

Building a New Kind of Graded-Z Shield for Swift's Burst Alert Telescope

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ABSTRACT

The Burst Alert Telescope (BAT) on Swift has a graded-Z Shield that closes out the volume between the coded aperture mask and the Cadmium-Zinc-Telluride (CZT) detector array. The purpose of the 37 kilogram shield is to attenuate gamma rays that have not penetrated the coded aperture mask of the BAT instrument and are therefore a major source of noise on the detector array. Unlike previous shields made from plates and panels, this shield consists of multiple layers of thin metal foils (lead, tantalum, tin, and copper) that are stitched together much like standard multi-layer insulation blankets. The shield sections are fastened around BAT, forming a curtain around the instrument aperture. Strength tests were performed to validate and improve the design, and the shield will be vibration tested along with BAT in late 2002. Practical aspects such as the layup design, methods of manufacture, and testing of this new kind of graded-Z Shield are presented.

1. Introduction

The Swift satellite is designed to detect and observe Gamma-Ray Bursts. One of the three instruments on Swift is the Burst Alert Telescope, or BAT. Its function is to detect Gamma Ray Bursts in its wide field of view and to report their locations to the spacecraft so that it may immediately point the other two onboard narrow-field telescopes to the burst for closer observation at UV and X-ray wavelengths. BAT's large (5243 cm^2) detector array detects X-rays (15-150 keV range) that pass through a very large (3.2 m^2) coded aperture mask. A graded-Z Shield surrounds BAT to reduce the background noise level of gamma rays that do not pass through the aperture of the mask. In keeping with the scale of BAT, this graded-Z Shield has more than 8.7 m^2 of exposed area, but a mass of only 37 kg. Constraints on mass, volume, and cost ruled out the use of metal panels or other stiff structures such as used in previous spacecraft and ground-based assemblies.

1.1 Purpose of a Graded-Z Shield

The purpose of the shield is to attenuate gamma rays that have not passed through the telescope aperture and therefore produce unwanted background counts in the detectors. Just as a camera needs a light-tight box to allow only light through the lens to hit the film, BAT needs to block radiation that does not pass through the coded aperture mask. Blocking hard X-rays is more of a challenge than blocking visible light. Whenever X-rays pass through a material they knock electrons from an atom's K-shell causing an effect called Compton scattering. This effect is often a significant contributor to noise in X-ray detector systems, since the resulting K-shell fluorescent line can obscure or overpower the desired signal. Graded-Z shields are used to attenuate Compton scattering by putting metal layers in the path of X-rays. Because each metal has its own fluorescent line, the metals are layered in descending order on the periodic table of the elements, so that each successive metallic layer absorbs the K-shell fluorescence line of the layer before it. In this fashion the energy of the X-ray is attenuated and Compton scattering is reduced.

Graded-Z Shields have been employed on many space-based telescopes, including those aboard HESSI and BEPOSAX, among those currently flying. Shield designs are tailored to the energy range and sensitivity of the spacecraft instruments, but generally have consisted of 1-2 mm thick layers of two or more of the following metals: lead, tungsten, tantalum, tin, iron, and copper. These metals have very high densities and can contribute greatly to the overall mass of the spacecraft.

2. BAT Graded Z Shield Requirements

A graded-Z Shield was necessary to close out the 1 meter separation between the detector array and the coded aperture mask. Also, a shield was needed underneath the detector array to block X-rays passing through the mostly hollow core of the spacecraft body and penetrating the detectors from the bottom up. The attenuation requirement for the shield was that at the low energy end of the detectors (15-20 keV), the shield leakage background should be no more than 10% of the aperture flux background. At high energies the shield should transmit no more than 10% of the incident radiation. The shield had to block the direct line-of-sight to the detectors, but it did not have to be continuous or seamless. Sections of the shield could overlap, and small gaps between shield layers were allowed, therefore eliminating the requirement of bonding metallic layers together.

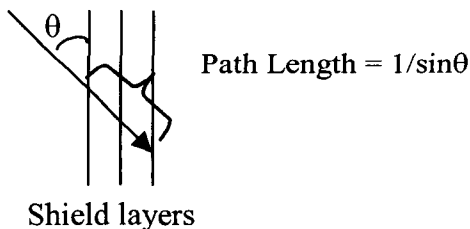
A set of stringent mechanical requirements was levied on the shield. The shield had to be robust enough to withstand the launch loads and avoid harmful resonant frequencies. It also had to be mounted to BAT in such a way as to not distort the mask and detector array through thermal expansion or contraction. Distortions of tenths of a millimeter of these parts cause significant errors in calculating the origin of gamma ray bursts and also reduce the detection sensitivity. Frequent shield installation and removal from BAT was required as well, since it restricted access to the detectors.

