STEREO Spacecraft Mechanical Design, Integration, and Testing

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This article describes the significant mechanical efforts stemming from the Solar TErrestrial RElations Observatory (STEREO) mission. Because of the unique two-observatory mission design, the STEREO observatory mechanical design and integration were confronted with several nonstandard difficulties. Impacts to the mechanical effort from the STEREO launch stack, dual-spacecraft requirement, and the observatories' nearly identical design are addressed. Each section details these aspects and how they specifically impacted the mechanical effort. Considerable attention is given to the unanticipated issues encountered and how they were either eliminated or mitigated. These issues resulted in several lessons learned, which also are presented, that are being carried forward for future dual-spacecraft missions throughout the space community.

INTRODUCTION

The Solar TErrestrial RElations Observatory (STEREO) spacecraft mechanical effort experienced many of the standard challenges that mechanical teams face throughout a spacecraft's development effort. In addition to these challenges, the STEREO mechanical effort encountered many others specific to the STEREO mission due to the unique dual-spacecraft mission design. Many of these challenges were anticipated; however, as with all complex engineering efforts, several were unanticipated or thought to be of minimal impact to the overall effort. This article introduces the evolution of the STEREO mission mechanical design and several of the more unique aspects of the mission that forced the mechanical team to maintain an adaptable approach to the STEREO mechanical engineering effort.

MECHANICAL DESIGN

The STEREO spacecraft mechanical design underwent considerable changes from origination to flight. Initially, the STEREO mission scheduled the two spacecraft to be launched independently from each other on two dedicated Athena launch vehicles. Because of Athena launch-vehicle availability problems, the STEREO mission was forced to find other candidate launch vehicles. Several different launch vehicles were considered, including a scenario with both spacecraft on a single Space Shuttle flight, as shown in Fig. 1. In the end, the STEREO mission determined that a single Delta II launch vehicle would be used. The choice to use a single launch vehicle to deliver the STEREO spacecraft into their proper orbits placed a packaging requirement on the physical launch configuration for both spacecraft. From this requirement, the STEREO spacecraft eventually were designed to launch in a stacked configuration, with STEREO B placed below STEREO A. The stacked launch configuration drove much of the mechanical design for the STEREO spacecraft and created unique challenges throughout both the design and the integration and testing (I&T) effort for the STEREO mission.

The final, as-flown mechanical design of both STEREO spacecraft was an efficient primary load-carrying central cylinder surrounded by honeycomb decks that supported the majority of the spacecraft's instruments and components. Each spacecraft structure was designed specifically to support the spacecraft's role in the launch-stack configuration. STEREO B, which supported STEREO A during launch, was designed with a stronger central load-carrying cylinder, whereas the central cylinder for STEREO A was designed to support lifting operations of the entire stack. The honeycomb decks supporting spacecraft components and instruments were consistent between both spacecraft and were mounted around the central cylinder, creating internal bays around the cylinder. These internal bays contained the majority of spacecraft components, whereas the instruments were mounted on the exterior of the panels. With components mounted on both the inside and outside of the spacecraft structure, access to internal components, while not disturbing externally mounted components, became a mechanical design focus.

As a part of the launch-vehicle requirements, the launch stack had to be static and dynamically balanced. Before the third-stage release and ignition, the launch stack was spun-up for stability during burn. The third stage had no attitude control system, and because of this, the balance requirement was levied on the STEREO launch stack by the Delta II launch vehicle. The physical layout and placement of spacecraft components were driven by this requirement. As component and instrument masses changed during development, the mechanical layout for both spacecraft had to be modified. Once instruments and components were packaged on the spacecraft to meet specific field-of-view (FOV) and thermal requirements, the mechanical design space to configure the spacecraft in a balanced state was very small. Figure 2 shows the STEREO launch stack mated to the Delta II launch vehicle during fairing installation.

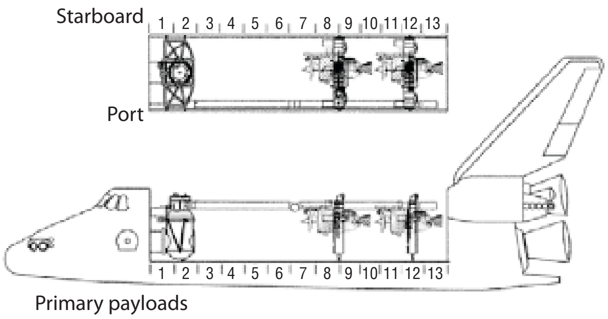

Figure 1. Proposed STEREO launch configuration in Space Shuttle.

