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CONCEPTS, ANALYSIS AND DEVELOPMENT FOR PRECISION DEPLOYABLE SPACE STRUCTURES

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Richard K. Miller, Mark Thomson,
and John M. Hedgepeth

ASTRO AEROSPACE CORPORATION
Carpinteria, California

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Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

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CONCEPTS, ANALYSIS, AND DEVELOPMENT FOR PRECISION DEPLOYABLE SPACE STRUCTURES, FINAL REPORT

SUMMARY

This report describes work that was performed under Task 8 of NASA Contract Number NAS1-18567. Task 8 was established to continue the development of structural technologies relevant to NASA's Precision Segmented Reflector (PSR) program. Such investigations were begun under Contract Number NAS1-17536 and resumed under Task 3 of the current contract.

Several issues surrounding the development of large Precision Segmented Reflector (PSR) designs are investigated. The concerns include the following:

Non-linear dynamics of large unruly masses such as the multi-layer thermal insulation of sunshades for instruments such as the precision pointing 20-meter-diameter Large Deployable Reflector (LDR).

- A study of the residual oscillations after "bang-bang" reorientation maneuvers of a rigid satellite with a string appendage is presented. Next, a generalization to the case of a membrane appendage is presented. Finally, application is made to the design of a sunshade (thermal blanket) for the LDR satellite. The complete study is presented in Reference 1.

Development of a deployable truss that has minimum structural redundancy (such as the tetrahedral truss) and can be configured with planar and doubly curved geometries.

- A kinematically synchronized articulation scheme for a deployable tetrahedral truss is presented. Called the Tetrapac, this truss is currently limited to a planar configuration that has two rings.

Development and demonstration of hardware that makes it possible for astronauts to attach large, cumbersome, and fragile precision reflector segments to an erectable truss structure. This task must be accomplished with a high degree of precision and with relative ease.

- A design for a Panel Attachment Device (PAD) was developed and manufactured for neutral buoyancy simulations to be performed by Langley.

SECTION 1

INFLUENCE OF UTILITY LINES AND THERMAL BLANKETS ON THE DYNAMICS AND CONTROL OF SATELLITES WITH PRECISION POINTING REQUIREMENTS

The complete results of this study were presented in a paper of the same title at the Fourth Annual NASA/DoD Conference on Controls/Structures Interaction Technology, 5–7 November 1990 in Orlando, Florida and are documented in Reference 1.

Most spacecraft control design techniques, for situations in which control-structures interaction is an important design consideration, require that the behavior of the spacecraft and its structure be very well known. On the other hand, most spacecraft have attached to them (or contain) nonstructural masses whose behavior is nonlinear and often not well known. Examples of such masses are cabling, insulation blankets, residual propellants, and astronauts. For past and current spacecraft, these "unruly" masses constitute a small fraction of the total mass and therefore do not seriously degrade the performance of the control system. For future spacecraft, even a small degradation may be unacceptable. Furthermore, large multipurpose spacecraft such as the Space Station will have a larger portion of their mass (e.g., the utility lines) in the ill-managed category.

As an initial step to address this problem, a study was performed of the residual free vibrations of a rigid body (satellite) with an appendage consisting of an initially slack string or membrane (utility line or thermal blanket) after completing a slew reorientation maneuver. The string and membrane were discretized using an assumed mode shape and the Galerkin procedure to obtain a single-degree-of-freedom nonlinear oscillator equation. The nonlinear elastic effects were obtained by accounting for the average change in tension as the string or membrane transitions from slack to taut behavior during each cycle of oscillation, while ignoring the axial or inplane inertia. An energy approach was used for this discretized system to provide exact solutions for the amplitude of angular oscillations as a function of the amplitude of applied angular acceleration during reorientation maneuvers. Parametric studies of the effects of the initial strain, both positive (initial tension) and negative (initial slack), were investigated, and results are presented in terms of nondimensional variables.

The results, which are summarized in the referenced documents with plots of the nondimensional variables for various reorientation accelerations, indicate that the amplitude of free oscillations increases dramatically when the initial strain is made negative (slack initial behavior). This result, which is quantified in the figures and specific numerical examples contained in the report, is particularly significant for high pointing precision applications, such as the Large Deployable Reflector (LDR), an infrared telescope with a 20-meter aperture. The LDR, shown in Figure 1-1, requires a large (2,500 kg including support structure) sunshade or thermal blanket, which may carry only very light tension in order to ensure effective insulation performance, as well as avoid excessive mass of the supporting structure.

Note that the sunshade contains nearly 20 percent of the total satellite mass. Furthermore, for slewing motions about any axis capable of changing the line-of-sight to the LDR, the mass moment of inertia of the sunshade is comparable in size to that of all other LDR components combined. Thus, the sunshade is expected to exert substantial influence on the pointing and slewing performance of the LDR.

Potential materials for fabrication of the sunshade include a layered thermal blanket consisting of alternate layers of Kapton film and insulation material. The effective mass per unit area of the blanket may vary widely, depending on the number and composition of layers included in the blanket.

For purposes of illustration, we consider a blanket design with a unit mass of 1 kg/m^2. We assume that the effective modulus of elasticity of the blanket is one-half that of Kapton, while the mass density is equal to that of Kapton. Furthermore, we assume that the height h of the sunshade is 10 meters, and the unsupported length ℓ is also 10 meters, corresponding to a hexagonal support structure with six equally spaced vertical struts around the perimeter of the reflector. We assume that the total blanket area is 1100 m^2. In addition, we assume an effective base radius R_o of 4 meters for the sunshade.

The results shown in Figures 10 through 12 of Reference 1, indicate that if a residual oscillatory pointing error as large as 1 milliradian can be tolerated, then a quite reasonable sunshade and support structure may be designed to avoid both excessive structural mass and undesirable pointing behavior using only passive means.

However, it is equally clear that very high precision requirements would lead to very different conclusions. For example, if the required pointing error is reduced to $\theta_p = 1 \times 10^{-5}$ radians, then the results shown in Figure 10 indicate that a very large initial strain of $\varepsilon_o \cong 0.3$ percent is required in the thermal insulation. Note that many thermal blanket materials are not able to sustain such large strains without either rupturing or creeping excessively. Even if the membrane behavior under such high strain is set aside for the moment, additional serious problems are created for the sunshade support struts which must be designed to withstand very large forces. In particular, the results shown in Figure 12 indicate that a peak strut force of $F \cong 500$ N is required. Such large tension forces would result in excessive structural mass of the sunshade supports. Clearly, if high pointing accuracy is needed, the supporting truss in the shroud must be more closely spaced so as to reduce the unsupported length of the blanket. In any case, passive structural design of the sunshade may not be capable of meeting the performance objectives associated with very high pointing accuracies. In such cases, use of appropriate active control techniques must be explored.

SECTION 2

DEPLOYABLE TETRAHEDRAL TRUSS

The Pactruss has been developed by Langley and Astro researchers to provide NASA with a synchronously deployable three-dimensional truss that offers the capability of high specific stiffness. As is usually the case with deployable planar or doubly curved truss geometries, more joints and members are required by the Pactruss than would be needed for an equivalent erectable tetrahedral truss. The specific stiffness that can be achieved by the Pactruss is therefore lower than that possible with the erectable tetrahedral truss assuming equivalent joint masses (it should be noted however that the Pactruss displays a higher degree of structural redundancy than the tetrahedral truss which, as reported in Reference 2, results in greater stiffness if the members in both trusses are equivalent. Thus the Pactruss's loss of specific stiffness due to it's number of members is partially offset by this phenomenon).

A deployable tetrahedral truss was designed and built for Langley by Astro in the early 1980s as described in Reference 3. The deployable tetrahedral truss, however, is not synchronized kinematically during deployment. It is stowed as a somewhat loose mass of sticks that must be sequentially unfolded in the correct order by an intelligent canister or some other form of dedicated mechanism. The deployable tetrahedral is therefore more useful for very large area structures that would be impractical to deploy synchronously and whose scale makes the added cost and mass of a dedicated deployment mechanism a relatively small inconvenience.

It is desirable therefore to have a synchronously deployable truss that displays the highest possible specific stiffness, i.e., something based on tetrahedral geometry. Such a truss would be useful for smaller precision trusses such as those envisioned for PSR applications (two to six or eight rings for instance) for which deployment by distributed actuators is still practical and a dedicated deployment mechanism is a relatively costly and massive extra item. The Tetrapac deployable tetrahedal truss geometry was therefore developed by Astro.

The Tetrapac can be best visualized deploying from its stowed geometry which is based on a fixed tetrahedron at the center of the truss as shown in Figure 2-1. All folding and non-folding members stack on top of the members in the central tetrahedron. For clarity, folding members are not shown in the illustrations, which depict deployment of the two-ring Tetrapac in increments as seen from two angles. The software used for this kinematic simulation has been presented in Appendix A.

Ninety percent of the members in the two-ring planar Tetrapac that is shown in the figures were verified to be without strain during deployment using single-degree-of-freedom (SDOF) hinges. Although time did not permit complete analysis of the remaining ten percent of the members, it is believed that SDOF hinges can be used on these members as well with zero or negligible strain during deployment. It is not known whether the Tetrapac geometry can be adapted to a doubly curved configuration with a useful amount of curvature.

A Tetrapac solution could be found for no more than two rings. All stowed members must be packaged on top of six of the triangular facets of the basic tetrahedron. As the number of circumferential bays increases geometrically with the number of rings, it becomes more and more difficult to stow the outer ring and especially difficult to maintain kinematic coupling. The solution for the articulation of each ring of bays was found to be a unique one which lends no insight into how successive rings should be articulated. The lack of a general solution for the Tetrapac's articulation makes it somewhat cumbersome as a generic structure, and if it is indeed restricted to only two rings it has limited utility.

SECTION 3

REFLECTOR PANEL ATTACHMENT DEVICE FOR PRECISION SEGMENTED REFLECTORS

This subtask is part of NASA's ground breaking effort to develop Precision Segmented Reflector (PSR) related technologies. It has resulted in some of the first practical hardware for in-space assembly of large precision reflectors as envisioned by NASA for instruments such as the 20-meter-diameter infrared observatory. The panel attachment hardware allows large, cumbersome and fragile precision reflector segments to be assembled with a high degree of precision onto an erectable truss structure without undue effort.

3.1 REQUIREMENTS

The following requirements were communicated to Astro by Langley at the beginning of the panel attachment subtask:

Truss

The reflector support truss is erectable, has tetrahedral geometry, a parabolic figure and is similar to others that are under development by Langley for the PSR technology program.

Panels

The reflector panels are similar to those that are under development by Jet Propulsion Laboratory researchers. The panels are hexagonally shaped, approximately 2 meters in diameter, have a thickness of approximately 8.0 cm and a mass of 5 to 10 kg per meter squared. Statically determinate support is to be provided for the panels by precision flexures that are attached to the truss nodes. The flexures should support the panels at panel attachment points that are as close as possible to equilateral vertices of the hexagon and the optical surface of the panel.

The panel attachment hardware must allow the panel to expand and contract through a range of 1 millimeter without affecting the location of the center of the panel relative to the truss (x and y directions) or the piston position of the panel vertices (z direction) by more than 0.5 micrometers.

The installed gap between the panels must be 3.0 millimeters or less.

A small force or moment may be applied at or near the panel attachment point if necessary to position and retain the panel on the flexure tip.

The panel attachment hardware concept should be adaptable to an electromechanical design that can quasi-statically control the piston position of the panel vertices across a range of 0.5 millimeters. Adjustments would be made with screw jacks or some other type of mechanism that can repeatably position the panel with accuracies in the sub-micron range.

The panel edges will be chamfered or raked back at 30 degrees.

Assembly Loads

The attachment hardware should be able to withstand a momentary load of 100 lbs from the bumps and shocks of extravehicular activity (EVA). This capability will be required only during assembly of the reflector.

Hardware Finish

The panel attachment hardware can have no sharp edges or other features that could scratch or damage EVA suits in any way.

Maintainability

It should be possible to remove a single panel from an operational reflector.

3.2 REFLECTOR ASSEMBLY SEQUENCE

The process for the attachment of hex panels to the truss by astronauts is depicted in Figure 3-1, which is a scene from the Precision Reflector Orbital Build Experiment (PROBE). This experiment has been proposed by Langley to validate panel attachment and other orbital construction technologies that are being developed. The truss would be assembled using a turntable to ease the astronaut's workload. The truss is assembled only enough to accommodate the first panel, which is attached to the truss nodes using the subject hardware system. Truss assembly then continues only enough to attach the second panel and so on until all rings of the reflector have been completed.

The assembly of truss struts and nodes is sequenced so that the panels can each be brought towards the reflector when two of the three nodes that support it are unencumbered by any prior panels. The panel is therefore easily docked by the astronauts on two corners first, and then rotated down to the third corner as shown in Figure 3-2. The astronauts guide the panel attachment points towards the unencumbered nodes at an angle of 5 to 15 degrees. The clearance that is provided by the approach angle eliminates the need to be exceedingly careful about bumping the panel that against the edges of previously docked panels. With two of its corners restrained the panel is limited to only one degree of rotational freedom. Therefore, the panel can be rotated down to the third attachment point without guidance from the astronauts. The panel corners are docked by simply snapping them onto the truss nodes using the panel attachment device (PAD). The PAD is then actuated by the astronauts to precisely position the panel for reflector operation.

