NASA/TP-2000-210317

Evaluation of Hardware and Procedures for Astronaut Assembly and Repair of Large Precision Reflectors

Mark S. Lake, Walter L. Heard, Jr., Judith J. Watson, and Timothy J. Collins
Langley Research Center, Hampton, Virginia

August 2000

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Abstract

A detailed procedure is presented that enables astronauts in extravehicular activity (EVA) to efficiently assemble and repair large (i.e., greater than 10m-diameter) segmented reflectors, supported by a truss, for space-based optical or radio-frequency science instruments. The procedure, estimated timelines, and reflector hardware performance are verified in simulated 0-g (neutral buoyancy) assembly tests of a 14m-diameter, offset-focus, reflector test article. The test article includes a near-flight-quality, 315-member, doubly curved support truss and 7 mockup reflector panels (roughly 2m in diameter) representing a portion of the 37 total panels needed to fully populate the reflector. Data from the tests indicate that a flight version of the design (including all reflector panels) could be assembled in less than 5 hours – less than the time normally permitted for a single EVA. This assembly rate essentially matches pre-test predictions that were based on a vast amount of historical data on EVA assembly of structures produced by NASA Langley Research Center. Furthermore, procedures and a tool for the removal and replacement of a damaged reflector panel were evaluated, and it was shown that EVA repair of this type of reflector is feasible with the use of appropriate EVA crew aids.

Introduction

Since the early 1960's, NASA has funded many technology-development programs that have endeavored to increase the feasibility of orbiting large (i.e., larger than 10m aperture) optical and radio frequency (RF) instrument systems (e.g., refs. 1 and 2). NASA's Office of Space Science is now engaged in the Astronomical Search for Origins and Planetary Systems (Origins) Program that will begin launching a series of astronomical telescopes, with increasingly larger apertures, starting around the year 2006. These large-aperture telescopes will be designed to detect and study Earth-like planets orbiting around distant stars, and to further our understanding of the birth and evolution of galaxies.

Currently, in support of the Origins Program, there is a rapidly building research program encompassing numerous engineering technologies for large-aperture telescopes. At present, most research is focused on component-level technologies (e.g., materials, actuators, and lightweight reflector panels) and deployed system behavior and performance (e.g., thermal response, microdynamic response, and active control of the deployed aperture). Very little research is currently being conducted on issues related to the process of on-orbit deployment or assembly of large aperture instruments. *Without conducting hardware-based research on assembly and deployment, it is impossible to truly understand the limitations of these processes and therefore, it is impossible to know whether assembly or deployment is the lowest risk and lowest cost process for a particular instrument application.*

The present paper describes a detailed experimental research program into astronaut assembly of a segmented, large-aperture reflector in simulated extravehicular activity (EVA) conditions. The program discussed herein was conducted from 1990 to 1992, and a condensed set of results from the program is presented in ref. 3. This program culminated over a decade of research on EVA assembly of structures (refs. 4 through 7). Although completed in 1992, the results of this program are very relevant today due to the technology needs of the Origins Program.

In a general sense, the goal of the present program was to demonstrate the feasibility of having astronauts perform such a complicated assembly in EVA. More specifically, *the present program was designed to identify precisely the techniques, equipment, and procedures necessary to make EVA assembly and repair of precision reflectors efficient and reliable.* The hardware utilized in the present tests was developed specifically for application to precision reflectors (ref. 8). Prior to the present test program, several test programs were conducted to determine the structural performance and precision of the hardware (ref. 9), and to determine compatibility of the hardware with astronauts in simulated (ref. 10) and on-orbit (ref. 11) EVA environments.

The development and verification of hardware and procedures for the efficient and reliable EVA assembly of precision reflectors is a significant step towards practical, large-aperture telescope systems. Coupled with the advancements in segmented optics anticipated in the near future, instrument systems with reflectors up to about 25m in diameter could be launched in the Shuttle or smaller launch vehicle and assembled on-orbit by astronauts using either the Shuttle or International Space Station as a construction base. Further in the future, as segmented optics technology continues to mature, reflectors up to 50m in diameter could be efficiently constructed by astronauts using the same procedures and hardware.

Background: Design Considerations for Large Reflectors

Many concepts have been identified for large-aperture reflectors. These concepts range from segmented, solid-surface reflectors that must be deployed or erected on-orbit to membrane monoliths that must be inflated or stretched on-orbit (ref. 2). The first space-based telescope to use a deployable mirror will be the Next Generation Space Telescope (NGST, Fig. 1) which is currently planned for launch in 2008. Although very technically aggressive, even the NGST's 8m-diameter deployable reflector is small enough that it can be segmented into a single circumferential ring of panels and folded for launch using a relatively simple arrangement of hinges and latches (e.g., ref. 12). So-called "one-ring" segmented reflectors are desirable due to their mechanical simplicity, but they are limited to deployed diameters no more than a factor of 2.5 to 3 larger than the launch vehicle shroud (ref. 13).

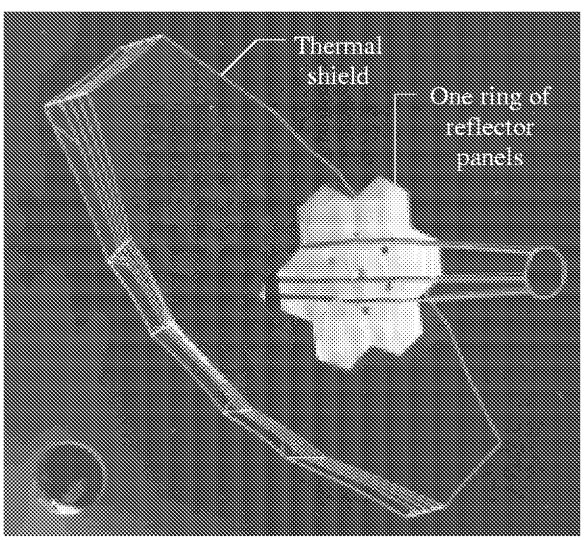


Figure 1. 8m NGST concept (2.6m panels).

