Mechanical Verification of the STEREO Observatories

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The Solar TErrestrial RElations Observatory (STEREO) mission requirements presented many challenges to the observatories' mechanical design, analysis, and test program. STEREO's tight pointing stability requirements were complicated by low-frequency motion of multiple deployed appendages. Meeting launch vehicle requirements for payload stiffness and mass was difficult for the 3-m-tall, 2.1-m-wide observatory stack. The observatory stack also required precision spin balancing to fly on the Delta II third stage—a challenge with a weight limit of 1285 kg. This paper describes how the STEREO mission requirements were verified through analysis and testing. The verification methods used for STEREO spacecraft stability, strength, vibration, deployment, shock, acoustic, spin balance, and mass properties are discussed.

INTRODUCTION

Mechanical verification of the Solar TErrestrial RElations Observatory (STEREO) spacecraft is discussed in this paper. Mission and launch vehicle requirements made for a challenging verification program. The methods used to verify pointing stability, structural strength and stiffness, deployments, robustness to shock and acoustic environments, and spin balance and mass properties are addressed.

OBSERVATORY CONFIGURATIONS

The STEREO observatories stacked in their launch configuration are shown in Fig. 1. The STEREO payload consists of two nearly identical observatories that are stacked on a Delta II 7925 3712A payload attach fitting (PAF) for launch. The observatories are named "A" for ahead and "B" for behind. For the launch configuration, Observatory B is at the bottom of the stack, and Observatory A is on top. Observatory A is rotated 180° about the *x* axis relative to Observatory B in an effort to locate the stack's center of mass at the geometric centerline of the PAF.

Each observatory supports four instrument suites, which are outlined in Fig. 2. Observatory B in its orbital configuration is shown in Fig. 3.

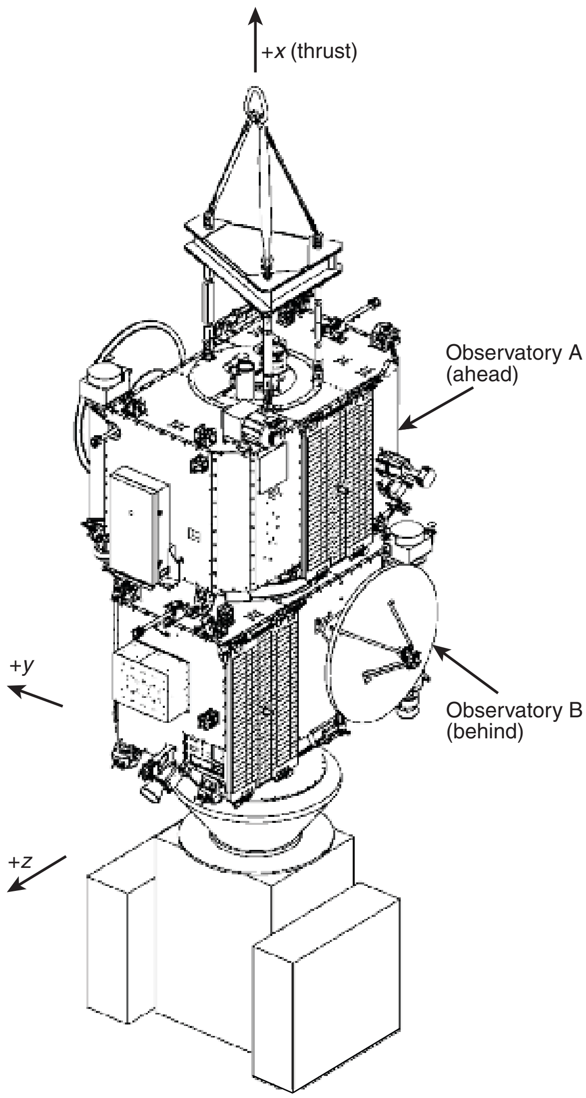


Figure 1. STEREO stacked observatories (Observatory B's coordinate system is used).

Each observatory is constructed of an aluminum honeycomb box structure connected to a center aluminum cylinder. A SAAB separation system connects the two observatories. The stacked observatories are attached to the launch vehicle with a Boeing 3712A PAF and clampband.

MECHANICAL VERIFICATION PROGRAM

Observatory stability was verified by analysis. All other requirements were verified by testing. A flow chart of the qualification test program is shown in Fig. 4. Primary structure pre-integration testing was performed at APL. Some post-integration testing was performed at APL, but facility limitations forced the remaining tests to be performed at the Goddard Space Flight Center (GSFC). The spacecraft structure strength was verified with static load and proto-flight vibration tests. The observatories' ability to withstand shock was demonstrated with separation/shock testing of the solar arrays, high-gain antennas (HGAs), umbilical doors, the observatory stack/Boeing test PAF (TPAF) interface, and the Observatory A/Observatory B SAAB interface. Observatory stack strength and stiffness were validated with the observatory stack proto-flight sine vibration test. Deployment tests were conducted to verify solar array, HGA, and umbilical door flight deployments. The observatories' ability to withstand the flight acoustic environment was demonstrated with the observatory stack proto-flight acoustic test. Preliminary spin balance of the observatory stack was performed at the GSFC, followed by mass property measurements. Final spin balance was performed at the Astrotech facility in Titusville, Florida.

JITTER ANALYSIS

The observatories must provide a stable platform to enable the Sun-Centered Imaging Package (SCIP) coronagraphs to obtain accurate images of the Sun. Reaction wheels are used to position the spacecraft so the SCIP is pointed at the Sun. Force from the wheels can produce a dynamic disturbance in the deployed appendages (solar arrays, HGA, and 6-m booms), causing the SCIP coronagraphs to "jitter." Stability was verified with a jitter analysis by using an MSC/NASTRAN finite element model (FEM) of Observatory B in its orbital configuration. The 108,045-element FEM is pictured in Fig. 5. Results from a normal modes analysis are used in a guidance and control Matlab model to predict the jitter initiated by reaction wheel forces.

SPACECRAFT STRUCTURE STATIC LOAD TEST

The strength of the cylinder structures was verified with static load testing. Testing of the observatories' primary cylinders and of the SAAB separation system was performed from October through December 2003 at the Vibration Test Laboratory (VTL) at APL. The loads used for testing were derived from the worst-case predicted loads from the STEREO/Delta II Coupled Loads Analysis. The Coupled Loads Analysis calculates the launch loads imparted on the observatory stack. A test factor of safety of 1.25 was applied to these predicted loads. The test configurations and loads applied are depicted in Fig. 6. Photographs of each test configuration are shown in Fig. 7.

SPACECRAFT STRUCTURE STACK VIBRATION LOAD TEST

The strength and stiffness of the spacecraft structure stack were verified with a Delta II proto-flight vibration test. Three-axis sine sweep vibration testing was performed on the 1267-kg stacked STEREO

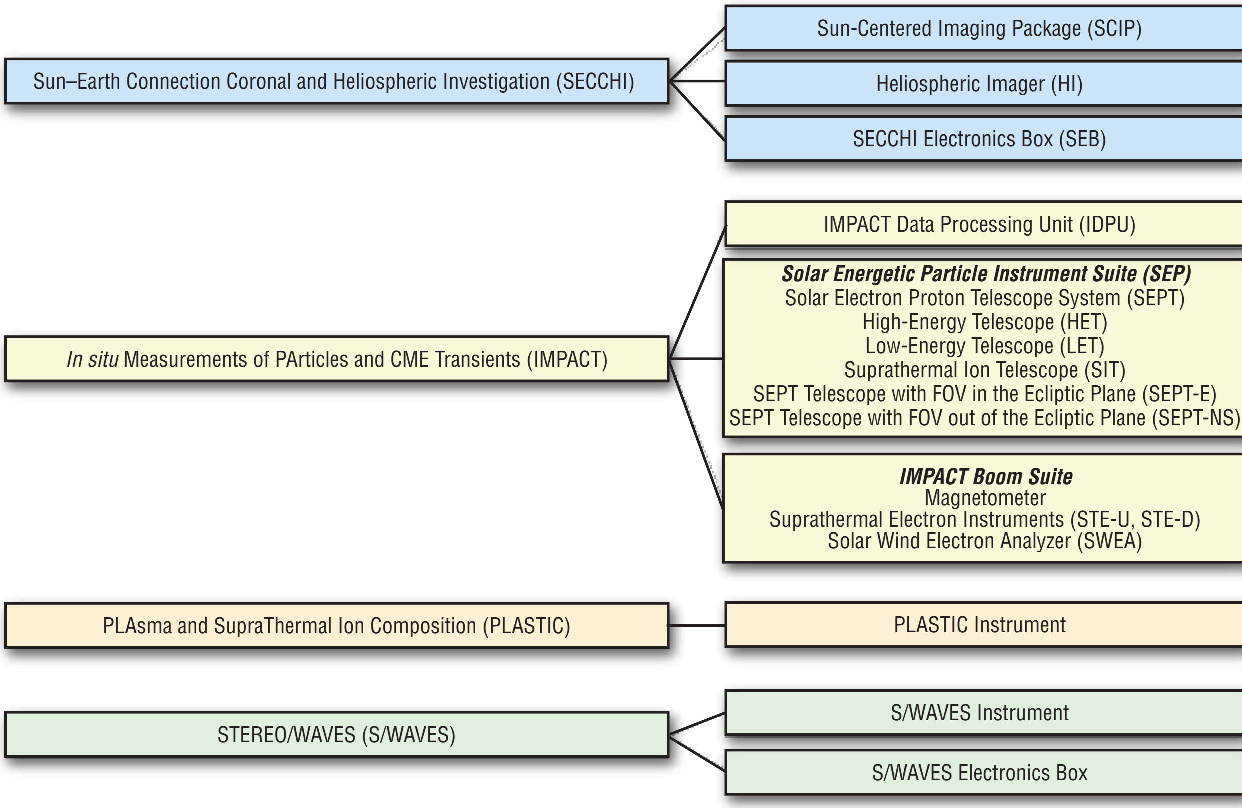


Figure 2. STEREO instruments.