DUAL-SPACECRAFT CHALLENGE

The dual-spacecraft mechanical operation carried with it rather obvious requirements related to the overall amount of hardware and ground-support equipment (GSE) needed to process two spacecraft. These requirements were relatively easily met. The design stage of the program essentially was carried out as a single-spacecraft design to be built twice with the majority of both spacecraft designs being identical. For mechanical assembly and I&T, space requirements were double that

Figure 2. STEREO stack on Delta II launch vehicle.

of a traditional spacecraft mission. However, because of the parallel processing of the New Horizons mission in the APL cleanrooms, both missions were relatively tight on space. I&T operations were conducted at times in a serial manner, and at other times they were conducted in parallel. All mechanical configurations and operations, with the exception of lifts, were conducted at least once in parallel. The potential for parallel operations necessitated that each piece of required GSE had to be provided in duplicate. Obviously, operations to assemble and test one spacecraft were repeated on the other, and some overall efficiency was realized by repeating the same effort. Although this originally was planned as a time-saving feature of the dual-spacecraft processing effort, much of this time was taken up by spacecraft-unique problems or dissimilarities that were not foreseen in the original planning of the STEREO effort. Concurrent operations with both spacecraft did provide the capability to switch from one spacecraft to the other when testing went long or unplanned events took place on one spacecraft. This feature of the program, which was utilized very well as the program continued, was the most time-saving and useful aspect of dual-spacecraft processing.

Some of the less obvious aspects of the STEREO dual-spacecraft mechanical processing effort are mentioned below. One item to be noted is that two spacecraft were assembled, integrated, tested, and launched by a small mechanical team of approximately six to seven individuals. This small team was able to maintain consistency between the two mechanical efforts while enabling lessons learned on one spacecraft to be passed quickly to others within the team. Because of this benefit, very few failures or problems were repeated on both spacecraft. Within this small mechanical team, each member specialized in a handful of operations for which they primarily were responsible. Each member's specialization also was coupled with cross-training in all other aspects of the mechanical effort, which created a highly trained and capable mechanical team that fully understood the entire spacecraft system and was able to add value to the entire STEREO mission, not just the mechanical effort. This mechanical team was able to be versatile and flexible with the constantly changing I&T schedule. This flexibility and understanding of the STEREO spacecraft system, exhibited by the entire I&T team, could not have been better illustrated than by the removal, repair, and reintegration of the STEREO A flight battery while on the launch vehicle 3 days before launch.

One aspect of the STEREO mission that is missed when simply thinking of the program as a dual-spacecraft program is that the I&T team, not just the mechanical team, had to think in terms of *three* unique spacecraft: STEREO A, STEREO B, and launch stack. Each spacecraft configuration had its own requirements, which were very different from the other two configurations. In many cases, the requirements for the launch stack were far more daunting and challenging than those at the single-spacecraft level. Because much of the environmental testing of the STEREO mission was conducted in the stacked configuration (vibration, acoustic, spin balance, and mass properties), the stack requirements had to be fully understood and planned for. Stack-specific requirements for testing, such as access and GSE setup, were much more involved than similar requirements for a single spacecraft. Because of the overall height of the stack and the unique configurations in which the stack ended up, the STEREO I&T team was challenged up to the very end of the program.

"IDENTICAL" SPACECRAFT

When the STEREO spacecraft are reported in the news, they usually are described as "nearly identical observatories." Although the spacecraft were designed similarly, the observatories did have significant differences. These differences became more apparent as assembly and I&T operations progressed. The individual characteristics of each observatory became important to understand in order to properly prepare the STEREO observatories for launch. Two of the key differences were the design of the top and bottom mounting interfaces of the central cylinder and the placement of the *In situ* Measurements of PArticles and Coronal mass ejection Transients (IMPACT) suite of instruments on the $+y$ decks. These two externally visible differences were used as quick references to distinguish STEREO A from STEREO B.

The primary cylinder designs of the two spacecraft were driven by the unique launch loads and interfaces required for each spacecraft. STEREO B, which was the bottom spacecraft in the launch stack, had a stronger, heftier cylinder design in order to support STEREO A during launch. At its forward end, the STEREO B cylinder protrudes above the top deck by 9 inches and supports a bolted interface for the flight interspacecraft separation system (supplied by SAAB Corporation in Sweden). The separation system required minor changes to the standard design to support STEREO-specific contamination control requirements. STEREO A also supports an identical bolted interface for its part of the SAAB separation system, but it is located at the aft end of the central cylinder. The forward end of the STEREO A cylinder, unlike the STEREO B cylinder, has no flight interfaces and terminates flush with the top deck. In addition, the STEREO B cylinder carried the Delta II launch-vehicle interface at its aft end.

These differences give each STEREO spacecraft a unique geometry at its top deck and are the primary distinguishing characteristic of the two spacecraft. Another factor driving the design of the two different central cylinders and the top deck geometry was the fact that lifting the spacecraft was accomplished through the forward side of the central cylinder, and thus, the lifting GSE required was different between the two spacecraft. Even the lift-point designs between the two spacecraft were greatly different because of the diverse loads each lift interface would support during processing. Figure 3 shows both spacecraft structures in the APL cleanrooms. In the foreground is STEREO B, with the cylinder extension and lift ring attached. STEREO A is in the background.

Loads for STEREO B lifts never exceeded 750 kg with flight and GSE hardware. STEREO A lift loads, by itself, were the same; however, when the spacecraft were configured for launch, the STEREO A lift points were used to lift the entire stack. Lifts of the launch stack, accomplished through the STEREO A lift points, were in excess of 1300 kg, which drove the STEREO A lift-point design specifications.