Assembly of the reflector can begin either from the center of the reflector or from an offset position for reflector types that have a central panel or opening. The truss assembly sequence described above is compatible with off-axis parabolic reflector geometries as well as centered designs.

3.3 PANEL ATTACHMENT DEVICE DESCRIPTION

The Panel Attachment Device (PAD) that has been designed and manufactured under this task permits the above assembly sequence to be carried out by suited astronauts without using any tools. Two versions of the PAD were designed to satisfy the requirements as previously described.

The first design, shown in Figure 3-3, reflects Astro's PAD concept applied to an operational reflector system for PSR applications. This design can quasi-statically position each panel attachment point in the out-of-plane (piston) direction to a sub-micrometer accuracy across a range of 500 micrometers. This range of adjustment should accommodate any initial truss fabrication errors or post-assembly distortion from thermal inputs and exposure to the space environment.

The second PAD hardware design is shown in Figure 3-4. This design was manufactured for Langley to use in a neutral buoyancy simulation of panel attachment concepts. The neutral buoyancy demonstration is a precursor to the PROBE flight experiment. The demonstrator design could also be adapted for use in an operational reflector system that has less demanding requirements for surface precision than the quasi-statically adjustable version. Photographs of the hardware that was shipped to Langley are presented in Figure 3-5.

3.3.1 PAD Operation and Detailed Design

Operation of both versions of the PAD during the panel attachment sequence entails three steps that are depicted schematically in Figure 3-6 and listed below:

PAD Operation

Step 1	Panel capture or soft docking on two of the three panel support points using the Quick Attachment Device (QAD).
Step 2	Soft docking on the third panel support point using the QAD.
Step 3	Actuation of the PAD cage to transfer support of the panel from the QAD soft docking device to precision flexures.

3.3.1.1 SOFT DOCKING

Steps 1 and 2 of PAD operation comprise the panel soft docking maneuver. All three panel support points could conceivably be soft docked simultaneously using the PAD, however, sequential attachment of the panel corners requires far less finesse on the part of the astronauts. This is because the number of degrees of panel freedom are sequentially reduced as each of its corners are docked.

Step 1 is completed by soft docking the two panel corners that correspond to the unencumbered nodes of the partially assembled truss. Soft docking of the panel corners is accomplished with the Quick Attachment Device (QAD) which is shown operating in step 1a and 1b of Figure 3-6. The QAD utilizes a probe and cone type docking mechanism that was developed by Astro for this application. During soft docking, the QAD secures the panel to the truss node with a course positioning capability that is tolerant of bumps and jolts from the astronauts of up to 100 lbf. The QAD probes are mounted on the cage of the PAD node assemblies. The cones are machined into the panel corner bodies as closely as possible to the panel vertices and precision flexure seats as shown in Figure 3-7. The reflector panel edges are chamfered at a 30-degree angle to eliminate the "keystone" geometry that would otherwise make assembly of the doubly curved reflector onto a truss virtually impossible. The chamfered panel edges also permit the support points on the corner bodies to be as close to the panel vertices and reflective surface as possible, which in turn allots the greatest length possible to the precision flexure struts.

The probe and cone of the QAD are self-aligning during soft docking. Angular misalignments of the probe and cone of ±15 degrees in 2 degrees of rotational freedom are accommodated by a spherical joint in the probe of the QAD. The rotational center of the spherical joint is as close to the tip of the probe as possible so that the probe will readily align itself with the cone during insertion as shown schematically in Figure 3-8. Positional misalignments of the probe and cone are accommodated by a large conical lead-in feature that precedes the cone in the corner body as shown in Figure 3-7. The lead-in permits an astronaut to guide the cone towards the fixed probe with approximately ±1-inch error in their alignment.

Finally, the QAD probe and cone are simply snapped together with a gentle push by the astronaut. Once the QAD probe is snapped together, it is positively locked inside of the cone. The probe cannot be removed from the cone without deliberate actuation of a separate PAD component from the backside of the truss. The mechanical design of the QAD causes it to behave as a ball detent during insertion and as a quick-disconnect which must be actuated for release. Detailed design of the QAD is shown in Figure 3-9. Proper functioning of this design has been verified with numerous models that also suggest that it is very reliable. Using the device is very simple and intuitive and many other EVA, robotic or earthbound applications could possibly benefit from it.

Soft docking of the panel is completed with Step 2 of the panel attachment sequence, as shown in Figure 3-6. With the panel at a 5 to 15 degree inclination relative to the local truss face, it is then rotated down to soft dock the third and final corner body. Maneuvering the panel at this point in the assembly sequence does not require careful guidance by the astronauts to avoid hitting the edges of the previously docked panels. The panel is constrained to motion in only 1 degree of rotational freedom for large movements by the two previously docked corner bodies.

The QAD probes are mounted in the cage assembly of the PAD with ±1 millimeter of play in a plane that is parallel to the reflector surface. The play is necessary because of the way that the doubly curved reflector geometry affects assembly clearances (this effect is briefly described in Section 3.3.1.2). Plus or minus 1 millimeter of play is sufficient to provide adequate clearances with reflector curvatures that result in a minimum included angle between any pair of truss surface struts of 170 degrees. This amount of play is equal to only one-third of the total gap between panels, but in order to ensure that third panel corner does not hit the edges or corners of previously docked panels during Step 2, a metallic guard has been provided on the upper surface of the cage. The guard, visible in Figure 3-10, protrudes above the vertices of docked panels during the docking maneuvers and is retracted below the reflective surface of the panels during assembly Step 3.

3.3.1.2 ACTUATION OF THE PAD CAGE

Retracting the PAD cage, as shown in Step 3 of Figure 3-6, completes the attachment process by transferring support of the panels to precision flexures. The cage is retracted once all three corner bodies of the mating panels have been soft docked with the PAD. The cage houses and protects the precision flexures until the completion of this step.

The cage is actuated from the backside of the truss by completing one-quarter turn of the cage actuation handle. The first portion of the quarter turn, which is detented, unlocks the cage. The cage is then automatically pushed down towards the node a distance of 1.0 cm by a spring within the handle shaft. The end of the spring's travel is coincident with the point at which the flexure tips make contact with the precision flexure seats in the panel vertices. This prevents the panel corner bodies and the engaged QAD probes from travelling any further towards the node. Further rotation of the handle, however, engages a helix in the handle body which forces the cage to retract further, which compresses the springs that are on the lower ends of the QAD probes. Previously the probe springs acted only to preload the probe shafts against the upper surface of the cage. The springs now act to exert a small normal force near the panel vertices to position and retain the flexure tips in the flexure seats as is required for operation of the reflector. Due to the lateral distance between the vertical axes of the flexure seat and the probe/cone QAD, a small moment is induced in the panel tips by the probe spring. This moment is higher for the ground demonstration hardware than would be required for an operational reflector because the ground demonstrator must retain the bulky panels on the flexure tips with the reflector inverted in gravity.

3.3.1.3 FLEXURE DESIGN

The detailed design of the flexure described below pertains only to the operational PAD design. The ground demonstration model is currently designed with simple posts of hexagonal cross section that flex in all directions. This was done to reduce the cost of the prototypes.

The operational flexure design provides a statically determinate support condition for the panel segments by flexing in only 1 degree of freedom as shown in Figure 3-11. As the panel strains thermally, its center remains in the same location relative to the plane of the three supporting nodes of the truss. The reduced section of the flexure beam where flexural strain occurs is as close as possible to the truss node so that the length of the non-flexing beam is a maximum. This feature minimizes the distance that the flexure tip will move in the piston direction (out-of-plane) as the panel strains in-plane due to thermal variations. The flexure length that is provided by the PAD design limits the maximum piston movement to -1.5 micrometers across the thermal deflection range of 1 millimeter.

The flexures have been placed as close to the vertices of the panels as possible with the flexure size that was baselined by Astro. The cross-sectional dimensions of the flexures are 20 x 6.4 millimeters. This size was chosen so that the flexure assembly would offer high stiffness in the other 5 degrees of freedom.

The length of the flexure can be adjusted electromechanically. A small stepping gearhead motor and cam mechanism are mounted below each flexure on the truss node as shown in Figure 3-3. The 0.5 millimeter range of adjustment is cycled through by one complete rotation of the cam. The step angle of the stepping motor is 90 degrees and the gearhead reduction is 1800:1. Therefore, for each step of the motor, an adjustment of 0.14 micrometers is effected.

The vertical movement of the cam follower, which is shown in Figure 3-3 as a small bearing, is transferred to the flexure tip by a thin rod made of beryllium alloy or graphite composite for thermal stability and stiffness. The thin rod is housed in a bore in the center of the flexure. The tip of the flexure is actually a dual flexure which is free to move parallel to the axis of the flexure body in the piston direction only in response to gear motor inputs.

3.3.1.4 PANEL RELEASE

As previously mentioned, the panel corner body cone cannot be released from the QAD probe without deliberate actuation from the back side of the truss. The cone can be released only if the probe and its internal piston, shown in Figure 3-9, are pulled together by the wire that is in the bore of the probe's mounting shaft. This action releases the balls from their locked position in the groove of the corner body cone. The wire is attached to levers that are mounted on node. Therefore, when the cage is close to the node in the operational position the wire is loose. The travel of the release lever is not great enough to tighten the wire sufficiently to release the panel when the PAD is in this position. The astronaut must therefore rotate the cage actuation handle back to the soft docking position in order for the panels to be released.

The release lever that has been provided to Langley on the demonstration hardware is designed to attach to a larger ring or paddle that will be designed by Langley at a later date for the direct EVA interface.

3.3.2 Vibration Frequency of the Reflector Panel Support System

An analysis has been conducted to estimate the vibration frequencies of PSR baseline hex panels on a PAD support system that is borne by a PSR-type truss. The analytical model includes stiffnesses of the PAD flexure assemblies and the PSR truss, which includes truss node rotational stiffnesses. The panels are assumed to be rigid bodies.

The worst-case truss node rotational stiffnesses were used in the calculations. Such nodes are those on the perimeter of the truss where as few as five struts (three surface struts and two interior struts) are connected to the node instead of the maximum number of 9. The analysis assumes that there is zero compliance in the joint between the strut and the node. Other parameters used in the analysis and the results are listed in the following tables. The fitting factor of 2.0 in Table 3-1 means that the mass of all truss joints, fittings, and struts is 2.0 times the mass of the struts alone.

As shown in Tables 3-1 and 3-2, the first vibration frequency of the panel on flexure mountings is 26.3 Hz. This mode is well removed from the first mode of the two-ring truss with its payload of panels, which is 14.1 Hz. Most analyses of PSR-type reflectors tend to place the first global mode between 10 to 20 Hz, therefore the PAD flexure support scheme appears to be viable for future work with PSR reflector concepts.

TABLE 3-1: VIBRATION FREQUENCIES FOR TWO-RING TETRAHEDRAL REFLECTOR

Struts: 2.5-cm OD, 1.0-mm wall, 2.0-m nominal length
Material: Graphite composite, E = 2.285E11 Pa, Density = 1,740 kg/cu m
Fitting mass factor: 2.0
Panel mass = 5.0 kg/sq m
Supported at three inner upper nodes.

	BARE TRUSS		TRUSS WITH PANELS	
Mode Number	Pin-end	Fixed-end	Pin-end	Fixed-end
1	29.8 Hz	29.2 Hz	14.1 Hz	14.1 Hz
2	29.8	29.2	14.1	14.1
3	51.0	48.1	24.0	24.0
4	56.8	48.6	26.3	26.4
5	80.5	48.9	35.9	36.1
6	80.5	48.9	35.9	36.1

TABLE 3-2; VIBRATION FREQUENCIES OF STIFF PANEL ON PAD FLEXURES

Truss nodes with zero displacement:
Rotational stiffnesses = 6666.7 Nm/rad
Panel width = 2.0 m
Panel density = 5.0 kg/sq m

Mode Number	Frequency	Mode Type
1	26.34	Sidewise in x-direction
2	26.34	Sidewise in y-direction
3	127.41	Rotation around z-direction
4	333.45	Pistoning in z-direction
5	1,145.04	Rocking around y-direction
6	1,145.06	Rocking around x-direction