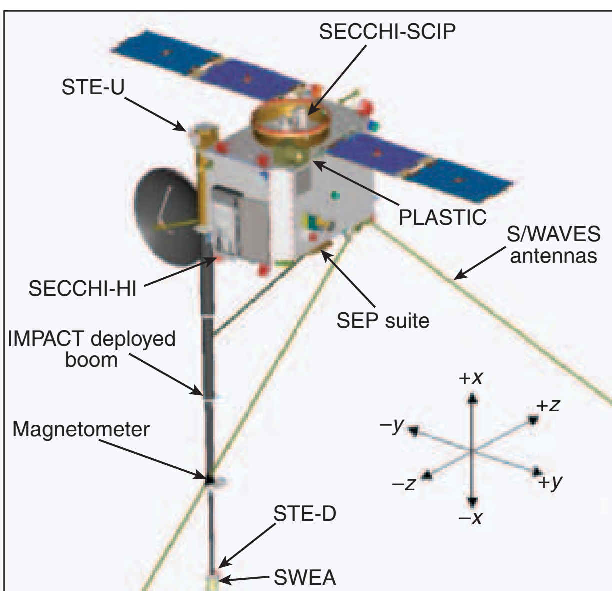


Figure 3. Observatory B orbit configuration.

observatory flight structures with mass simulators representing instruments and spacecraft components. Testing was performed in April 2004 at APL's VTL facility by using a Spectral Dynamics control system and a Synergistic Technologies Inc. data acquisition system. A test factor of safety of 1.25 was applied to worst-case load predictions from the STEREO/Delta II Coupled Loads Analysis. Lateral (y and z) axis vibration was used to develop equivalent lateral-plus-compression loading from the maximum lateral coupled-loads case. The axial (x-axis) vibration was used to develop equivalent lateral plus compression for the maximum axial coupled-loads case. The goal of the lateral vibration tests was to obtain 5.1 g at the stack center of mass; 5.2 g and 4.7 g were obtained at the center of mass for the y- and z-axis vibrations, respectively, and 8.6 g was obtained at the center of mass for the x-axis vibration, just shy of the goal of 8.8 g. The loads obtained were considered close enough to predictions to be acceptable. The x-axis vibration test is pictured in Fig. 8. Obtaining the required load on the 1267-kg structure stack was a challenge for the vibration facility, so structural resonances were used to assist in the development of these loads.

A 56,933-element pre-test FEM was produced to predict the observatory stack stiffness and responses. A comparison of predicted modes and test-measured modes is presented in Table 1. Lateral stiffness predictions were within 10% of actual, and axial stiffness predictions were within 20% of actual. The FEM primary mode shape plots are presented in Fig. 9.

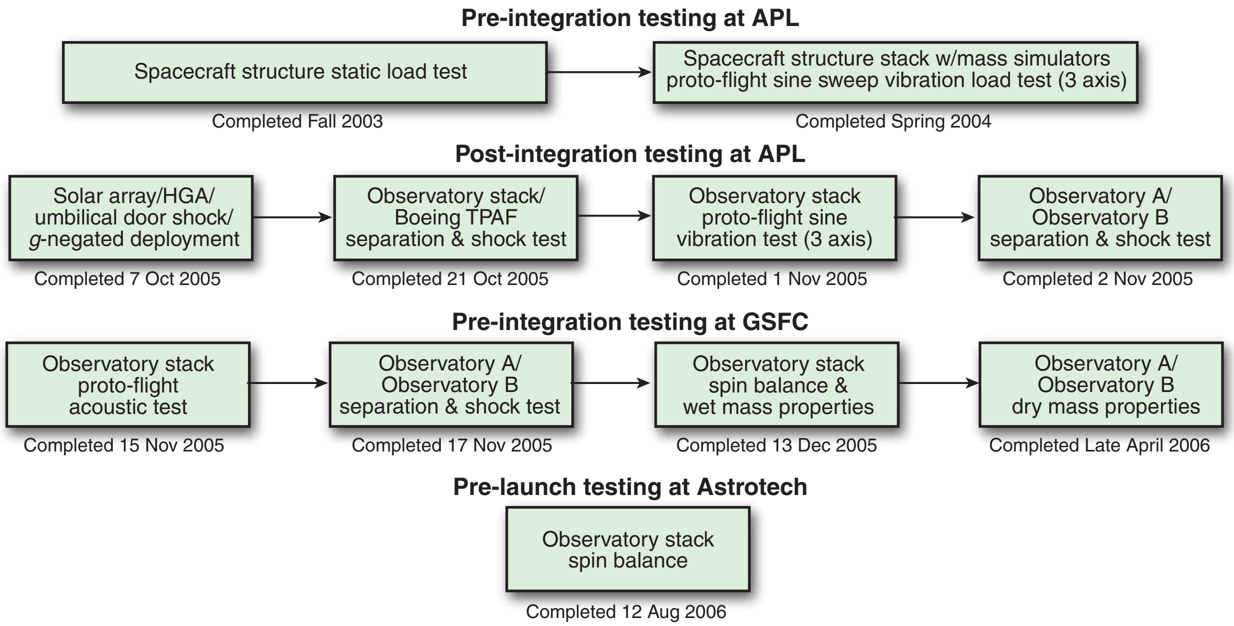


Figure 4. Structural test flow.

SOLAR ARRAY/HGA/UMBILICAL DOOR SEPARATION/SHOCK TEST

Solar array, HGA, and umbilical door deployment/separation/shock tests were performed from September through October 2005. The purpose of these tests was to demonstrate separation at all interfaces in flight configuration and to measure the shock induced on the spacecraft by the separation.

Solar Array Deployment

The stowed STEREO solar array subsystem is pictured in Fig. 10. The subsystem included solar cells, substrates, interconnect wiring, hinges, snubbers, cup/cone interfaces, a retractor bolt assembly (RBA), a pinpuller, and a pyrotechnic separation nut (pyro sepnut) actuation device.

The STEREO solar array on-orbit deployment took place in two stages. Before deployment, the entire subsystem was held in a preloaded state. It was preloaded through the center of the array at the pyro sepnut cup/cone interface, and it was held off of the spacecraft body with snubbers at the four corners of the array. In addition, both the P1 and P2 hinge line springs were preloaded in their stowed positions.

