopes of the uneven floor had led to lateral forces once the array was deployed out over the floor on the low-friction air pads. The hand-held force gauges were utilized once again to measure the lateral component of the downslope force. Up to 2 N (.44 lbf) was measured in some of the worst locations on the epoxy floor.

At the closest-in hinge line, with a moment arm of several array panel lengths, and multiple panels, the slope-induced torque was an order of magnitude greater than the torques the two hinge springs produced, drastically affecting the deployment paths of the panels and invalidating measurements of deployment time. In fact, the panel assembly clearly deployed downhill into the low spots on the deployment floor. The contours were measured and plotted to gain an understanding of the degree of unevenness of the floor. An attempt at filling the lowest spots on the floor was made using a low viscosity epoxy, but the labor involved was intense and less than a square meter (~10 sq ft) was so treated.

As the array deployed across the floor on its original square air pads, the corners of the air pads would come into contact with the floor as they tried to span small fluctuations in the floor's surface. This caused the assembly to stop repeatably in various locations. Smoothing at these locations was attempted but it became obvious that this would not be practical across the entire floor measuring 4.9 m (16 ft) wide by 9.1 m (30 ft) long. When the problems with the square pads were heard of back at NASA Goddard Space Flight Center, it was suggested that round air pads left over from TRMM spacecraft's solar array deployment testing be employed. The proper fitting adaptations were implemented by Swales Aerospace and the round air pads were added to the support stands in time for the next deployment test.

Major Problems Surface

On April 28, 1998, the first pyrotechnically initiated deployment from the spacecraft was attempted. This major test involved almost the entire I&T team at LMMS and was attended by numerous managers. The spacecraft was powered up and loaded with flight software. Special test equipment included the yoke strain gauges and a computer-based data system to monitor them, accelerometers on the spacecraft tied into a multi-channel high-speed data collection system, local RF intercom headsets for key test personnel, and three VHS video cameras. After everything was checked out and everyone was synched-up, the countdown began and the spacecraft software operated just as if it were in flight. At the appropriate time, shortly after simulated separation from the upper stage of the booster, the pyros were fired in the corners-first sequence. The array panels popped out about a centimeter (0.4 in), but that was all they moved. The test was aborted at that point.

Close up inspections of the jammed hardware initially indicated several possible causes for the failure of the cables to release fully. One thing became clear: firing the redundant cables cutters had jammed some of the cables even though they had been fully severed by the primary cable cutters. But a full inspection was thwarted because access to all the hardware was not possible with the arrays still held close to the spacecraft and with the RRS cables themselves entrapped. Before unjamming the hardware, numerous measurements were taken of the configuration just as it was to prevent the loss of any potential evidence.

Meetings were held frequently over the next several days, giving everyone present the opportunity to consider the mounting evidence, suggest and study possible causes for the failure, and develop deliberate plans on how to proceed. The entrapped cables were removed from the hardware one by one, measuring the force required to pull them free. It was decided that the test should be resumed with an attempt at a manual release of the array.

A test plan was quickly pulled together and the GSE was set up in record time. But the team's hopes for a smooth deployment were just as quickly crushed. Numerous failed manual deployment attempts over the next two days revealed the floor was still a problem. The numerous orientations into which the solar array deployed were plotted on top of a map of the floor contours. Two such plots are shown in Figure 4. The solid dark lines show the final positions of four deployments of the array assembly. Note the relative smoothness of the upper right of the floor that is due to the filling that was attempted previously.

