# New Deployable Truss Concepts for Large Antenna Structures or Solar Concentrators

K. A. Takamatsu*
*Fuji Heavy Industries, Ltd., Tochigi, Japan*
and
J. Onoda†
*Institute of Space and Astronautical Science, Kanagawa, Japan*

**Three types of newly proposed deployable concepts, Spatial Diagonal-stiffened Truss (SDT), Sliding Hinge Double Fold-II ( SHDF-II), and Deployable Solar Concentrator (DSC), are described. The SDT and the SHDF-II are two-dimensional deployable truss structures that can be applied to large antenna structures; whereas the DSC is available for large solar concentrator systems. Typical advantages of the SDT and the SHDF-II are their good packaging efficiency and the small number of mechanisms necessary for deployment and/or folding. The SDT has the best packaging efficiency among existing deployable concepts while the SHDF-II has the smallest number of deployable mechanisms (0.25 per module). The DSC is a deployable truss structure with rigid reflector plates. The DSC has the advantage of being able to deploy large-size concentrators automatically. Functional test models of both the SDT and the DSC were fabricated and tested. The test results showed the practicality of the concepts by demonstrating smooth and consistent deployment movement.**

## Introduction

THE concept of large space structures envisioned for future application has promoted the introduction of various deployable structures. This is because of the need to construct structures larger than the limited volume capability of the Space Transportation System. In this paper, two newly invented two-dimensional deployable truss structures and one deployable truss structure with rigid solar reflectors are proposed, investigated, and demonstrated. The Spatial Diagonal-stiffened Truss (SDT) and the Sliding Hinge Double Fold-II (SHDF-II) are the two-dimensional deployable structures, and the Deployable Solar Concentrator (DSC) is the deployable truss structure with solid reflectors.

The SDT and the SHDF-II are investigated and compared with existing deployable concepts from the points of view of 1) packaging efficiency, 2) number of lock mechanisms, and 3) design flexibility to form arbitrary configuration. The investigation of the DSC is devoted mainly to its mechanism, which enables synchronous deployment of the rigid solar reflector and the supporting back structure without any external assistance such as Extra-Vehicular-Activity (EVA). This fully automatic deployment capability is the chief advantage of the DSC over previously proposed deployable solar concentrators,[1,2] which fail to deploy large-size concentrators in a purely automatic fashion.

## Two-Dimensional Deployable Truss Structures

### Basic Concept

*Spatial Diagonal-stiffened Truss*

Figure 1a shows the basic module of the SDT in a fully deployed state. In this state the SDT module by itself is unstable. However, if the SDT module is combined with the Sliding Hinge Single Fold (SHSF),[3] as shown in Fig. 2, the overall structure becomes stable. The basic configuration of the SHSF is shown in Fig. 3 for reference.

The half-deployed SDT module is shown in Fig. 1b. In the folded state, the sliding hinge, to which the diagonal truss is

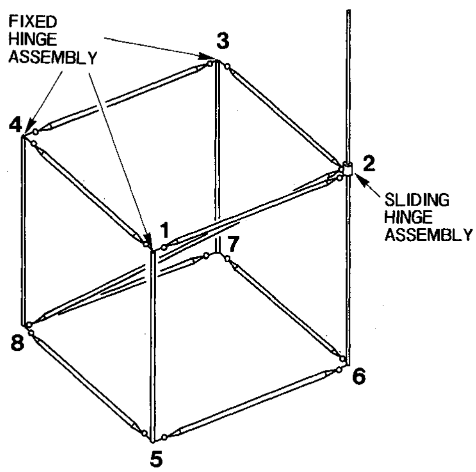



Fig. 1a Fully deployed module of the SDT.

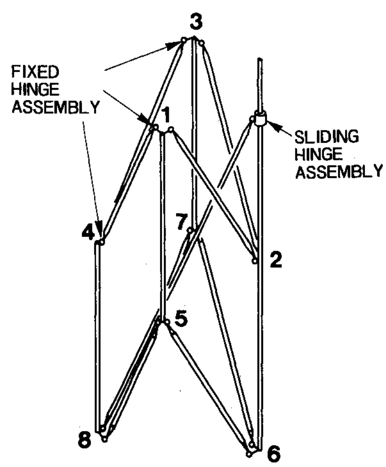



Fig. 1b Half-deployed module of the SDT.

---

Presented as Paper 89-1346 at the AIAA 30th Structures, Structural Dynamics, and Materials Conference, Mobile, AL, April 3–5, 1989; received Aug. 28, 1989; revision received Sept. 17, 1990; accepted for publication Sept. 26, 1990. 

*Supervisor, Aerospace Engineering Division. Member AIAA.
†Associate Professor, Research Division for Space Transportation. Member AIAA.

connected, is separated from node 2. Deployment motion is initiated by the downward movement of the sliding hinge toward node 2. Since the movement is reversible, the overall structure is able to not only deploy but also fold automatically in orbit.

*Sliding Hinge Double Fold-II*

Figure 4a shows the basic module of SHDF-II in its deployed state. This is the modified pattern of the original SHDF, which the authors have proposed in Ref. 3. Similar to the SDT, the basic module of SHDF-II is not stable by itself. However, combination of the SHDF-II with the SHSF makes the overall structure stable. An example of a two-dimensional stable platform using the SHDF-II and the SHSF is shown in Fig. 5.

The half-deployed SHDF-II module is shown in Fig. 4b. In the folded state, the sliding hinge is separated from node 1. Deployment motion is initiated by the upward movement of the sliding hinge toward node 1. Similar to the case of the SDT, reversible motion is possible, allowing automatic folding.

**Number of Mechanisms**

A deployable structure should be designed to minimize as much as possible the required number of mechanisms to fold and deploy the structure. Fewer mechanisms will increase the reliability of automatic deployment. Also, a smaller number of mechanisms results in an inherently rigid structure, because a lock mechanism induces geometrical imperfection or stiffness discontinuity of a truss member. Additional mechanisms also increase the total mass of the structure, which reduces the natural frequencies.