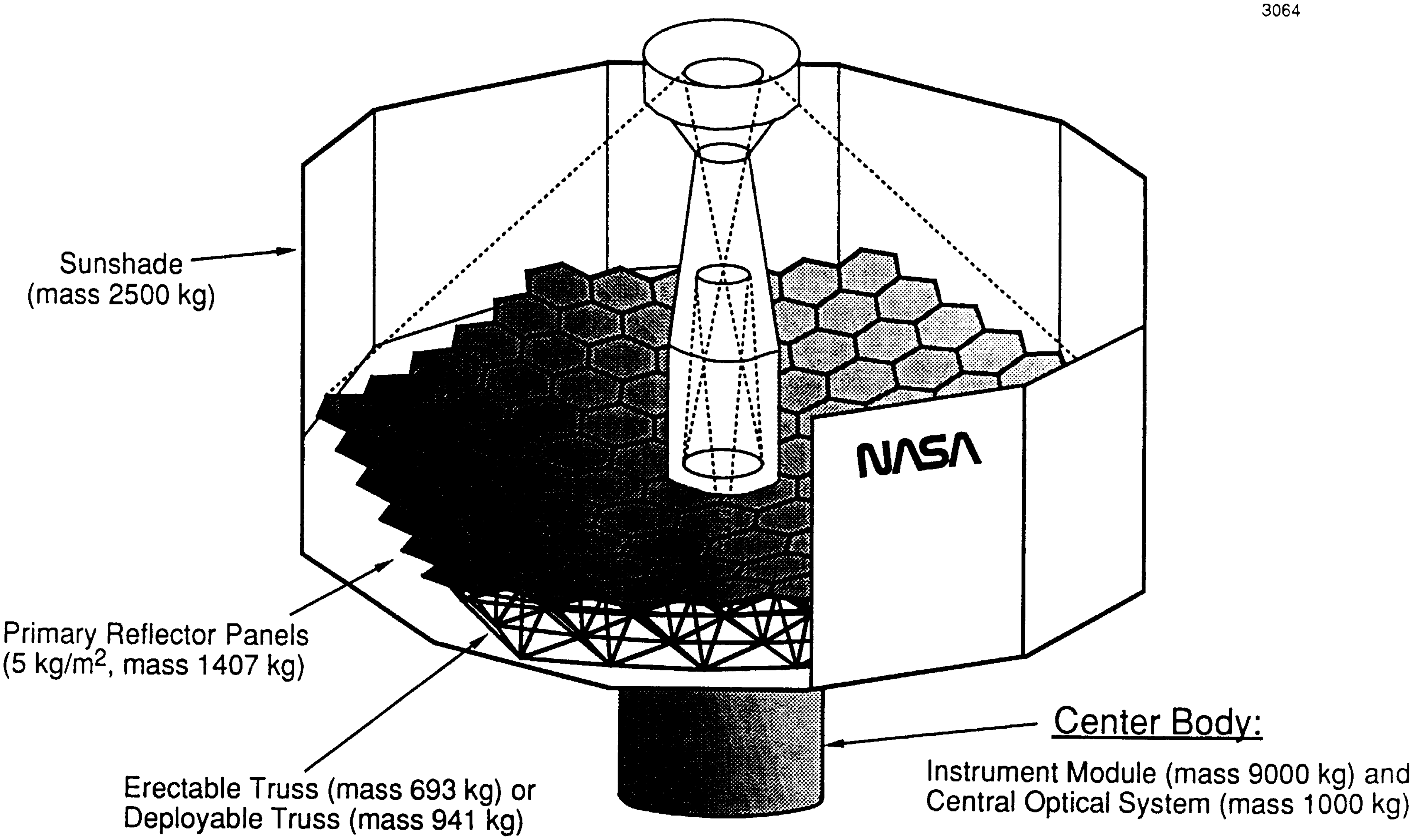


Figure 1-1. Large Deployable Reflector (LDR) Concept.

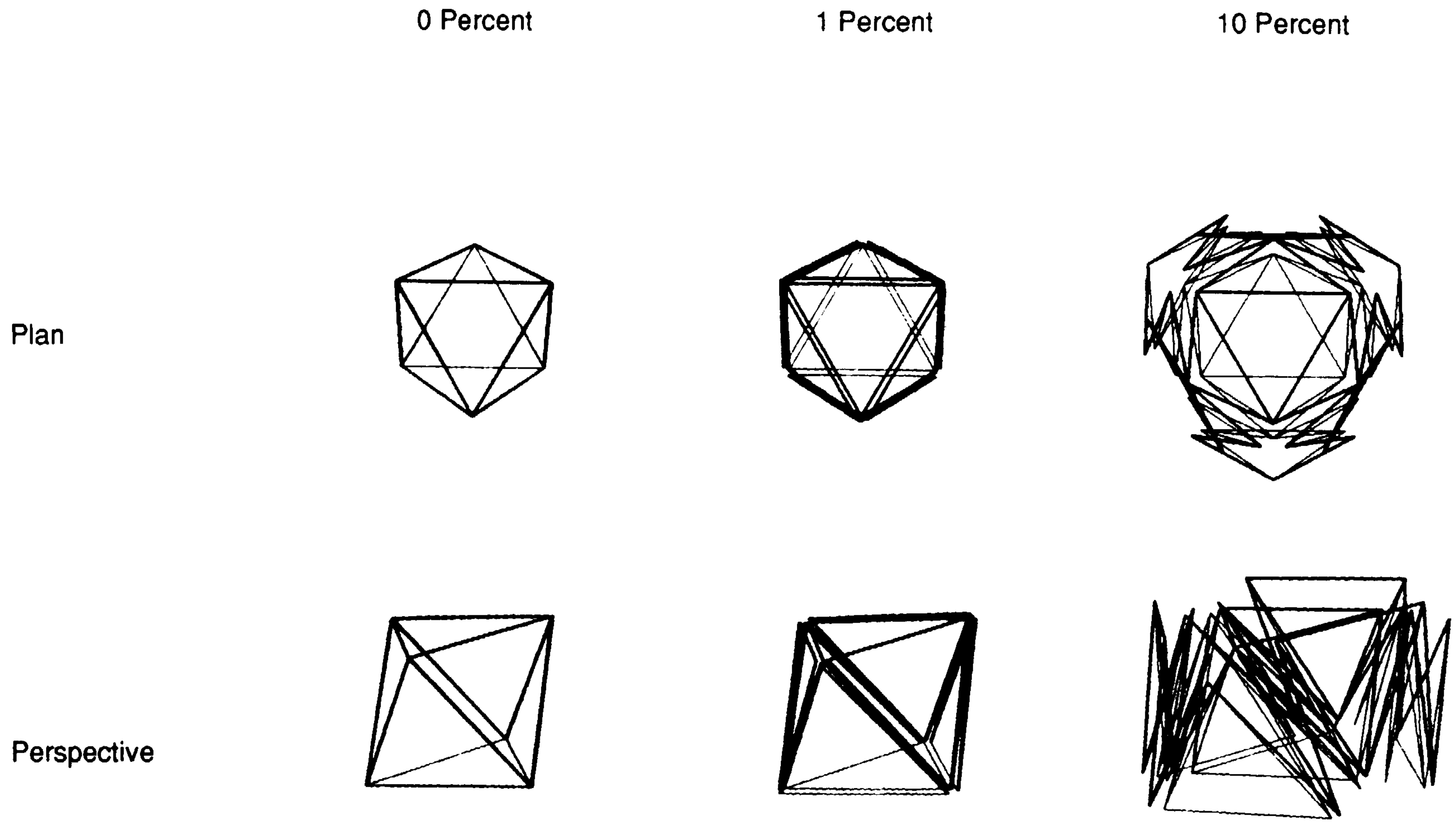


Figure 2-1. Tetrapac at 0, 1 and 10 Percent of Deployment; Plan and Perspective Views (folding members not shown).

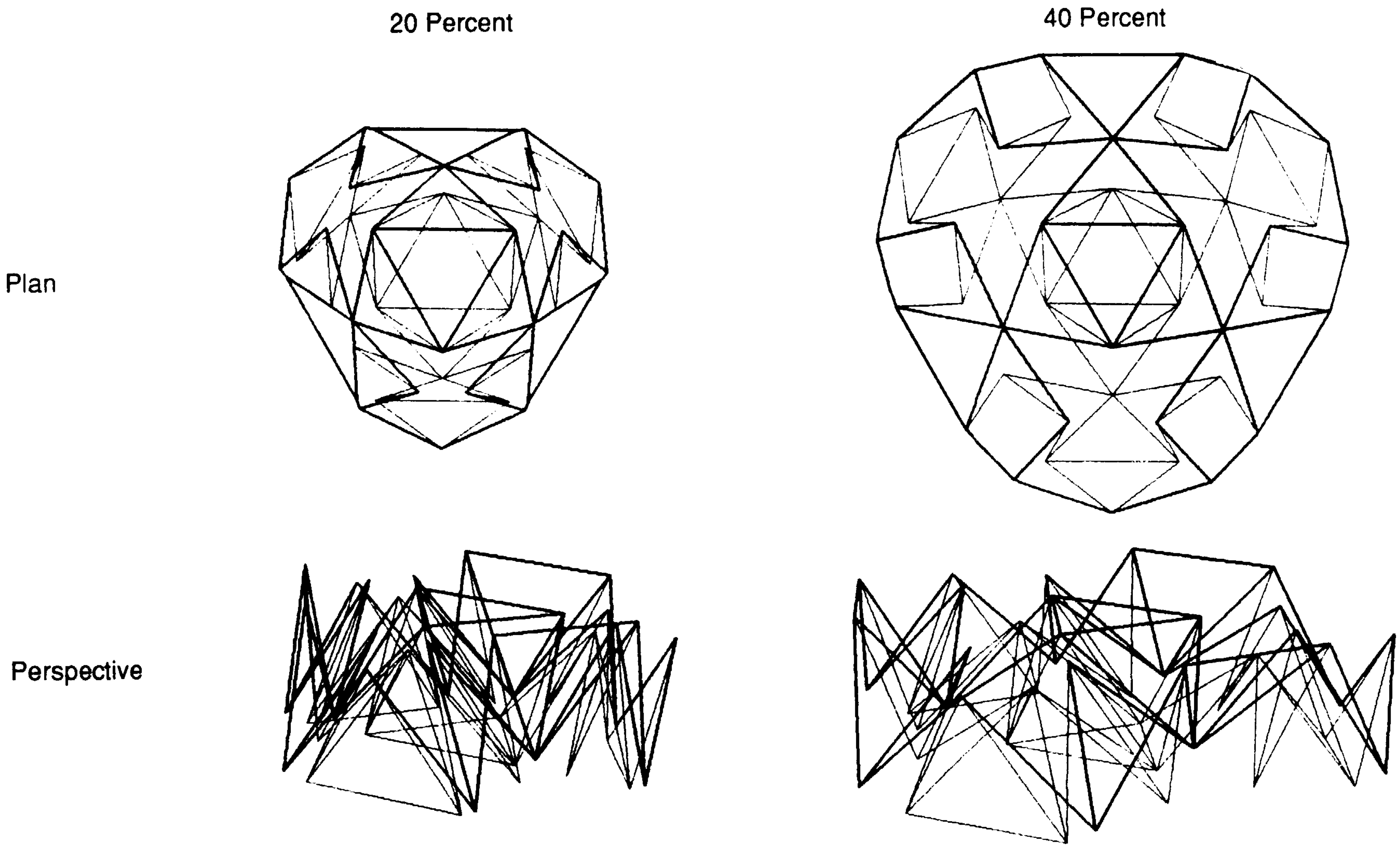


Figure 2-2. Tetrapac at 20 and 40 Percent of Deployment; Plan and Perspective Views (folding members not shown).