The early mass allocation for the shield was just 30 kg. Preliminary calculations showed that the surface area of shielding (one side only) was about 8.7 m². A shield with just one millimeter each of tin and lead would weigh about 160 kg, or more than 50% of the entire mass of the telescope. Thick metal layers were clearly not feasible, and alternatives were explored.

3. BAT's Graded-Z Shield Concept

The BAT science team performed a lengthy analysis to determine the most efficient graded-Z shield configuration for the given mass allocation. Colleagues at the European Space Agency performed Monte-Carlo simulations of scattering and subatomic interactions using a program called GEANT. With the analysis completed, the team determined that a four-metal graded-Z shield would maximize attenuation for the minimum mass. The metals chosen were lead, tantalum, tin, and copper.

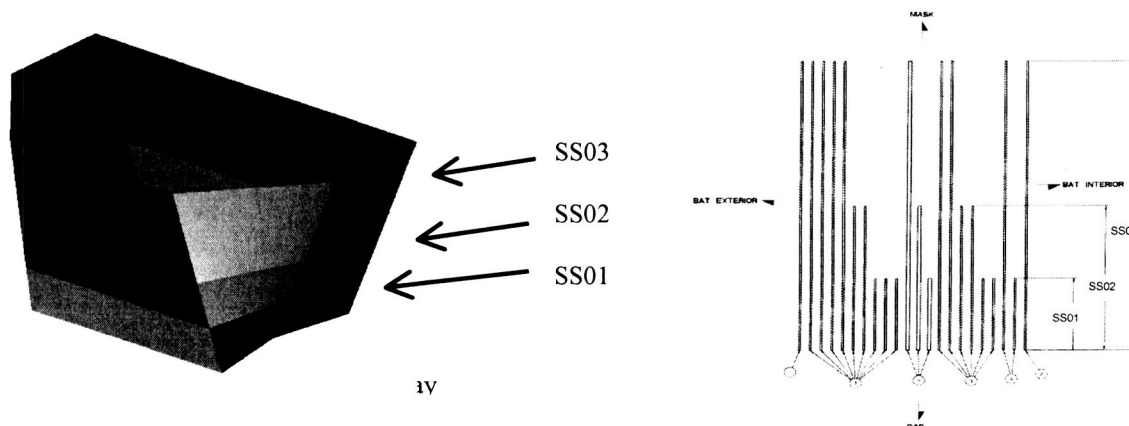
Early in the project it was recognized that X-rays with a trajectory nearly normal to the detector array would have a longer path length through the shields. The path length increases as $1/\sin\theta$ where a θ of 90 degrees is normal to the shield surface.



Taking advantage of this effect, the shields were optimized into three thickness zones (SS01, SS02, SS03), and the shield underneath the detector array comprised the fourth zone (SS00). The flight configuration is summarized below in a 4x4 matrix of numbers, where each matrix element is the number of .001 inch (.04 mm) layers required of a particular material.

$$\begin{bmatrix} \text{Cu(SS00)} & \text{Cu(SS01)} & \text{Cu(SS02)} & \text{Cu(SS03)} \\ \text{Sn(SS00)} & \text{Sn(SS01)} & \text{Sn(SS02)} & \text{Sn(SS03)} \\ \text{Ta(SS00)} & \text{Ta(SS01)} & \text{Ta(SS02)} & \text{Ta(SS03)} \\ \text{Pb(SS00)} & \text{Pb(SS01)} & \text{Pb(SS02)} & \text{Pb(SS03)} \end{bmatrix} = \begin{bmatrix} 1 & 2 & 1 & 1 \\ 2 & 6 & 4 & 2 \\ 0 & 6 & 4 & 2 \\ 6 & 9 & 6 & 4 \end{bmatrix}$$

The SS01 zone extended about 37 cm up from the detector array towards the mask, while the SS02 layer extended another 14 cm. The SS03 layer extended the remaining 49 cm to the mask.



Simplified representations of the Graded-Z Shield zones SS01, SS02, SS03

Rather than attach three different thickness shields together in patchwork fashion, the team requested that the foil layers be continuous throughout the shield length, as shown in the illustration above and to the right. This design feature eliminated discontinuities at the SS01/SS02 and SS02/SS03 interfaces.