A comparison of the numbers of mechanisms for both the SDT and the SHDF-II with other existing deployable structures is shown in Table 1. The numerical value represents the number of mechanisms per module necessary for full deployment in the case of an infinitely large two-dimensional platform. The number of mechanisms per module for existing deployable structures fall in the range from one [Vought Bi-Axial Double Fold (BADF)] to four [Martin Marietta Box Truss (MBT), Vought Double Fold (VDF)]. However, both the SDT and the SHDF-II require only one sliding hinge per module to fold an independent basic module. Furthermore, in the case of the SHDF-II, one sliding hinge is shared by four neighboring modules (see Fig. 5), which reduces the number of mechanisms per module to 0.25.

The small numbers of mechanisms are definite advantages of the SDT and the SHDF-II. It should be noted that the value of 0.25 per module, in the case of the SHDF-II, is the minimum possible value for a unit structure consisting of four modules, since each module must share at least one mechanism to be deployable.

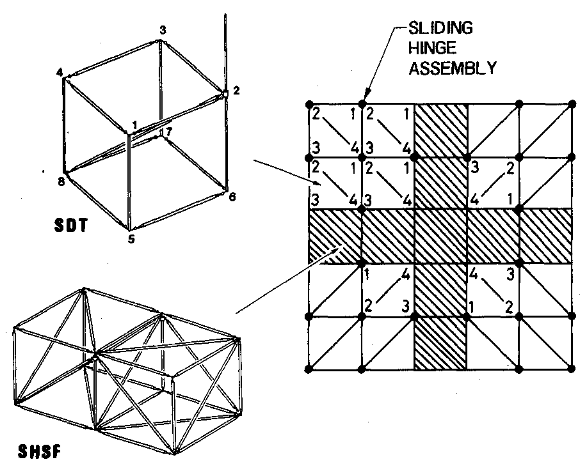



**Fig. 2 Deployable platform constructed by combination of the SDT and the SHSF.**

**Packaging Efficiency**

Packaging efficiency, defined by the ratio of the deployed volume to the folded one, is of course an important design characteristic. For the convenience of simplicity, all truss members are assumed to be tubes having a diameter of $d$ and all modules to be cubes whose edge length is $l$. It is also assumed that the central axis of all of the members connected to a node coincides exactly with the nodal point in the deployed state.

Figure 6 shows the most compactly folded platform consisting of the SDT and the SHSF modules based on the above assumptions. In the case of a platform with $N \times N$ cells, the deployed volume of the structure is

$$V_D = N^2 l^3 \tag{1}$$

whereas the folded volume is

$$V_F = 2l\left\{l + 2\left[2.5 + \frac{\sqrt{2}}{2} + 3d\left(\frac{N-1}{2} - 1\right)\right]\right\}^2 \tag{2}$$

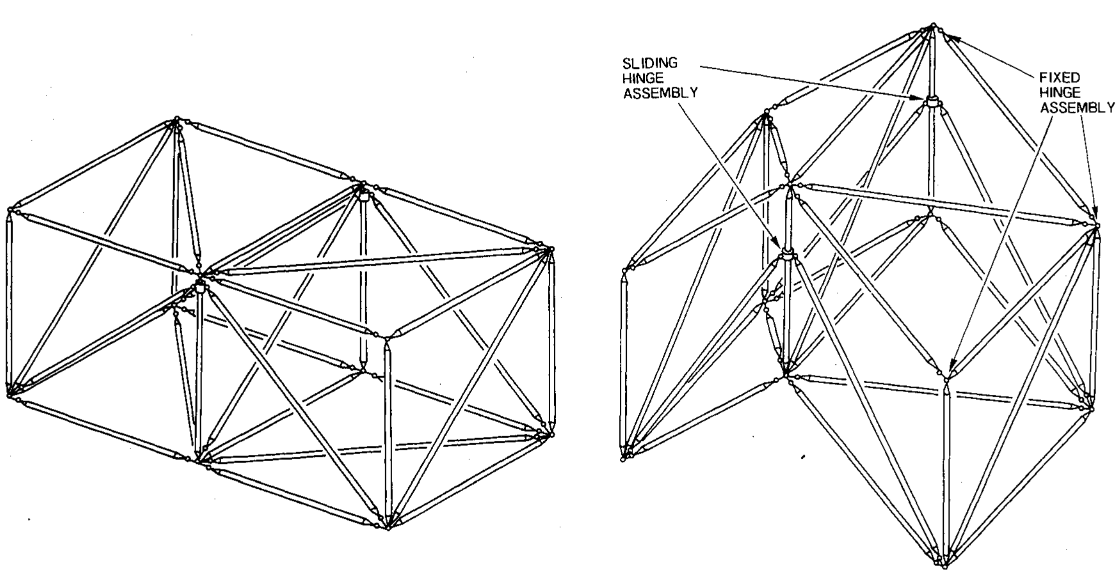



**Fig. 3 Basic module of the SHSF.**

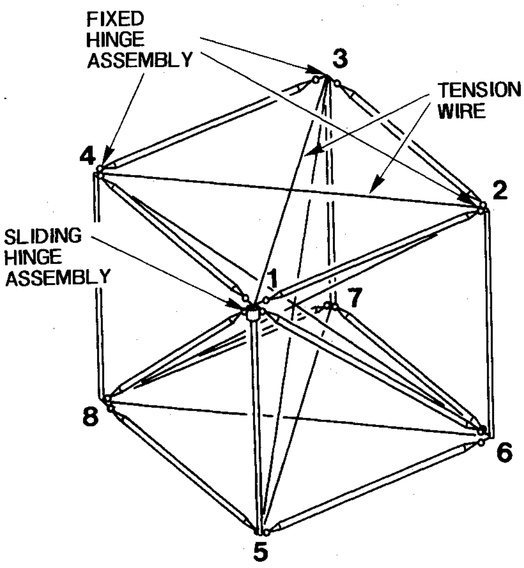



Fig. 4a Fully deployed module of the SHDF-II.