The aft portions of the two spacecraft cylinders were not identical either. STEREO A mated at the aft end to the top of STEREO B or to GSE work stands. STEREO B mated at the aft end to the Delta II third stage or to GSE work stands. These unique interface requirements between the two spacecraft at the aft portions of their central cylinders required different flight and GSE mating designs.

All of these differences drove the mechanical design of the central cylinders to be surprisingly unique between the two spacecraft. These differences, required to support the mission design and helpful in spacecraft identification, became factors to consider during assembly and I&T planning for the two STEREO spacecraft.

Both STEREO observatories were based on the same mechanical design, with observatory-specific designs at key interfaces being driven by observatory-unique requirements. One of these observatory-unique requirements was the different placement of the IMPACT instruments between the two spacecraft. Because of the spacecraft orbits, STEREO A ahead of Earth and STEREO B behind Earth, these instruments were placed in different locations to provide the proper FOVs for these sensors. The STEREO A suite was clustered together on the $+z$ side of the $+y$ deck (see Fig. 4), whereas, on STEREO B, two of the three IMPACT instruments were on the $-z$ side of the $+y$ deck with the third placed on the $+z$ side (see Fig. 5). To save time and simplify fabrication efforts, the STEREO structural decks were designed to carry both IMPACT suite mounting locations.

Although this design approach resulted in some deck inserts existing without a purpose, it did simplify the design, analysis, documentation, and fabrication efforts. The standard deck design approach had another unplanned benefit to the mechanical effort as well. Because of problems with the fabrication of the structural decks, a handful of decks were found to have some structural inconsistencies in key locations caused by fabrication flaws. Because both STEREO A and B y decks were identical in design, the mechanical team

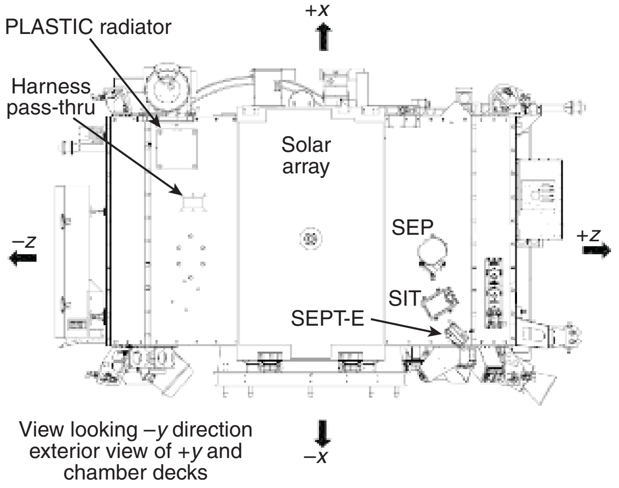

Figure 4. STEREO A spacecraft layout.

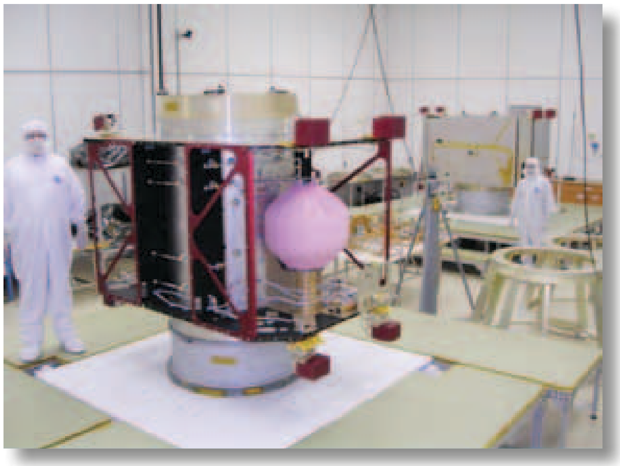

Figure 3. STEREO spacecraft in APL cleanrooms (foreground, STEREO B; background, STEREO A).

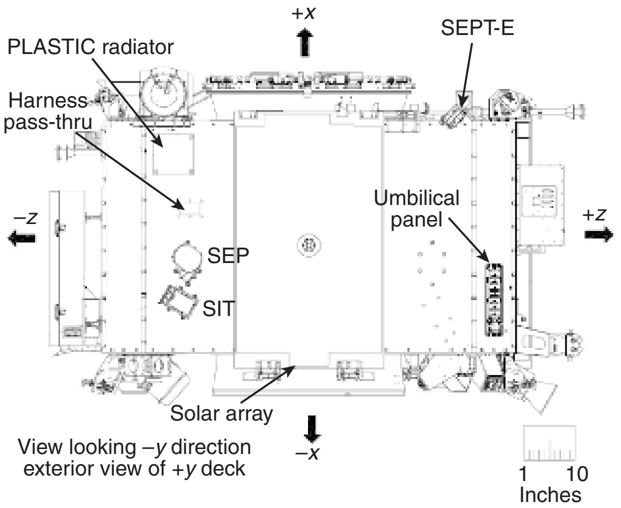

Figure 5. STEREO B spacecraft layout.

was able to custom-assign each deck to either the A or the B observatory based on its distinct fabrication flaws and the detailed load cases for each observatory. This capability, one not originally planned, enabled the mechanical effort to remain on schedule despite the less-than-perfect fabrication of structural panels.