For large aperture diameters of 5 to 10 times the launch vehicle shroud diameter, it is necessary to consider either multi-ring segmented reflectors or unfurled membrane reflectors. In the distant future, it is hoped that advances in active-control and wavefront-correction technology will make membrane reflectors practical. However until then, it is likely that multi-ring, segmented reflectors will provide the only viable alternative for large precision reflectors.

Requirements for a Support Truss

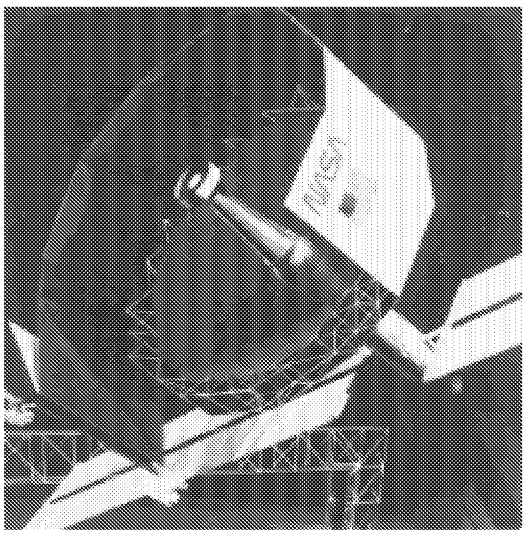
Numerous concepts for the deployment and assembly of multi-ring, segmented reflectors have been studied. During the mid 80's and early 90's, NASA studied several such concepts under the Large Deployable Reflector (LDR) Program (refs. 14 and 15). The LDR Program focused on the development of a 20m-diameter, far-infrared telescope and considered many system performance issues such as dynamics and control of the deployed mirror. The baseline design that evolved out of the LDR program was a 20m-diameter reflector made up of panels that were approximately 2m in diameter and supported on a truss (see Fig. 2).

The use of a support truss on the LDR was driven by the desire to minimize the deployed areal density and to increase passive dimensional stability of the reflector. Although a support truss adds mechanical complexity to the design of the reflector, its inherent structural efficiency can more than compensate for the added complexity by providing lower overall mass and higher system frequencies for easier pointing and microdynamic control (ref. 16).

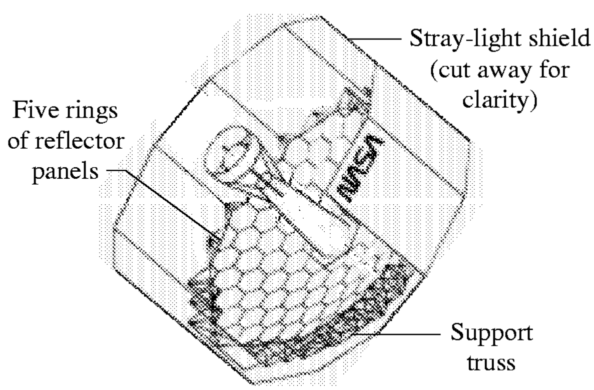
Although many aspects of the LDR program are dated by the technology advancements of the past decade, the design requirements for LDR are still considered aggressive today. The surface precision requirement of tens of microns, rms, and the areal mass density requirement of 15 kg/m^2 are goals that have yet to be achieved in a flight system. In theory, these requirements can be met by a truss-supported, segmented reflector like that considered herein. Furthermore, this stiff reflector architecture would exhibit minimum vibration frequencies on the order of 10 Hz, making the problems of pointing and figure control easier to solve.

Reflector Panel Size Considerations

The design of a large segmented reflector involves a compromise between structural performance, ease of fabrication, launch vehicle packaging, and EVA assembly considerations. A key variable in this design trade is the size of the reflector panels (ref. 17). Large panels can be packaged more efficiently than small panels in a launch vehicle. Furthermore, the support truss to support large panels consists of long struts, thus the truss is stiffer (due to its increased depth), has a lower part count, and has larger lattice openings (which facilitate EVA access) than the truss to support small panels. Conversely, large reflector panels are more difficult and costly to fabricate, and may be more difficult to manipulate by EVA astronauts than small panels. As a compromise, most LDR concepts considered using reflector panels that were between 2 and 3 meters in diameter.



(a) Painting of astronaut assembly at the Space Station.



(b) Sketch showing reflector panels and support truss.

Figure 2. 20m LDR concept (2m panels).

Deployment Versus Assembly

Clearly, the use of a support truss complicates the problem of on-orbit deployment or assembly. During the time of the LDR program, mechanical deployment, automated assembly by robots, and manual assembly by astronauts were all studied as possible techniques for on-orbit construction. The key discriminators used to compare these construction methods were reliability and cost, and impact on the performance of the completed structure. *After years of study of these options, the LDR program baselined on-orbit assembly by astronauts as the preferred method of construction.*

One of the reasons that the LDR program discounted mechanical deployment was that, at the time, there was a lack of test data in the open literature to verify that high-precision deployment mechanisms could be developed with predictable micron-level structural behavior. Without such mechanisms, it was feared that a deployable LDR would require extensive and costly active control. Since the time of LDR, we have learned a great deal about how to design optical-precision deployment mechanisms, reduced dramatically the risk associated with this technical isssue (e.g., refs. 18 and 19).

However, there still remains a significant technical risk regarding the deployment of multi-ring, segmented reflectors, due to the complex deployment kinematics required to package multi-ring reflectors and the increased risk of deployment failure of such complex systems. For example, the 20m-diameter LDR concept shown in figure 2 would require over a thousand precision hinge and latch mechanisms for deployment! To avoid such complexity and risk, segmented reflectors with more than one or two rings of panels should probably be erected rather than deployed.

Conceptually, either robotic devices or astronauts in EVA could erect multi-ring, precision reflectors on-orbit. However, preliminary ground-based studies of a robotic system for constructing precision reflectors has shown that a reliable, low-cost, flight system will take many years of additional research to develop (ref. 20). At the same time, simulated 0-*g* structural assembly tests (refs. 4, 5, and 7) and the Assembly Concept for Construction of Erectable Space Structure (ACCESS) space construction experiment (ref. 6) have shown that astronauts can rapidly construct large-scale, beam-like structures using currently available EVA equipment and procedures. The question remaining to be answered by the present tests is whether or not astronauts in EVA can efficiently assemble large-scale, complex structures like precision reflectors.

