Stacer Driven Deployment: The Stereo Impact Boom

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Abstract

The Impact Booms carry 3 scientific instruments each on the twin NASA Stereo satellites. When stowed for launch the boom is 1.54 m in length, when deployed the boom extends to 5.80 m. The boom consists of 5 concentric graphite epoxy (Gr/E) tubes extended by the spring force of a Stacer. The Stacer is fabricated from a flat strip of Elgiloy® spring material, rolled with a constant diameter and fixed helix angle. It supplies the motive force for deployment, and requires no external power once released. The deployed boom exhibits excellent rigidity, the natural frequency first mode occurring at 1.96 Hz. Discussed is the implementation of a Stacer to deploy the 5 segment telescoping boom and some of the activities performed during its design, qualification and testing.

Mission Introduction

The NASA Stereo mission consists of twin, three-axis stabilized satellites orbiting and viewing the Sun in the plane of the ecliptic at ~1 AU. Spacecraft A (Ahead) will be sent into an Earth preceding path with an Earth-Sun-Spacecraft angle increasing at a rate of 22° per year, while Spacecraft B (Behind) is sent into an Earth lagging orbit, also at a rate of 22° per year. The imagers on board will yield true 'stereoscopic' views of coronal mass ejections, while other instruments perform concurrent in-situ measurements of a large portion of the electro-magnetic spectrum. The telescoping boom was conceived to interface 3 instruments from the Impact suite: the Magnetometer (Mag), the Solar Wind Electron Analyzer (SWEA), and the Supra-Thermal Electron – Downward looking instrument (STE-D) to the Stereo spacecraft. The program requirements demanded a new concept, as existing hardware was deemed too expensive or unsuitable. The boom was initially developed via three 'proof of concept' models for the tube locking mechanism, and a final mock up using the Stacer to deploy four concentric, telescoping graphite/epoxy tubes from the center of the fixed 5th tube. An engineering model (EM) was then built to verify end to end design via qualification testing. The challenge for this mechanism was demonstrating that the design met the requisite GEVS SE force (torque) margin. Two flight models (FMs) were then produced, with the EM being refurbished as a flight spare. The FMs are currently mounted to the spacecraft and mission I & T is progressing. Launch is scheduled for May 2006 from Cape Kennedy on a Delta II.

Figure 1 Magnetometer, SWEA and STE-D mounted on the end of the (stowed)

Figure 2. Magnetometer

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1 Space Sciences Lab, University of California, Berkeley, CA

1 In-situ Measurements of Particles And Coronal mass ejection Transients

2 Solar – TErrestrial RElations Observatory

3 See References Section

The Science Flowdown Requirements

The requirements for the Impact boom were based on the scientific needs of the three instruments mounted to it: the Mag (built at Goddard Space Flight Center); the SWEA, supplied by CESR, Toulouse, FR; and the STE-D, supplied by UCB - SSL. The magnetometer for this mission is very sensitive: the magnetic \( B \) field at 1 Au heliocentric orbit is \( \sim 3 \) to \( 4 \) orders of magnitude smaller than near Earth. This slight field strength was a driver for the EMVEMC design for the spacecraft and the devices near it. To avoid 'sensing' the spacecraft, the Mag needed to be 3 meters away from it. This requirement set the minimum boom length. To ensure a low magnetic signature from the boom assembly, no ferritic alloys were allowed for its construction.

Titanium screws were used to mount the magnetometer to its tray on the 4\textsuperscript{th} tube element and the tray itself is made of carbon impregnated PEEK, a high-strength, conductive engineering plastic. To lower Mag exposure to any eddy currents present in the harness or structure of the boom, the mounting tray offset the Mag 200 mm from the nearest metal on the tube. Additionally there were not to be any other instruments closer than 1 m to the Mag. To allow accurate inter-experiment correlation of data, the angular alignment accuracy and repeatability requirement has an allowable deviation of \( \angle 0.88' \) (52.5 arcmin) between the Impact boom mounting feet and the magnetometer housing from the stowed condition to the deployed state, for the two axes that form the mounting plane of the Mag.