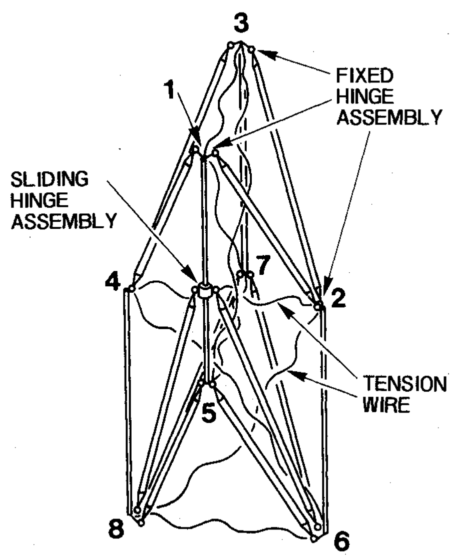



Fig. 4b Half-deployed module of the SHDF-II.

The packaging efficiency of this platform is obtained by dividing Eq. (1) by Eq. ( 2), which is calculated to be

$$P_{\rm eff} = V_D/V_F = \left\{18\left(\frac{d}{l}\right)^2 + \frac{1}{N}\left[24\left(\frac{\sqrt{2}}{2}-2\right)\left(\frac{d}{l}\right)^2 + 6\left(\frac{d}{l}\right)\right] + 2\left[1 + (\sqrt{2}-4)\left(\frac{d}{l}\right)\right]\frac{1}{N^2}\right\}^{-1} \qquad (3)$$

For a large-size structure, the second and the third term of the equation approach to zero (i.e., the value of $N$ becomes large), and thus the packaging efficiency of the infinitely large platform will be $P_{\rm eff} = (1/18)\ (l/d)^2 = 0.056(l/d)^2$.

It should be noted that the above mentioned packaging efficiency is dominated by the folding pattern of the SDT modules that are constrained by the less efficient folding of the SHSF modules as shown in detail A in Fig. 6. From Fig. 6, it is clear that the packaging efficiency of the SDT alone is better than $0.056(l/d)^2$. For example, if the diameter of the diagonal truss members for the SHSF that are connected to the sliding hinge assembly is assumed to be zero, the packaging efficiency will increase to $0.125(l/d)^2$. Therefore, it can be

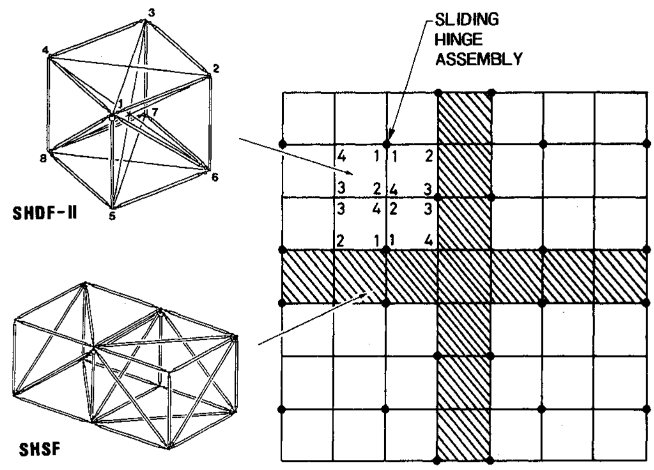



Fig. 5 Deployable platform constructed by combination of the SHDF-II and the SHSF.

demonstrated that the actual packaging efficiency of the SDT platform ranges from $0.056(l/d)^2$ to $0.125(l/d)^2$.

In the same manner, the packaging efficiency of the SHDF-II can be calculated. The deployed volume of the platform consisting of $N \times N$ cells of the SHDF-II and the SHSF is $V_D = N^2 l^3$; whereas the folded volume is $V_F = 2l\{l + (N-1) \times (2+\sqrt{2})d\}^2$. The total packaging efficiency will be

$$P_{\rm eff} = \left\{4(3+2\sqrt{2})\left(\frac{d}{l}\right)^2 + \left(\frac{1}{N}\right)\left[2(2+\sqrt{2})\left(\frac{d}{l}\right) - 8(3+2\sqrt{2})\left(\frac{d}{l}\right)^2\right] + \left(\frac{1}{N^2}\right)\left[2 - 2(2+\sqrt{2})\left(\frac{d}{l}\right) + 4(3+2\sqrt{2})\left(\frac{d}{l}\right)^2\right]\right\}^{-1} \qquad (4)$$

For an infinitely large platform, the packaging efficiency will be $P_{\rm eff} = 0.043(l/d)^2$. The packaging efficiency of both the SDT and the SHDF-II are compared with other existing deployable concepts in Table 1.

Currently, the MBT is regarded as having a very high packaging efficiency, but when the diagonal trusses of the SHSF are designed with a small diameter, the packaging efficiency of the SDT will be better. Furthermore, this high efficiency of the SDT can be achieved with only one lock mechanism per module which is one-fourth that required for the MBT.

The packaging efficiency of the SHDF-II is better than that of the VDF or the BADF and is the same as the SHDF. It must also be noted here again that the SHDF-II could achieve this value with only 0. 25 lock mechanisms per module, which is the minimum value known to date.

### Design Flexibility in Forming a Curved Surface

In the preceding section, the overall platform surface was assumed to be flat. However, an overall curved surface, for instance a parabolic surface, is generally required in actual application.

It is possible to form a curved surface by changing the lengths of the truss members. This can be done, because most deployable structures still have the design freedom in determining the lengths of constituent members even after satisfying the geometrical constraints for the module to be folded. Therefore, a weaker geometrical constraint means more design freedom to form an arbitrary shape. This geometrical constraint was initially investigated by Onoda in Ref. 4.