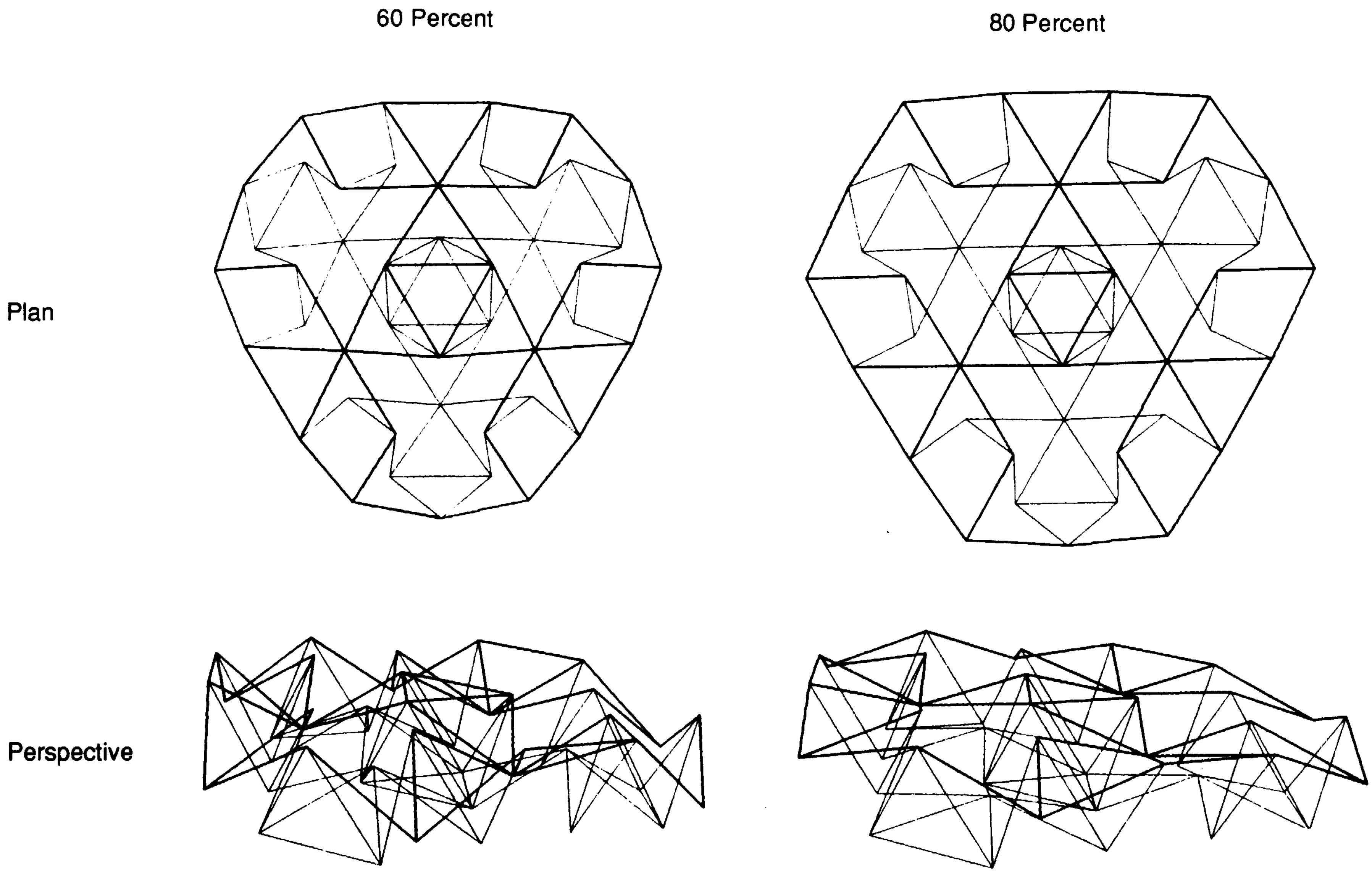
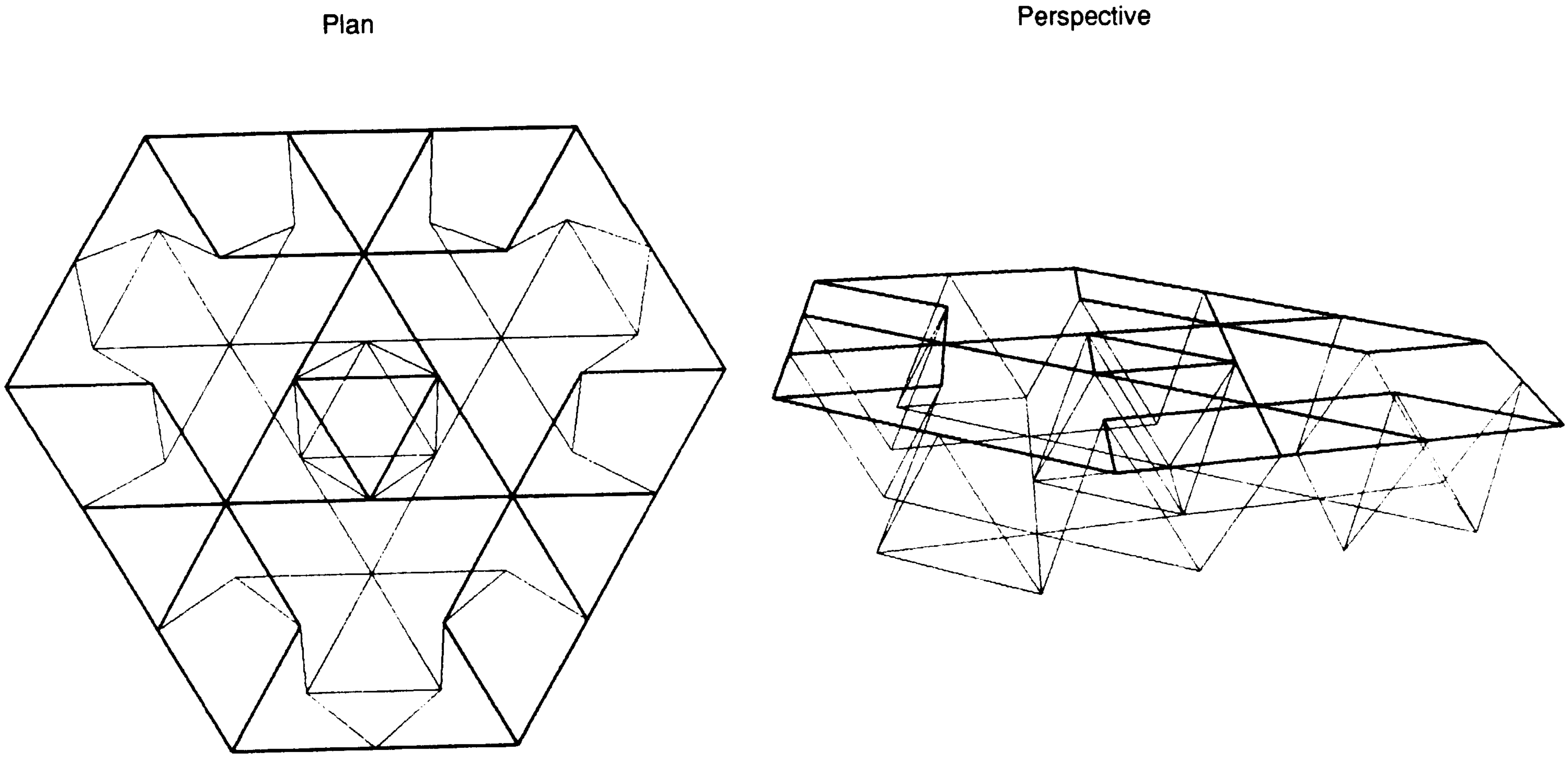


Figure 2-3. Tetrapac at 60 and 80 Percent of Deployment; Plan and Perspective Views (folding members not shown).


Plan

Perspective

Figure 2-4. Tetrapac Fully Deployed; Plan and Perspective Views (folding members not shown).

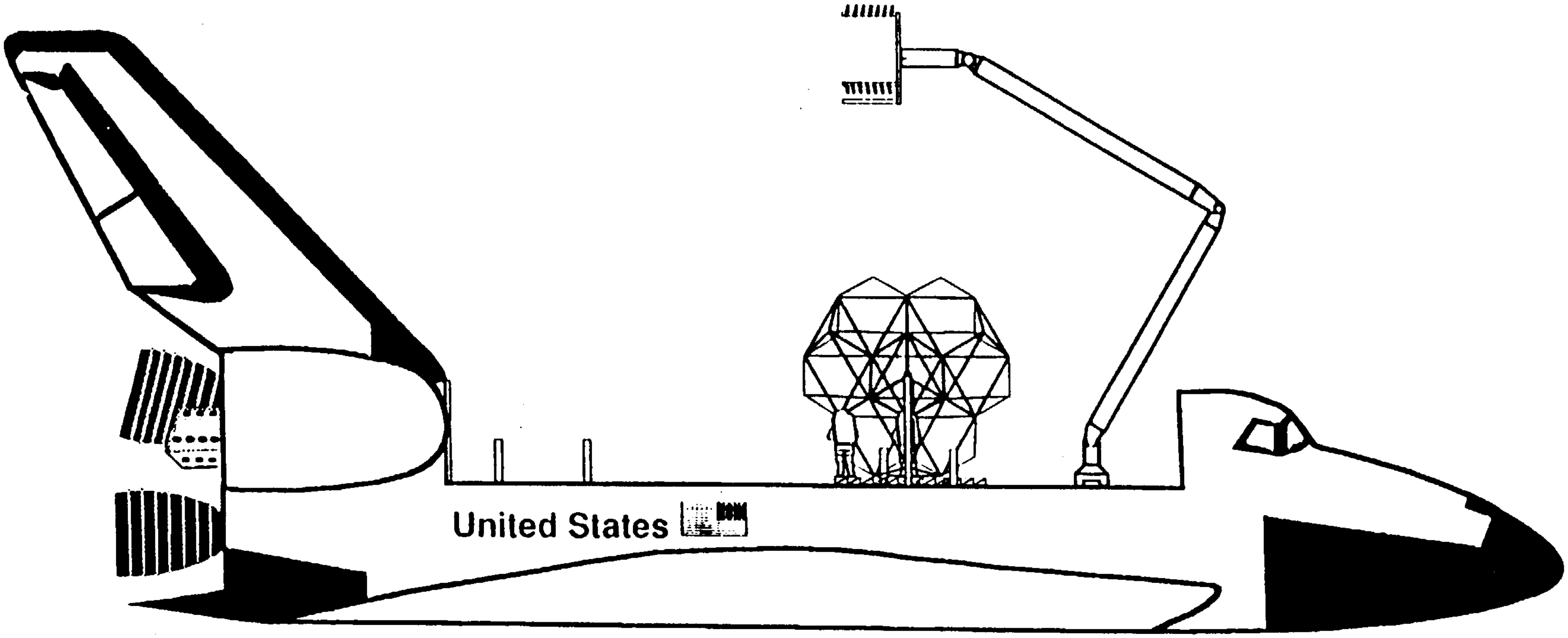


Figure 3-1. Reflector Orbital Assembly Process.

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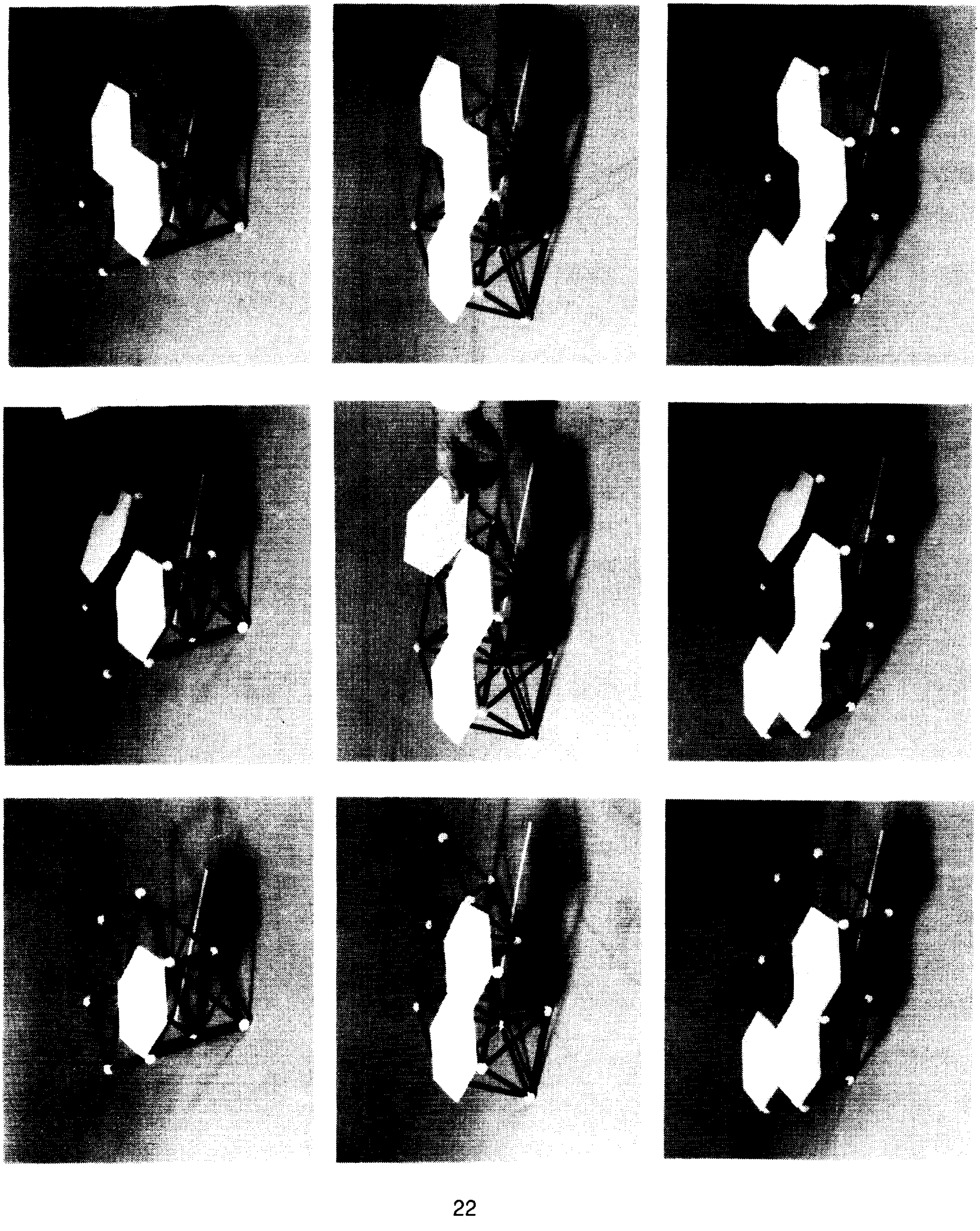

Figure 3-2. Assembly Sequence for Reflector Truss and Panels.