The Challenge of Assembling a Reflector in EVA

Each of the trusses studied in references 16 through 19 consisted of struts having only two different lengths and nodes having no more than two different geometries. Hence, different strut and node types were easily stored in separate locations to minimize the risk of interchanging dissimilar parts during stowage and retrieval, and identical struts and nodes were incorporated randomly during assembly, thus speeding up the assembly process.

In contrast, a doubly-curved precision reflector such as that shown in fig. 2 contains a large number of unique struts, nodes, and panels, each of which must be retrieved by the astronauts in the proper sequence for installation in a unique location (ref. 10). An additional complication to this hardware stowage and retrieval problem is that the differences between unique struts, nodes, and panels are subtle and not easily discernible by the EVA crew. Therefore each hardware component must be clearly labeled such that the EVA crew can rapidly and accurately identify its proper location in the reflector, and the risk of interchanging parts during the assembly must be minimized.

Guidelines for the EVA Assembly and Repair of Large Reflectors

The following guidelines were used to develop hardware and procedures for efficient assembly of a large, truss-supported, segmented reflector by astronauts in EVA. These guidelines were derived from many neutral buoyancy structural assembly tests in which the authors of the present report performed as pressure-suited test subjects (refs. 3 through 5 and 10). These guidelines also draw on experience from the ACCESS structural assembly flight experiment performed on the Shuttle in 1985 for which one of the authors was the Principal Investigator (ref. 6).

Use Two EVA Astronauts

It is standard NASA procedure for an EVA to be conducted by two astronauts working together, but three astronauts have been used on occasion (ref. 11) for particularly challenging EVA tasks. In considering the complexities of assembling a precision reflector in EVA, it was determined that the cost and complexity associated with providing a third set of EVA crew aids and life support system would more than offset the possible reduction in assembly time due to the third astronaut. Therefore, the present study assumes the use of only two EVA astronauts.

Sequence Tasks to Minimize Astronaut Idle Time

Past experience has shown that overall efficiency is maximized, and total assembly time is minimized, when tasks are divided between astronauts in such a way that both astronauts are nearly equally employed (i.e., neither astronaut has significant idle time.) In previous simulated EVA assembly tests (refs. 4 and 7), and in the ACCESS flight experiment (ref. 6), idle time was avoided by having both astronauts perform nearly identical sequences of tasks in parallel. This approach was practical in previous tests because the structures were simple enough (i.e., beam-like trusses) to allow both astronauts to simultaneously access the structure and the strut and node storage canisters.

However, for assembly of curved reflector support trusses it is probably more efficient to *use only one astronaut to assemble the truss, and one to manage the building material.* This strategy reduces the diversity of assembly tasks required of each astronaut, and it requires only one of the EVA astronauts to have access to a strut/node canister, thus reducing clutter by eliminating the need for a second canister in the confined work space. Finally, by requiring both astronauts to handle and identify each piece of hardware during the assembly, this strategy reduces the risk of interchanging hardware thus improving the reliability of the assembly process.

In addition to dividing tasks equitably between the astronauts, it is important to *sequence the tasks so that they can be executed in parallel* to minimize idle time. Similarly, it is important to *maneuver the Remote Manipulator System (RMS) or other mechanical positioning devices simultaneously with the astronauts' assembly tasks* when possible because RMS motions are characteristically slow and could creating long idle periods if no other activity is conducted in parallel.

Maximize Productivity with Easy EVA Procedures and Appropriate Mechanical Aids

It is also desirable to simplify EVA procedures as much as possible and develop an easily learned sequence of steps to *minimize the need for prompting the astronauts with verbal instructions.* Each time instructions must be communicated, the astronauts inevitably must slow or stop their activity to receive and respond to the instructions. Although a single instruction may only result in a small amount of idle time, procedures which involve continual prompting will be significantly less efficient than those without prompting. By simplifying the reflector assembly procedure to a repetition of a few basic operations and including easily readable identification labels on the reflector hardware, it is possible to virtually eliminate the need for prompting the astronauts. Not only does this approach streamline the procedure by minimizing idle time, but it also has the additional benefit of increasing the likelihood that all steps will be executed in the proper order since simplicity implies reliability.

Even with simple EVA tasks, achieving optimal efficiency requires a balance between manual and mechanical operations. Numerous experiences both on orbit and underwater have shown that purely manual EVA is fairly inefficient due to the physical limitations of the space suit. The challenge in designing for efficient EVA is to *identify and use the minimum set of mechanical crew aids (passive and motorized tools and* *positioning devices) which augment the astronauts' manual capabilities and minimize the time required to execute the task.*

EVA truss construction is efficient when the truss hardware is stowed near the astronauts' work site and the astronauts manually unstow, align, and connect the hardware components together. Other tasks, such as translating between work sites and repositioning hardware stowage canisters should be performed using motorized positioning devices when possible. Furthermore, experience has demonstrated that EVA tasks are generally much easier to perform from foot restraints than while free floating. Therefore, *astronauts should be provided with mobile foot restraints* for all tasks that would otherwise result in the expenditure of significant energy, and *free floating should be considered only in cases where tasks can be easily and quickly accomplished in this mode.* To reduce the range of motion and simplify the design of the mobile foot restraint system, *the reflector should be held by an assembly fixture* that provides some relative movement between the reflector and the astronauts.

Design Reflector-Panel Installation Procedures to Minimize Risk of Panel Damage

To minimize the need for large-range motions of the foot restraints, and hence minimize the total assembly time, reflector panels should be installed on the truss during its assembly rather than after the truss is fully assembled. This procedure permits the astronauts to work in foot restraints along the outer edges of the truss where there is ample room to maneuver while attaching panels, rather than free-floating inside the crowded interior of the assembled truss where manipulation of the panels would be more difficult and time consuming.

In addition, the panels should be attached only after the truss nodes have been structurally stabilized by a sufficient number of connected struts (i.e., each node should be stabilized by at least three, non-co-planar struts). This ensures that panels will be held securely after they are attached to the truss. Finally, to reduce the chance of damage to the reflector surface, the astronauts should avoid working on the reflective side of the panels. Thus, the assembly procedure confines the astronauts to work behind, and near the edges of, the reflector panels at all times.