The conditions necessary for the SDT and the SHDF-II to be folded are derived from Onoda's equation as follows (see

**Table 1 Comparison with existing double fold concepts**

| | SHDF[a]-II | SDT[b] | SHDF | MBT[c] | VDF[d] | BADF[e] |
|---|---|---|---|---|---|---|
| $\frac{\text{Deployed volume}}{\text{Stowed volume}} \times \left(\frac{d}{l}\right)^2$ | 0.043 | 0.056 ~0.125 | 0.043 | 0.110 | 0.029 | 0.044 |
| Number of lock mechanisms (per one module) | 0.25 | 1 | 0.5 | 4 | 4 | 1 |
| Number of geometrical constraints (per one module) | 3.75 | 3 | 4.5 | 3 | 3 | 4 |

[a]SHDF: Sliding Hinge Double Fold.[3] [b]SDT: Spatial Diagonal-stiffened Truss. [c]MBT: Martin Marietta Box Truss.[6] [d]VDF: Vought Double Fold.[7] [e]BADF: BiAxial Double Fold.[7]

Figs. 1 and 4). For the module of the SDT,

$$L_{12} + L_{26} = L_{15} + L_{56} \tag{5a}$$

$$L_{23} + L_{26} = L_{37} + L_{67} \tag{5b}$$

$$L_{37} + L_{78} = L_{34} + L_{48} \tag{5c}$$

$$L_{14} + L_{48} = L_{15} + L_{58} \tag{5d}$$

$$L_{12} + L_{34} = L_{23} + L_{14} \tag{5e}$$

For the module of SHDF-II, Eqs. (5a–5e) plus

$$L_{16} - L_{56} = L_{18} - L_{58} \tag{6}$$

where $L_{ij}$ denotes an effective length of the member connecting node $i$ and $j$ as measured along the lengths of the members in the folded state.

It should be noted here that Eqs. (5a–5d) are shared by two adjacent modules. In this sense, Eqs. (5a–5d) should be counted as a half-constraint per module. Furthermore, if Eq. (6) is satisfied by any three of four adjacent modules sharing a cross member, the condition is automatically satisfied by the remaining module. Therefore, Eq. (6) should apply only three times to four modules, or in other words three-fourth per module. The final resultant number of constraints equivalently imposed per one SDT module is

$$4 \times ½ + 1 = 3 \tag{7}$$

In the same manner, the necessary conditions to fold the SHDF-II can be calculated as

$$4 \times ½ + 1 + 1 \times ¾ = 3.75 \tag{8}$$

A comparison of the number of geometrical constraints with that of existing deployable concepts is summarized in Table 1.

The number of geometrical constraints of the SDT is 3, which is the same as that of the VDF in Ref. 4. The second author investigated the design flexibility of the VDF in detail and showed that any arbitrary shallow surface can be formed.[4] The number of the SHDF-II is 3.75. Although this value means less design flexibility than that of the SDT, it is better than that of the SHDF whose value is 4.5. It is also demonstrated in Ref. 4 that even the SHDF still has the design flexibility to form a parabolic surface. In summary, it can be concluded that both the SDT and the SHDF-II have sufficient design freedom to form shapes required in practical application.

#### Dynamic Characteristics

Since both the SDT and the SHDF-II have relatively small numbers of diagonal truss members, they should be considered as partially stiffened structures rather than fully stiffened. In this section, the dynamic characteristics of the platform consisting of SDT modules are investigated since the SDT is a more flexible structure than the SHDF-II. All platforms analyzed here have an equal number of modules in both directions with a depth equal to the module width. Vibration modes and frequencies are determined by MSC/NASTRAN. The structure is modeled using beam elements that are pinned at each end and that have bending and twisting stiffness large enough to insure the local pin-ended modes have frequencies well above that of the overall platform frequencies (see Fig. 7).

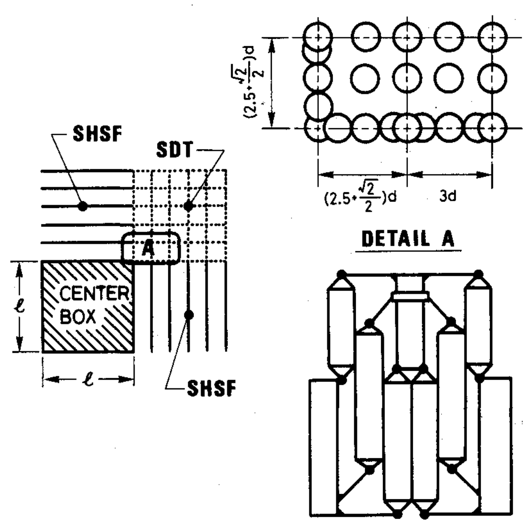
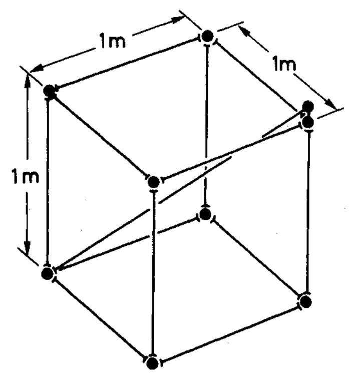



**Fig. 6 Most compact folding of the SDT and the SHSF.**

The vibration modes and the lowest three nondimensional frequencies are shown in Figs. 8 and 9, respectively. The nondimensional frequency is defined by the ratio of the calculated frequency divided by the corresponding frequency of the equivalent homogeneous plate. In Fig. 9, the nondimensional frequencies of the SHDF are also shown for reference.

Since the SHDF is classified as a fully stiffened structure, the nondimensional frequencies approach that of continuum theory as the number of modules increases.[3,5] The nondimensional frequencies of the SDT, however, decrease slightly as the number of modules increases. This result can be attributed to the fact that the SDT is a type of partially stiffened or nearly statically determinate structures. It can be seen in Fig. 1 that SDT has only one diagonal member and thus very weak shear stiffness. This can also be observed from the mode shapes. The mode shape of the third natural frequency clearly shows that the platform is formed from the relatively flexible SDT modules attached to the relatively stiff SHSF core structure running through the centers of the platform.