The second experiment mounted on the Impact boom is the Solar Wind Electron Analyzer (SWEA, supplied by CESR, Toulouse, FR). The SWEA has two variably charged hemispheric surfaces that attract electrons into an anode assembly which counts them as they impinge on to it. The SWEA would have a limited field of view when mounted directly to the spacecraft deck, hampering its ability to characterize the electron regime in the volume around it. Proximity to the spacecraft also causes deflections of the electrons due to the almost unavoidable static fields that develop near the spacecraft surface. Since this effect is difficult to model, a better solution was found. The implementation of the SWEA on the Stereo mission is extremely good: it is mounted on the extreme end of the boom, allowing a full \( 2\pi \) radians x 135\textdegree field of view (FOV). The demands of the SWEA for mounting to the boom are not complex: power lines, command lines supplied to it, data return lines from it.

The final instrument is the STE, a Supra-Thermal Electron detector, mounted on the side of the SWEA pedestal. It needs a clear 80\textdegree x 80\textdegree field of view looking along the plane of the ecliptic at a 45\textdegree angle (aligned with the Parker spiral), and to stay at \( \sim -40 \) C.

The fixed base of the Impact boom is pointed towards the Sun for all science activities, and the only off-points scheduled are for momentum dumping. The boom deploys away from the Sun, so that there is minimal solar input to the boom suite, giving very low operational temperatures for the instruments. Thermal control was a large concern for the instrumenters.
Impact Boom Mechanism

The Impact Boom consists of five concentric Gr/E Tubes, ranging from 50 mm to 210 mm in diameter, with a pair of aluminum rings bonded to each end. Each ring pair contains three lock pins, pointing outward at the Sun-ward end, and inward pointing at the release mechanism end, and three sockets, in their corresponding orientations. The pins are spring loaded, and have rollers mounted in their tips. When released, the Stacer spring extends the tubes until the end of travel where the pins drop into sockets, locking the assembly rigid. The mounting feet are integral to the outermost rings on the Ø210-mm tube. There is a spool for the electrical harness while stowed, a flyweight brake to govern the deployment speed, a shape memory alloy release mechanism with pretensioning adjustment, deployment assist rods and kick springs to initiate the deployment. Combs at each end hold the tubes in alignment prior to deployment, and during vibration/launch. A provision for individually adjusting the combs to remove any play in the stowed tubes due to fabrication tolerances is also provided. The design was performed in Solidworks™, utilizing its 3-dimensional solid modeling and multiple configuration capabilities.

Tube Details

The use of telescoping concentric tubes is not a new idea. Each telescope application brings its own set of challenges however. For the Impact Boom, the tubes needed loose tolerances on their cylindricity callout to allow for simple tube manufacture. The deployment / locking scheme required compliance regarding the inter-tube fit since there is a relatively low force available from the Stacer. The boom needed to be very rigid when deployed, so locking pins were utilized at end of travel, rather than relying on spring force to hold them in place. The tubes have three longitudinal concave grooves equispaced about their circumference, running their length, with a precise profile that doesn’t jam the rollers. These grooves kept the pins on track to be aligned with the sockets at the far end of the tube. The tubes are a five-layer Gr/E composite designed to be quasi-isotropic: three 0°-90° layers interleaved with two 45° layers of 0.12-mm woven epoxy pre-impregnated material (Fiberite Hy-E 1034C prepreg). The tubes were fabricated by Vision Composites of Signal Hill, California on internal mandrels, with a slight taper to enhance ease of extraction after cure. The cure regimen was specified to be ‘dry’: the ratio of epoxy to carbon filament was held to a minimum to ensure low surface resistance. This was achieved by using a higher autoclave pressure with a slower ‘warm up to cure’ temperature ramp and a thick layer of absorbent over the bleeder sheet. The process determination was somewhat lengthy, however, the final result met requirements.
At both ends of each tube there are inner and outer interlocking aluminum rings that 'sandwich', and are bonded to, the Gr/E. After an extensive search, Loctite Hysol 9309NA was used to form the bond. The thermal environment for the boom is rather severe: it will be in the shadow of the spacecraft for all of the science activity; thermal analysis estimates put the operating low temperature at 30K. There is very little data for epoxies at this temperature, so we performed an FEA for the bond between the aluminum and the Gr/E to establish what parameters minimized the stresses in the glue, the weakest part. Several cases for the glue design were examined: thickness of the bond, edge conditions of the bond and effects of the aluminum ring thickness (internal and external) on the joint stresses. Optimized, the glue line was chosen to be ~0.4-mm thick, with a fillet onto a tapered aluminum ring edge. This best case predicted a stress value of 110\(\text{MPa} (16 \text{ksi})^4, which exceeded the glue published maximum stress value of 38 \text{MPa} (5.5 \text{ksi})^5.