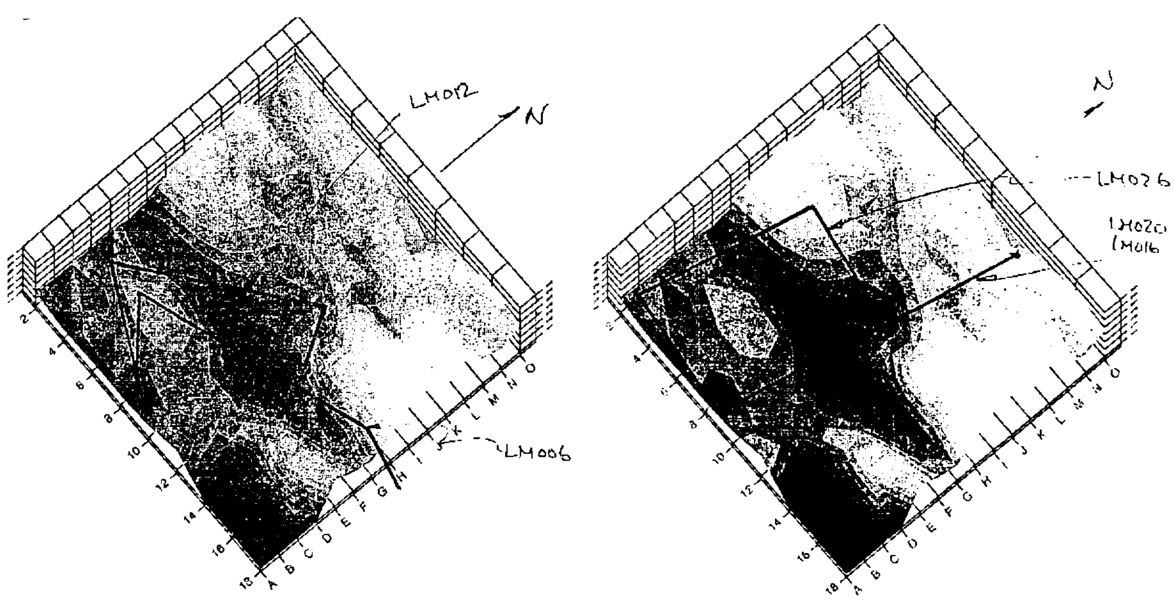


Figure 4. Solar Array Deployment Maps

A complex failure recovery plan evolved over the days and weeks following the failed deployment. Simultaneous activity in quite a few technical areas was required to resolve all the issues in a timely manner.

Failure Recovery Testing

Individual Hinge-line Torque Tests

Individual hinge lines were tested on a nearby high-precision granite table within a week just to show those components were working properly and wouldn't need to be reworked. It was quite fortunate that other deployment testing was ongoing on another program and was being performed in the same building. The granite table used for those tests provided a suitably flat location to begin the recovery testing. More corrective actions on the RRS and the deployment MGSE were implemented while the spacecraft and array were dispatched for system-level environmental testing in nearby facilities.

Restraint Cable Preload

With the removal of the cut cables, it was possible to examine them closely. When the cable fittings were compared to their drawings, some important dimensional discrepancies were discovered. The length of the cables had been unwittingly increased! The discrepancies had been overlooked during the incoming inspection and source inspections at the vendor. (The statistical sampling approach in place at the time did not uncover the part problem.) The carefully determined torques applied to the restraining nut were invalidated with the lengthened cables, which had allowed the tensioning nut to bottom out and induce a counter-twist in the cable, reducing the estimated preload by an unknown amount. With the proper functioning of the RRS directly dependent on the preload, this was a very serious problem indeed.

It was decided that it would be better to rely on load washers for determining the preload in the cables, so this design change was immediately implemented. Simultaneously, a thorough analysis was completed by LMMS to make sure that the new cable configuration wouldn't lose it's preload due to flight vibrations and cup-cone settling. The load washers were checked several times over the remaining months before launch, and they showed the expected minor relaxation over that time which was entirely tolerable. Just before the final closeout of the launch vehicle fairing, the load washers were read for the last time, confirming that full pre-load was still intact for all six cables. The electrical leads were then clipped off, leaving the load washers in place for flight.

Shock Absorber Redesign

The extensive investigation following the April 1998 deployment failure concluded that the two primary causes for the failure were:

1. Inadequate cable release movement due to low cable pre-load and excessive shock absorber friction, and
2. Firing the corner redundant cable cutters prior to firing all six primary cutters and allowing the solar array to deploy and complete the extraction of the successfully cut cables.

At first, it was thought that the counter-twist induced in the cables was a primary cause for the excessive splaying of the cable ends, and that the splaying was a condition for jamming. Bench testing was undertaken to test this theory. Cables with a normally cut end were positioned in the path of a second cutter, which when fired still entrapped the pre-cut cable. The conclusion was obvious: splaying from a normal cut like what would be seen on-orbit was enough to interfere with the cable cutting of the redundant cable. Therefore, to truly retain redundancy, after commanding the primary cutter, each cable must be cut and fully extracted, or not cut at all. To be cut and only partially extracted was never seen in any *properly configured* tests, so this redundancy-threatening failure mode was labeled "non-credible".