If the frequency performance of the aforementioned SDT platform is not desirable, an alternative concept which can improve the dynamic characteristics while retaining the advantages of the concept is possible. An example of such modification is shown in Fig. 10. A pair of tension wires is added to




| ITEM | NASTRAN MODEL | PROPERTY | NOTE |
|---|---|---|---|
| TRUSS MEMBER | CBEAM | $E=1.7\times10^{11}\,N/m^2$ $A=1.13\times10^{-4}\,m^2$ $\rho=1600\,kg/m^3$ | PIN-ENDED OPTION |
| NODE | GRID CONM2 | $m_g=1\,kg$ | |

**Fig. 7 Finite element model.**

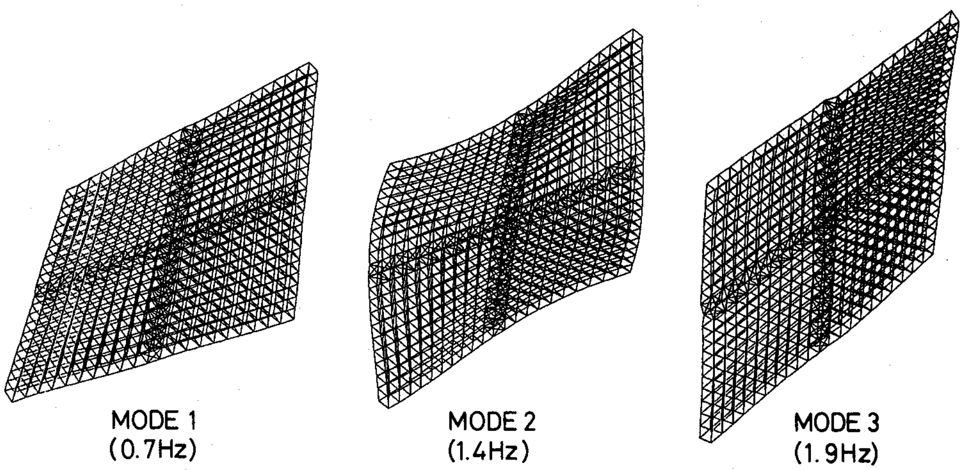



**Fig. 8 Mode shapes of 21 × 21 cells platform.**

both the upper and lower faces of the original SDT to increase the shear stiffness. Of course, this addition of tension wires does not deteriorate the packaging efficiency nor increase the number of mechanisms.

Additional frequency calculations were made for this alternative configuration, and results are shown in Fig. 11. It is clear that a significant improvement of dynamic characteristics was obtained by using the tension wires.

### Deployable Solar Concentrator

Most investigations of deployable structures have been devoted to only the folding of the truss structures, presuming the use of a flexible film for the reflector surface. The film-type reflector surfaces are of course attractive from packaging and weight standpoints. Furthermore, only the film surface affords uncomplicated deployment.

However, if a film-type surface is applied to a solar concentrator, the following problems can develop.

1) Surface accuracy: High performance solar concentrators impose stringent requirements for the geometrical precision in the design of reflectors. Since the required surface geometry is doubly curved with positive Gaussian curvature, the film-type reflector cannot achieve this because it is stabilized by tensile stresses. The film-type reflector is only able to form the desired surface in the macroscopic sense, and, locally, its surface inevitably deviates from the optimum configuration.

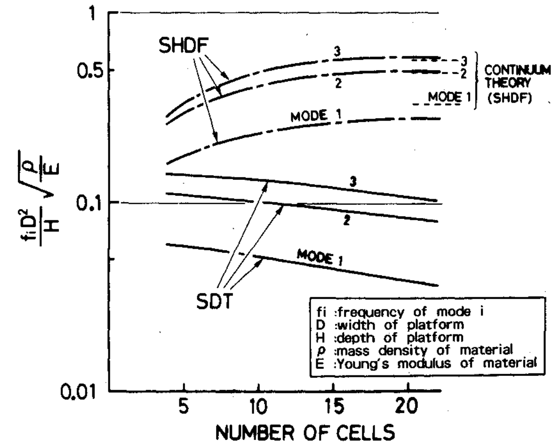



**Fig. 9 Frequency of the SDT and the SHSF platform.**

2) Durability problems: Only metallized films can be used for a solar reflector, since a mesh-type reflector cannot reflect sunlight. A significant problem with metallized films is the weak durability of the films in the space environment. The specular reflectivity has been reported by others to be reduced to perhaps 80% of the original value after long exposure.[2]

The necessity of a rigid reflector surface is, therefore, still a major constraint. Current studies on state-of-the-art solar concentrators are summarized in Refs. 1 and 2. Although various types of solar concentrators are presented, they still fail to deploy large-size concentrators in a purely automatic fashion. In some cases, EVA is required to attach panels to previously deployed support trusses. In other cases, the unit structure consisting of a panel and supporting truss can be deployed, but further assembly is later required to connect each unit with its neighbors in orbit. In both cases, such additional manual assembly is costly and, time consuming and thus limits the maximum size of the structure. The newly invented DSC, which is a deployable rigid reflector plate with supporting structure, is the answer to the aforementioned problems.