There was concern that the joint would not be sound after exposure to the thermal gradient, so an actual test was needed. A test GR/E tube / aluminum ring assembly was fabricated, with a large cantilever mass attached at the extremity providing ~2X expected loads for this test. This test 'tube' assembly was installed in a cryogenic liquid helium chamber, which was then installed into a cryogenic liquid nitrogen chamber in turn was placed inside of a refrigerated chest. We performed a multiple cycle thermal test (in a dry air environment), utilizing four candidate glues. The cold temperature was set to 25K (-248°C), and warm was 150K (-123°C). The 9309 performed nominally, with no crazing or cracking and was accepted for use. As a side note, only one of the tested epoxies exhibited any signs of thermal distress. As a hedge against exceeding our thermal predicts, small solar absorbers were attached to the two joints in the mid boom. These little flags raise the expected temperature by ~5 degrees, buying some margin for the assembly (Figure 6).

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4 Besuner Consulting, Madera, CA 93638
5 Loctite Hysol Applications Note, April /01, Loctite Aerospace, Bay Point, CA 94565
Lock pin details

Once the rings are bonded to the tubes, the locking pins / rollers are installed into precision radial bores in these inner and outer rings. When the segment locks, the pins are pushed into the sockets by custom wound torsion springs, two for each pin. The 'arms' of the springs also provide alignment for the pins, keeping the roller in the groove. The pin / roller combination allows any tube dimensional change to be insignificant during the deployment, as the spring compliance takes up any bumps or dips. When the tube section reaches end of travel, the locking pins are pushed into tapered holes, causing the tubes to become rigid with respect to each other. Guide ramps are provided at the end of travel to ensure that the pins are aligned with the sockets. Each locking pin has a slight taper (i.e., <20° included angle) that fits into the corresponding tapered socket. This gives a 'self-locking' feature to the pin, offering increased rigidity and prevents the pins from backing out under slight vibrations. With six lock pins engaged per joint, three inward acting, three outward, the boom exhibits great rigidity, and offers redundancy in the event that one pin (or more, up to three maximum, as long as they are not in same ring) does not lock.

Rollers are fitted to the tips of the locking pins to minimize deployment drag when rolling in the tube's grooves. Repeated deployments have shown no signs of wear to the tube or the rollers. To provide conductivity, the tapered portion of the pins and sockets were Alodined, while the sliding cylindrical parts were Type III black anodized to give good wear and low friction sliding properties. The Gr/E exhibits a low surface resistance too, enabling the boom to easily meet the surface resistance requirement of $<10^6$ ohms per square, throughout its stroke. The drag was measured to be 3.1 N on average for the assemblies. The main function of the rollers is to keep the tubes aligned during deployment, so that the pin engagement is virtually guaranteed at the end of stroke.