Proof-of-Concept, 14m-Diameter Reflector

To demonstrate the feasibility of astronaut assembly and maintenance of large, truss-supported, segmented reflectors, the present study focuses on the development and verification of assembly and repair procedures for a 14m-diameter, offset-focus reflector for a microwave radiometer (see fig. 3). The radiometer was selected as the basis of the test article design because there existed a complete set of instrument-performance requirements from a well-developed mission concept (ref. 21), against which a detailed reflector design could be developed. However, the hardware and procedures are generally applicable to other RF and optical instrument concepts. Figure 4 includes a schematic and photograph of the 14m-diameter test article in the 12.2m-deep Neutral Buoyancy Simulator (NBS) at the NASA Marshall Space Flight Center (MSFC).

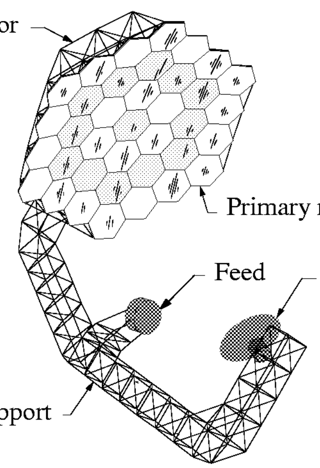
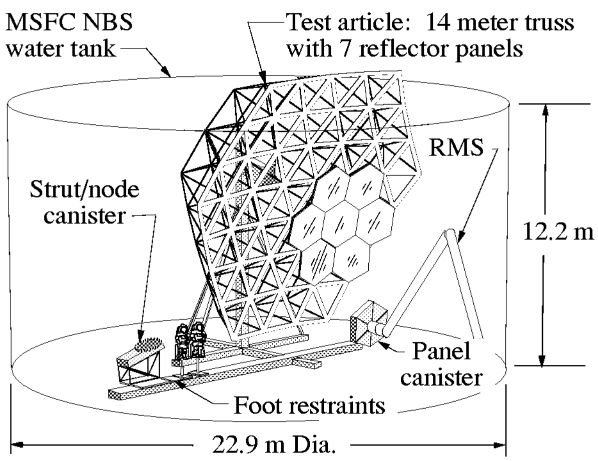


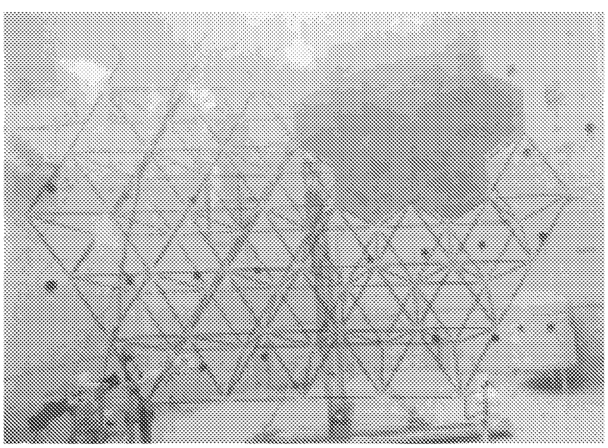
Figure 3. Offset-fed microwave radiometer.

Being an offset-focus geometry, the reflector is non-axisymmetric causing all reflector panels and truss components to be unique – a worst-case scenario for component handling and assembly. The reflector surface is comprised of 37 hexagonal panels that are roughly 2m in diameter. The truss is comprised of 84 nodes and 315 struts and is designed to passively position the reflector panels to an accuracy of between 50 and 100 microns. The truss is fabricated using the hardware described in reference 3. The center of each concave-surface node is located 12cm behind the reflector surface to allow room for the reflector panel attachment hardware. The distances between the centers of adjacent nodes range between 2.038m and 2.206m. There are 107 different node-center to node-center dimensions for the 315 struts. However, each strut is set to a unique length to compensate for manufacturing tolerances in the nodes, and no interchanging is allowed between struts during assembly of the reflector (using the procedures described in ref. 8).

Studies have shown that this erectable truss hardware can provide adequate passive precision to meet the dimensional stability requirements of a microwave reflector (ref. 9). In addition, at the time that the present test article was developed, it was assumed that the panel-attachment hardware could provide adequate positioning and alignment precision for the reflector panels without active adjustment. Hence, the present reflector test article includes no actuator components or wiring for such components. For an optical-quality reflector, it would be necessary to integrate actuators into the panel-attachment hardware, and develop procedures for integrating the actuator wiring harnesses efficiently into the overall assembly procedure.



(a) Schematic of test apparatus



(b) Photograph of assembled reflector

Figure 4. 14m-diameter reflector test article in the MSFC NBS.

Test Apparatus

The apparatus used in the present tests consists of a near-flight-quality test article representing the 14m-diameter reflector, and functionally flight-like EVA crew aids and support hardware (see fig. 4). The EVA crew aids consist of mobile foot restraints to position the EVA crew and a tool to aid in the removal and replacement of a damaged reflector panel. The support hardware consists of an assembly fixture to position the test article, storage canisters to hold the truss hardware and panels during reflector assembly, and a mockup of the Shuttle Remote Manipulator System (RMS) for positioning the panel canister.

Reflector Test Article

A test article representing the 14m-diameter reflector was fabricated using near-flight-quality truss (ref. 8) and panel attachment hardware (ref. 10) and mockup reflector panels made of sheet metal. Only seven mockup panels were fabricated because panel fabrication was time consuming. These panels are arranged in a single cluster with six of the panels surrounding a middle panel (see fig. 4) so that removal and replacement of an interior panel could be investigated.

Truss. The truss is comprised of 84 nodes and 315 struts that are fabricated using designs described in reference 8. Figure 5 illustrates typical strut and node assemblies. Each node consists of a node ball to which numerous joint-halves are attached using studs. All interior nodes (nodes lying in the interior of either the concave or convex surface of the truss) are fitted with nine joint-halves, whereas perimeter nodes (nodes lying around the edge of the truss) are fitted with between four and seven joint-halves.