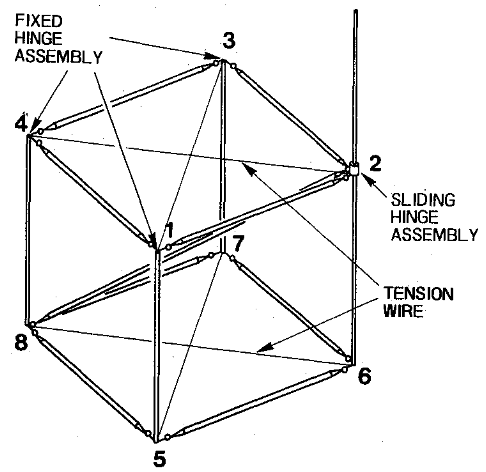



**Fig. 10 An alternative configuration of the SDT.**

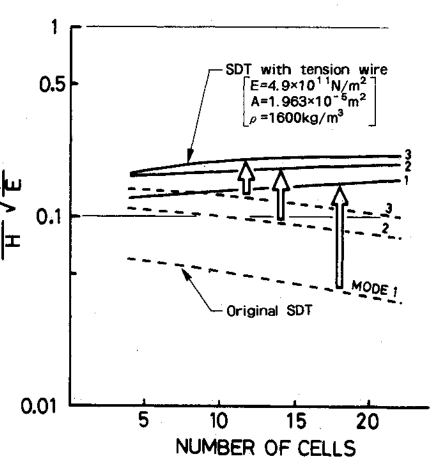



**Fig. 11 Effect of tension wire on frequencies.**

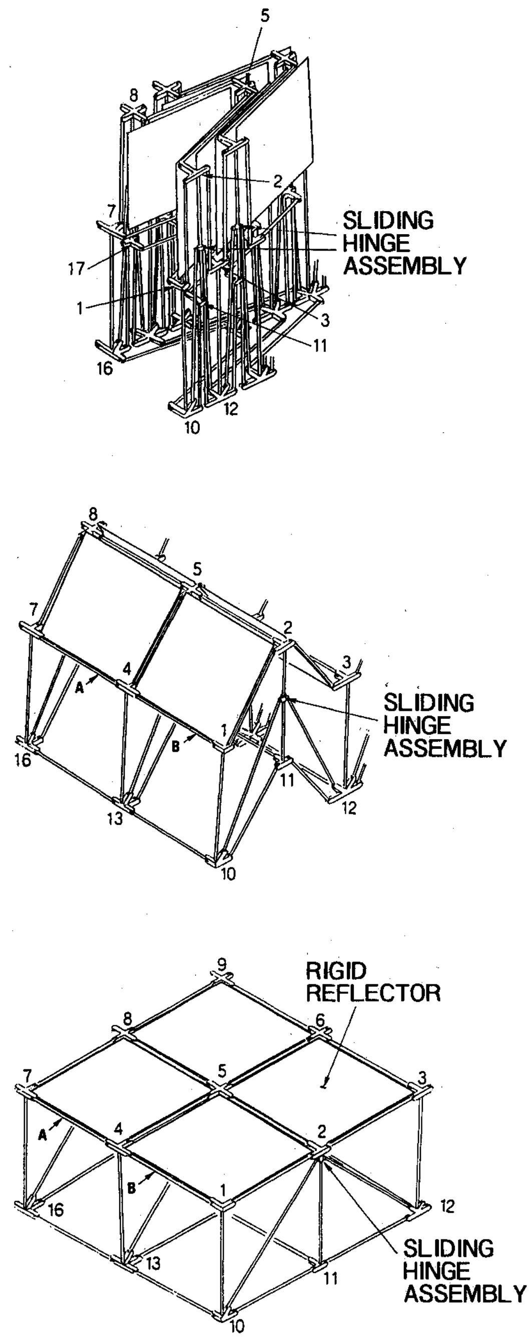



**Fig. 12 Deployable structure with flat reflector.**

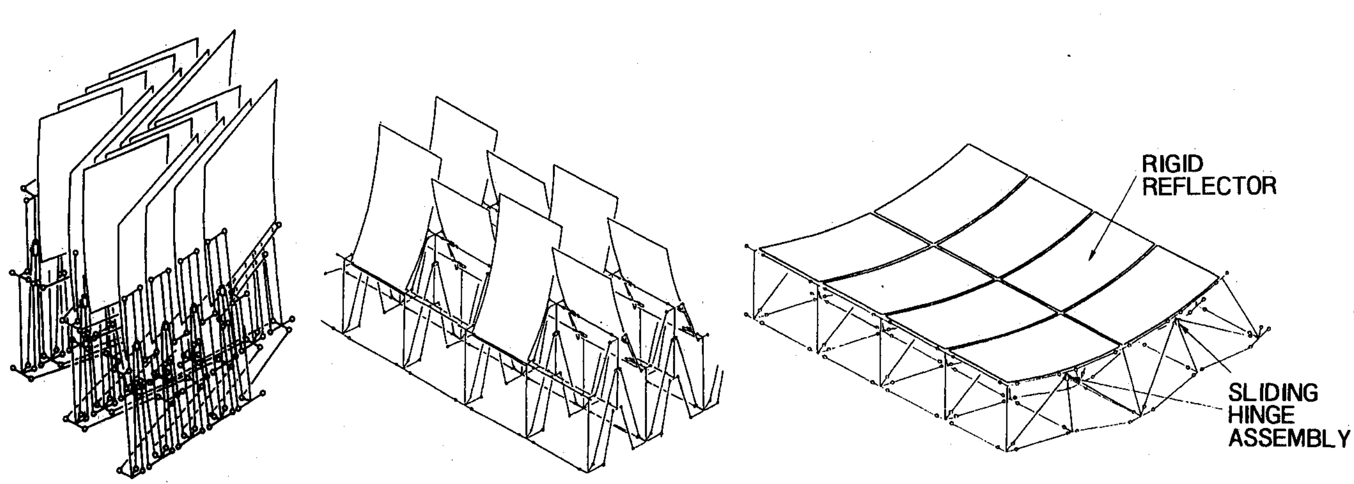



**Fig. 13 Deployable structure with reflector with one-dimensional curvature.**

## Basic Concepts

### *Flat Reflector*

The simplest application of the proposed concept is a flat solid plate with a deployable support structure as shown in Fig. 12. The support structure uses the modified SHDF module. The deployment motion is activated by the movement of the sliding hinges as well as the rotation of transverse truss members (e.g., member A, B). It is possible to substitute a pair of variable-length diagonal members for a sliding hinge. Deployment can be performed by either microactuators or springs.