The following design modifications were implemented as a result of the follow-up investigation:

1. Decrease the friction drag force between the cable fitting and the split washer, using a series of bench tests prior to installation of hardware on the spacecraft.
2. Increase the strain energy stored in the cables by increasing the flight pre-load.
3. Change the firing sequence to fire all primary cutters first in three pairs, followed much later by an automatic firing of the redundant cutters if needed or abort by command.
4. Change the cutter installation procedure to get better alignment of the cable in the cutters.

Granite Deployment Table Expansion

A trade study began shortly after the failure of the epoxy floor to support the full manual deployments. As much filling and sanding had already been done as seemed practical, so other alternatives were brought up for consideration. Besides adding new granite blocks to the existing granite table and repouring an epoxy surface over the old one, options considered included machining the existing floor, transferring an existing deployment table from the Easy Windsor facility, and laying out inexpensive honeycomb panels over the existing floor or on sets of individually adjustable jack stands as had been done successfully for TRMM deployment tests. With the greatest confidence held for the expanded granite table, and without substantial cost savings presented by the other options, the decision was made to obtain three new granite tables to adjoin the existing table yielding a surface with enough area to meet the deployment test objectives. On July 22, 1998, the solar array was manually deployed on the expanded granite table proving its effectiveness for when the next pyro-initiated deployment test could be performed.

RRS Problems Live On

On August 24, 1998, the solar array was successfully deployed off of the spacecraft in a second deployment test of the entire system. With that success, the array deployment system became fully qualified for flight, but unfortunately the test revealed yet another flaw in the shock absorber mechanism. Full extraction of the cables was not achieved at all six restraints, nullifying the benefit of the redundant cable cutters, as previous testing showed the cables had to fully extract or become entrapped upon the firing of the redundant cutters. Even more testing on the bench and some additional design changes were required before the six shock absorber mechanisms could truly be considered single fault tolerant and thereby flight-worthy.

It was found in bench tests that there was frictional variability that could cause greater energy loss (and less extraction) than expected. Increasing the pre-load was not perceived as the best way to ensure full extraction, so that route was not traveled. Three final modifications as shown in Figure 5 were implemented on the bench and incorporated into the flight design to reduce frictional variability:

1. Stepping down the diameter of the friction shaft for the first inch of travel, reducing it's role in the energy dissipation to help ensure maximum travel through the split washer.
2. Adding a short taper between the stepped-down diameter and full diameter regions.
3. Adding an elastomeric O-ring at the end of travel to absorb impact shock.
4. Adding an elastomeric O-ring to keep the stop washer in better alignment.