Each strut consists of a tube with strut-end joint-halves threaded into both ends. Flight-quality strut tubes would be made of a high-stiffness, low coefficient-of-thermal-expansion material, but to minimize cost, the strut tubes in the present test article are made of aluminum. To simulate weightlessness underwater, buoyancy compensators are included at both ends of each strut (fig. 6). The buoyancy compensator provides an O-ring, which seals air in the aluminum strut tube for buoyancy, and a ballast chamber in which lead shot is added to neutrally buoy and trim the strut so that its center of buoyancy is coincident with its center of mass. The nodes can not be made neutrally buoyant without adding external floatation that would alter their external appearance and impede handling. Therefore, no attempt is made to neutrally buoy the nodes.

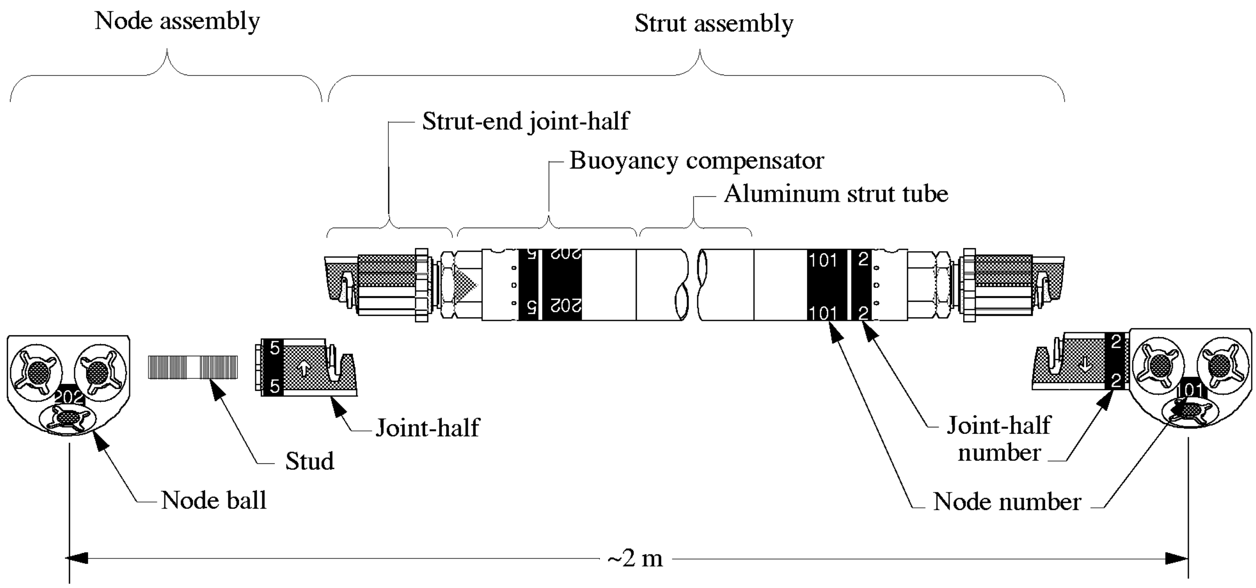


Figure 5. Details of strut and node assemblies.

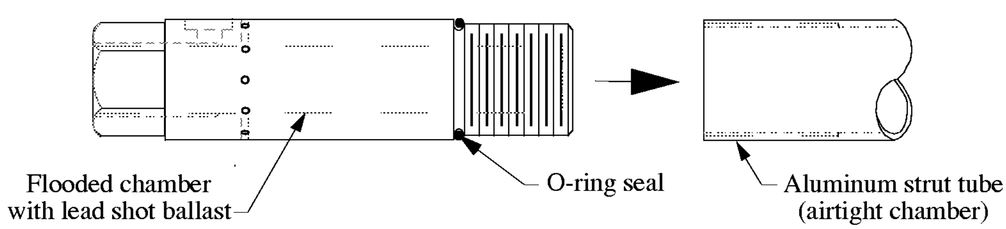


Figure 6. Details of buoyancy compensator.

The strut-end joint-halves incorporate the joint locking mechanisms while the node joint-halves are passive receptacles. Figure 7 illustrates how these components operate during EVA assembly. The struts are stowed in their storage canister with the joint locking collars rotated to the intermediate (capture) position (fig. 7(a)). This “capture” position of the locking collar frees the internal locking mechanism within the joint to retract against a soft spring as the joint halves are aligned and closed by the astronaut (fig. 7(b)). Once alignment and closure of the joint halves has been affected, the soft spring forces the internal locking mechanism to engage, thus capturing the joint halves and preventing them from inadvertently disengaging. The joint is locked by rotating the locking collar on the strut joint-half 45° into a detent position, which aligns the colored bars on the sides of the joint (fig. 7(c)). Although EVA disassembly is not considered in the present tests, the joint can be unlocked by retracting the locking collar (away from the node) while rotating it 90° in the direction opposite to that used during assembly (fig. 7(d)). With the joint unlocked, the joint halves can be disconnected as shown in fig. 7(e).