### *Reflector with One-Directional Curvature*

The concept of the deployable flat reflector plate can be easily modified for curved reflectors. Figure 13 shows the case of the curved panel with the curvature in one direction. Note that the panel was partitioned differently from the case shown in Fig. 12 so that each panel can be nested to obtain better packaging efficiency when stored.

### *Reflector of Parabolic Surface*

The most practical application is the reflector of parabolic configuration. Figure 14 shows the basic folding concept of the parabolic reflector with support structure. For easy comprehension, the movement is shown sequentially, but the actual deployment motion will be carried out simultaneously. Although the folding pattern in this case is essentially the same as those shown in Figs. 12 and 13, the following are different.

1) A link mechanism, which eliminates the geometrical mismatch between the panel and the support truss due to the shear deformation of the truss that takes place in the sequence A-B is required.

2) Diagonal members of the support truss must be variable-length members, because the use of sliding hinges cannot satisfy the geometrical restriction for such a truss when folded.

## Function Test

To demonstrate the kinematic consistency of the proposed deployable structures, the functional model of the DSC was

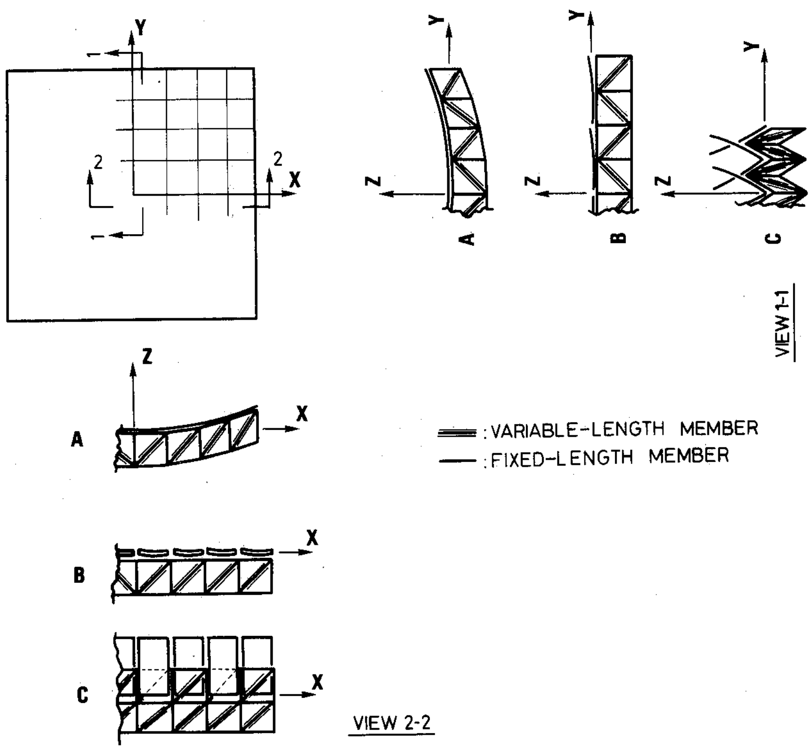
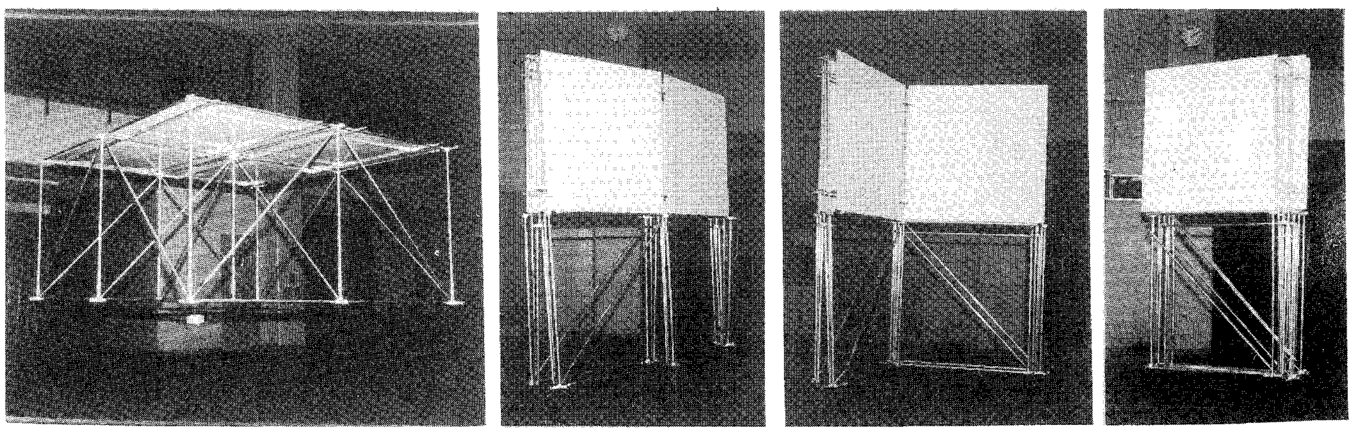



Fig. 14 Deployable structure with parabolic reflector.



a) b) c) d)

Fig. 15 Function test of the DSC model.

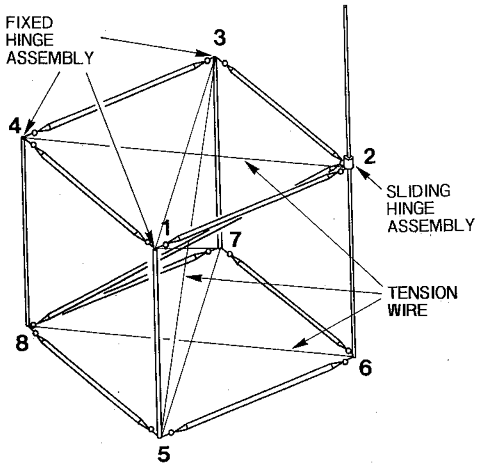



**Fig. A1 Another alternative configuration of the SDT.**

fabricated and tested. Figure 15a shows the fabricated model in the fully deployed state. Diagonal members of the model are variable-length members, which use springs to provide the deployment force. Each variable-length diagonal member is provided with lock mechanism that fixes the length after deployment.