Shape Memory Alloy Release (SMAR) details

The SMAR uses the interesting phase change properties of a 50% titanium – 50% nickel alloy (trade named Nitinol initially) to provide the actuation of the Impact Boom. This device, pioneered by TiNi Aerospace in cooperation with UCB-SSL, takes advantage of the -4% dimensional change in the drawn alloy wire when heated above its transformation temperature to let a ball detent assembly release a large spring loaded retracting pin. Since there was a large design load (50 Gs), >2.5 kN retraction force was needed. A force amplifier was added to the TiNi standard P50 (~200-N [50-lb] pin puller). The force amplifier contains a stack of Belleville washers, preloaded and held by the P50 pin in another ball detent assembly, providing a final pull force exceeding 3 kN. When an electric current is passed through the Ti-Ni wire, it changes phase, elongates, releasing the primary pin, which then retracts and releases the main pin, which retracts with great force, allowing the Stacer to deploy. The main benefit of using an SMAR, aside from increased safety as no explosives are used, is that the flight unit can be tested over and over again (hundreds of cycles), and is simply resetable with a hand tool, with no temperature or time dependant constraints.

Flyweight Brake

After the SMAR has been triggered, kick springs push the tubes out of the combs and the deployment assist device pushes the Stacer out of the canister with a force of ~90 N, giving the assembly a good initial velocity. The Stacer continues to provide force throughout the travel, so the deployment velocity would continue to increase until a balance between drag and push is achieved. This balance is never reached by the boom, so the deployment velocity reaches a 'run-away' condition rapidly, with the possible issues of lock pin shearing, ring-tube separation or other damage as consequences. As with every Stacer, a means to limit deployment velocity is incorporated. For the Impact Boom, a flyweight brake mechanism is attached to

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6 TiNi Aerospace, San Leandro, CA 94577
the Stacer via a woven Dacron (parachute shock) cord. Similar to the device found on (old) dial telephones that prevented the dial from being rotated faster than an old telephone exchange could count, the flyweight brake supplies braking force proportional to the rotational speed of its weight assembly. If the force (speed) increases, the brake shoes are centripetally accelerated against the brake drum, increasing the braking force and slowing the rotational velocity. Over a wide range of forces, the brake typically can control the speed to ±10%. For the Boom, a deployment velocity of ~0.5 m/s was chosen. This allows a certain momentum to build, but is slow enough to avoid shearing damage to the lock pins at the end of travel.

Harness and Spool
The power and electrical signals between the data processing unit and the instruments are carried by a cable routed down the center of the tubes, and is stowed on a spool for launch. This harness is a custom-fabricated conductor assembly consisting of seven coaxial cables and five twisted shielded pairs. Built of silver-plated copper with Gortex® dielectric, the harness is wound onto a bobbin when stowed and is pulled off when the boom deploys. This 'straight through' design provides greater signal strength, higher reliability and allows longer harness length as there are no slip rings or other connections between the data processing unit and the instruments. Care is taken to prewind the harness to avoid kinking or 'birdnesting' when stowing.

The Stacer
The Stacer is a rolled, constant helical pitch, fixed diameter flat spring. The strip width, thickness, roll diameter, and helical pitch are selectable for each application, allowing each Stacer to be tailored for optimum properties. Stacers range in size from <1 m to >10 m in length, from 4 mm to 55 mm in diameter at the tip, and can provide extensive force from almost nothing to 200 N. Trade studies can balance mass versus length, force, etc. In the last 30 years, more than 650 units have been utilized in aerospace applications, from sounding rocket sensors to gravity gradient booms with large masses on the end. What makes the Impact Boom unique is the use of the Stacer as a spring 'motor' without using it as the structure or sensor surface. Most applications have the Stacer with the sensor(s) mounted directly on it, or the Stacer as the sensor, for example as an antenna (a total of six 6-m-long beryllium copper Stacers are used on the Stereo satellites for the Swaves experiment in this manner).