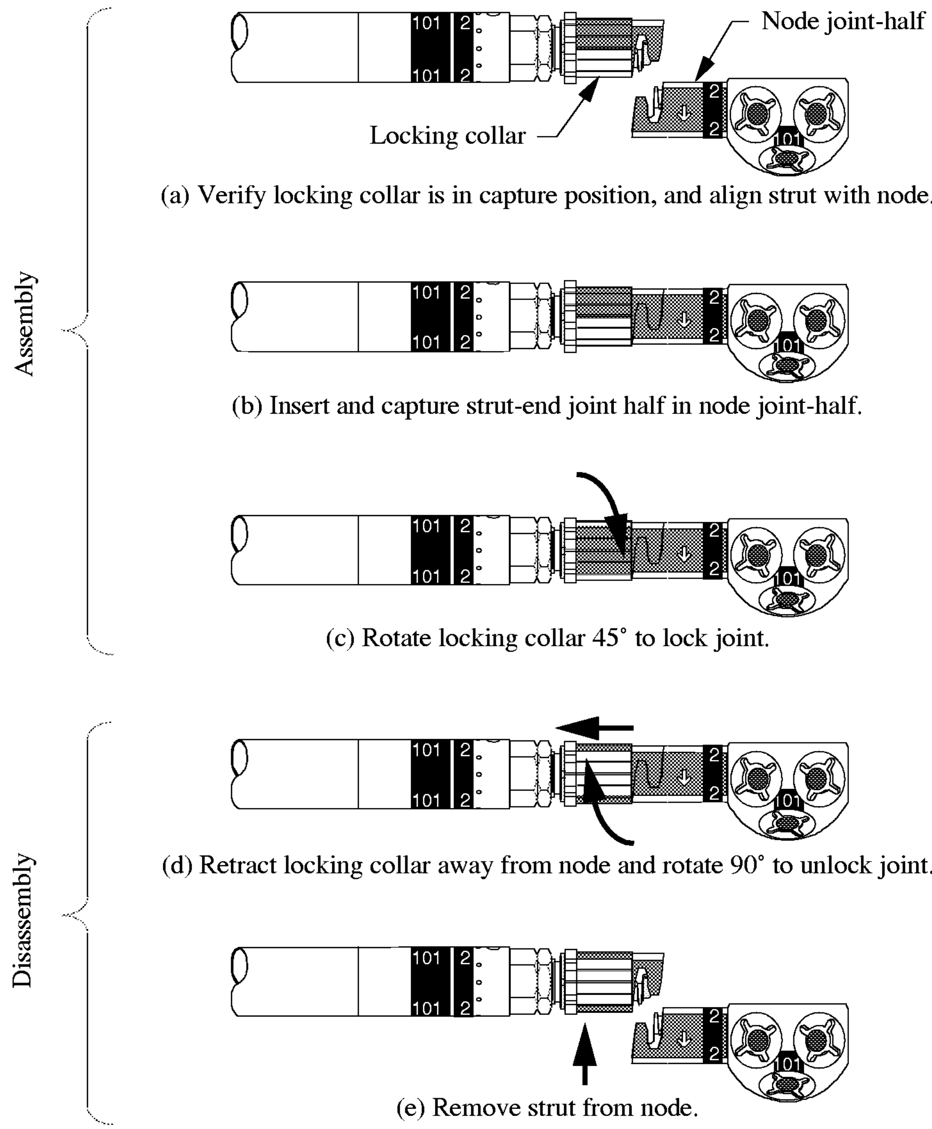


Figure 7. Operation of quick-attachment, erectable truss joint.

Reflector panels. Figure 8 shows the seven mockup reflector panels attached to a segment of the truss. Each panel is approximately 2.3 m from corner to corner and 5 cm thick. The gap between the edges of adjacent panels is approximately 0.3 cm, and all panel edges are beveled to provide adequate clearance for installation and removal. Figure 9 shows the details of the back (non reflective) side of one mockup panel. Although flight quality panels would be curved and probably incorporate a composite construction, for neutral buoyancy testing each mockup panel is fabricated at minimal cost from six flat, aluminum, triangular sheets riveted to an aluminum frame. To approximate the curvature of the reflector surface, the six corner points and the center point of each mockup panel are designed to lie in the theoretical surface of paraboloidal reflector. EVA handles are attached to the panel frame in three locations to facilitate handling and maneuvering by the EVA crew. Rigid closed-cell foam is bonded around the edges of the panel frame for floatation and three ballast chambers (with lead shot added as necessary) are attached to interior points on the panel frame to trim for neutral buoyancy.

Each panel is attached to three convex-surface truss nodes using three panel-corner joints located at panel corners that are approximately 120° apart. Each panel-corner joint is designed to restrain two degrees of freedom between the panel and the truss (the out-of-plane and the circumferential degrees of freedom relative to the plane of the panel), and thus, behave like a flexure. Collectively, the three panel-corner joints provide restraint to the panel in all six rigid-body degrees of freedom, and thus, the panel-to-truss interface is kinematic.

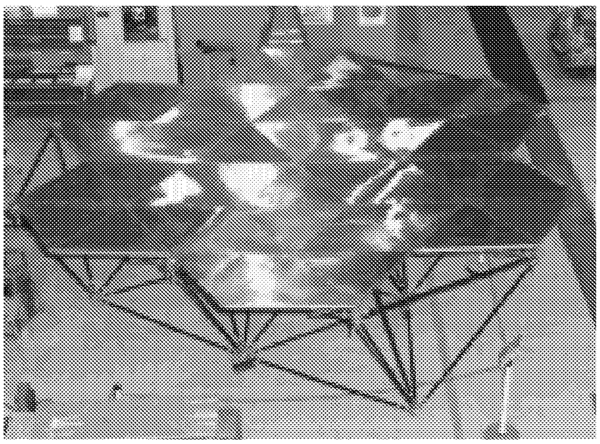


Figure 8. Seven mockup reflector panels attached to a segment of the test article truss.

The main challenge addressed in the present panel-corner joint design is to provide the necessary compliance (like that of a flexure) in a mechanical joint that is durable and simple enough for EVA operation (ref. 10). To accomplish this, the panel-corner joint includes a hinged linkage that functions like a flexure (i.e., providing stiffness in only two degrees of freedom) but is durable enough to preclude damage during routine handling. This linkage is shown in fig. 10. The linkage is connected to the panel-corner fitting by an upper pin, and is connected to the truss node by a lower pin. Together, these two pins allow the linkage to rotate freely in the same way that a flexure would be able to rotate in its weak direction.

To prevent the panel-corner joint linkage from moving freely prior to attachment of the panel to the truss, the lower pin of the linkage is also connected to a strap which terminates at a fitting in the center of the panel (see also fig. 9). The strap serves to position the free end of the linkage in roughly the right location for attachment to the truss, but is compliant enough to not over constrain the panel once installed.