At a detailed level, the spacecraft had many more differences, and those individuals involved in day-to-day operations were able to see the two spacecraft develop characteristics that further differentiated them from each other. The harness for each spacecraft was different in its routing and size, making panel opening and closing operations different for each spacecraft. Harness bridge brackets, break brackets, and shielding brackets were used in different places within each spacecraft, while sometimes only being used on one spacecraft and not on the other. IMPACT suite instrument placements on the STEREO A spacecraft blocked mounting bolts for the +*y* deck but not on STEREO B. The PLAsma and SupraThermal Ion and Composition (PLASTIC) instrument on STEREO B carried a radiator that had to be disconnected from the instrument before +*y* deck opening, whereas the STEREO A PLASTIC instrument had no radiator. STEREO B had four separation switches, and STEREO A only had two, with different set heights at each spacecraft interface. All of these differences between the two observatories needed to be clearly understood and taken into account during the I&T campaign.

LAUNCH STACK

The STEREO launch stack was one of the more unique aspects of the STEREO mission. By stacking the two observatories on top of one another, the STEREO mission was able to launch both observatories on a single Delta II launch vehicle. Using this launch configuration forced the I&T team to plan for three instead of two specific spacecraft, which came with many anticipated and unanticipated challenges.

To support the launch-stack configuration and subsequent separation after launch, a spacecraft-controlled interspacecraft separation system was placed between the two spacecraft. This interspacecraft separation system was a SAAB aerospace 937S spacecraft separation system with a marmon-type clampband system having two pyro-initiated bolt cutters located 180° apart from each other. The separation system was designed to bolt to both spacecraft, the top of STEREO B and the bottom of STEREO A, with the marmon-type clampband holding these two separate rings, and spacecraft, together during launch. The bottom portion of the separation system, which was bolted to STEREO B via a 60-bolt interface pattern, was the active portion of the separation system (see Fig. 6). The active portion contained both bolt cutters with pyro initiators, the marmon-type clampband, and all required support bracketry to remove and retain the clampband after release. STEREO B supported the active side of the separation system via two dedicated harness runs connecting the pyro initiators to the spacecraft electrical system. The passive side of the separation system was bolted to the aft portion of the STEREO A central cylinder also with a 60-bolt interface pattern. It was a simple ring with a mating interface to the active side and supported the eight kick-off springs that separated the two spacecraft once the clampband was released. With the interspacecraft separation system placed at the top of STEREO B and the bottom of STEREO A, as well as the individual interface requirements on each side of the separation system, both spacecraft layouts were completed with accommodating this hardware in mind.

For installation and access accommodations, all components on the top of STEREO B and the bottom of STEREO A had to stay outside of a designated 360° keep-out zone surrounding the separation system. A larger keep-out zone also was required at the two clampband half-mating areas located at the tangency point of the central cylinder and both *y* decks. It was at these two points that final tensioning of the separation system clampband was completed. Final tensioning of the separation system was a 3- to 5-h process involving coordinated efforts on both sides of the spacecraft stack.

Specific tensioning GSE was required to measure, tension, and complete assembly of the separation system. Without clear access to these mating points, delicate measurements and final assembly operations would not have been able to be completed on a controlled and consistent basis. Once both spacecraft were stacked in the launch configuration, from launch-vehicle separation plane on STEREO B to the highest point on STEREO A, the height of the launch stack was more than 10 ft. Although this height was anticipated, complications did arise in gaining access to the stack throughout the I&T process. Mechanical GSE to support the stack as well as to grant access to both spacecraft became a very

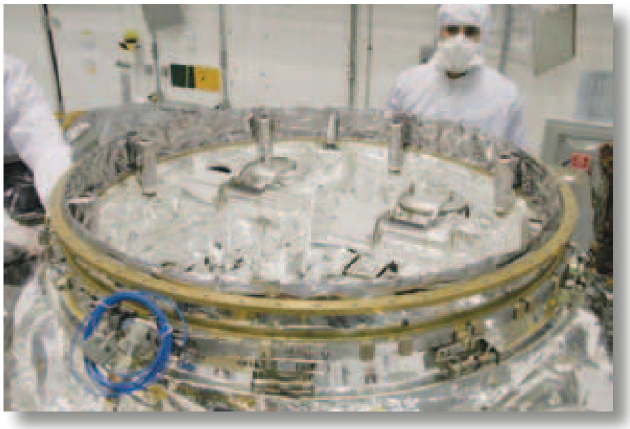

Figure 6. SAAB separation system installed on STEREO B.