To accommodate the Mag requirement of low magnetic signature for the boom, Elgiloy® was selected as the spring material over the more traditional beryllium copper (Be-Cu). This alloy was chosen to minimize any eddy currents that could be developed between the SWEA / STE and the spacecraft. Originally invented in the late 1940's in Elgin, IL for use in watches, it has been used for exacting Stacer applications several times. Its internal resistance is higher than copper, and cuts down the eddy currents accordingly. It has a higher modulus (E), and can provide greater force in the same physical volume as the Be-Cu. Elgiloy is a cobalt 'super-alloy', having an E ~190 GPa and a yield strength of ~1600 MPa⁷.

At deployment, the formation of the Stacer starts with the initial coil winding out of the storage canister onto a cylindrical tip piece, which is slightly larger than the free coil diameter of the Stacer. Thus the Stacer grabs the tip piece tightly, and the subsequent coils ‘stack’ up on the prior, producing the characteristic spiral appearance. The typical helix angle provides for significant overlap, such that a section taken at any point along the Stacer would yield at least two thicknesses of strip material. Since the ‘outer’ layer of strip is rolled to the same diameter as the inner layer, the outer grips the inner with a force normal to the surface. So between layers, significant inter-coil friction exists and prevents inter-coil slipping for small disturbances. This gives the Stacer one of its more useful properties: it behaves as a thin walled tube for small displacements, with similar bending strength and stiffness. If a larger displacement occurs, the coils slip, dissipating the strain energy, serving as a friction damper. The damping ratio value is typically 5 – 15% for the non-slipping regime, and can reach 30 – 40% with the slipping. Of course, the displacement limit is buckling, as any tube would experience when taken beyond its yielding strength.

As described, the motive force for the deployment is a Stacer. When compressed (stowed) it is a very compact package: it fits in a cylinder Ø50 X 130-mm long. When the Stacer is stowed, the strip is flexed into the canister, laying each coil inside its predecessor, and wound tightly to the outside of the can. When released, this stored strain energy is reclaimed, giving the motive effort needed to move the tubes along their path. The Stacer generates a higher force at the beginning of stroke, ~46 N for this application, and the force curve dropped to 1 N at the end of stroke (this was an isolated minimum value obtained from one force test). The force that the Stacer provides is shown in the polynomial fit curve in Figure 13.
For the purposes of torque (force) margin analysis, the initial push is 45 N, final thrust 18 N (the lowest value obtained). This lower value was used to bound the design force available for deployment. The Torque (force) Ratio ($t_R$) requirement from GEVS SE (Sec. 2.4.5.3) is:

$$t_R = \frac{t_{\text{avail}}}{t_{\text{required}}} \geq 3.0$$

(Equation 1)

and the Torque (force) Margin ($t_M$) requirement from GEVS is:

$$t_M = \frac{t_{\text{avail}}}{t_{\text{required}}} - 1 \geq 2.0$$

(Equation 2)

for systems dominated by resistive torques due to friction. This assumes worst case for the boom, taking the lowest force for the Stacer and applying it to the entire stroke. There is additional margin as there is a significant mass at the end of the boom SWEA / STE-D which contributes momentum towards full deployment stroke. Using the given values it can be shown that the force available, the minimum Stacer force of 18 N, divided by the force required, the tube drag of 3.1 N yields a torque ratio of 5.8, and a torque margin of 4.8. The Stacer satisfies the force requirements by analysis. Still, the device must show functionality to prove that manufacturing has been in accordance with design.

The graph shows the need for a deployment initiator. The stowed Stacer is in a ‘meta-stable’ condition. If left by itself, it would partially deploy in either direction, therefore a back plate on the canister is required. To ensure that it deploys a deployment assist device (DAD) is incorporated. The final upturn in the force curve is an artifact of how the force was measured. The Stacer in this case is 5-m long, and when it is fully deployed, the coils have tightened onto themselves. The force value was taken at the moment the Stacer began to slip back into the canister. For this case, the coil needs to be expanded significantly, and requires greater effort.