During the primary deployment stage, the pyro sepnut was actuated, and the preloaded bolt was released but contained by the RBA. This 90° deployment released both the inboard and outboard panels from their preloaded state and away from the spacecraft body. The panels deployed 90° and over-traveled 35°. A deformable metal damper was used to slow the deployment of the array during its over-travel by absorbing kinetic

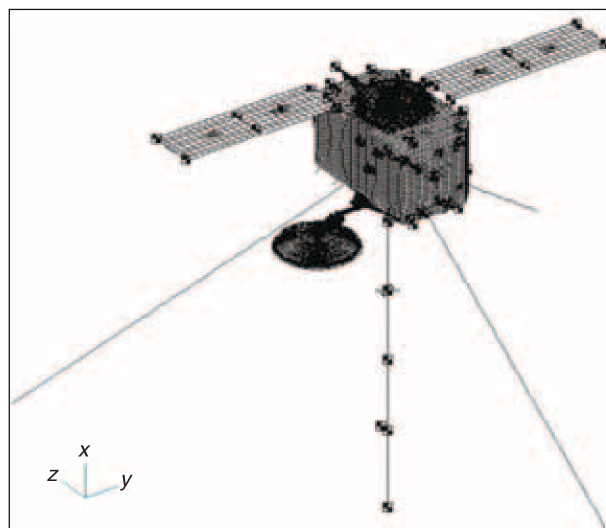
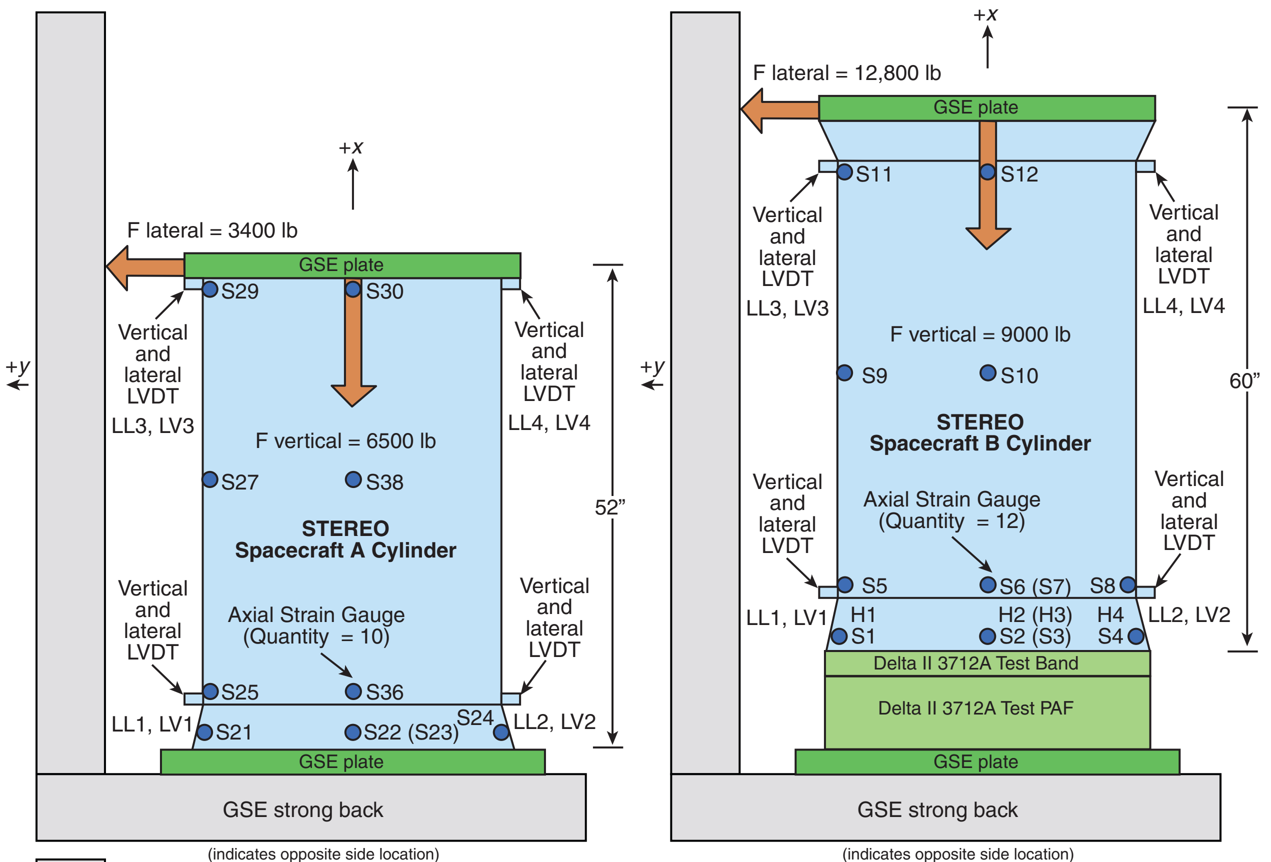


Figure 5. Observatory B jitter FEM.

Table 1. Primary structure modes for the structure stack vibration load test.

	Primary modes	
Axis	Predicted (Hz)	Actual (Hz)
x	46.0	55.6
x	53.1	64.81
y	14.3	13.5
y	48.8	50.0
z	13.3	12.4
z	36.3	38.6



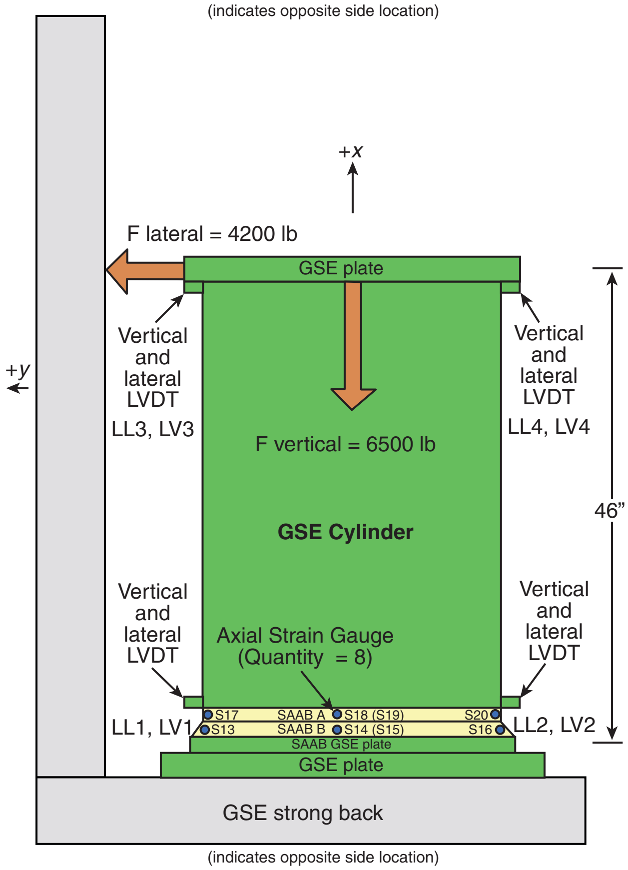


Figure 6. Cylinder A, cylinder B, and SAAB static load test configurations. LVDT, linear variable differential transformer.

energy as it twisted. The semideployed panels remained attached to the spacecraft at the P1 hinge line and were held together by both the P2 hinges (at the bottom) and the pinpuller (at the top).

During the secondary stage of the deployment, the pinpuller was actuated, and the outboard panel was released so that it deployed 180°, over-traveled 75°, and remained attached to the inboard panel through the P2 hinge line. Two dampers, one on each hinge, were used in this deployment. The deployed solar array is shown in Fig. 11.

Observatory-level ground testing required *g*-negation ground support equipment (GSE). For the primary deployment, the array was preloaded by tightening the RBA bolt. A stainless steel damper was installed in one P1 hinge. A crane was positioned above the P1 hinge line to provide support for the *g*-negation cable, and an “L” channel with holes along its length was attached to the inboard substrate to provide attach points for the crane. The *g*-negation cable attached at the center of gravity (CG) of the assembly. The crane was then used to offload the assembly mass. Once the pyro sepnut was actuated, the primary deployment took place, and the bolt was caught by the RBA. The array deployed and over-traveled, settling out in 22–30 s.

Next, the solar array was set on a stand, and the inboard L channel was replaced with an outboard substrate L channel. Two dampers were installed in the

Figure 7. Static load test configurations.

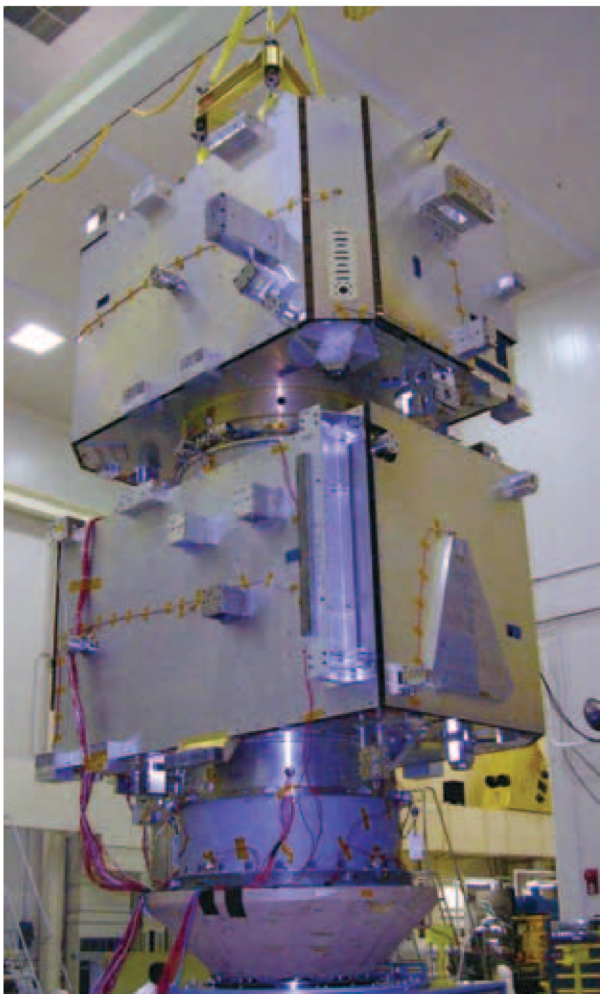


Figure 8. Spacecraft structure stack vibration load test.