important aspect of the stacking effort. During actual stacking operations, the full stack was mated to the STEREO stacking dolly. This dolly had a low mating surface, approximately 1 ft above the ground, which kept the top of the STEREO stack at reasonable height above the ground. However, when the launch stack was installed to test equipment such as vibration and spin balance tables, the top of the STEREO A deck was placed more than 20 ft off the ground. The final stack operation, placing the launch stack on the Delta II third stage while mated to a transportation dolly, put the top deck more than 30 ft off the ground. During testing and flight-mating operations, access was needed all over the spacecraft stack to attach test equipment, clean, take engineering data, and complete final flight closeouts. Delicate operations with the spacecraft became increasingly difficult as the stack height grew, and choices in platforms enabling access to these areas were reduced. Platforms and equipment initially planned to be used for these operations many times did not work in the way planned, and new forms of GSE had to be found to provide safe access to the STEREO stack. During final flight closeouts for launch, the launch-vehicle provider made a specialized cleanroom bucket-style manlift available to the STEREO mission. Although this manlift provided unparalleled access to the top deck of the stack, it was incredibly unstable when placed at that height, and it was determined that the manlift should not be used above the stack for closeout operations. As with many of the unique challenges of the STEREO effort, the I&T team was required to deal with these trials up to the very end of the STEREO I&T program.

Testing and handling of both spacecraft simultaneously in the stacked configuration was conducted during system vibration, acoustic testing, and spin balance testing as well as during final launch operations. During these operations, a significant amount of planning was required to ensure that both spacecraft were not placed at risk. Unique handling procedures were required for stacking (and unstacking) operations and handling. STEREO mission handling procedures had to be created as complements to the existing SAAB separation system installation procedures. During much of the I&T planning stages, the STEREO team focused on the requirements of the program to complete actual stacking of the spacecraft. Figure 7 shows the STEREO stacking effort in process, with STEREO A being lowered onto STEREO B and the SAAB separation system. The spacecraft were stacked four times during testing and once for flight. Handling operations and procedures were relatively simple to plan for and ensure that the proper equipment was provided for these operations. However, for every time the spacecraft were stacked during testing, they also needed to be unstacked, which turned out to be a relatively challenging effort to plan for as well as to execute. Two of the four unstacking efforts were initiated by an actuation of the separation system, whereas the other two required a manual detensioning and removal of the separation system clampband. For all of these efforts, a SAAB-specific procedure was used to either initiate or manually detension and remove the clampband. Removal of the clampband allowed for the two spacecraft to be separated from one another, with STEREO A simply being lifted off of STEREO B. Removal of the top SAAB ring, however, had to be covered by an APL procedure.


Figure 7. Stacking operation of STEREO A onto STEREO B.

The ring then was removed from under the spacecraft, and, finally, the spacecraft was able to be lowered onto a mounting payload attachment fitting, completing the removal effort. This task was a cumbersome and highly coordinated task to execute, ensuring that both hardware and personnel never were placed at risk.

The STEREO launch-stack configuration was by far the most unique aspect of the mechanical effort. All efforts associated with the launch stack were time-consuming operations demanding a considerable amount of attention to detail. Figure 8 shows the STEREO stack during a lifting operation. Although the stack configuration was one of the most demanding aspects of the STEREO mechanical effort, it was definitely the most rewarding. Completion of the final stacking operation for flight, followed by the mating of the launch stack to the Boeing third stage, was an incredibly fulfilling operation with which to be involved. Seeing the STEREO launch stack sitting over 30 ft above the floor, prepared for flight, was one of our most satisfying experiences on the program.

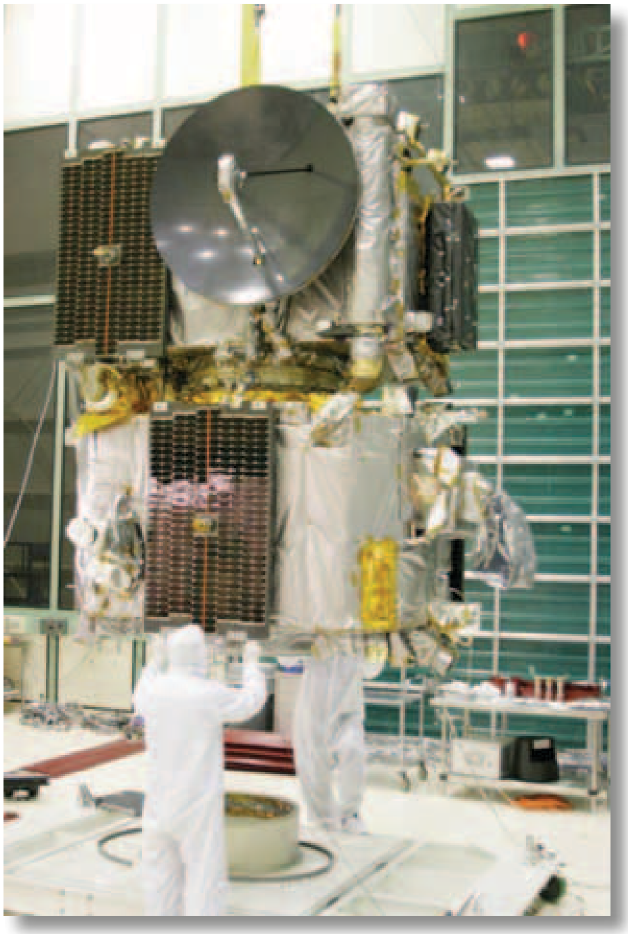

Figure 8. Lifting operation of STEREO flight stack.

