Origami Sunshield Concepts for Space Telescopes

Lee Wilson^{*} and Sergio Pellegrino[†]

California Institute of Technology, Pasadena, CA 91125

Rolf Danner[‡]

Northrop Grumman Aerospace Systems, Redondo Beach, CA 90278

This paper presents two origami inspired concepts for sunshields for a deployable Xray space telescope. Analytical models of the fold layout and sunshield deployment have been derived, and these models have been used to match the sunshield design to a set of geometric constraints. To validate the design, a proof-of-concept physical model of the optimized analytical design was constructed at 1:10 scale.

Nomenclature

$d_f =$	length of	f vallev f	old when	fully der	ploved (m)
						/

- d_1 = parallelogram side A-D (m)
- d_2 = parallelogram side A-B (m)
- $d_3 = \text{length of valley fold A-C (m)}$

 g_1 = projection of d_1 onto x-y plane (m)

 $g_3 = \text{projection of } d_3 \text{ onto } x - y \text{ plane (m)}$

h =height of folded unit formed by one parallelogram (m)

- h_{ref} = height of parallelogram on cutting pattern (m)
- n = number of parallelograms required to encircle a cylindrical polyhedron
- n_2 = number of parallelograms stacked vertically
- R_{max} = radius of fairing (m)
- δ = angle between parallelogram sides (°)

I. Introduction

Space telescopes need to be shielded from the sun to maintain high dimensional stability, but the design and ground testing of very large sunshields pose a number of difficult problems. Significant challenges to be addressed include the management of large membranes during packaging and ground deployment testing, hold down during launch, venting of trapped air, reliable deployment behavior, deployment accuracy and repeatability, as well as stability in the space environment.

Northrop Grumman has proposed a deployable tensegrity structure concept for the International X-ray Observatory (IXO). An overview of the concept is presented in Fig. 1, where it should be noted that the telescope structure includes a long cable truss that is pretensioned by two telescoping booms. This whole structure needs to be shrouded in a sunshield to maintain thermal stability. The sunshield, not shown in the figure, has to deploy to a length of 18 m and needs to store within a ≈ 0.5 m high envelope when it is folded. The envelope available for the packaged sunshield is defined by the telescope and the rocket fairing,

^{*}Graduate Student, Graduate Aerospace Laboratories, 1200 E. California Blvd. MC 205-45. lwilson@caltech.edu

[†]Joyce and Kent Kresa Professor of Aeronautics and Professor of Civil Engineering, Graduate Aerospace Laboratories, 1200 E. California Blvd. MC 301-46. AIAA Fellow. sergiop@caltech.edu

[‡]One Space Park, rolf.danner@ngc.com

corresponding to the inner and outer profiles of the shaded area in Fig. 2. The sunshield will be made from Multilayer Insulation (MLI).



Figure 1. IXO structural architecture concept.





This paper investigates origami-inspired techniques to develop a conceptual design for the IXO sunshield that addresses several of these challenges in a integrated way, leading to solutions that are easier to build and test. Our approach benefits from significant advances that have been made, over the past few years, in using origami inspired solutions to solve complex engineering problems. Miura pioneered the development of double-corrugation surfaces that can be packaged compactly through a process of inextensional deformation.¹ Guest and Pellegrino² proposed triangulated cylindrical polyhedra that fold axially through twisting; the deformation of these cylinders is nearly inextensional and, by varying a set of design parameters, the magnitude of the maximum strain imposed during folding can be made smaller than any set limit. Kresling³ identified a special case of Guest and Pellegrino's solution that can be implemented more easily as it allows simpler end conditions. Lang⁵ provides the fold pattern for a cylindrical spring. Miura and Tachi⁴ proposed a polyhedral cylinder that can be folded all the way between two extreme, flattened configurations, without any strain.

The range of solutions outlined above provide a rich landscape in which to search for good, practical

solutions for a sunshield for IXO. Two particular solutions out of this range, the Kresling and the Miura-Tachi solutions, have been investigated in detail for the present application as shown in Sections II and III. The Kresling pattern was then selected in Section IV, and a proof-of-concept demonstration model was built in Section V. Section VI concludes the paper.