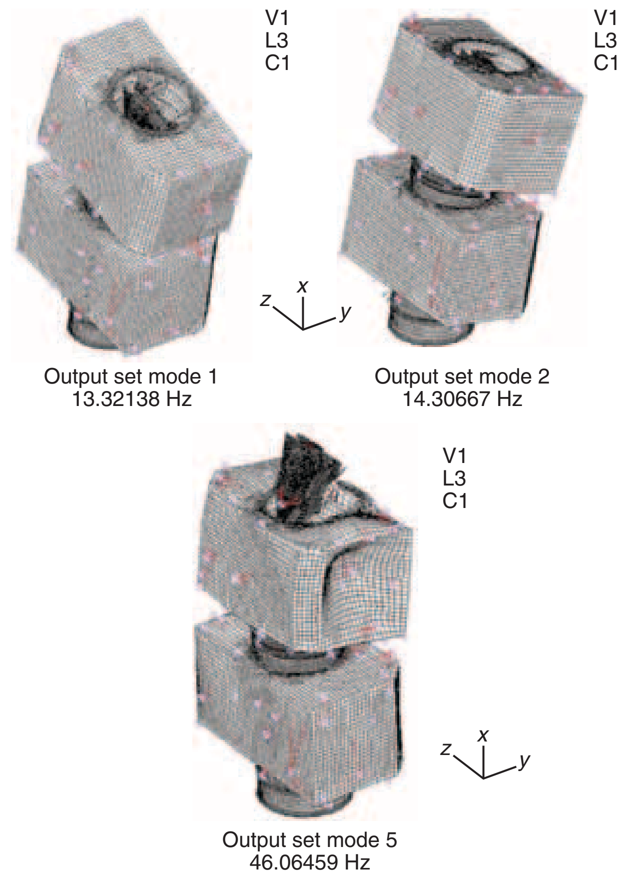


Figure 9. Structure vibration test predictions primary mode shapes.

P2 hinges before the primary deployment. The crane was repositioned above the P2 hinge line to provide support for the *g*-negation cable, and the *g*-negation cable attached at the deployed center of gravity of the assembly, offloading the assembly mass. Once the pin-puller was actuated, the secondary deployment took place. The outboard substrate deployed and over-traveled, settling out in 17–19 s.

HGA Deployment

The HGA assembly in its stowed position is shown in Fig. 12. The HGA assembly consists of a graphite composite HGA dish assembly, rotary actuator with bracket, rotary joint with bracket, titanium boom, Frangibolts with housings, Frangibolt interface brackets, rigid and flexible waveguide, and the hinge assembly. The HGA is held in its stowed position by three Frangibolts. The HGA is released by firing each Frangibolt separately. The +*x*, +*z* Frangibolt is fired first, followed by the +*x*, –*z* Frangibolt, and ending with the –*x* center Frangibolt.

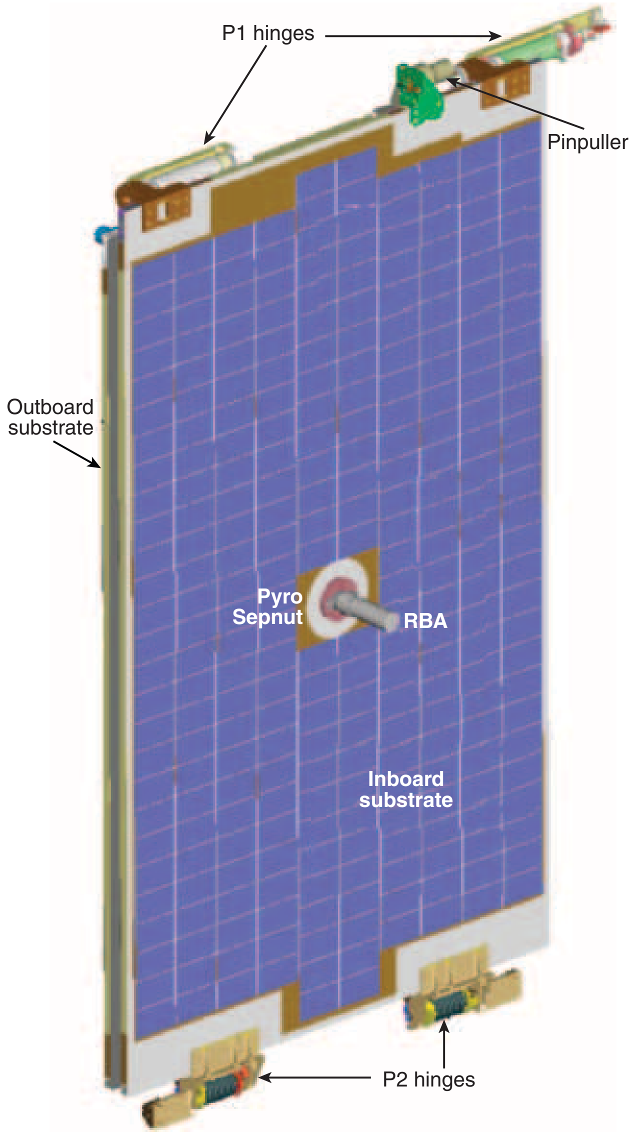


Figure 10. Stowed solar array subsystem illustration.

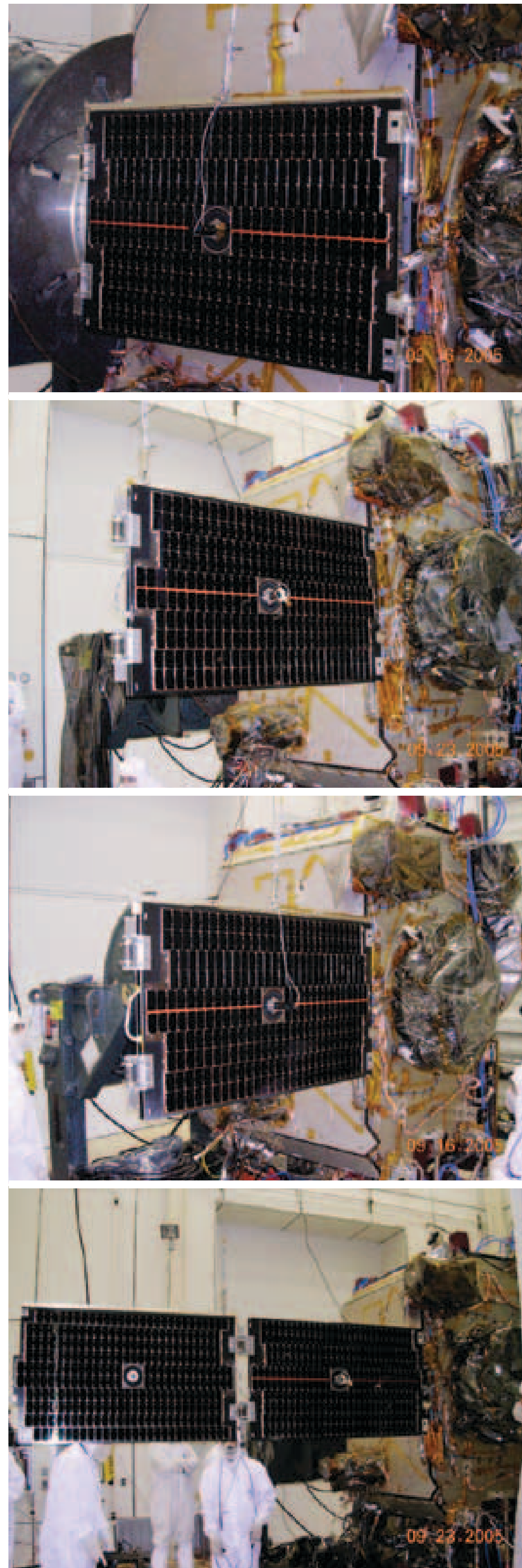


Figure 11. Observatory A +*y* solar array shock/*g*-negated deployment test.

The HGA separates once the third Frangibolt has fired. A preloaded Elgiloy torsion spring deploys the HGA to a position 90° from the stowed position. The spring will cause the HGA to over-travel past the 90° position, where deformation of a stainless steel torsion damper limits the over-travel angle. The spring is preloaded from both sides so that the HGA will settle to the 90° position, where the holding torque of the preloaded spring "locks" the HGA into its deployed position. The Moog rotary actuator allows the HGA dish to be rotated over a 180° angle as it tracks the position of Earth.