Figure 9. STEREO A, after propulsion system integration, with all decks opened.

HINGED DECKS

The majority of the STEREO components were placed inside the structural body surrounding the central cylinder. Once all decks were installed to the structure, there was no access to these components without removing the decks. Further complicating this problem was the presence of the spacecraft harness, which was designed to be physically tied down to these structural decks. After the installation of the flight harness to the spacecraft, complete removal of the structural decks to gain access to the internal volume of the STEREO spacecraft was not possible. With this constraint on the mechanical design of the spacecraft, a method allowing for access to the internal volume of the spacecraft was needed. To meet this need, the vertical structural decks (±*z* and ±*y* decks) were designed with the ability to open via GSE hinges. Figure 9 shows the STEREO A spacecraft with all four decks opened in preparation for I&T. By doing so, the entire internal volume of the STEREO spacecraft was able to be accessed without major impacts to the harness or other already integrated subsystems. Specialized GSE stands also were required to support the decks while in the open configuration. Once this GSE was in place, the STEREO mission was able to utilize this distinctive aspect of the STEREO mechanical design.

Hinging the spacecraft decks did add considerable accessibility and flexibility in scheduling to the I&T team; however, this design attribute required that several interfaces between the opening decks be carefully designed. One of the most impacted subsystems of this hinged-deck design was the spacecraft telecommunication subsystem. Figure 10 shows the telecommunication system fully integrated to the STEREO spacecraft. The majority of the telecommunication system was mounted to the –*y* deck with significant interfaces bridging from this deck to other portions of the spacecraft. To aid in integration of the telecommunication system, the –*y* deck was designed to open by 90° to horizontal from its closed vertical configuration. Because of this design, closing out of interfaces across the –*y* deck GSE hinge line during I&T operations and for flight had to be considered carefully. While the –*y* deck was open, many telecommunication system interfaces were unable to be flight-mated, so specific testing and GSE configurations had to be developed. Unique GSE waveguide pieces were used to close out the waveguide runs to the traveling-wave tube amplifier (TWTA)/electrical power converter (EPC) assembly and RF plate, while coaxial cables were used to connect the primary waveguide run on the –*y* deck to the +*z* low-gain antenna. Before closing the –*y* deck, all GSE was removed, and then the deck was closed. The final flight mates were completed after deck closing. This overall concept worked incredibly well for the integration of the telecommunication system. The ability to integrate the complicated runs of X-band waveguide on a horizontal surface simplified a very difficult assembly process.

Problems that did arise in the installation of the telecommunication system were easily addressed, and final assembly was able to be completely inspected. Although

Figure 10. STEREO –*y* deck before flight closing. Note the extensive run of X-band waveguide across the deck.

efforts were trouble-free when the deck was opened, the ease of initial integration of the telecommunication subsystem with the –*y* deck in the open configuration stood in stark contrast against the difficulty of the final closeouts once the –*y* deck was closed. Final closeouts after –*y* deck closing in several areas were tighter than initially expected, especially around the TWTA and transponder interfaces. During the first –*y* deck closing on STEREO A, a primary transponder cable was damaged, forcing the –*y* deck to be reopened for repair. This was the very first closing and mating operation for the program; lessons learned from this experience were applied going forward, and this problem was not repeated.

The telecommunication system example illustrates one of the drivers for the spacecraft I&T effort. Accessible areas in the internal volume of a populated spacecraft once certain decks were closed initially were overestimated. Once I&T efforts began in earnest, and this problem was fully appreciated, the mechanical team endeavored to do as much as possible with the spacecraft in the open configuration to eliminate efforts after deck closing. This process simplified operations as well as lowered the risk to components directly and indirectly involved in final closeout operations. Gaining access to components mounted deeper in the spacecraft bays sometimes was extremely difficult once the two spacecraft were fully integrated. As the spacecraft continued through I&T, access to component mounting bolts, harness, and other interfaces needing attention became increasingly difficult. Components integrated to the spacecraft early in the I&T process became obscured by components installed later in the process. Once the decks were closed, and access into the spacecraft bays was more limited, access to components became more restricted. Though some of this reduced access was predicted, the full extent of reduction of accessibility was not fully understood until the spacecraft began to be built up throughout the I&T process. The STEREO I&T team quickly learned to plan efforts with as much of the spacecraft opened as possible. In the cases of reduced access, many times multiple decks were opened. By doing so, the risk of damage to components directly and indirectly being worked on was lowered.

Certain constraints on the spacecraft I&T effort arising from these hinged decks did appear that were not fully appreciated during the initial design effort. The order of operations as to which decks had to be opened in order to open the desired deck was realized quickly. Many times, to access a component within the spacecraft, several other spacecraft components needed to be disturbed. To access the power distribution unit (PDU), the +*y* deck needed to be opened, shown in Fig. 11. But to safely open the +*y* deck, both *z* decks had to be opened first. Opening the +*y* deck carried with it the need to remove components that obstructed mounting holes as well as components that possibly would be damaged by the opening process and/or by support GSE. At an even finer level, the act of opening the +*z* deck required the partial deintegration of solar array mounting components, an instrument mounting bracket, and portions of the +*z* low-gain antenna assembly. All of these details had to be considered and accounted for during I&T planning and scheduling.