II. Outline of Folding Schemes

A. Kresling Scheme

The first scheme is based on the Kresling folding pattern for a cylindrical polyhedron. The surface of the deployed polyhedron is developable and can be made from a flat sheet with the fold pattern shown in Fig. 3. There are six folds meeting at each vertex, four hill folds (solid lines) and two valley folds (dotted). The three variables defining the fold pattern are δ , d_1/d_2 and n, where n is the number of parallelograms required to encircle the polyhedron.

The polyhedral surface is shown fully deployed in Fig. 4(a). Note that it consists of pairs of ring structures, each skewed in a clockwise or anticlockwise sense. The skewness of these rings results from the arrangement of the parallelograms forming the cutting pattern, which can be imagined as produced by shearing the central horizontal line in an initially rectangular lattice. Each ring structure behaves essentially independently of the others, and the folding sequence shown in Fig. 4 assumes that all rings twist by the same amount.



Figure 3. Kresling's folding pattern; valley folds are dotted, hill folds are solid. The pattern shown generates a cylindrical polyhedron with n = 6 and $\delta = 60^{\circ}$ and consisting of two ring structures.



Figure 4. Kresling cylindrical polyhedron consisting of two pairs of ring structures, at various stages of deployment.

As the ring structures are folded, they become strained. The exact amount of strain and its variation with the degree of folding are a function of the three design variables, and can be easily estimated with a simple wireframe analytical model, where the hill folds are represented by pin-jointed rods of fixed length and the valley folds by springs. The strain experienced by the springs is a qualitative measure of the overall level of strain in the membrane. In addition, if the spring strain is zero then so too is the membrane strain.

Another assumption of the model is that every parallelogram unit deploys at the same rate. With this assumption the wire frame model allows for only a single degree of freedom, given by the height h of a ring structure. A geometrical relationship between the strain experienced by the valley fold and the height of the ring structure can be found as follows.



Figure 5. Bottom left - Single parallelogram unit developed on flat surface. Top left - Isometric view of same unit. Top right - Top view of same unit. Bottom right - Hill fold BC (=AD) and valley fold AC and their projections.

From Fig. 5 we can see that the x-y projections of the valley fold and hill fold are:

$$g_1 = \sqrt{d_1^2 - h^2}$$
(1)

$$g_3 = 2R_{max}\sin\left((\alpha + \beta)/2\right) \tag{2}$$

Thus, the valley fold length d_3 is

$$d_3 = \sqrt{h^2 + g_3^2} \tag{3}$$

$$= \sqrt{h^2 + 4R_{max}^2 \sin((\alpha + \beta)/2)^2}$$
(4)

Finally, α and β can be found from Fig. 5,

$$\alpha = 2 \arcsin\left(g_1/2R_{max}\right) \tag{5}$$

$$\beta = 360^{\circ}/n \tag{6}$$

The valley fold length is now only a function of the height h and the original parallelogram parameters d_1 , d_2 and δ . The valley fold strain is therefore:

$$\epsilon = (d_3 - d_f)/d_f \tag{7}$$

American Institute of Aeronautics and Astronautics

B. Miura-Tachi Scheme

The second folding scheme has the feature that it is inextensional. The fold pattern for the repeating unit is displayed in Fig. 6 and the range of shape transformations for a cylindrical polyhedron consisting of several units is depicted in Fig. 7. Note that both the fully deployed configuration and the fully packaged configuration are completely flat.



Figure 6. Fold pattern for repeating ring of Miura-Tachi cylindrical polyhedron; edges AA and A'A' are joined.



Figure 7. In extensional deformation of Miura-Tachi cylindrical polyhedron between two extreme, flattened configurations. Image reproduced from ${\rm Ref.}^4$

Note that this polyhedron has two different corner types, shown in Fig. 7, four corners of Type 1 and two corners of Type 2. The unfolding behavior of each individual corner type is illustrated in Fig. 8 and Fig. 9.