Observatory-level *g*-negated deployment testing was performed at APL before observatory-level vibration testing and at GSFC after observatory-level acoustic testing. The test configuration for Observatory B is shown in Fig. 13.

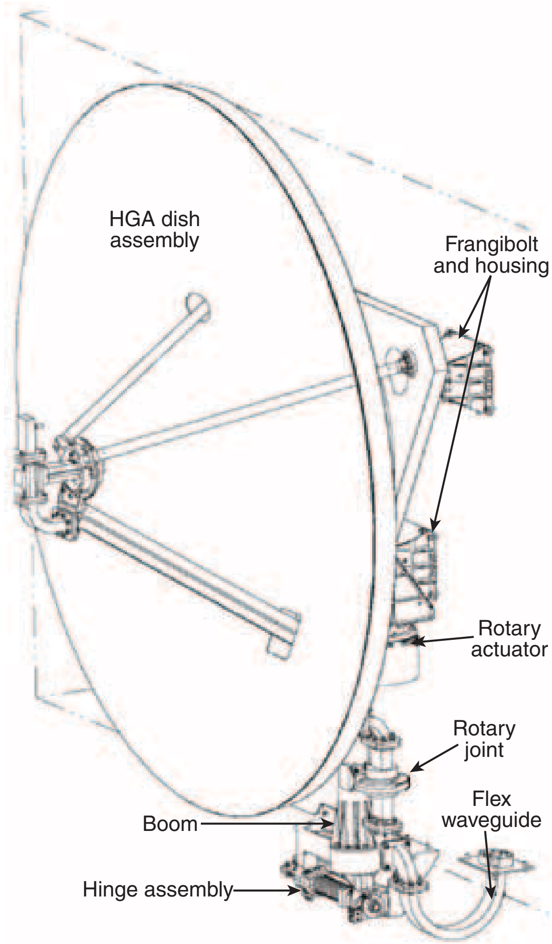


Figure 12. HGA assembly.

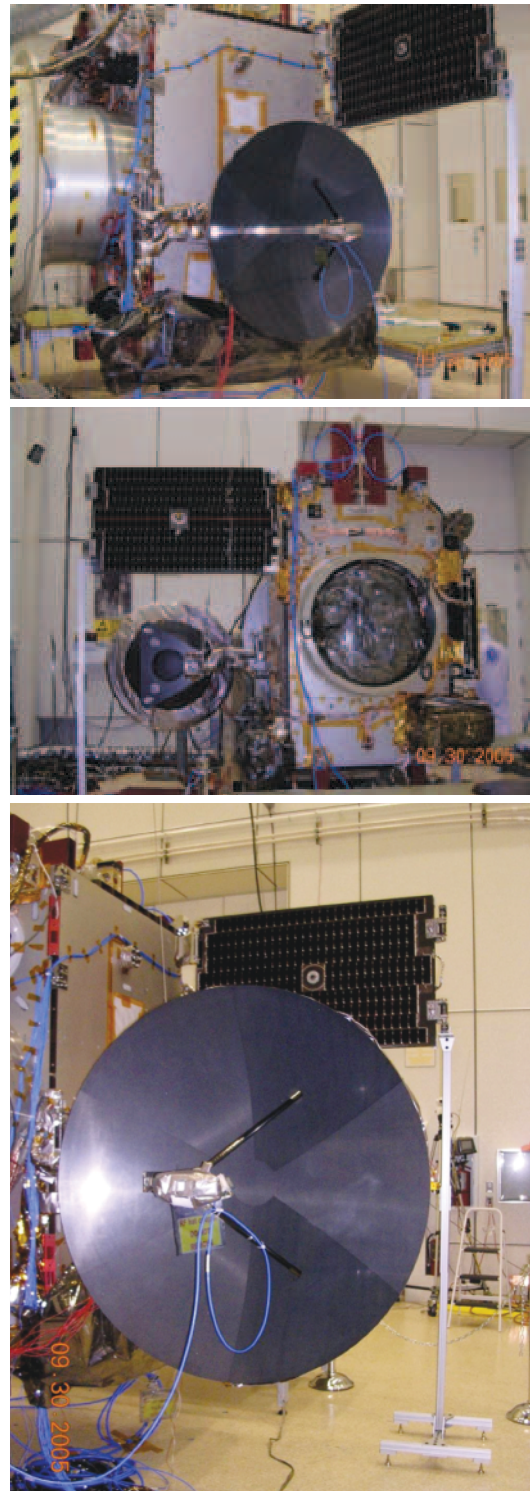


Figure 13. Observatory B HGA shock/*g*-negated deployment test.

Umbilical Door Deployment

The umbilical door assembly in its stowed (open) and deployed (closed) positions is shown in Fig. 14. The umbilical door assembly consists of an aluminum door preloaded with a steel spring on an aluminum shaft. This assembly is attached to the umbilical door bracket. The door is held open during launch by a TiNi P50 pinpuller. Once in space, the pinpuller is commanded to actuate, allowing the preloaded spring to close the door.

In the observatory-level umbilical door deployment testing, the pinpuller firing was actuated through the spacecraft with the umbilical harness in place and with a GSE firing box.

Solar Array/HGA/Umbilical Door Shock Results

At least 10 channels were used to record acceleration responses to the shock/deployment events. A summary of acceleration responses is presented in Table 2.

OBSERVATORY STACK/DELTA TPAF SEPARATION/ SHOCK TEST

The observatory stack/Delta TPAF shock/separation test was conducted on 20 October 2005. The test configuration is pictured in Fig. 15. Pre- and post-TPAF separation are shown in the middle and bottom parts of Fig. 15. Acceleration responses were recorded for 177 channels of data. A summary of acceleration responses is presented in Table 3. The separation test was performed twice to account for data scatter.

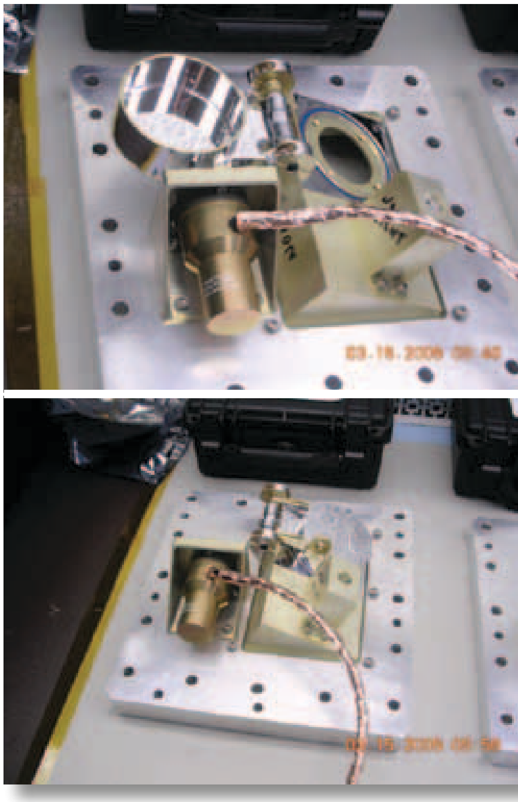


Figure 14. Umbilical door assembly.

OBSERVATORY STACK PROTO-FLIGHT SINE VIBRATION TEST

The STEREO observatory stack proto-flight vibration testing was performed in conjunction with base drive modal survey testing from 24 October through 1 November 2005. The purpose of the observatory stack vibration test was to verify strength and stiffness. All observatory vibration testing was performed at APL's VTL facility.

The stacked STEREO observatories are shown positioned on the vibration table in Fig. 16. The stacked observatories were nearly flight-configured with the exceptions of a mass simulator representing the heliospheric imager (HI) B instrument, water representing propellant, calculated balance mass, some missing electromagnetic interference (EMI) harness wrap, some lightweight instrument red tag items, lifting hardware on the top observatory, air conditioning ducts for the batteries, contamination bags for all 26 instruments, and the Delta II TPAF with clampband.

The stack test configuration weighed 2804 kg and included 34.5 kg of water in each of four propulsion tanks. Vibration testing was conducted by using the Mahrenholz and Partner (M+P) control and data acquisition system.