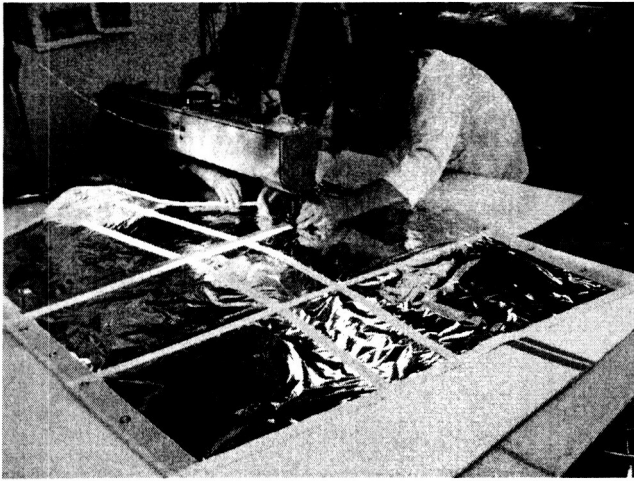
There were some practical considerations factored into this design. Initially tungsten was considered instead of tantalum, but the team quickly discovered that thin foils of tungsten are quite brittle. Tantalum foil is a suitable substitute from the atomic number point of view and is sufficiently ductile, but finding 15 kg of thin metal foil was challenging because the few American suppliers depended on uncertain shipments of ore from third world countries. At over \$1000 per kilogram of .001 inch thick foil, the cost was prohibitive as well. At one point, BAT may have owned a significant percentage of the US supply of thin tantalum foil.

Another problem surfaced with the use of pure tin. At low temperatures such as would be seen during spaceflight, an obscure metallurgical phenomenon known as “tin pest” causes the tin crystals to transform from the beta phase to the alpha phase where tin essentially turns into powder. Fortunately a small addition of an alloy metal such as antimony prevents this phenomenon. Surprisingly, tin foil is not manufactured in quantity in the US. After a lengthy search, a German vendor was found that supplied BAT with tin foil alloyed with 2% Antimony, at a very reasonable cost.

4. Engineering the Graded-Z Shield

Because of BAT’s large size, the project quickly determined that it was not feasible to make the shield from rigid panels. Instead the project decided to make the graded-Z shield as a layup of metal foils sewed and taped together much like conventional multi-layer insulation (MLI) blankets used on spacecraft. Making the shields from thin foils avoided a host of engineering problems as compared to mounting metal layers on rigid panels. Being rather loose fitting, the shield did not become part of the primary load path and therefore did not have to carry any loads other than its own. The foil layers are so flexible and heavily damped that they do not have a natural frequency of significance. In other words, vibrating the shields at their natural frequency could not put harmful loads into the BAT structure. Also, temperature swings on the shields were not a concern since the shields can expand and contract freely without distorting the mask or detector array.

Initial fabrication tests by the NASA Goddard Space Flight Center MLI Lab showed that layers of .001-inch thick metal foils were easily stitched together with Nomex thread. We found that the metal foils tend to start tearing or ripping at the stitch holes, so Beta-cloth tape was applied to those areas prior to stitching. Beta-cloth tape is a tough rip-resistant woven beta-silica fiber commonly used in multi-layer insulation.

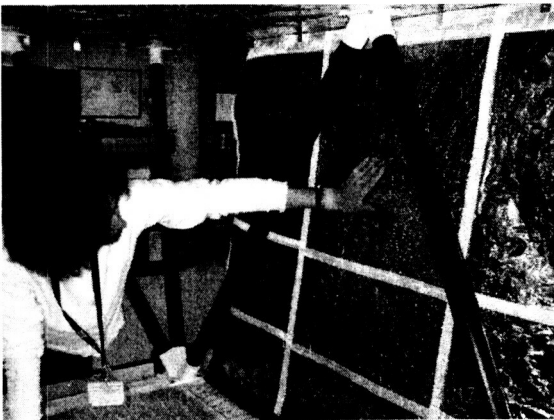


Technician stitching a graded-Z shield section

An engineering model, or prototype, was fabricated in 2001 by the NASA Goddard MLI Lab. Making the prototype helped give the project the confidence to proceed with this unusual design. Because of its large size and the need to fit it around BAT, the blanket technicians decided to make the shield in fourteen different shield sections that were overlapped and connected together. To save cost, copper layers were substituted for tantalum. The general process of fabrication started with making plastic sheet templates of the various sections. The templates were fitted on a geometric mockup of the BAT instrument, much like a dressmaker might use a mannequin as a guide. After the initial fitting, the templates were used as patterns for the cutting and stitching of the various foil layers.