There is an additional use for the Stacer after deployment as the secondary EMI/EMC shield. While each of the conductors in the harness is shielded, the mission’s low noise requirement demanded a second, ‘over-shield’ for all conductors. Since the harness runs down the center of the Stacer, the Stacer was tied to ground, and serves this purpose.

Deployment Sequence

Deployment is initiated when a TiNi Aerospace shape memory alloy release device (SMAR, Model P50-810-1RS) is triggered causing the restraint pin to pull out of the tail of the Stacer tip piece. To give the stacer and tube deployment an initial ‘kick’, a deployment assist device (DAD) is incorporated between the SMAR mount plate and the 50-mm tube base. The DAD consists of three long coil springs compressed when stowed, and when released provide ~90 N of push at the very beginning of the stroke. After the first 100 mm of travel, the initial coils of the Stacer are fully formed around the tip piece, and the flyweight brake has been spun up to speed. At this time the DAD has completed its stroke. The Stacer is attached to the base of the 50-mm tube via a swivel, allowing the Stacer to wind down while extending, recapturing the strain energy stored when the Stacer was wound ‘out’ against the canister. At the end of the 50-mm tube travel, the six lock pins pop into their sockets, and transfer the Stacer push force, as well as momentum, to the 90-mm tube, pulling it along until it latches; the process continues with the 130-mm tube and the 170-mm tube, and finally the entire four tube rigid assembly locks onto the 210-mm tube, which is fixed to the spacecraft. While the actual sequence follows this description fairly closely, occasionally the tube drag would cause one or another tube to partially deploy. There is no provision or requirement for any tube to deploy in any set sequence. To control the velocity of the tubes during deployment, the flyweight brake is attached to the 50-mm tube via a lanyard, limiting the speed of deployment to ~0.5 m/s, giving a total deployment time of ~10 sec. There are position alignment blocks for stowed (launch) condition holding the tubes aligned.
relative to each other, and carrying the vibration loads. These also incorporate ‘kick’ springs to aid in their deployment, and to alleviate any possible “stiction” from the alignment blocks.

The boom is not retractable once deployed. Re-stowing is achieved by removal from the spacecraft, and hand retraction of each set of pins followed by each tube segment being (de) telescoped; after which the Stacer is compressed into its canister; and the harness and flyweight brake are rewound. Finally, the SMAR is reset reinstalled, and preload is set.

Verification

The Impact Boom’s qualification activities were based on GEVS SE, as modified by JHU-APL for mission specific needs. The test regime selected for the Stereo mission was Protoflight, meaning new (unflown or non-heritage) hardware is tested with a combination of prototype (EM) levels (i.e., temperature or vibration) with flight (FM) durations. This method is typically used to shorten development times by eliminating the engineering / qualification model fabrication and test period. However, the Impact Team did build up an engineering model, and tested all 3 assemblies to the protoflight levels. The main changes and additions pertinent to this paper: Level 300 cleanliness, UV + Visible light inspection, no silicones used for fabrication, and testing for silicone residuals. Vibration levels were taken from the Delta II user’s manual* modified by APL analysis for the ‘stacked’ configuration. Stringent EMI/EMC levels were levied, due to the extremely sensitive radio receiver and magnetometer on board.

Testing procedures were standard NASA mission fare. The main tasks to be performed for this application were: demonstration of sufficient force (torque) margin for extension of telescoping sections throughout the Boom’s stroke; thermal design validation at 25K (discussed previously); and thermal vacuum cycling and deployment verification at hot and cold operational temperatures.