Three-axis proto-flight vibration testing was performed on the stacked STEREO observatories. The

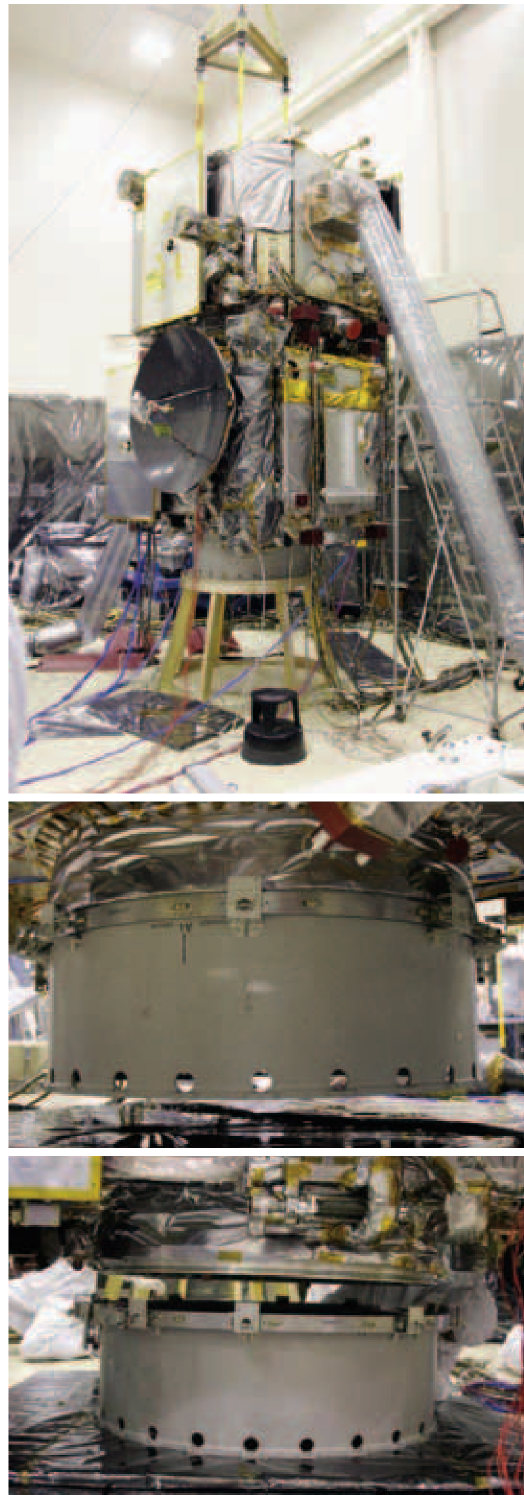


Figure 15. Observatory stack/Delta TPAF shock/separation test.

Boeing Delta II sinusoidal vibration specifications were applied with responses notched to 1.25 times the coupled loads response predictions. Pre- and post-test sine surveys show good linearity of the structure. Two hundred sixty-eight channels recorded acceleration responses from 112

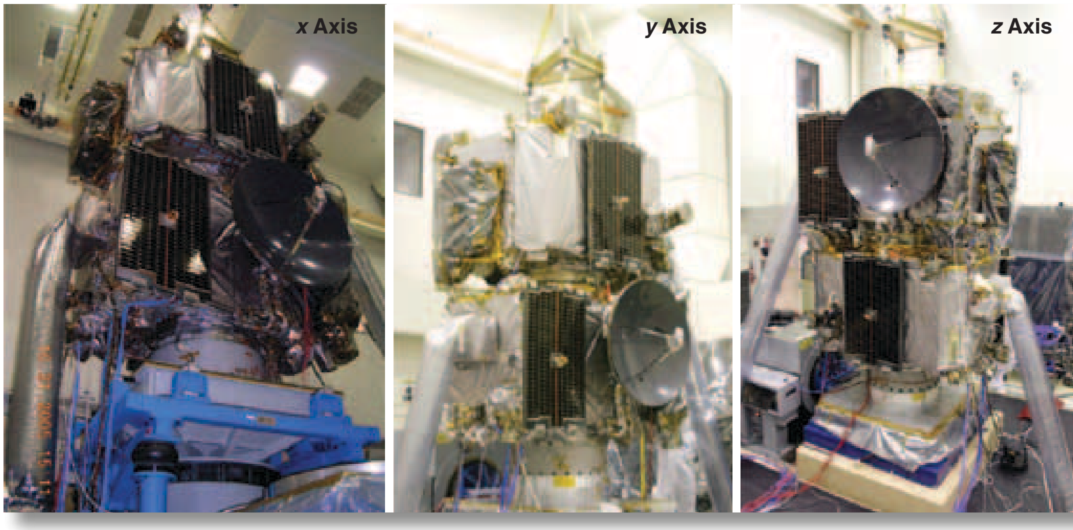


Figure 16. Observatory stack proto-flight sine vibration test.

Table 2. Solar array/HGA/umbilical door shock/deployment test acceleration response summary.

Shock/deployment test event	Location	Time history peak (g)[a]
Solar array P1	Near pyro sepnut	600
Solar array P2	Near P50 pinpuller	400
HGA	Near Frangibolt	500
Umbilical door	Near P50 pinpuller (door impact)	440

[a]g, acceleration due to gravity.

Table 3. Observatory stack/Delta TPAF shock/separation test acceleration response summary.

Observatory	Location	Time history peak (g)
A	Top of cylinder	17
A	Solar array	14
A	General	<10
B	Near SAAB	16
B	−*x* panel	140
B	+y panel near low-energy telescope (LET)	87
B	Solar array	27
B	HGA	19
B	Propulsion tank	74
B	SCIP bracket	82
B	General	<50

locations on the observatory stack. Measured responses were used to calculate a center of mass response for each observatory. Observatory A center of mass responses were calculated to be 3 *g* in the axial (*x*-axis) direction and 5 *g* in the lateral (*y*-axis and *z*-axis) directions. Observatory B center of mass responses were calculated to be 2.5 *g* in the axial direction and 2 *g* in the lateral axes.

A 78,949-element MSC/NASTRAN FEM was created to predict primary structural modes and responses of the STEREO observatory stack. The pre-test FEM, shown in Fig. 17, was created from the November 2004 STEREO/Delta II Coupled Loads model. An M+P Smart Office test modal model was created by using the geometry of 57 locations on the observatories where responses were

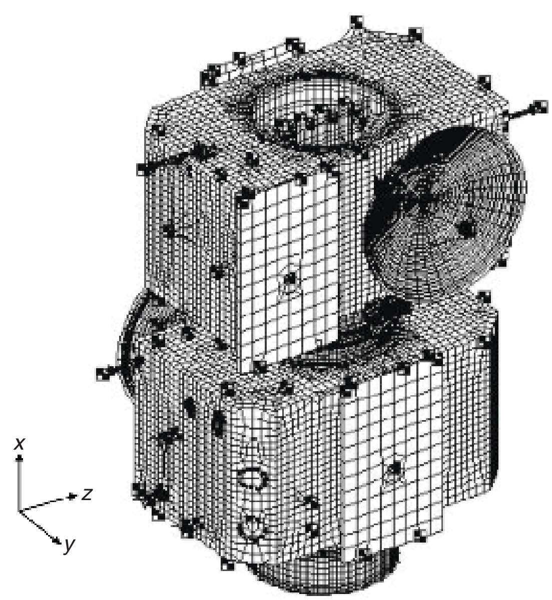


Figure 17. Observatory stack previbration test FEM.

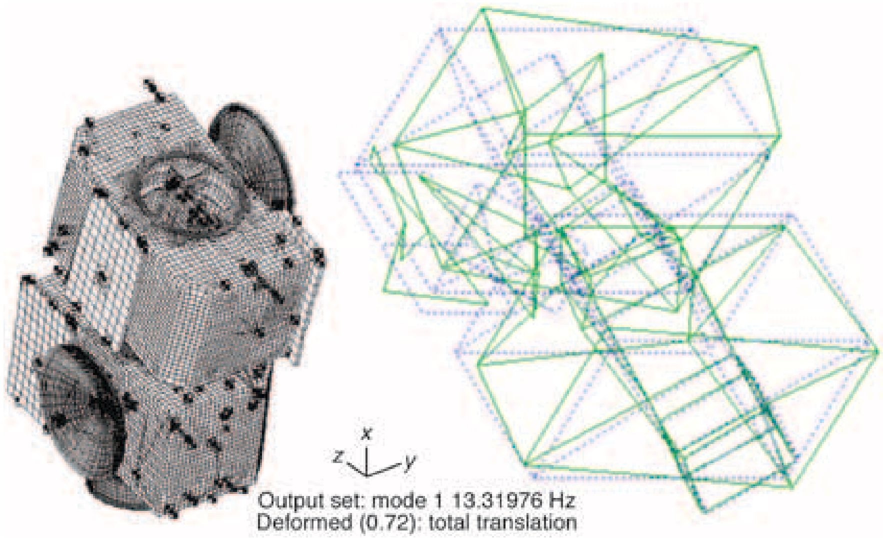


Figure 18. FEM and test mode shape mode 1 ($x = 0.1\ g$).