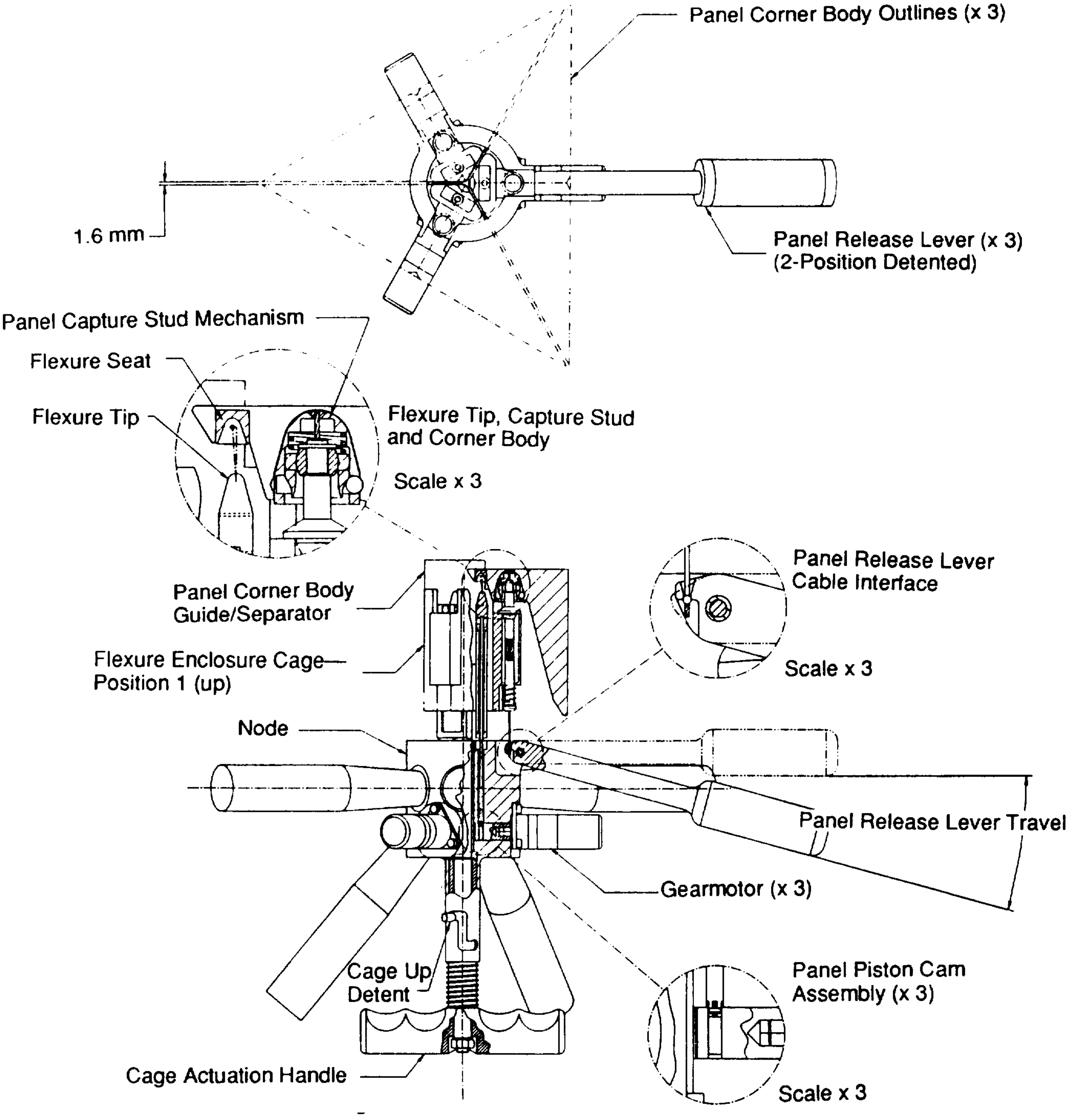

Figure 3-3. Operational Panel Attachment Device Design.

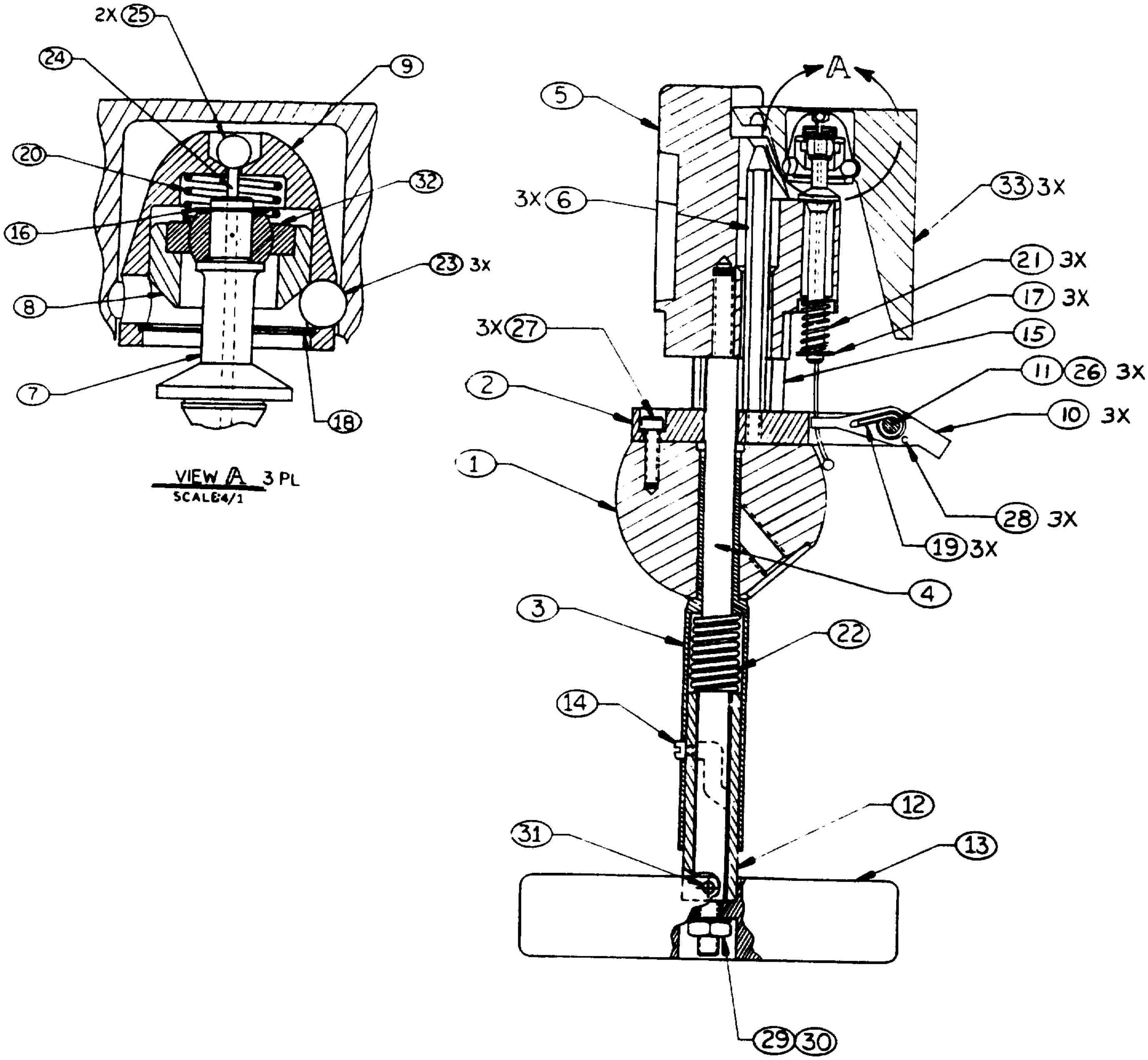

Figure 3-4. Panel Attachment Device Prototype Design (Details from Astro Drawing S6041800).

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BLACK AND WHITE PHOTOGRAPH

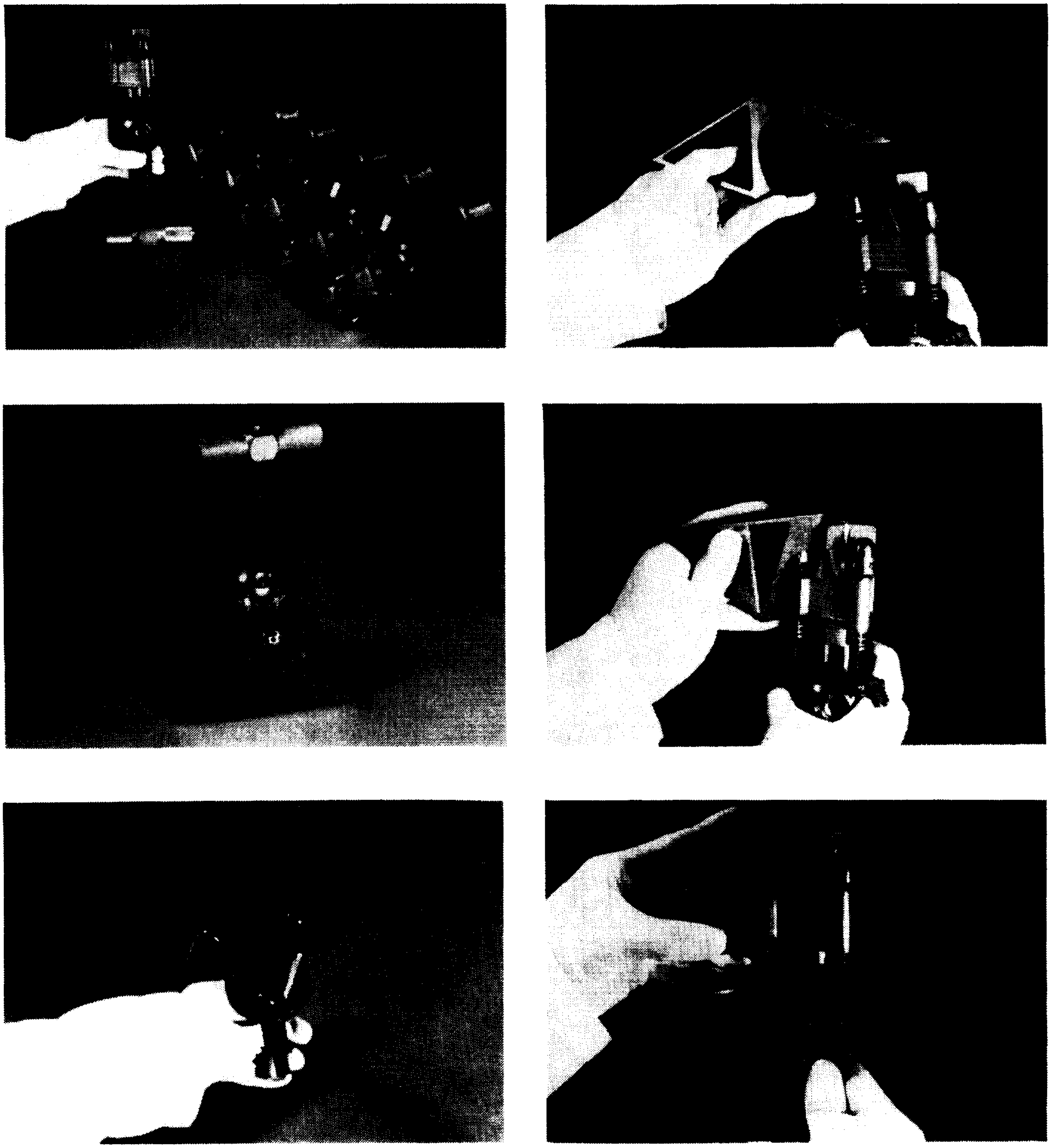


Figure 3-5. Prototype PAD Hardware Manufactured for Langley.

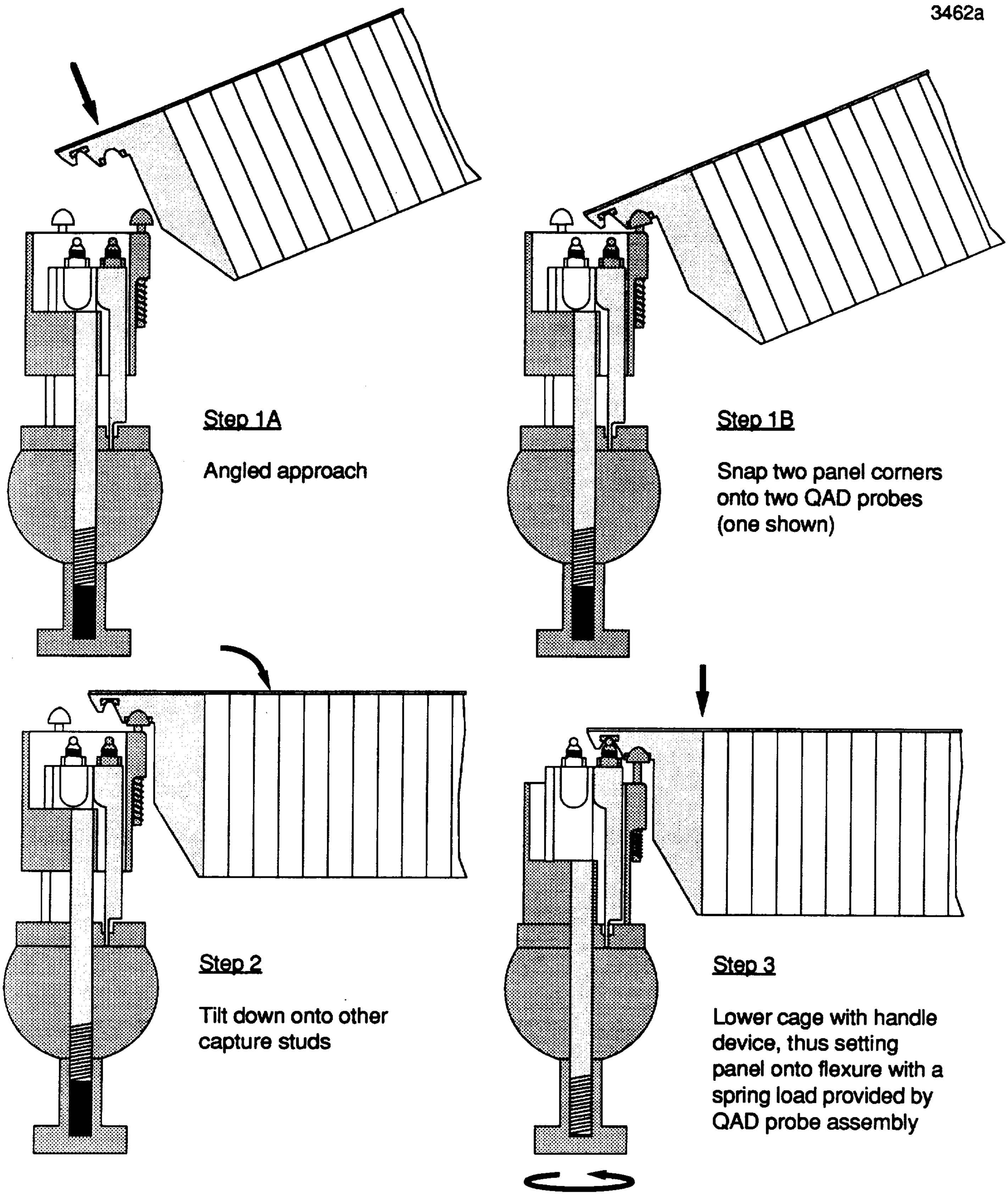


Figure 3-6. Three-Step Panel Attachment Sequence Using the PAD.