Consider the Type 1 corner shown in Fig. 8. In the folded configuration it forms an internal angle θ_0 in the *x-y* plane, where $\theta_0 = 180^{\circ} - 2\xi$ and ξ is defined in Fig. 6. Regardless of the value of θ_0 , θ increases to 180° when the Type 1 corner is fully deployed, at which point the four faces become coplanar.

Next, consider the Type 2 corner shown in Fig. 9. It also starts with a non-zero internal angle κ_0 , where $\kappa_0 = 4\eta$ and η is defined in Fig. 6. In Fig. 9 this corner has been deployed by rotating the two panels in contact with the *x-y* plane by equal amounts from 0° to 90° with respect to the *x-y* plane while constraining the panel edge to remain in the *x-y* plane. During deployment, κ decreases until it reaches 0° when fully deployed. The behavior of Type 1 and Type 2 corners is shown in Fig. 7, assuming $\xi = 45^{\circ}$ and $\eta = 45^{\circ}$.

III. Sunshield Packaging

A. Solutions Based on Kresling Scheme

The Kresling-type solutions are controlled by three parameters, the number of sides n, the ratio of parallelogram sides d_1/d_2 and the angle between the hill folds in the flattened fold pattern δ . As n decreases the size of the triangles increases and it becomes more difficult to satisfy the constraints imposed by the telescope and the fairing. In Fig. 10 it can be seen that for $d_1/d_2 = 1$ the lowest number of sides is n = 12.

For each value of n, changing δ alters the strain in the valley folds predicted by the model in Section II.A, allowing the behavior of the cylindrical polyhedron to be tailored to fit the design requirements. Figure 11



Figure 8. Unfolding of Type 1 corner in Miura-Tachi polyhedron with $\xi = 45^{\circ}$ and $\theta_0 = 90^{\circ}$. Top: perspective views. Bottom: views along z-axis.



Figure 9. Unfolding of Type 2 corner in Miura-Tachi polyhedron with $\eta = 22.5^{\circ}$ and $\kappa_0 = 90^{\circ}$. Top: perspective views. Bottom: views along z-axis.



Figure 10. Top views of Kresling pattern in packaged configuration for n = 12 (left) and n = 20 (right), $d_1/d_2 = 1$.

shows that as n increases so too does the valley fold strain in the packaged configuration. It also reveals that decreasing δ also decreases the initial strain in the packaged configuration.



Figure 11. Strain in the valley folds during deployment assuming $d_1/d_2 = 1$, for n=12 and n=20. The height has been normalized by h_{ref} in Fig. 3.

The variables n and δ also control the surface area of the sunshield and the corresponding fold length. The area is important because it is proportional to the overall mass, while the total fold length is important because thermal shorts may occur at the folds. Increasing the fold length would thus decrease the effectiveness of the sunshield to maintain uniform thermal conditions. Figure 12 shows plots of area and fold length vs. normalized deployed height. Here the normalized deployed height is h/h_{ref} .

Figure 12 shows that both the area and the fold length are inversely proportional to how high the cylindrical polyhedron is allowed to deploy. In addition, as δ increases, the total area of sunshield and the fold length decrease for a given normalized deployed height. As n increases, for all values of δ both the total area required and the fold length also increase. This implies that when using the Kresling pattern the optimum number of sides will also be the smallest that satisfies the constraints imposed by the fairing and the telescope.

In conclusion, the Kresling-type solutions have several advantages. First, the end cross-sections of the cylindrical polyhedron do not change during deployment, and hence the interfaces between the sunshield



Figure 12. Surface area of sunshield and corresponding fold length, assuming $d_1/d_2 = 1$. Left, solutions for n = 12; right, solutions for n = 20.

and the rest of the telescope should be straightforward. Second, the membrane strain can be tailored. This means that in the absence of an externally applied force, the sunshield will self-deploy to a known height where the membrane strain is zero everywhere and so only minimal forces need to be applied by the telescope structure on the sunshield to hold it deployed. The main disadvantage is that the sunshield is not unstrained in the packaged state and hence a preload will be required. This would cause wrinkling within the MLI membrane, which may remain after deployment. Physical prototypes incorporating MLI would need to be investigated to determine if this is a problem.