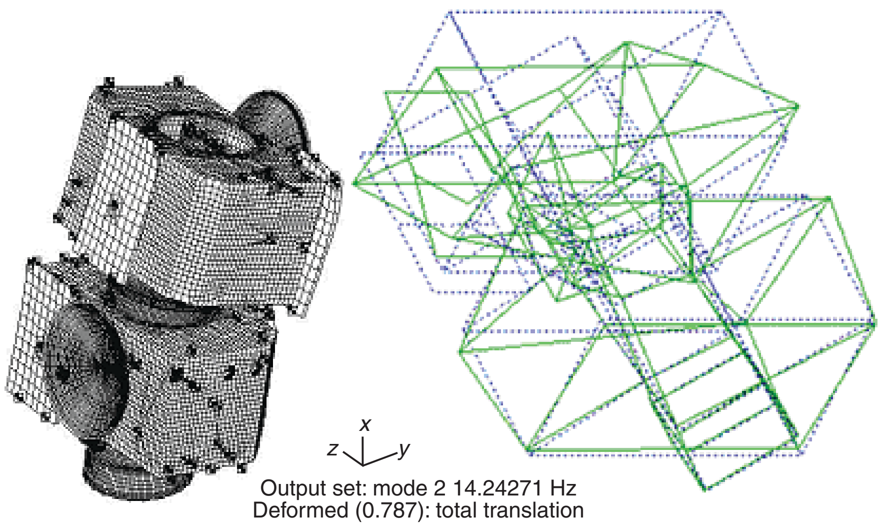


Figure 19. FEM and test mode shape mode 2 ($y = 0.1\ g$).

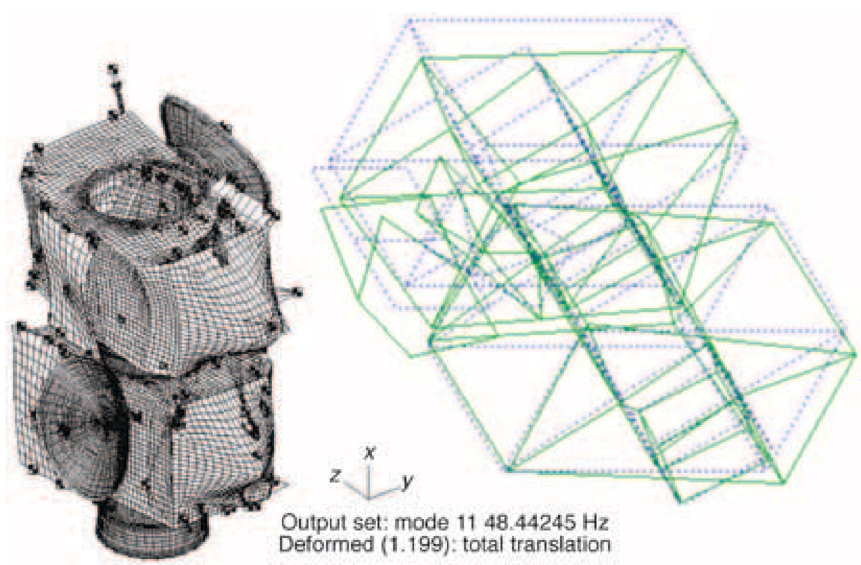


Figure 20. FEM and test mode shape mode 1 ($z = 0.1\ g$).

mapped in three translational degrees of freedom. FEM and test model primary mode shapes are plotted in Figs. 18–20. The undeformed test model is indicated by dotted lines. An overall summary of the primary structure modal correlation is presented in Table 4. Correlation is better for full-level testing, where the FEM damping is more accurately represented.

OBSERVATORY A/ OBSERVATORY B SEPARATION/SHOCK TEST

The SAAB Observatory A/Observatory B separation/shock test was conducted after the observatory stack vibration on 2 November 2005 at APL and after the observatory acoustic test on 17 November 2005 at GSFC. The test configuration is pictured in Fig. 21. Pre- and post-SAAB band separations are shown on the right side of Fig. 21. Acceleration responses were recorded for 179 channels at APL and 183 channels at GSFC. A summary of peak time history responses is presented in Table 5.

OBSERVATORY PROTO-FLIGHT ACOUSTIC TEST

Delta II proto-flight acoustic testing was performed at the NASA GFSC acoustic test cell on 15 November 2005. The stacked STEREO observatories are shown positioned in the acoustic cell in Fig. 22. The stacked observatories were nearly flight-configured with the exceptions of a mass simulator representing the HI-B instrument, water representing propellant, calculated balance mass, some missing EMI harness wrap, some lightweight instrument red tag items, a contamination tent, and the dummy PAF with band. The observatory stack was secured to a GSE dolly.

Table 4. STEREO observatory stack modal correlation summary.

Sine test	*x* = 0.1 *g*				*x* = 1.4 *g*			
Mode	1		2		1		2	
Data source	Test	FEM	Test	FEM	Test	FEM	Test	FEM
Frequency (Hz)	52	48	59	56	45	45	52	55
Input at base (*g*)	0.09	0.10	0.09	0.10	1.31	1.40	0.24	0.27
Obs. A response (*g*)	0.4	0.8	0.5	0.7	3.0	7.0	1.5	2.0
Obs. B response (*g*)	0.3	0.3	0.2	0.3	2.5	4.0	—	—
Structure damping (%)	5.5	5.0	3.7	5.0	8.4	5.0	5.0	5.0
Test/FEM correlation (%)	7.7		5.1		0.0		3.8	
Sine test	*y* = 0.1 *g*				*y* = 1.0 *g*			
Mode	1		2		1		2	
Data source	Test	FEM	Test	FEM	Test	FEM	Test	FEM
Frequency (Hz)	16	14	51	47	14	14	45	45
Input at base (*g*)	0.15	0.10	0.12	0.10	0.26	0.35	0.72	0.86
Obs. A response (*g*)	1.5	2.0	0.5	0.7	3.0	7.0	1.5	4.0
Obs. B response (*g*)	0.3	0.5	0.3	0.5	1.0	2.0	2.0	4.0
Structure damping (%)	5.3	5.0	4.4	5.0	4.9	5.0	7.2	5.0
Test/FEM correlation (%)	12.5		7.8		0.0		0.0	
Sine test	*z* = 0.1 *g*				*z* = 1.0 *g*			
Mode	1		2		1		2	
Data source	Test	FEM	Test	FEM	Test	FEM	Test	FEM
Frequency (Hz)	16	13	42	36	13	13	42	36
Input at base (*g*)	0.16	0.10	0.10	0.10	0.46	0.42	0.47	0.37
Obs. A response (*g*)	1.2	2.0	0.6	0.5	4.0	7.0	2.0	2.0
Obs. B response (*g*)	0.4	0.5	0.5	0.5	1.0	2.0	1.5	2.0
Structure damping (%)	3.2	5.0	2.5	5.0	3.6	5.0	3.2	5.0
Test/FEM correlation (%)	18.8		14.3		0.0		14.3	

Table 5. SAAB shock/separation test acceleration response summary.

Observatory	Location	Time history peak (g)	Observatory	Location	Time history peak (g)
A	Top of cylinder	198	B	+*x* panel	56
A	−*x* panel	204	B	+*y*, +*z* chamfer panel	119
A	Near SAAB	759	B	+*y* panel near low-energy telescope (LET)	61
A	Solar array	171	B	−*x* panel	74
A	HGA	56	B	Near SAAB	500
A	Propulsion tank	216	B	Solar array	107
A	SCIP bracket	227	B	HGA	34
A	SCIP	65	B	Propulsion tank	247
A	General	<44	B	SCIP bracket	385
			B	SCIP	99
			B	General	<50