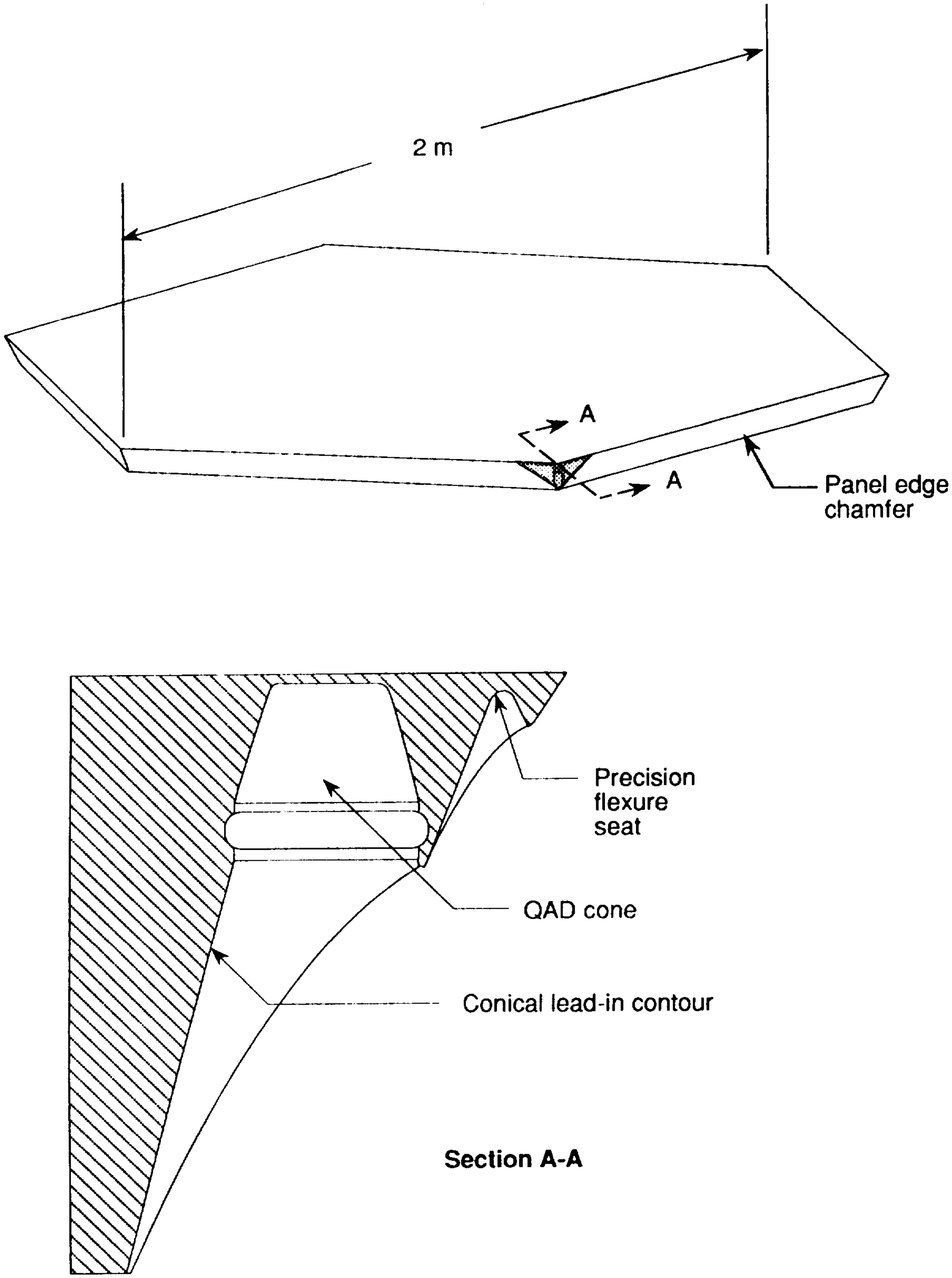
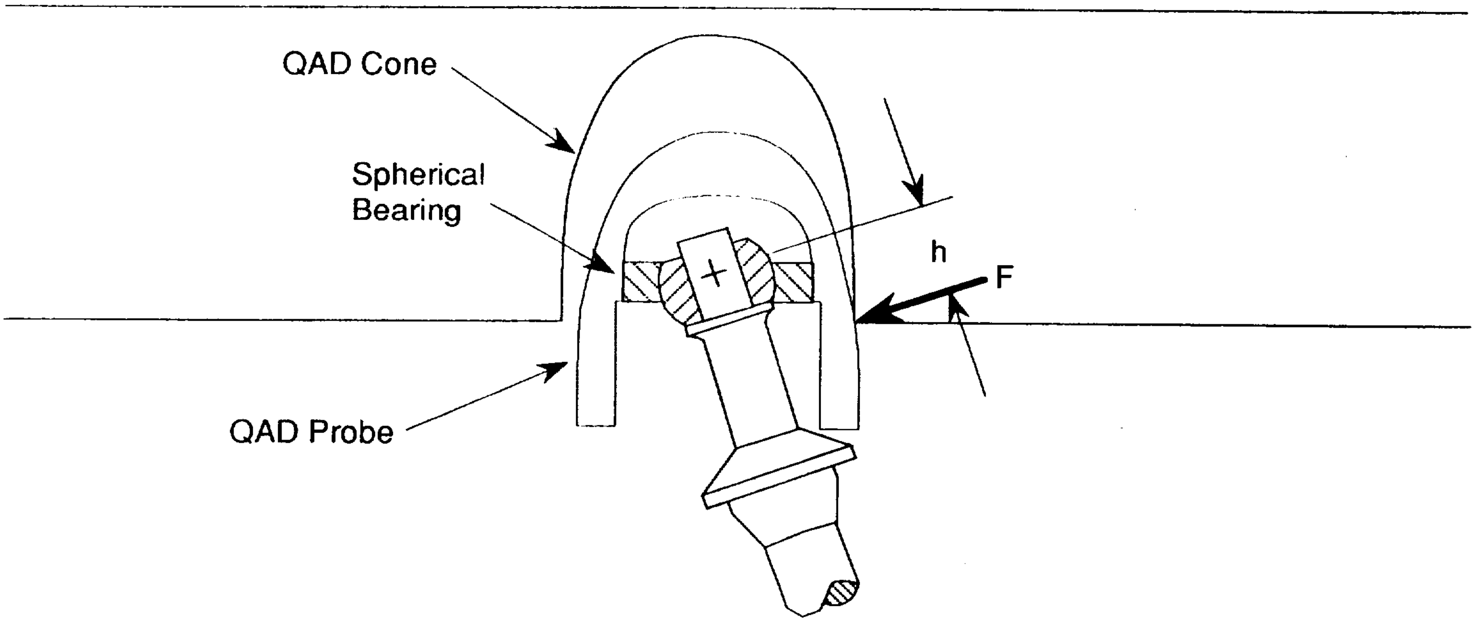
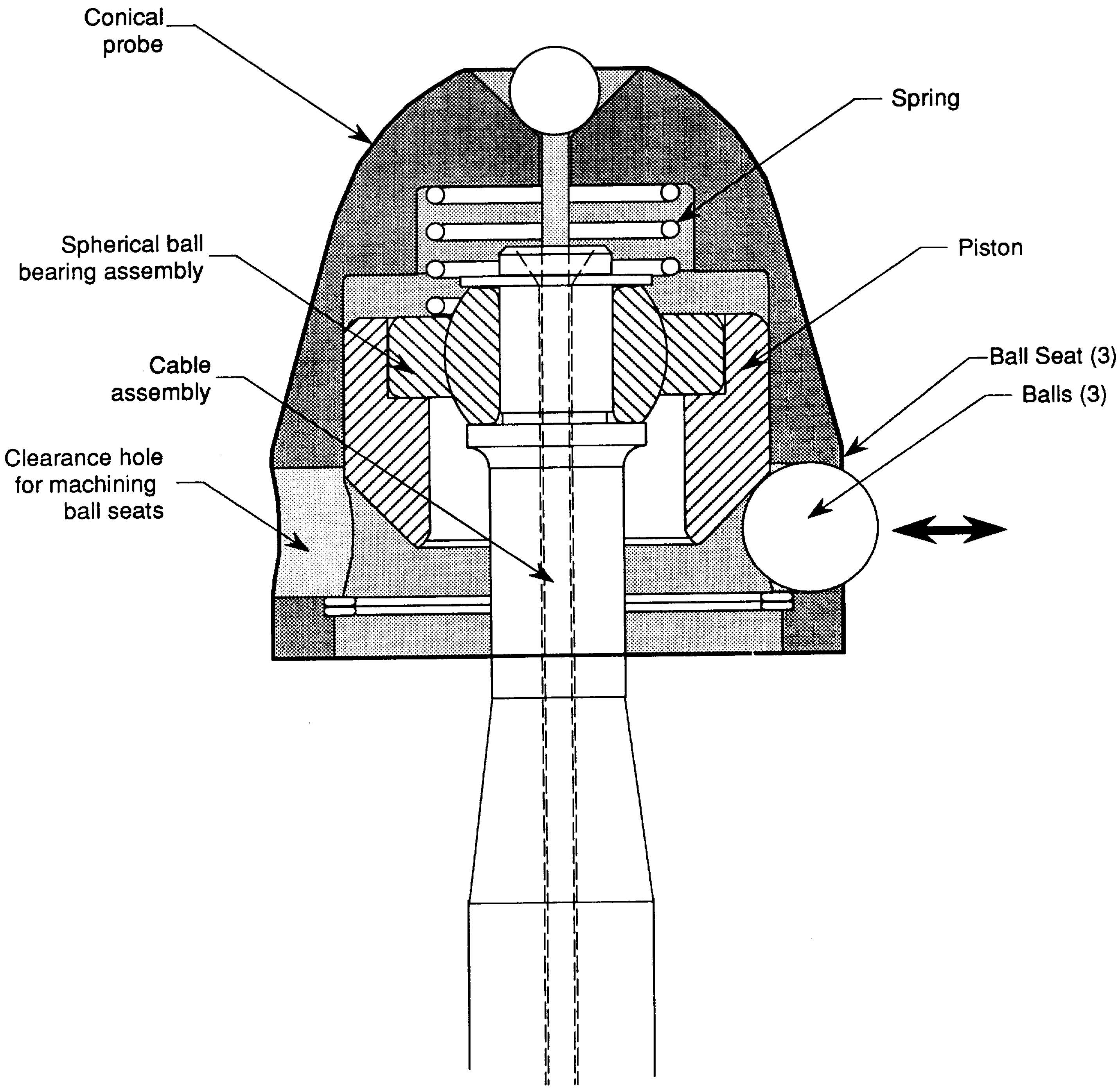


Figure 3-7. Panel Corner Body Design for the PAD.



The moment Fh causes the probe to align itself with the cone.

Figure 3-8. QAD Probe and Cone Self-Alignment During Insertion.



Section View

Figure 3-9a. QAD Probe Detailed Design Features.