The model was initially hung by long flexible expandable strings to simulate zero-gravity and subsequently deployed by the spring force. Figures 15b–15d show the model in partially and fully folded states during the test. Through the test, the smooth deployment motion was confirmed demonstrating the kinematic consistency.

## Conclusions

Three newly invented deployable structures were described, investigated, and demonstrated. The SDT and the SHDF-II were concepts for two-dimensional structures while the DSC was for the solar concentrator systems. Features of these three concepts can be summarized as follows.

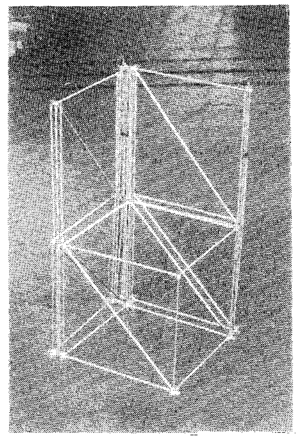
1) The SDT and the SHDF-II show good and in some case the best packaging efficiency with a small number of mechanisms.

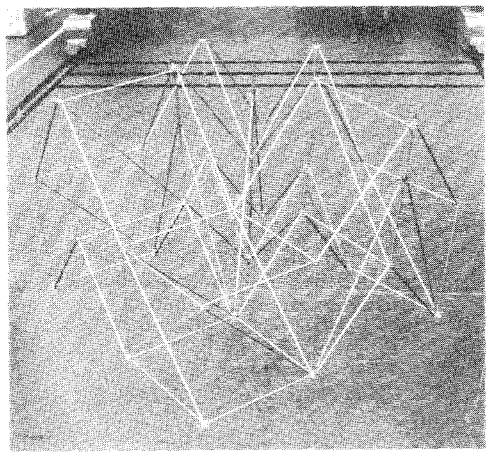
2) The DSC has the capability to deploy the solar reflector plate and its supporting structure automatically without any external assistance. A function model of the DSC was fabricated and tested to demonstrate the kinematic consistency of the structure.

## Appendix: Alternative Configuration of the Spatial Diagonal-stiffened Truss

In Fig. 10, an example of the modified configuration of the SDT is shown. Further addition of tension wires will give another alternative configuration and is shown in Fig. A1. This configuration enables the same connecting pattern of the basic modules as in the case of SHDF- II to form a two-dimensional platform. The advantages of this configuration is its small number of mechanisms and good packaging efficiency. The number of mechanisms required for deployment will be 0.25 per module, which is the same value in the case of the SHDF-II.

An actual test of this concept was performed and is shown in Fig. A2. This concept is quite unusual in that the module is stabilized by numerous tension wires, and it must be deployed by an extremely small number of actuators. Therefore, to demonstrate the practicality of this concept, a functional model was fabricated and tested. The functional model was designed so that it would form a parabolic surface. Smooth and substantially synchronized motion was confirmed to demonstrate the kinematic consistency of the structure.





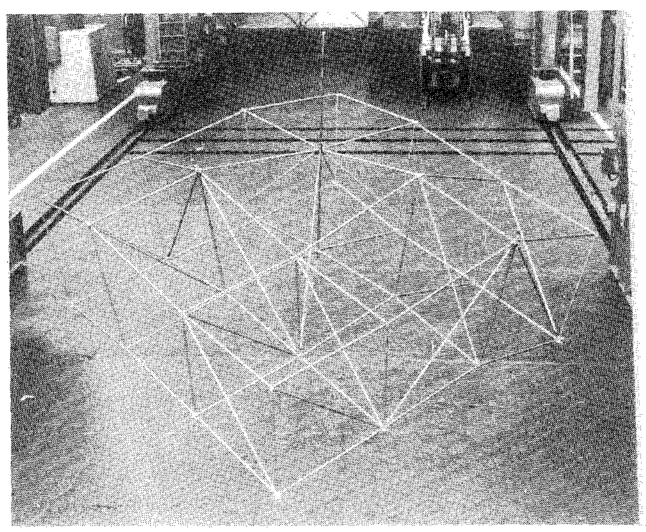


**Fig. A2 Function test of the modified SDT.**

## Acknowledgments

The authors express their gratitude to Hiroshi Miura, Hiroko Oda, Junji Takaki, Mizuho Takaki, and Kurt C. Gramoll for their contribution to this work.

## References

[1]Hedgepeth, J. M., "New Concepts for Precision Reflector Support Structures," International Astronautical Federation, Stockholm, Sweden, Paper 85-208, Oct. 1985.

[2]Hedgepeth, J. M., and Miller, R. K., "Structural Concepts for Large Solar Concentrators," International Astronautical Federation, Innsbruck, Austria, Paper 86-202, Oct. 1986.

[3]Takamatsu, K., Onoda, J., and Higuchi, K., "New Concepts of Deployable Truss Units for Large Space Structures," AIAA Paper CP-0868-87, April 1987.

[4]Onoda, J., "Two-Dimensional Deployable Truss Structures for Space Applications," *Journal of Spacecraft and Rockets*, Vol. 25, March–April 1988, pp. 109–116.

[5]Anderson, M. S., and Nimmo, N. A., "Dynamic Characteristics of Statically Determinate Space-Truss Platforms," AIAA Paper CP-85-0819, April 1985.

[6]Herbert, J. J., Postuchow, J. R., and Schartel, W. A., "Technology Needs of Advanced Earth Observation Spacecraft," NASA CP-3698, Jan. 1984.

[7]Cox, R. L., and Nelson, R. A., "Development of Deployable Structures for Large Space Platform Systems," NASA CR- 170690, Oct. 1982.

[8]Natori, M., and Miura, K., "Deployable Structures for Space Applications," AIAA Paper 85-0727, April 1985.

David H. Allen
*Associate Editor*