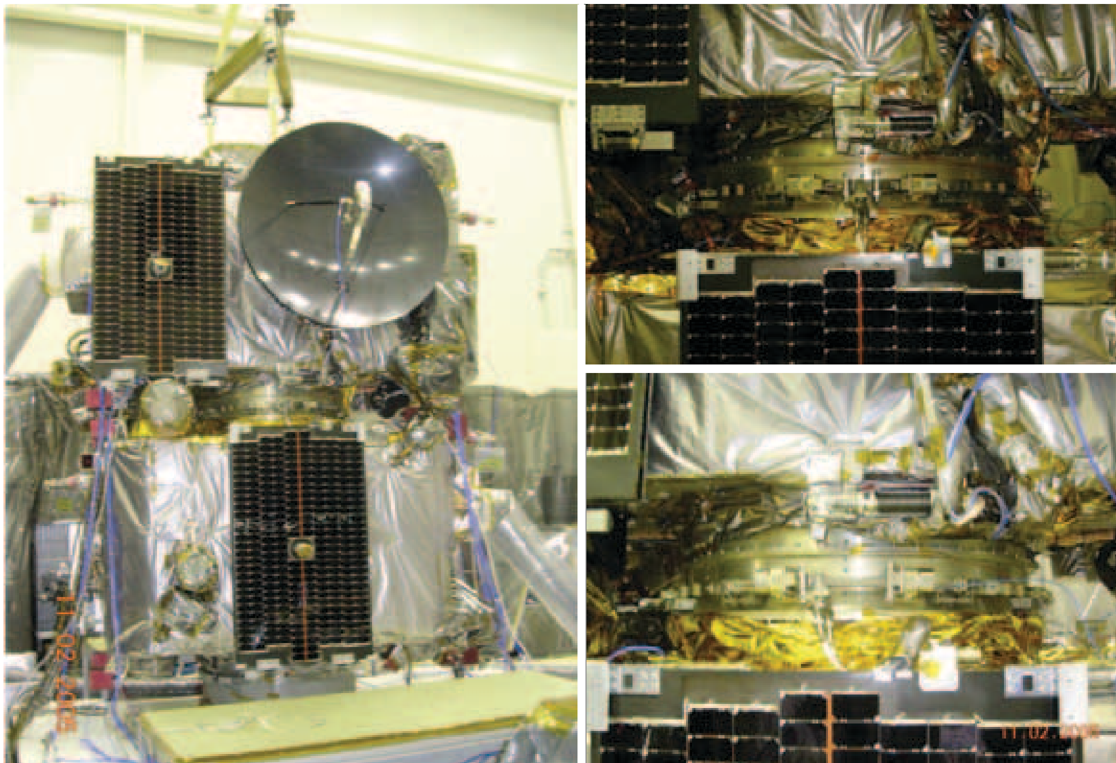


Figure 21. SAAB shock/separation test.

Figure 22. STEREO observatory stack acoustic test configuration.

Figure 23. Stacked STEREO observatories, spin balance and vertical mass properties configuration with water-filled tanks.

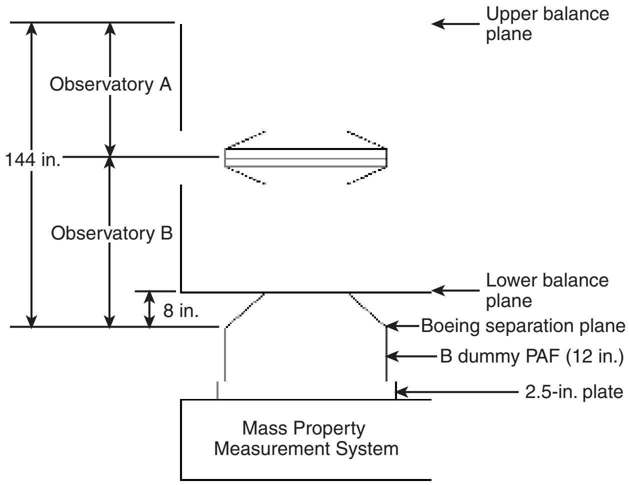


Figure 24. Stacked STEREO observatories balance mass planes.

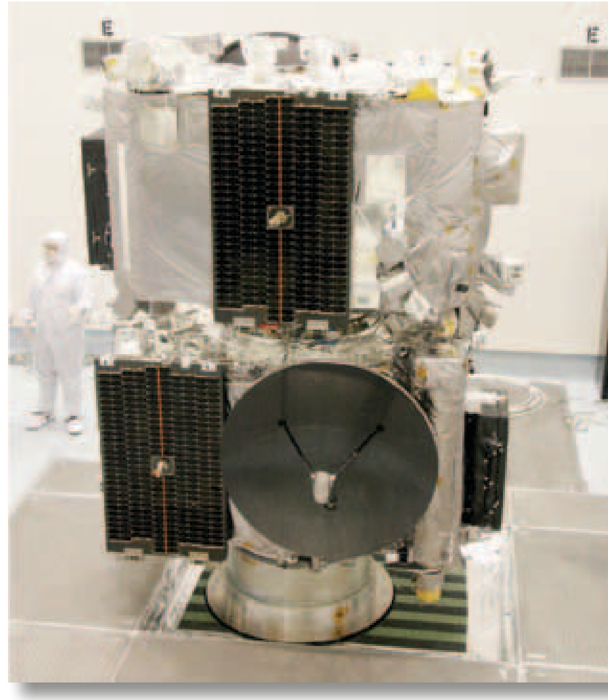


Figure 26. STEREO observatory stack final spin balance operations.

OBSERVATORY STACK SPIN BALANCE AND MASS PROPERTIES

Observatory stack spin balance and "wet" (water-loaded) *x*-axis mass property tests were performed on 2–13 December 2005 at GSFC. Observatory A "dry" mass property tests were performed on 5–13 April 2006. Observatory B "dry" mass property tests were performed on 21–25 April 2006. Mass properties were measured for 13 configurations (test fixture and flight structure). All tests were conducted in the GSFC Building 7 cleanroom.

The observatory stack spin balance/*x*-axis wet mass properties configuration is shown in Fig. 23. The stack is configured as it was for acoustic testing. The balance mass planes for the observatory stack are depicted in Fig. 24. Spin balance operations were performed, and a total of 26.45 kg of balance mass was required to balance the stack. The upper balance plane was located at the +*x* panel of Observatory A, and the lower balance plane was located at the –*x* panel of Observatory B. Of the 26.45 kg of balance mass, 15.84 kg was attached to the lower plane, and 10.61 kg was attached to the upper plane. Observatory mass property configurations are pictured in Fig. 25. The dry mass properties configurations did not include solar arrays but did include the flight HI-B. Test data were used to calculate flight mass properties for 8 launch and 12 orbit configurations.

Final post-propellant load spin balance operations were conducted on 11–12 August 2006 at the Astrotech

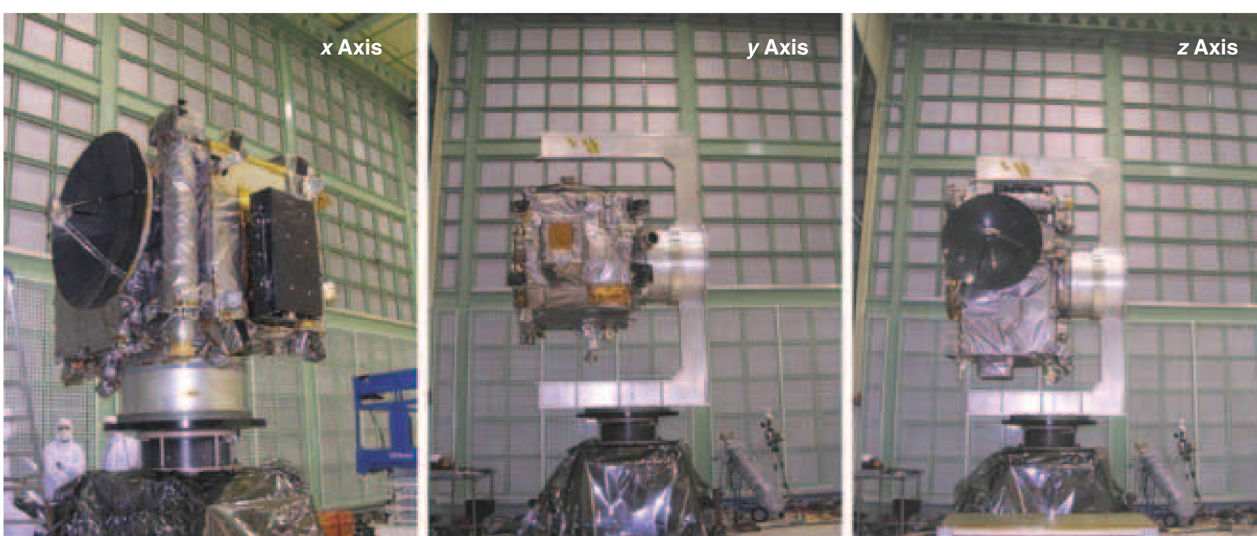


Figure 25. STEREO Observatory B mass properties configurations with empty tanks.

facility in Titusville, Florida. The better accuracy of the Astrotech Spin Facility resulted in removal of 1.12 kg of balance mass from the stack. The final 1281-kg flight-configured observatory stack is shown in Fig. 26.

SUMMARY

The STEREO mission and launch vehicle requirements made for a challenging verification program. Qualifying two observatories with multiple deployments resulted in many test and analysis configurations. A large amount of instrumentation was required to properly monitor the observatories and their instruments and components during vibration, acoustic, and shock testing. The analysis and test methods used to verify pointing stability, structural strength and stiffness, robustness to shock and acoustic environments, and spin balance and mass properties have been presented in this paper. The structural qualification test program took place from October 2003 through August 2006.

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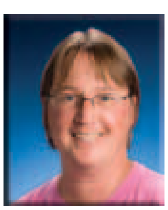

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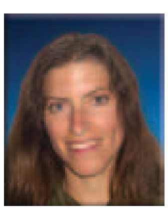

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