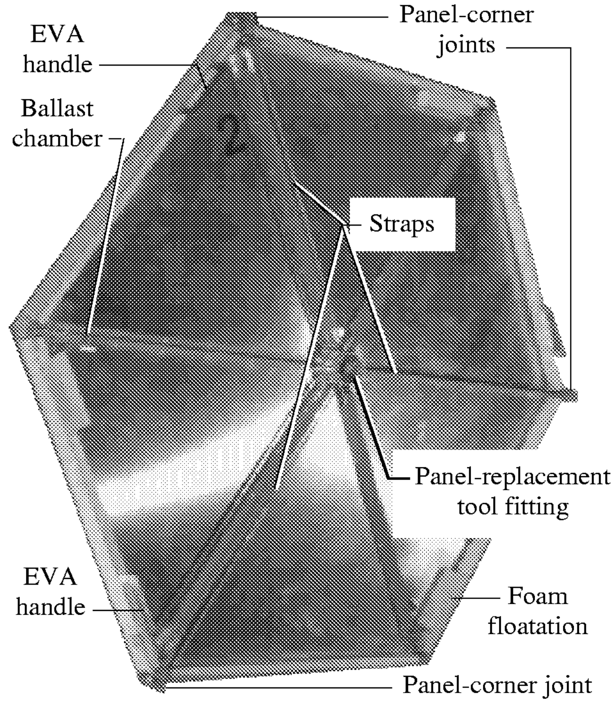


Figure 9. Back side of mockup reflector panel.

A detailed sketch and photograph of the latch mechanism that connects the panel-corner joint to the truss are shown in fig. 11. The panel latch mechanism is mounted onto a convex-surface truss node, and includes the following components: a guide to aid in the alignment and capture of the panel-corner joint; a seating plate into which the lower pin of the panel-corner joint seats, a latch that engages and locks the lower pin of the panel-corner joint, and a housing to hold the latch and latch handle.

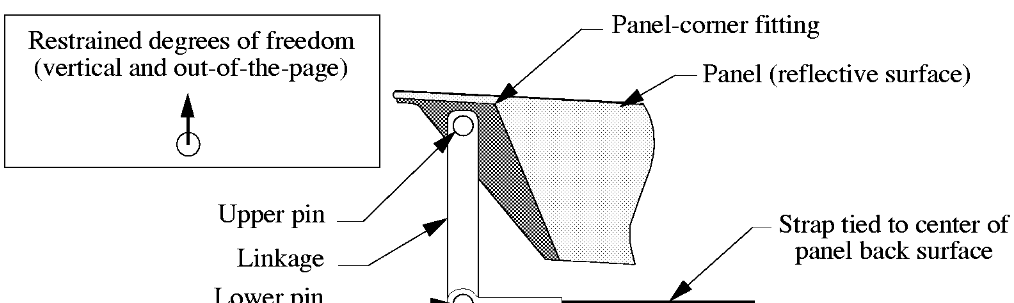
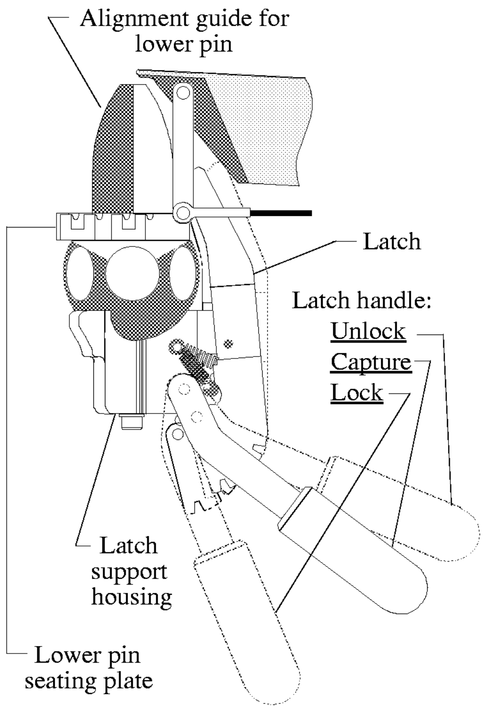
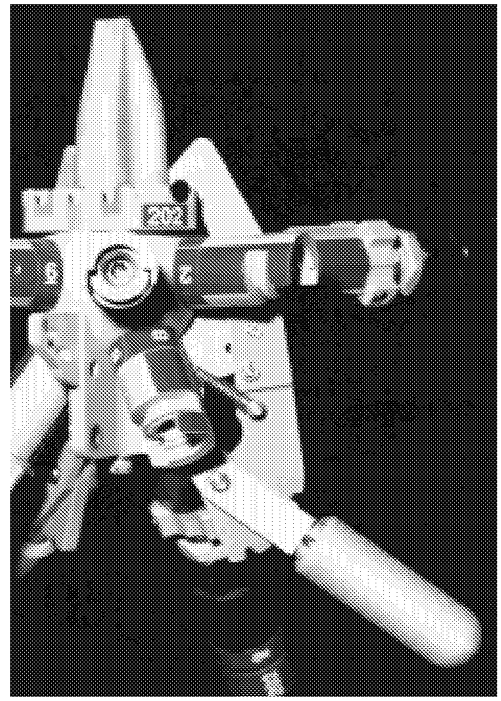


Figure 10. Kinematic linkage in panel-corner joint.



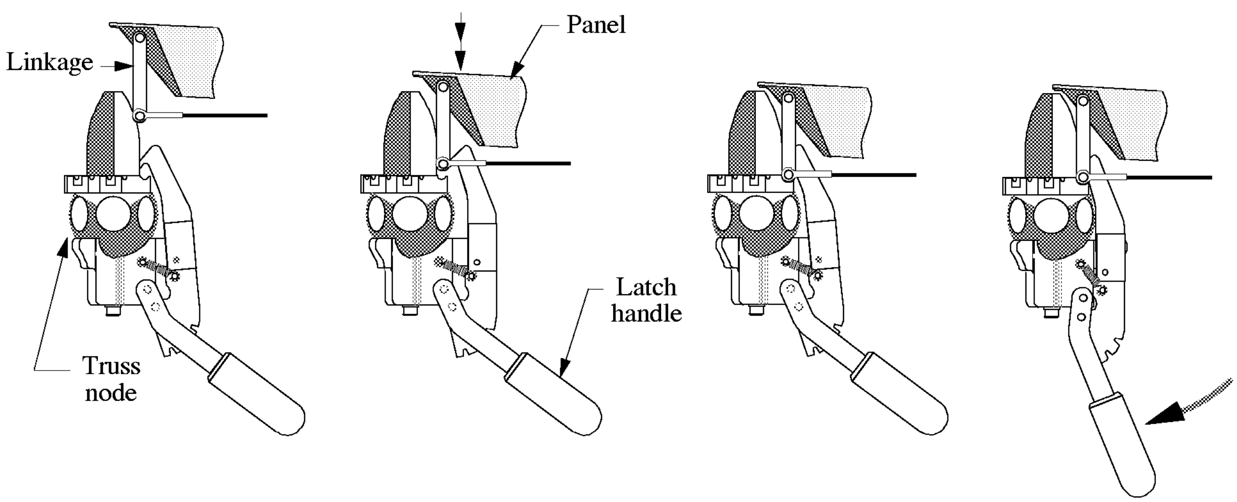
(a) Sketch



(b) Photograph

Figure 11. Panel latch mechanism.