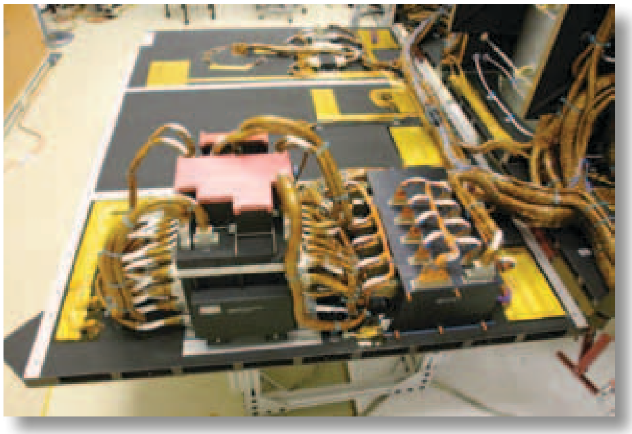

Figure 11. STEREO B +*y* deck before vibration test closing.

The overall I&T flow coupled with the interrelated nature of the structural decks resulted in the decks being opened and closed multiple times over the 1.5-year I&T phase leading up to launch. Unfortunately, when the design for the hinged decks was incorporated into the mechanical design, no accommodation was made for temporarily securing the decks closed other than through the flight interface. Efforts were made to reduce the overall wear on these flight-interface HeliCoil inserts by using alternate mounting holes during temporary closing operations. These efforts did reduce the amount of wear, but the continual opening and closing operations still put an incredible amount of wear and tear on the flight-interface HeliCoil inserts, which created problems for the mechanical team later in the I&T effort. Leading up to final flight closeouts of the spacecraft decks, many flight HeliCoil inserts were cleaned and/or replaced to ensure proper running and holding torques were realized at these critical flight interfaces.

The hinged-deck design was the correct design option to grant access to the internal bays of the STEREO spacecraft. These hinged decks provided the access and flexibility needed by the STEREO I&T team to successfully integrate both spacecraft. Without these hinged decks, the STEREO I&T team would not have been able to complete the effort without even larger challenges than the ones encountered with this hinged design.

STEREO MECHANICAL LESSONS LEARNED

Spacecraft Handling

STEREO had to be placed in several different orientations during the I&T phase, with each of these orientations requiring a unique piece of mechanical GSE (MGSE) as listed below with the corresponding work stand.

- Vertical, mobile: I&T dolly
- Vertical, stationary, with access to inner portion of central cylinder: Elephant stand
- Vertical, low as possible to the floor for stacking, mobile: Stacking dolly
- Horizontal, stationary: Ransome table
- Horizontal, mobile: MESSENGER turn-over fixture
- Inverted, mobile: MESSENGER turn-over fixture

STEREO would have greatly benefited from a more accurate MGSE/I&T plan that contained all spacecraft and instrument orientation requirements. From this plan, and with time and money available, the program could have designed and built two spacecraft support stands replacing the 10 stands listed above (5 stands per spacecraft) that would have allowed the spacecraft to be placed in as many, if not all, of the orientations listed above and allowed all necessary access and clearances for testing. A piece of MGSE such as this would have saved the program significant amounts of time and labor by eliminating the need for spacecraft moves that required not only mechanical effort but also electrical effort to power down, de-cable, re-cable, and power up, both before and after the move.

Stacking Efforts

Several useful aspects of the STEREO design that aided in the stacking efforts were as follows:

- An external electrical GSE (EGSE) access panel for the spacecraft allowing I&T engineers to monitor the position of the separation switches before, during, and after spacecraft stacking. This panel allowed for the mechanical team to position these switches physically such that they had sufficient stroke for the deployment, mitigating the risk of a possible false deployment signal during vibration from the separation switch.
- Narrow physical dimension across the *y* axis of the spacecraft. Having a narrow dimension across the spacecraft along this axis allowed for easier access to the separation system during installation and stacking operations. This access provided the majority of all access needed for full stacking operations. Along the *z* axis however, access was severely limited because of the long dimension in that axis.
- There were few spacecraft components placed in the actual separation system area. Several components were at the same height as the separation system when the spacecraft were stacked, but these components were kept far enough away from the separation system to allow for adequate access

Overall, the stacking operations went very well; however, additional access with shorter reaches to the actual separation system would have simplified some of the stacking efforts in terms of physical access for hands-on work and inspection.