As the team worked on the testing it became clear that Stacer thrust force is not easy to measure accurately or repeatably. The deployment of a Stacer is a ‘stick – slip’ affair: and once stopped, it sticks, then when released slips, giving a wide range of force values due to the hysteresis built into the inter coil friction. For consistency, the force value used at any point was the force needed to start the Stacer being pushed back into the canister, after overcoming the ‘stiction’. This does not accurately convey the sliding force, but is as close as can be statically measured. Attempts to measure Stacer force dynamically were fruitless. Another difficulty lay in measuring the drag from rollers and harness. Each tube has a 1.1-m stroke, and pulling steadily for that distance vertically while monitoring force is a challenge. The weight of the tube assembly was subtracted from the pull out force, giving the drag value.

Finally it was seen that proving force margin analytically was not conclusive as the uncertainties in each measurement, when combined, exceeded the margin requirements. A different path was chosen: show that the boom deploys while using 1/3 of the available Stacer force. By definition, there is sufficient margin. This is how the boom was verified.

Figure 15. Thermal Vacuum Chamber

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* Delta II Payload Planner’s Guide, The Boeing Company, Huntington Beach, CA 92647
When testing deployables, the desire is to prove beyond question that the mechanism will deploy in space, however, it must be tested here on the ground first. How many times? GEVS provides a minimum, and each program defines how many additional operations. This brings up wear margin: the design must show that it is sufficiently robust to survive testing and flight without degradation. The EM served this purpose, getting many deployments more than the FMs did. After identifying these values, a test plan was developed, reviewed and implemented.

Testing large deployables in a simulated space environment is difficult, and ensuring that the test actually verifies functionality is critical. Deploying the boom horizontally was initially considered since it is easier to develop a 6-m-long test rig that rests on the floor. After a few small efforts in this orientation, it was realized that the only way to ensure that roller drag on the tubes was representative of actual orbital deployment would be to deploy the boom vertically. While several interim off load pulley systems were used, all the verification deployments were performed on the thermal vacuum gantry.

To this end, a tall vacuum chamber was designed and built to allow the tests to be performed (Figures 14 & 15). Inside the chamber ‘chimney’ a gantry that allowed a counterbalance pulley system to provide G negation was installed (Figure 16). The distance from the top of the boom to the pulley was maximized to provide the least possible restorative (centering) force to the sections of the boom during deployment.

Figure 16. Gantry Detail

Counterweight Description
To demonstrate the force (torque) margin, the masses to be used for the counterbalance force had to be chosen to show that the Stacer would be energetic enough to deploy the boom. The mass of each of the tubes (in flight configuration) was added to give neutral balance, plus the Stacer neutralization mass (determined by bare Stacer vertical deployments to be 164 g). This mass (5214 g) was decreased by 2/3 of the Stacer minimum force (31 N * 0.67 = 20.7 N, converted to kg: 20.7 N / 9.98 kgm/s² = 2.07 kg) and subtracted from the counterweights. All 10 verification deployments were ‘force margin’ deployments and were successful. After deployment, each boom was inspected for wear, with no signs of degradation of rollers or Gr/E. The EM has been deployed ~20 times, and is still in good condition.

Initially, the counterweights far exceed the G negation requirements for deployment as only one tube is being deployed, while it is being pulled by the counter weight for 4 tubes. This is not invalid for our testing needs, as the flyweight brake dissipates the extra force, keeping the velocity in correct range. The area of interest is the very end of travel, where the Stacer force is lowest, and the full mass is being acted on. It was this point that the gantry design was built on.

Magnetometer Alignment Verification
After deployment, the alignment of the Mag needed to be measured to determine compliance with the specification. A very accurate digital level (resolution: 0.01 degree ±0.02) was used for this activity. The measurements were taken relative to the origin and coordinate system established in the Interface Control Document (ICD) for the boom. The relative angles for the mounting feet for the X – Z and X – Y planes were recorded at the mounting foot. The angles for the same planes (translated out to the Mag tray) were then measured. The difference was taken, yielding the deviation of the Mag tray from the mounting plane. Figure 17 shows the measured differences of the deviations for the FMs for each plane.