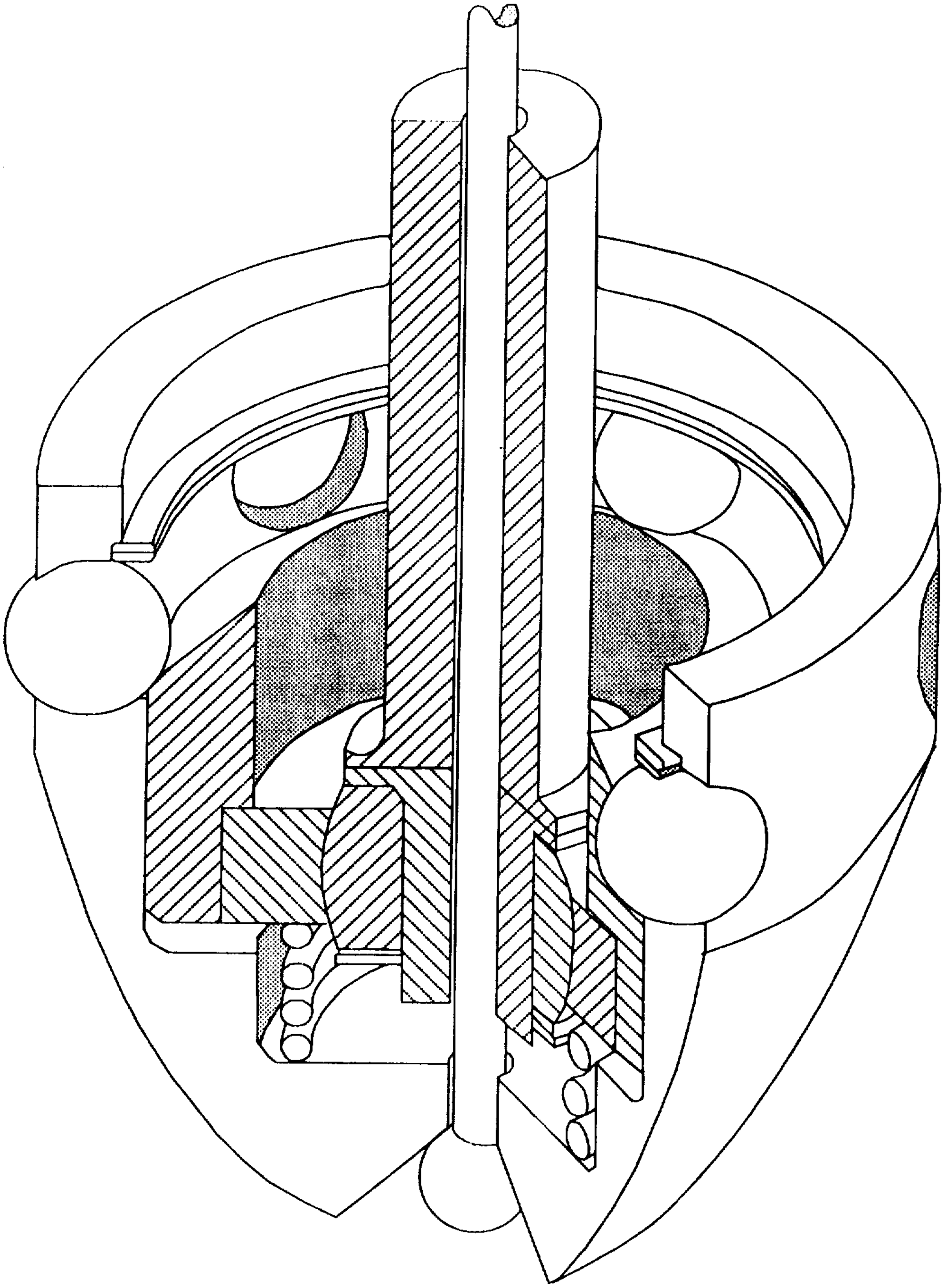


Figure 3-9b. QAD Probe Cutaway View.

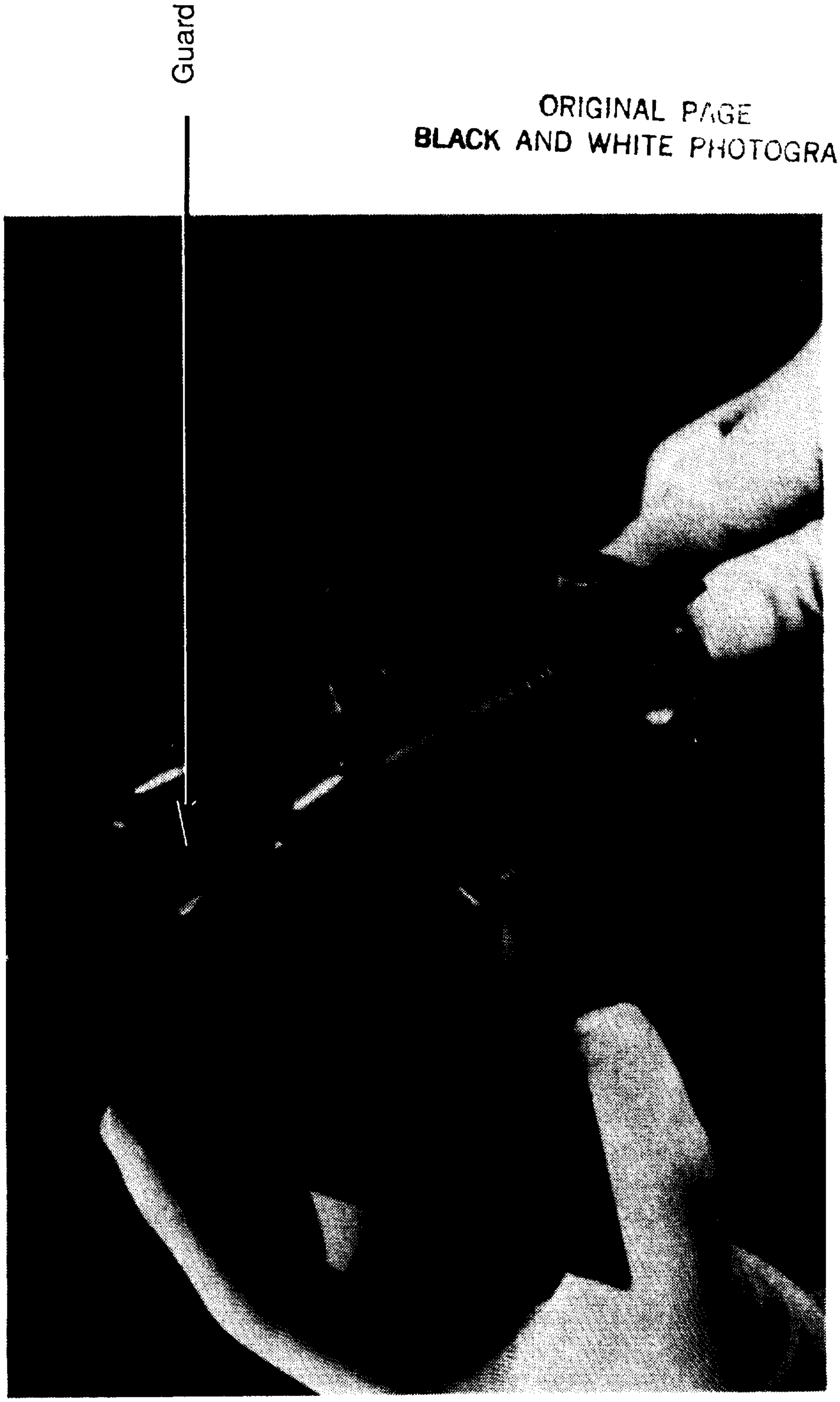


Figure 3-10. Metallic Guard for Protection of Panel Vertices.

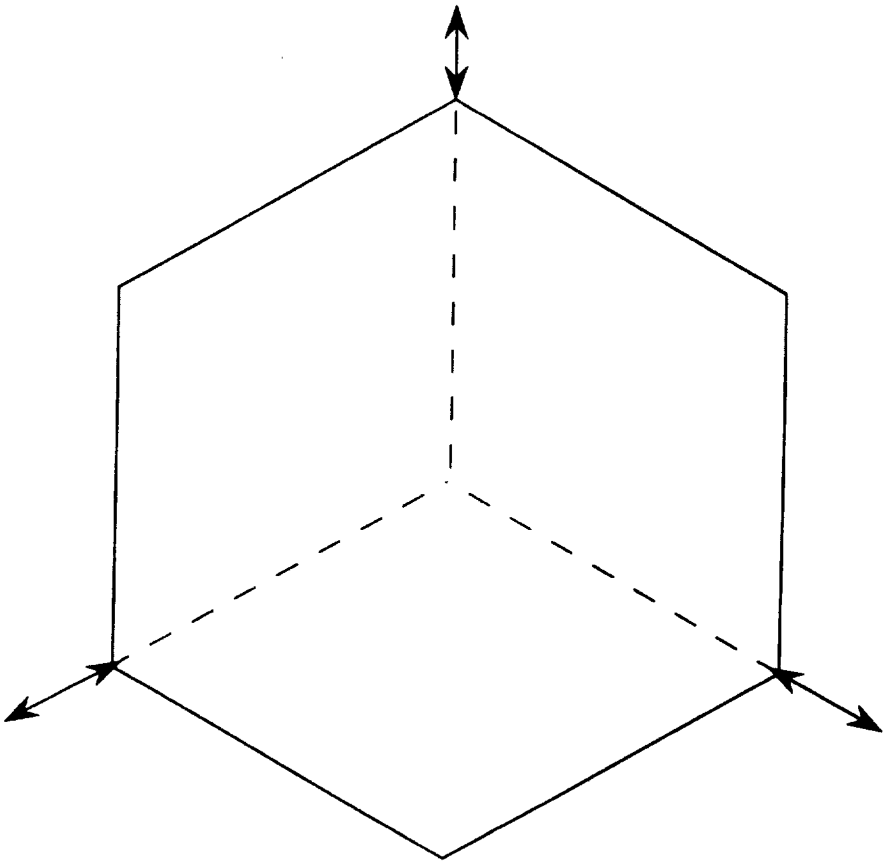


Figure 3-11. Hexagonal Panel with a Single Degree of Freedom at Each Attachment Point.

REFERENCES

1 Miller, Richard K.; Thomson, Mark W.; and Hedgepeth, John H.: Influence of Utility Lines and Thermal Blankets on the Dynamics and Control of Satellites with Precision Pointing Requirments. NASA CR-4366, May 1991.

2 Miller, Richard K.; Thomson, Mark W.; and Hedgepeth, John H.: Concepts and Analysis for Precision Segemented Reflector and Feed Support Structures–Final Report. NASA CR-182064, December 1990.

3 Adams, Louis R.: Hinge Specification for a Square-Faceted Tetrahedral Truss–Final Report. NASA CR-172272, January 1984.