Brass grommets were installed around the perimeter of the shield sections. Bolts through the grommets into hard points in the mask and detector array plate held the shield in place. Where different shield sections overlapped, they were connected with G10 fiberglass buttons commonly used for MLI blankets.

Several lessons were learned while making the prototype. It was discovered that the lead, tin, and copper foils wrinkled and contracted during handling as much as 5% of their length and width. Also, the exposed lead foil was delicate and prone to tearing during handling. To alleviate these problems, an inner and outer layer of .001" thick Kapton film was added to the shield, and extra care was taken during handling to avoid wrinkling the materials. Flight fabrication proceeded without difficulty.



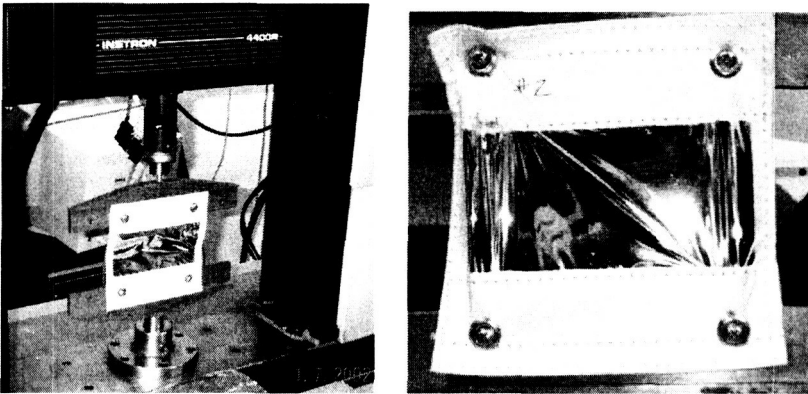
Installing the prototype shield on the BAT mockup

5. Strength Testing of Shields

The graded-Z shields had to hold together during launch loads of up to 14 G's of acceleration. Because the shields were designed from thin foils, there was concern about the ability of the shields to remain intact under those loads. A conservative stress analysis showed that the grommets in the shield should be able to withstand a tensile force of about 200 pounds (890 N) to survive launch with ease. A design and test program was initiated to determine shield strength and how to increase it, if necessary.

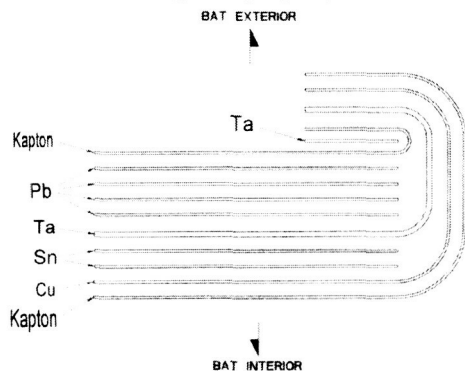
Sample coupons of shielding were fabricated and then pulled apart on a tensile testing machine. Coupons were about 20 x 18 cm and had two pairs of grommets installed about 13 cm apart. Both the thinnest (SS03) and thickest (SS01) sections were tested. Initial tests showed that the two main failure modes were grommets tearing out from the foils and foils ripping at the stitched seams when about 100 pounds of force (445 N) was applied. The primary strength of the shields came from the tantalum, copper, and Kapton layers, with additional help from the Beta-cloth tape. As expected, tin and lead proved to have very little tensile strength.

The stitch holes weakened the foils considerably and rips usually started there and "unzipped" down the stitch line. Clearly the distance between stitches was an important variable to be optimized.