9 See Appendix A for ICD Details
I Impact Magnetometer Alignment

![Graph: Impact Magnetometer Alignment Error](image)

**Figure 17. Magnetometer Alignment Error**

For the final determination of pointing error, the root of the sum of the squares was calculated to give the magnitude of the deviation (the direction is not of interest as long as the specification is met). Flight Model 1 measured deviation “used up” 0.10° of its allowable 0.88° margin, while FM2 used 0.11°. The Impact Boom deploys accurately, repeatably, and exceeds requirements by a large margin.

**Lessons Learned**

**Design for test.**
The final validation of any design is complete when the device performs as expected in its orbital environment. GEVS SE gives guidelines, developed over many programs, as to what tests must be run, and how much extra (or over-) testing is needed. For the boom to be tested, a vacuum chamber was required to be built in a vertical orientation. The initial plan had been to use a horizontal track, using an existing facility. This plan did not give sufficient demonstration of the boom’s ability to deploy in a straight line as the track would have given alignment to the sections through out their travel. Additionally, the drag induced by the lock pin rollers when the tubes deploy horizontally far exceeded the Stacer deploy force. At the time the decision was made to go vertical, the Stacer should have been sized to allow a non-counterweighted deployment. There would have been a mass hit, but being able to leave off the gantry would have been a great savings, as the chamber would not have had to be as tall.

**Safety**
One person was injured during initial installation of the Stacer into its canister. As the final portion was stowed, the safety retaining pin would not fit into the hole provided for it. When additional force was tried, the operator lost control of the Stacer and it deployed in an uncontrolled manner to -1 m, when it was grabbed, cutting their finger deeply through two sets of latex gloves.

Some points arose from the review of the accident:

a) Check fit all safety related parts, sub-assemblies and fixtures. The size + tolerance of the hole for the safety pin were too small after plating to allow the pin to be inserted. This would have been an easy test, prior to assembly.

b) Have back up hardware and personnel: the operator was working virtually alone, and had no back up person there to hold the Stacer while the pin was being inserted. After the finger was cut, a colleague from another part of the lab had to run to help control the Stacer and finger damage. Another
point for spring loaded deployables: don't rely on a single safety path. A lock down plate in front of the stacer assembly would have caught the stacer, preventing damage. These recommendations have been implemented in the procedures, and stowing fixture used now: the stowing procedure has a minimum requirement of two persons to proceed.

**Materials Specifications**

Often materials can be useful beyond supplier's data, one only needs to verify what limits to the previous testing exist. The search for a cryogenic temperature suitable glue was fruitless. In the end a test was performed to establish suitability, after much effort. The question to add after "At what temperatures does the product perform satisfactorily?" is "Has it been tested beyond that?" A fair number of days could have been saved by realizing the manufacturers don't have all the information.

**Margin**

While most programs have a margin requirement, it is good to carry some margin for additional mass demands while designing. This is almost rhetorical. The proposal mass for the instruments at the end of the boom was 1.2 kg. After deliberation, it was determined that the data would be significantly better if pre-processing were done closer to the detector, so additional circuit boards were added out at the end, raising the deployed end mass to 2.2 kg. This drove the size of the release mechanism from being 'off the shelf' to a new, custom version, requiring additional testing, with the usual learning curve associated with new mechanisms. The entire structure needed 'beefing up' to accommodate the added loads.

**Summary**

The Impact Boom has completed qualification and acceptance verification for use in flight for the NASA Stereo mission. This application has shown the use of a Stacer spring can be implemented for major deployables as a motive force, not only as a sensor or sensor support. This represents a major cost savings from traditional motor driven deployables, with their associated high cost electronics. Currently, the launch is planned for 26 May 2006, with deployment of the boom occurring within a 3 - 30 day window after launch.

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Figure 18. Stereo “B” Spacecraft: Impact Boom location

References

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Appendix A

Figure 19. Impact Boom ICD Detail: “B” Stowed
Figure 20. Impact Boom ICD Detail: “B” Deployed