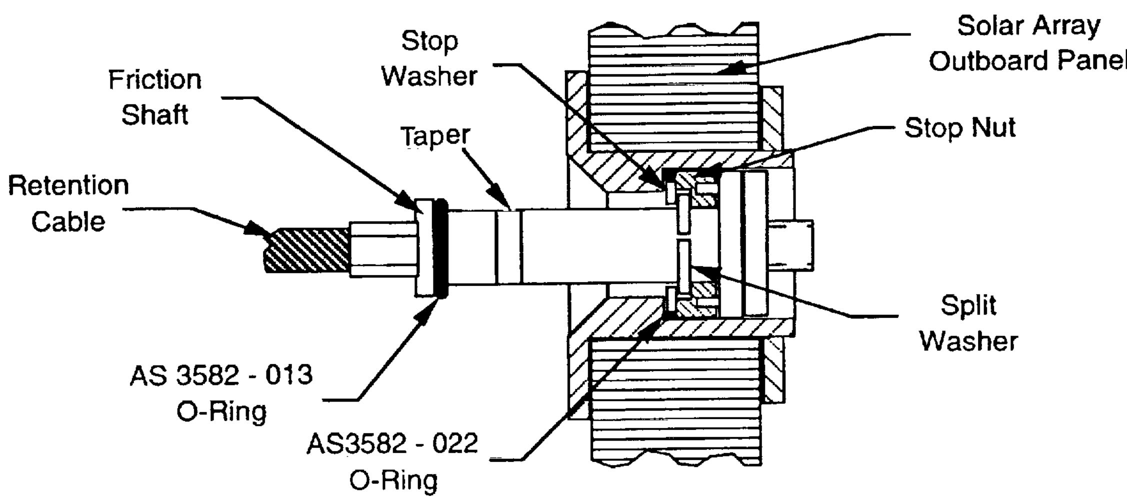


Figure 5. Final Design of Shock Absorber Mechanism

Lessons Learned

- As seen in the tailoring of the Restraint/Release System to Landsat 7, is it unwise to change critical functional dimensions such as those in the shock absorber mechanism. If you must do so as an element of the design, document such seemingly unimportant things as bench test procedures and known design limits and be sure to record them in the assembly drawing. It is essential to indicate key functional dimensions as such so they won't be treated lightly. Keep in mind that friction is present when you don't want it, and disappears when you do!

- Testing deployables early in satellite I&T can uncover problems before they affect the critical path. If the choice had been made to defer the Landsat 7 S/A deployment test until later in the I&T flow, shipment could have easily been shifted out in time, ultimately leading to a slipped launch date.

- Test g-negation MGSE ahead of time and even so be ready for problems, especially when taking a new approach. Don't ignore or brush off seemingly minor checkout issues with MGSE unless there is more than enough time to correct unforeseen problems when its used the first time. If you check out MGSE way ahead of time, make adequate plans to fully protect the MGSE while it's in storage.

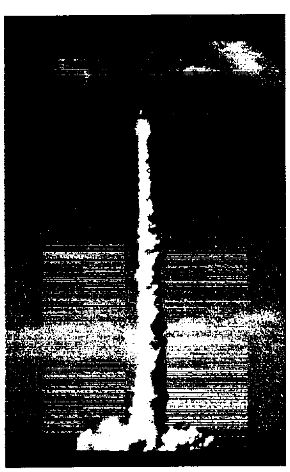
- Load washers can be a very helpful element for assurance of cable preload. Don't use nut torque only when preload is as critical as it was in this application.

- Using a rigid granite deployment surface (even if it is comprised of several large granite blocks with seams) beats a cheap epoxy floor. In addition, elevated surfaces are easier to clean and stay cleaner.

Conclusion

As can be seen from the monumental effort expended to get the friction force in the shock absorber mechanism just right, it can be unwise to rely on friction in mechanisms. To dissipate energy, other approaches such as crushable honeycomb should be considered. The third pyrotechnic deployment of the Landsat 7 solar array occurred on Dec. 8, 1998. This final full deployment was completely nominal and laid to rest the remaining concerns about the L7 RRS.

Many hours of problem solving, brainstorming of new ideas, and hardware re-testing were consumed in the flight qualification testing of the Landsat 7 solar array and its restraint/release system. It took the concerted teamwork of both prime contractor and government engineers to get the job done as well as communicate the progress of the recovery efforts back to NASA Goddard Space Flight Center.



In resolving the numerous testing problems that arose, the importance of well-tested MGSE was re-enforced in the minds of all involved, and it is hoped that this paper extends that message to many more in the aerospace mechanisms community. Finally, it should never be forgotten that heritage hardware is often taken for granted and that it requires special consideration unless it is truly an exact copy of what was previously used and it will be applied very similarly.

Epilog

The Landsat 7 spacecraft was launched on a Delta 7920-10 booster from VAFB Space Launch Complex #2 (SLC-2) at 11:35 am (1935Z) on April 15, 1999. The solar array released correctly approximately 12 minutes later and deployed successfully. The deployment time was estimated at 40 seconds, +/- 20 seconds, based on a rough plot of ACS telemetry of the spacecraft attitude rates. To date, the solar array performance has been flawless, both mechanically and electrically.

Acknowledgements

The author wishes to recognize the outstanding technical efforts of Mr. Hugh McMenamin, LMMS, under the very capable management of Mr. Robert LeRoy. Also at LMMS, Mr. Neal Shepard contributed his expertise across the board and left the author in awe of his ability to cut through the noise and churn out new knowledge on a steady basis. Finally, for his ability to analyze a situation and quickly get to the root of any mechanical problem he was presented with, the author gratefully acknowledges the talents of Mr. Charles Teleki of Swales Aerospace. The success of the solar array on-orbit speaks to the value added by the members of the entire team of technical managers, engineers, and technicians who brought the flight qualification of the array to a successful conclusion.

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