B. Solutions Based on Miura-Tachi Scheme

There were two primary constraints in developing these solutions. The first constraint was the folded sunshield had to fit within the envelope defined by the rocket fairing and the telescope. The second constraint was that during deployment the sunshield must not interfere with the telescope, although the faring constraint is no longer active at this point.

Although the original Miura-Tachi cylindrical polyhedron does not satisfy these geometrical constraints, a different combination of Type 1 and Type 2 corners provides an acceptable solution. Note that, when fully deployed, Type 2 corners form a vertical crease, separating two flat surfaces, as shown in Fig. 7. Hence, instead of using two Type 2 corners as in the original scheme, the best solution identified utilizes two Type 1 corners and six Type 2 to obtain a hexagonal prism in the fully deployed configuration, as shown in Figure 13. The Type 2 corners provide the basic hexagonal prism shape and the Type 1 corners allow a design with narrower panels that still clear the internal constraint imposed by the telescope. In this arrangement however, the corners constrain each other's motion, forcing κ to remain almost constant during deployment. To satisfy these internal constraints the membrane becomes strained during deployment, although it is strain-free in the fully folded and fully deployed configurations.

Table 1.	Properties of	Best Miura-	Tachi Inspired	Sunshield	Design.
----------	---------------	-------------	----------------	-----------	---------

Area of Membrane	$295~{\rm m}^2$
Fold Length	$459~\mathrm{m}$

Advantages of the solution based on the Miura-Tachi scheme are as follows. First, they do not experience any strain in either the deployed or folded configurations, which decreases the possibility of wrinkling in the



Figure 13. Top views of Miura-Tachi pattern. Left, folded configuration inside the rocket fairing. Right, fully deployed.

sunshield. Second, in the fully deployed configuration these solutions can provide a straight prism, with flat surfaces (which may have the undesired implication of making the sunshield too stiff in the axial direction). No light would be reflected from sunshield onto itself and thus the insulation properties of the sunshield would be increased. The main disadvantage of these solutions is that the end cross-sections change shape during deployment, which needs to accommodated by the attachments between the sunshield and fixed end mounts.

IV. Concept Selection

A key advantage of the Kresling cylindrical polyhedron for the present application is that the end crosssections do not change during deployment, which greatly simplifies the attachment between the sunshield and telescope. Both this solution and Miura-Tachi inspired solution undergo strain during deployment, but only the Miura-Tachi solution is strain-free in the packaged configuration. When fully deployed, the Miura-Tachi solution forms a hexagonal prism which has better reflective properties than the Kresling solution. A disadvantage of the Miura-Tachi solution is that the fully-deployed structure is axially much stiffer than the Kresling cylindrical polyhedron, which is likely to be undesirable as the sunshield structure will become elastically coupled with the telescope. Finally, the Kresling polyhedron has a much simpler fold pattern and so manufacturing can be expected to be simpler. Overall, the Kresling pattern was considered as the best choice for IXO and it was decided to build a proof-of-concept model to ensure there were no unexpected problems with the design.

V. Model

A. Dimensions

An important requirement is that the sunshield should be designed in such a way as to occupy the smallest possible volume when it is packaged, and this was achieved by selecting the design parameters of the prototype such that the packaged height would be minimized. There are three factors that determine the packaged height. First, the number of ring structures that make up the sunshield, n_2 , second the thickness of the sunshield and third the number of layers of sunshield that become overlapped when a single ring structure is packaged, which is influenced by d_1/d_2 . This last effect is analyzed in Table 2.

The parameter n_2 was found from setting to zero the valley fold strain at the fully deployed height, and arbitrarily setting it to 1% in the fully packaged configuration. The number of ring structures required for the full sunshield was then found for each set of values of d_1/d_2 and n. The results have been plotted in

$0 < d_1/d_2 < 1$	4 layers
$1 < d_1/d_2 <\approx 2$	6 layers
$2 < d_1/d_2 <\approx 3$	8 layers

Table 2. Maximum number of sunshield layers that become overlapped when a single ring structure is packaged.

Figure 14. The optimum combination to minimize the packaged height was found to be n = 10, $n_2 = 38$, $d_1/d_2 = 0.952$ and $\delta = 38.54^{\circ}$. These were the parameters chosen for the proof of concept prototype, and the number of ring structures was set to 6.