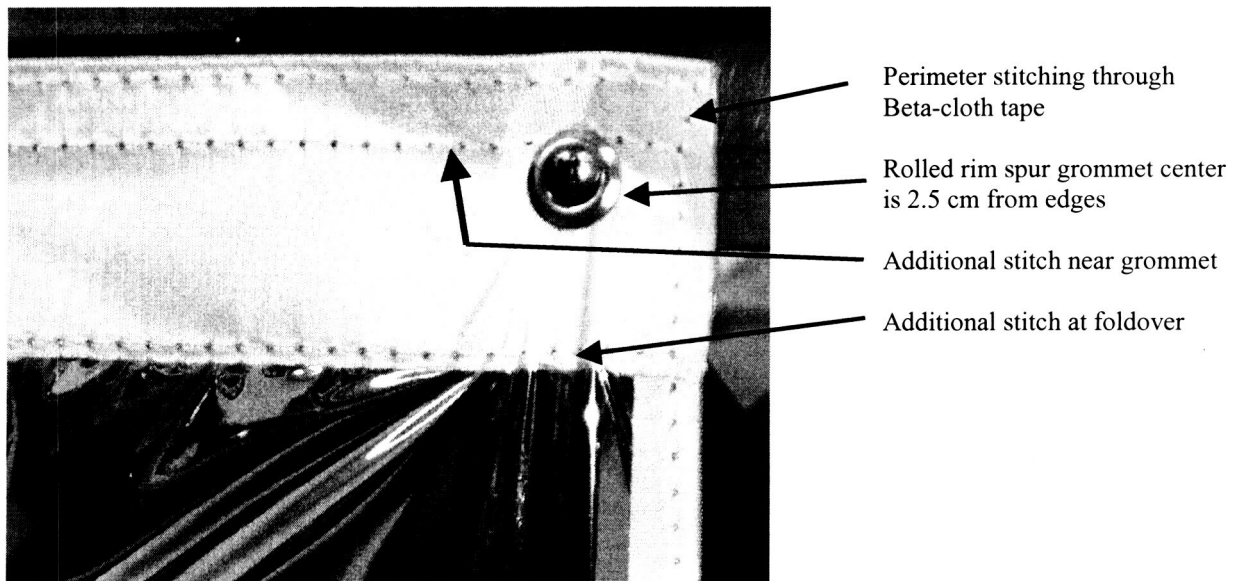


Photos showing coupon in test machine and a shield coupon under high tensile load

Improvements were made in the design of the shield that increased strength. Rolled rim spur grommets were found to have more gripping capability than washer grommets. The shield edges were folded over (doubled) about 2" (5 cm) all around the perimeter of the shield, and an additional layer of .001" thick Tantalum foil was added in the folded over section to make it difficult for grommets to tear out. Also, the optimum distance between stitches was found to be 4 stitches per inch (approximately 10 stitches in 4 cm). An extra line of stitches was added between the grommet and the edge to strengthen this area, since it was also found that the Nomex thread strengthened stitched areas as long as the stitch holes were spaced properly.



Cross-section of fold-over



Fabrication details greatly improved strength.

After these improvements were made, the tensile strength of the shield was increased to about 250 pounds (1110 N) before failures began occurring. Shield strength was considered optimized since multiple failure modes began occurring at the same high load. Also beneficial was the fact that failures under load were “graceful” in the respect that they occurred gradually and without sudden snaps or rips. In many cases over 3 cm of displacement was required to cause the shield to actually separate into two pieces.

6. Installation of Shields on BAT

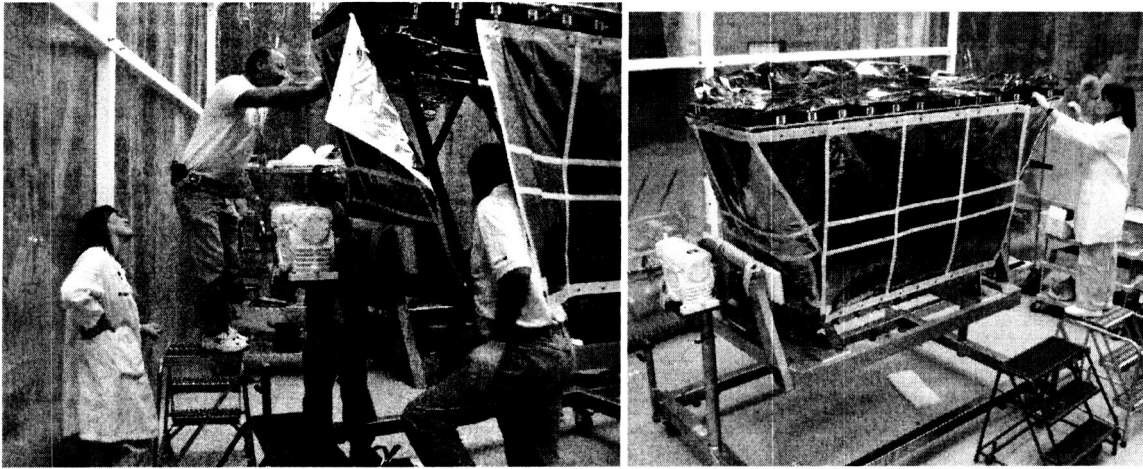
The first part of the graded-Z shield to be installed on BAT was the SS00 layer that provides shielding underneath the CZT detectors. This layer was made in two sections that overlapped 1 cm and installed on the top surface of the detector array panel. The sections were attached to the panel with Y966 transfer adhesive.