As successful as the stacking operations were, there are several design issues that need to be fully thought out in relation to the overall mechanical design and handling plan for the spacecraft. Interfaces around the separation system mounting planes need to be thoroughly considered with at least the following engineering disciplines involved: mechanical, structural, thermal, harness, contamination, and electromagnetic compatibility. Additional disciplines may need to be brought in as well on a program-by-program basis. There were issues uncovered during the stacking operations, especially in terms of thermal blanketing in and around the separation system, that drove the flow of the operations. Final flight stacking is not a simple mechanical operation that places one spacecraft on top of the other; rather, it is a coordinated effort that places all spacecraft components (blankets, harness, initiators, seals, contamination protection, etc.) in place for flight for the final time. The

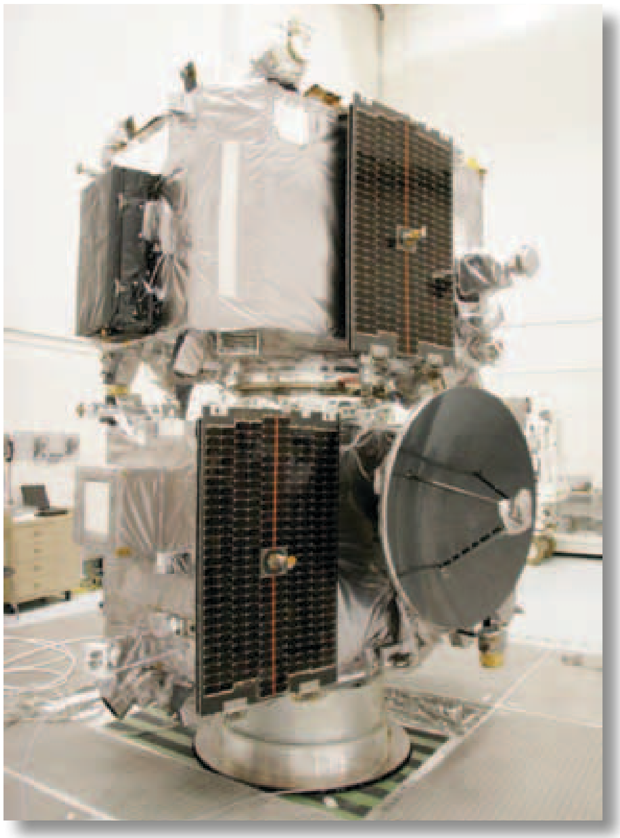

Figure 12. STEREO flight stack before spin balance.

STEREO launch stack can be seen fully configured for flight in Fig. 12.

Mechanical Team

All mechanical efforts were conducted with a small and flexible team of four individuals, which allowed for clear lines of communication and essentially no drop off in information flow between the two spacecraft as well as among team members. Having such a small mechanical team did threaten to bottleneck spacecraft I&T operations when both spacecraft required attention, but the mechanical team was able to manage these challenges.

The mechanical team successfully conducted 35 system-level deployment tests, more than 50 spacecraft lifts, five stacking operations, and the full gamut of system-level environmental tests. In addition, all 17 flight deployments under the responsibility of the mechanical team were successful, with the exception of a tell-tale switch on the STEREO B high-gain antenna hinge being the only anomaly.

To handle a dual-spacecraft mission, the mechanical team should be kept at a relatively small size. Two independent teams should not be used to handle each spacecraft because of the possibility of loss of information between the spacecraft teams. There should be two experienced mechanical technicians scheduled full time. With these two technicians, all mechanical operations can be covered with consistency, and lessons learned on one spacecraft can be applied to the other spacecraft. In addition, there should be a second mechanical engineer to design all needed mechanisms and oversee their fabrication, assembly, and testing. This second engineer would free up the lead mechanical engineer to focus on spacecraft I&T and issues stemming from that effort.

One caveat to this two-technician guideline is that, during lift operations at facilities that do not supply a crane operator, one technician is busy running the crane, leaving only a single technician for spacecraft handling. In these situations, a third mechanical technician should be trained to assist. STEREO used a quality assurance inspector as the second mechanical technician during lifts, which worked well.

Facility Space Availability

As with the MGSE required to work a dual-spacecraft mission, the overall space required for I&T for a dual-spacecraft mission needs to be twice what would be needed for a single-spacecraft mission. Figure 13 shows a standard STEREO I&T room setup for daily I&T efforts. I&T configurations for each spacecraft should be fully thought out during the planning phases of the program to allow for proper allocation of I&T space. Detailed room layouts showing the locations of MGSE/EGSE while being used and stored should be generated as part of I&T planning.

Figure 13. STEREO spacecraft at Goddard Space Flight Center.

CONCLUSION

The dual-spacecraft STEREO mechanical effort required very little additional effort at the design phase but a significant amount more planning and effort at the I&T phase compared to a single-spacecraft mission. Although this I&T effort was challenging and more complex than for a single-spacecraft mission, a small, dedicated mechanical team was able to keep up with the needs of the program while providing consistency between both spacecraft. Challenges, both predicted and unpredicted, did arise, and the mechanical team was able to adjust and overcome them while keeping the program on track. STEREO was a program whose mechanical effort was very different from recent single-spacecraft missions produced by APL. Thus, STEREO proved to be an incredibly rewarding experience to share with the dedicated members of the mechanical team.

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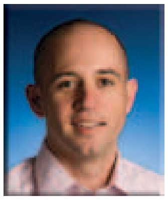
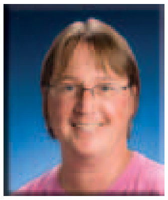


Stuart W. Hill



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