Figure 14. Number of ring structures required by the sunshield, assuming valley fold strain is 1% in packaged state, according to the wire frame analysis.

B. Construction

A 1:10 scale structural model of the IXO telescope had been provided by Northrop Grumman, hence the proof-of-concept model of the sunshield was designed to fit on this model. Kapton film with a thickness of 50μ m was used selected for the sunshield, after testing different films with different thickness, since it had been found that this film forms sharp creases when it is folded and a roller is passed over the fold. Also, cylindrical polyhedra made of this film and with the required dimensions for a 1:10 scale model, are sufficiently stiff to be handled with ease. The fold pattern for the Kapton film are provided in Figure 15.



Figure 15. Fold pattern for prototype. Solid lines are hill folds, dotted lines valley folds.

The prototype was made from two sheets of Kapton joined with polyamide tape and 1/4" diameter holes

were punched from each vertex to relieve stress concentrations caused by folding. Polyamide tape was also used to join the Kapton film to top and bottom mounting plates that were attached to the telescope model. Figure 16 shows the prototype in the fully packaged and fully deployed configurations. The sunshield model is shown mounted on the telescope model in Figure 17.

Before attaching the mounting plates, the Kapton film model had a fully deployed free-standing height of 350 mm. The packaged height of the model was measured with two different preloads; the height was 13 mm for a preload of 40 N and 6.5 mm for a preload of 180 N. Hence, a model with the full number of ring structures, $n_2 = 38$, that is made from a single layer of 50μ m Kapton film would have a compressed height on the order of 42 mm.



Figure 16. Sunshield model in fully folded and fully deployed configurations.

VI. Conclusion

Two structural concepts for sunshields for an X-ray telescope have been investigated. Both concepts allow the whole sunshield to be made from a single sheet of material, thus minimizing the number and length of seams between different parts. The selected concept is based on a cylindrical polyhedron that consists of identical triangulated ring structures that are twisted in alternate directions. The parameters of an optimum design for a sunshield based on this concept have been obtained $(n = 10, n_2 = 38, d_1/d_2 = 0.952 \text{ and } \delta = 38.54^{\circ})$ and a 1:10 scale proof-of-concept model was built from 50 μ m Kapton film and designed to these specifications. The model has proved both that the concept works as expected and that during deployment the sunshield does not interfere with the telescope. Also, measurements of the thickness of this model in the folded configuration have shown that, with a preload of 180 N, an 18 m long sunshield made from film layers with a total thickness of 50 μ m would have a thickness of less than 50 mm.

A future step in the present study should be to investigate the effect of changing the material from Kapton to MLI. A more detailed analysis of the strains incurred during packaging, using a detailed finite element analysis, would also be useful.

References

 1 Miura, K. (1980). "Method of packaging and deployment of large membranes in space", 31st IAF Congress, Tokyo, Japan, September 1980.

²Guest, S.D., and Pellegrino, S. (1994). "The folding of triangulated cylinders, Part 1: geometric considerations", Journal of Applied Mechanics, Vol 61, pp. 773-777.

 3 Kresling, B. (2008). "Natural twist buckling in shells: from the hawkmoth's bellows to the deployable Kresling-pattern and cylindrical Miura-Ori," Proceedings of 6th International Conference on Computation of Shell and Spatial Structures, May 28-31, 2008, Cornell University, Ithaca, NY, USA

⁴Miura, K., and Tachi, T. (2010). "Synthesis of Rigid-Foldable Cylindrical Polyhedra", Journal of the International Society for the Interdisciplinary Study of Symmetry (ISIS-Symmetry), Special Issues for the Festival-Congress, Gmuend, Austria, August 23-28, pp. 204-213, 2010.



Figure 17. Sunshield model mounted on 1:10 scale structural model of telescope. Note that the sunshield model was not preloaded when the photo of the packaged structure was taken.

⁵R. J. Lang, "Origami in Action: Paper Toys That Fly, Flap, Gobble and Inflate." New York, NY: St. Martin's Press, 1997.