APPENDIX A

GENTETRA: ALGORITHM IN "C" FOR GENERATING DEPLOYMENT GEOMETRY OF TETRAPAC

```
/* GENTETRA.C - Generates the .DTA file for a deploying tetrahedral truss with
 *          two rings.  Only those members which do not fold are shown.
 *
 *          The command is
 *
 *                  gentetra ratio
 *
 *          where ratio is the deployment angle of the inner bay divided by its
 *          full value.  If ratio is omitted, the operator is asked for a value.
 *
 *          The results are output to TETRAxyz.DTA
 *          which is an ASCII file in the format needed for input to
 *          SEETRUSS.EXE and xyz is the percent of deployment.
 *
 *          The types of struts are:
 *
 *              Numbering
 *          External Internal
 *
 *             a        0   Upper-surface struts in first ring
 *             b        1   Lower-surface struts in first ring
 *             c        2   Core struts in first ring
 *             d        3   Upper-surface struts in second ring
 *             e        4   Lower-surface struts in second ring
 *             f        5   Core struts in second ring
 *
 *                                          John M. Hedgepeth       12/12/89
 *
 ************************************************************************
 *
 *
 **************************************************************************
 */

#include <scitech.h>

int Nseg = 15;
int Ntypes = 6;
double h;
double l = 1.0;

int uppsurf(int (*aptr)[3]),lowsurf(int (*bptr)[3]),core(int (*cptr)[3]);
void setnodes(double, double [15][3]);
char *get_record(FILE *);

void main(argc,argv)
int argc;
char *argv[];
{
    int i,j,n,Nnodes,Nstruts,type,r,n1,n2;
    int Nupp,Nlow,Ncore,Nhexagon,Nstandoff;
    int (*conupp)[3],(*conlow)[3],(*concore)[3],(*cptr)[3];
    double theta;
    static double x,y,z,coord[15][3],*ptr,cosv,sinv;
    char outname[50];
    FILE *outfile;

    if(argc > 1) {
        strcpy(outname, argv[1]);
    }
```

```
    printf("\nEnter fraction of full deployment?  ");
    gets(outname);
}
while(1) {
    if(sscanf(outname," %lf", &theta) == 1)
        break;
    else {
        printf("\nEnter fraction of full deployment?  ");
        gets(outname);
    }
}

sprintf(outname,"TETRA%.3d.DTA", (int)(100.*theta + 0.5));

if((outfile = fopen(outname,"r")) != NULL) {
    fflush(stdin);
    printf("\nFile %s exists.  Do you want to write over it? (Y/N) <N>",
                                                            outname);
    if(toupper(getch()) != 'Y')
        exit(1);

    fclose(outfile);
}
outfile = fopen(outname,"wt");
fprintf(outfile,"           %s\n\n",outname);

theta = (1. - theta)*acos(1./3.);

setnodes(theta, coord);

Nnodes = 3*Nseg + 1;

conupp = (int (*)[3])calloc(14, 3*sizeof(int));
conlow = (int (*)[3])calloc(8, 3*sizeof(int));
concore = (int (*)[3])calloc(10, 3*sizeof(int));

Nupp = uppsurf(conupp);
Nlow = lowsurf(conlow);
Ncore = core(concore);

Nstruts = 3*(Nupp + Nlow + Ncore);

fprintf(outfile, "Nnodes, Nstruts, Ntypes\n\n");
fprintf(outfile," %d, %d, %d\n\n",Nnodes, Nstruts, Ntypes);

fprintf(outfile,"ORIGIN - 1 node\n\n");
fprintf(outfile," %.8le, %.8le, %.8le\n", 0., 0., 0.);

fprintf(outfile,"\n        TRUSS NODE COORDINATES - %d\n\n",Nnodes - 1);

for(j=0; j<3; j++) {
    cosv = cos((double)2*j*PI/3);
    sinv = sin((double)2*j*PI/3);
    for(i=0; i<Nseg; i++) {
        x = coord[i][0]*cosv - coord[i][1]*sinv;
        y = coord[i][0]*sinv + coord[i][1]*cosv;
        z = coord[i][2];
        fprintf(outfile," %.8le, %.8le, %.8le\n", x, y, z);
    }
```

```
    }

    fprintf(outfile,"\n          TRUSS MEMBERS - %d\n\n",Nstruts);

    for(j=0,cptr = conupp; j<Nupp; j++,cptr++) {
        for(i=0; i<3; i++) {
                        n1 = (*cptr)[0] + i*Nseg + 1;
                        n2 = (*cptr)[1] + i*Nseg + 1;
                        if(n2 >= Nnodes)
                                n2 -= Nnodes - 1;
                        fprintf(outfile," %d, %d, %d\n",n1,n2,(*cptr)[2]);
        }
    }

    for(j=0,cptr = conlow; j<Nlow; j++,cptr++) {
        for(i=0; i<3; i++) {
                        n1 = (*cptr)[0] + i*Nseg + 1;
                        n2 = (*cptr)[1] + i*Nseg + 1;
            if(n2 >= Nnodes)
                n2 -= Nnodes - 1;
                        fprintf(outfile," %d, %d, %d\n",n1,n2,(*cptr)[2]);
        }
    }

    for(j=0,cptr = concore; j<Ncore; j++,cptr++) {
        for(i=0; i<3; i++) {
                        n1 = (*cptr)[0] + i*Nseg + 1;
                        n2 = (*cptr)[1] + i*Nseg + 1;
            if(n2 >= Nnodes)
                n2 -= Nnodes - 1;
                        fprintf(outfile," %d, %d, %d\n",n1,n2,(*cptr)[2]);
        }
    }

    fclose(outfile);

    printf("\n\nData file %s successfully written.\n",outname);
}

/*******************************************************************
 *  Skip over non-formatted text and replace commas with spaces.
 */

char *get_record(file)
FILE *file;
{
    int chr,old;
    char *ptr,*line;
    static char buffer[250];

    while( fgets(buffer,250,file) != NULL) {
        ptr = buffer;
        while(isspace((chr = (int)*ptr)))
            ptr++;
        if(isdigit(chr) || chr == '.' || chr == '+' || chr == '-') {
            line = ptr;
            while(*ptr) {
                if(*ptr == ',')
                    *ptr = ' ';
                ptr++;
```

```
            }
            return line;
        }
    }
    if(feof(file))  {
        printf("\007End of file reached.\n");
        return buffer;
    }
    printf("\007Error in getting input record.  Abort.\n");
    exit(1);
}

/*******************************************************
 */

void setnodes(double theta, double buf[15][3])
{
    double x,y,z,a,temp1,temp2,temp3,cosv,sinv,theta2,costh2,sinth2,cosom,sinom;
    double costh, sinth;

    cosv = 0.5;
    sinv = sqrt((double)3.)/2.;

    costh = cos(theta);
    sinth = sin(theta);

    h = sqrt(6.)/3.*l;

    temp1 = 3.*costh - 1.;
    temp2 = sqrt(32.) - 6.*sinth;
    temp3 = (-5.*temp1 + sqrt(8.)*temp2)/3.;

    theta2 = acos(temp3/sqrt(temp1*temp1 + temp2*temp2));

    theta2 -= atan(temp2/temp1);
    costh2 = cos(theta2);
    sinth2 = sin(theta2);

    z = h/2.;

    buf[0][0] = cosv*l;
    buf[0][1] = sinv/3.*l;
    buf[0][2] = z;

    buf[1][0] = 1.5*costh*l;
    buf[1][1] = sinv/3.*l;
    buf[1][2] = z;

    buf[3][0] = 0.;
    buf[3][1] = (1./3. + costh)*sinv*l;
    buf[3][2] = z - sinth*sinv*l;

    buf[4][0] = (1. + 3.*costh)*l/4.;
    buf[4][1] = (9.*costh - 1.)*sinv*l/6.;
    buf[4][2] = z;

    buf[6][0] = -0.5*l;
    buf[6][1] = buf[3][1] + costh2*sinv*l;
    buf[6][2] = buf[3][2] + sinth2*sinv*l;
```

```
     buf[7][0] = 0.5*l;
     buf[7][1] = buf[6][1];
     buf[7][2] = buf[6][2];

     buf[9][0] = 0.0;
     buf[9][1] = 2.*sinv*l/3.;
     buf[9][2] = -z;

     buf[10][0] = buf[3][0]*cosv + buf[3][1]*sinv;
     buf[10][1] = -buf[3][0]*sinv + buf[3][1]*cosv;
     buf[10][2] = -buf[3][2];

     buf[11][0] = buf[7][0]*cosv + buf[7][1]*sinv;
     buf[11][1] = -buf[7][0]*sinv + buf[7][1]*cosv;
     buf[11][2] = -buf[7][2];

     buf[14][0] = buf[6][0]*cosv + buf[6][1]*sinv;
     buf[14][1] = -buf[6][0]*sinv + buf[6][1]*cosv;
     buf[14][2] = -buf[6][2];

     buf[13][0] = buf[4][0] - l/2.;
     buf[13][1] = buf[4][1] + sinv*l/3.;
     buf[13][2] = -z;

     buf[12][0] = -buf[13][0];
     buf[12][1] = buf[13][1];
     buf[12][2] = -z;

     buf[5][0] = buf[11][0];
     buf[5][1] = buf[11][1] +2.*sinv*l/3.;
     buf[5][2] = buf[11][2] + 2.*z;

  /* Determine the median point between nodes 5 and 7.
   */
     x = (buf[5][0] + buf[7][0])/2.;
     y = (buf[5][1] + buf[7][1])/2.;
     z = (buf[5][2] + buf[7][2])/2.;

     templ = sinv*(costh + costh2)/2.;
     temp2 = sinv*(sinth2 - sinth);
     temp3 = 3.*(costh2 - costh)/2. + 1.;

     a = sqrt(1. - (templ*templ + temp2*temp2));

     cosom = (1. - a*a - temp3*temp3/4.)/(a*temp3);
     sinom = -sqrt(1. - cosom*cosom);
     temp3 = a/sqrt(1. - a*a);

     buf[8][0] = x + a*cosv*cosom + sinv*temp3*temp2*sinom;
     buf[8][1] = y + a*sinv*cosom - cosv*temp3*temp2*sinom;
     buf[8][2] = z + temp3*templ*sinom;

     x = buf[8][0] - buf[4][0];
     y = buf[8][1] - buf[4][1];
     z = buf[8][2] - buf[4][2];

     templ = x*x + y*y + z*z - l*l;
     if(fabs(templ) > 1.0e-10) {
        printf("\nError in location of node 8.  Abort.");
        exit(1);
```

```
    }

    buf[2][0] = cosv*buf[8][0] + sinv*buf[8][1];
    buf[2][1] = sinv*buf[8][0] - cosv*buf[8][1];
    buf[2][2] = buf[8][2];
}

/*****************************************************************
 */

int uppsurf(buf)
int (*buf)[3];
{
    int type, p;

    p = 0;

/* First cover the first ring.
 */
    type = 0;

    buf[p][0] = 0;
    buf[p][1] = 15;
    buf[p][2] = type;
    p++;

    buf[p][0] = 0;
    buf[p][1] = 3;
    buf[p][2] = type;
    p++;

    buf[p][0] = 3;
    buf[p][1] = 15;
    buf[p][2] = type;
    p++;

    buf[p][0] = 3;
    buf[p][1] = 4;
    buf[p][2] = type;
    p++;

    buf[p][0] = 3;
    buf[p][1] = 16;
    buf[p][2] = type;
    p++;

/* Cover the second ring
 */
    type = 3;

    buf[p][0] = 3;
    buf[p][1] = 6;
    buf[p][2] = type;
    p++;

    buf[p][0] = 3;
    buf[p][1] = 7;
    buf[p][2] = type;
    p++;
```

```
    buf[p][0] = 4;
    buf[p][1] = 8;
    buf[p][2] = type;
    p++;

    buf[p][0] = 1;
    buf[p][1] = 2;
    buf[p][2] = type;
    p++;

    buf[p][0] = 2;
    buf[p][1] = 5;
    buf[p][2] = type;
    p++;

    buf[p][0] = 5;
    buf[p][1] = 8;
    buf[p][2] = type;
    p++;

    buf[p][0] = 8;
    buf[p][1] = 7;
    buf[p][2] = type;
    p++;

    buf[p][0] = 7;
    buf[p][1] = 6;
    buf[p][2] = type;
    p++;

    buf[p][0] = 6;
    buf[p][1] = 17;
    buf[p][2] = type;
    p++;

    return p;
}

int lowsurf(int (*buf)[3])
{
    int p,type;

    p = 0;

/* First cover the first ring.
 */
    type = 1;

    buf[p][0] = 9;
    buf[p][1] = 10;
    buf[p][2] = type;
    p++;

    buf[p][0] = 9;
    buf[p][1] = 24;
    buf[p][2] = type;
    p++;

    buf[p][0] = 9;
    buf[p][1] = 25;
```

```
        buf[p][2] = type;
        p++;

        buf[p][0] = 12;
        buf[p][1] = 25;
        buf[p][2] = type;
        p++;

        buf[p][0] = 10;
        buf[p][1] = 13;
        buf[p][2] = type;
        p++;

/* Cover the second ring
 */
        type = 4;

        buf[p][0] = 10;
        buf[p][1] = 11;
        buf[p][2] = type;
        p++;

        buf[p][0] = 10;
        buf[p][1] = 14;
        buf[p][2] = type;
        p++;

        buf[p][0] = 14;
        buf[p][1] = 11;
        buf[p][2] = type;
        p++;

        return p;
}


int core(buf)
int (*buf)[3];
{
        int p,type;

        p = 0;

/* First cover the first ring.
 */
        type = 2;

        buf[p][0] = 0;
        buf[p][1] = 9;
        buf[p][2] = type;
        p++;

        buf[p][0] = 9;
        buf[p][1] = 15;
        buf[p][2] = type;
        p++;


/* Cover the second ring
 */
```

```
        type = 5;

        buf[p][0] = 1;
        buf[p][1] = 11;
        buf[p][2] = type;
        p++;

        buf[p][0] = 11;
        buf[p][1] = 5;
        buf[p][2] = type;
        p++;

        buf[p][0] = 5;
        buf[p][1] = 14;
        buf[p][2] = type;
        p++;

        buf[p][0] = 14;
        buf[p][1] = 4;
        buf[p][2] = type;
        p++;

        buf[p][0] = 4;
        buf[p][1] = 13;
        buf[p][2] = type;
        p++;

        buf[p][0] = 13;
        buf[p][1] = 7;
        buf[p][2] = type;
        p++;

        buf[p][0] = 6;
        buf[p][1] = 12;
        buf[p][2] = type;
        p++;

        buf[p][0] = 12;
        buf[p][1] = 16;
        buf[p][2] = type;
        p++;

        return p;
}

/***********************************************
 */
```

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15. Supplementary Notes

Langley Technical Monitor: W. B. Fichter

16. Abstract

Several issues surrounding the development of large Precision Segmented Reflector (PSR) designs are investigated. The concerns include the following: (1) Nonlinear dynamics of large unruly masses such as the multi-layer thermal insulation of sunshades for instruments such as the precision pointing 20-meter-diameter Large Deployable Reflector (LDR). A study of the residual oscillations after "bang-bang" reorientation maneuvers of a rigid satellite with a string appendage is presented. Next, a generalization to the case of a membrane appendage is presented. Finally, application is made to the design of a sunshade (thermal blanket) for the LDR satellite. The complete study is presented in Reference 1.
(2) Development of a deployable truss that has minimum structural redundancy (such as the tetrahedral truss) and can be configured with planar and doubly curved geometries. A kinematically synchronized articulation scheme for a deployable tetrahedral truss is presented. Called the Tetrapac, this truss is currently limited to a planar configuration that has two rings. (3) Development and demonstration of hardware that enables astronauts to attach large, cumbersome, and fragile precision reflector segments to an erectable truss structure. This task must be accomplished with a high degree of precision and with relative ease. A design for a Panel Attachment Device (PAD) was developed and manufactured for neutral buoyancy simulations to be performed by Langley Research Center.

17. Key Words (Suggested by Author(s)) Controls-Structure Interaction (CSI) Large Deployable Reflector (LDR) Precision Segmented Reflector (PSR) Precision Pointing, Nonlinear Dynamics, Sunshade Dynamics, Reflector Assembly		18. Distribution Statement Unclassified - Unlimited Subject Category 18	
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