Installation of the SS00 layer on the detector array panel

The remaining graded-Z shield pieces (SS01, SS02, SS03) were hung on the BAT structure. Brackets with tapped holes were bonded around the perimeter of the coded aperture mask. Inserts were installed on the front and back of the detector array panel, and L-shaped brackets were installed on top of the panel. The shields were attached to these hard

points with #10 screws fitting through grommets and threading into these brackets and inserts. To avoid squashing the grommets when torquing the fastener, an aluminum ring spacer was placed in the grommet hole. This provided a hard stop for the fastener to clamp against.



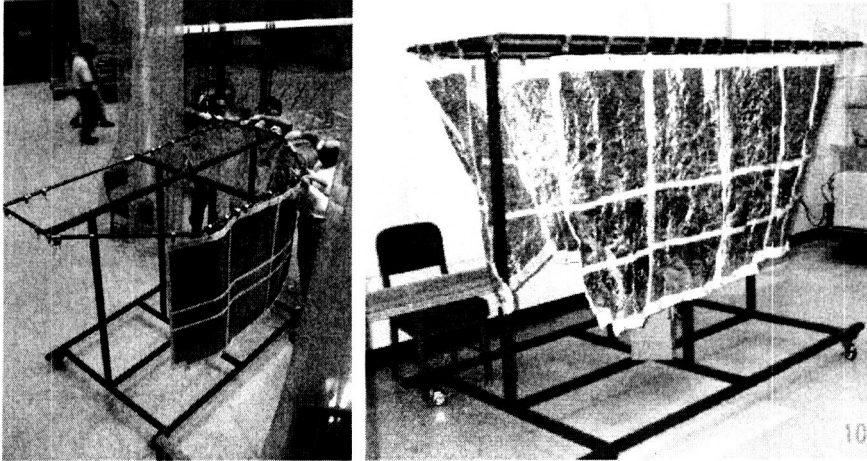
Installation of Graded-Z Panels on BAT

To overlap the shield sections together, small G10 fiberglass buttons, commonly used with MLI, were fitted through small holes in the shields. These buttons look like a flanged post with a snap ring groove on the shaft. A G10 washer over the shaft is held in place with the snap ring.



Installing MLI buttons on the graded-z shield.

Since the shields were so heavy and were susceptible to wrinkling, a special transportation fixture was made. It consisted of aluminum tubes welded in the shape of the mask perimeter, raised off the floor several feet, and attached to a wide base of support with casters. The shields were hung from pipe hangers and S-hooks through the grommets. The fixture was dubbed the "rolling shower curtain" and proved to be quite useful.



The graded-Z shield sections were stored on a special transportation fixture until installed on BAT

7. Conclusions

Making the graded-Z shields out of thin metallic foils similar to multi-layer insulation proved to be a good solution for BAT. Complexity and mass were minimized, and a host of problems were avoided compared to using rigid panels for the shields. After a few iterations of testing, the shield's strength and mass were optimized by the use of foldovers, spur grommets, and judicious use of stitches and Beta-cloth tape. Hard points were designed into BAT to simplify installation. The author hopes that future large-scale spacecraft may benefit from this type of graded-Z shield design.

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REFERENCES

The HESSI Spectrometer, D.M. Smith, R.P. Lin, et al, High Energy Solar Physics, Anticipating HESSI, ASP Conference Series, 2000, R. Rumaty, N. Mandzhavidze, eds.

Spectral capabilities in the hard X-ray band with the HPGSPC onboard the Italian-Dutch satellite SAX, Giarrusso, S.; Santangelo, A.; et al, Proceedings of 'Röntgenstrahlung from the Universe', eds. Zimmermann, H.U.; Trümper, J.; and Yorke, H.; MPE Report 263, p. 667-670., 1996.

Burst Alert Telescope (BAT) on the Swift MIDEX Mission, S. Barthelmy, 2000, in "X-Ray and Gamma-Ray Instrumentation for Astronomy XI", ed. K. Flanagan and O. Siegmund, SPIE August 2000 (SPIE: Bellingham)

Parsons, Ann, "Final Flight Graded-Z Shield Layer Configuration for the BAT", NASA-GSFC internal memo, 10/29/01.

<http://swift.gsfc.nasa.gov>