The operation of the panel latch mechanism is shown in figure 12. Prior to attaching a panel to the truss, the astronauts visually verify that each latch handle is in the "capture" position (fig. 12(a)), then they align the panel using the alignment guides on the truss nodes (fig. 12(a)). As a panel-corner joint is aligned and drawn inward, the lower linkage pin is captured by the spring-loaded latch (figs. 12(b) and 12(c)). The panel-corner joint is locked by moving the latch handle into the locked position (fig. 12(d)) to preload the lower linkage pin into the seating plate. To remove a panel, all three latch handles must be rotated to the "unlock" position (Fig. 12(a)) thereby releasing the three lower linkage pins.



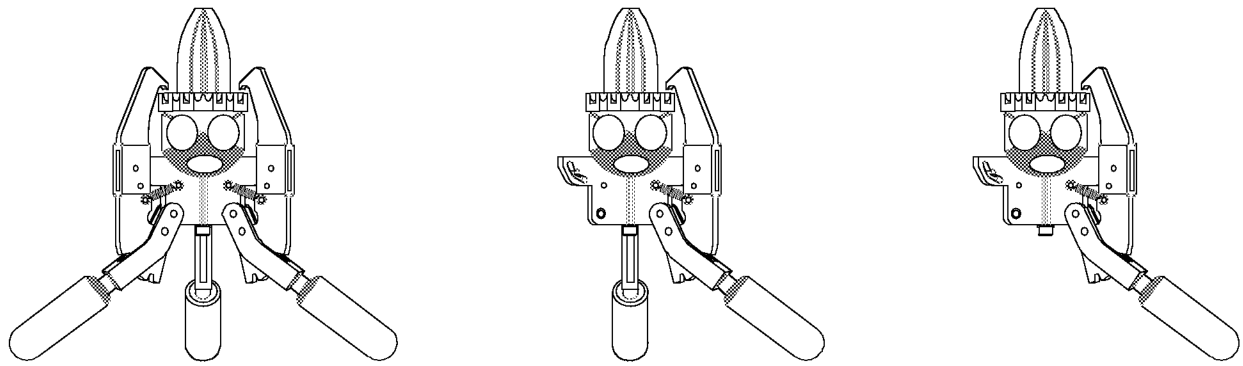
(a) Lower pin placed on alignment guide.

(b) Panel pulled in on alignment guide.

(c) Panel captured.

(d) Panel locked to node.

Figure 12. Operation of panel latch mechanism.



(a) Interior node of truss with three panel latches.

(b) Perimeter node of truss with two panel latches.

(c) Perimeter node of truss with one panel latch.

Figure 13. Arrangement of panel latches on interior and perimeter convex-surface nodes.

Note: the latch support housings can support from one to three latches and latch handles. Since the corners of three adjacent panels are attached to each interior concave-surface node, three panel latches and latch handles are incorporated into these nodes (see fig. 13(a)). Nodes located along the perimeter of the truss accommodate the corners of only one or two panels, thus only one or two panel latches are incorporated into these nodes (see figs. 13(b) and 13(c)). Since only seven panels are included in the present test article, panel attachment hardware is incorporated on only 12 of the 48 concave-surface nodes.

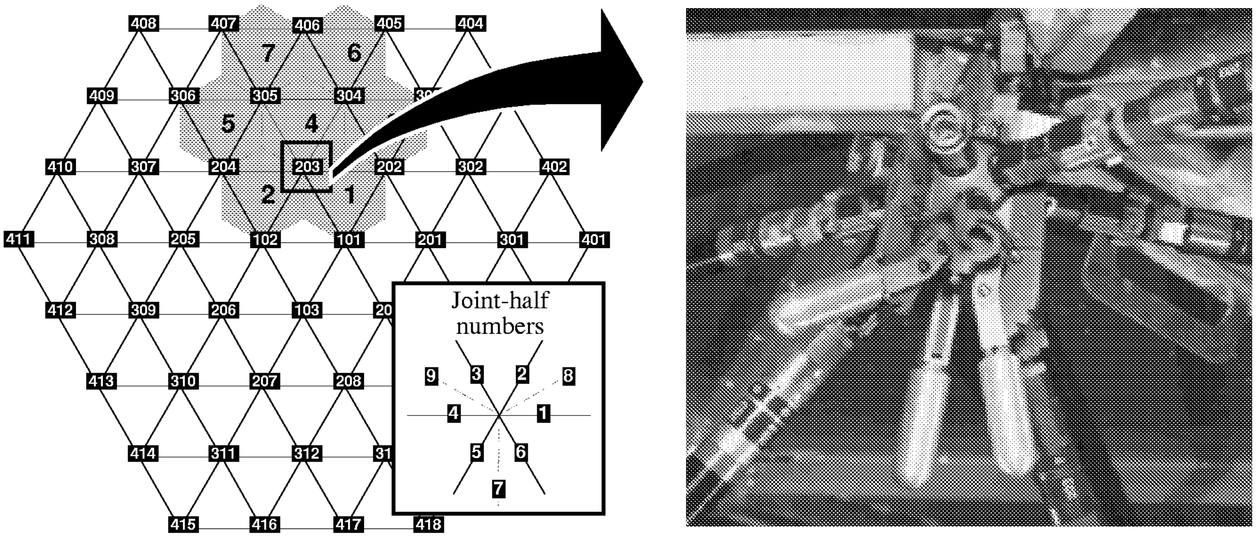
Unlike attaching components within the truss, attaching a panel requires both EVA astronauts. A key feature in the operation of the panel-attachment hardware is that simultaneous alignment of any two of the three panel corner-joints with their respective latch mechanisms will automatically align the third panel-corner joint. Therefore, two astronauts can align and capture a panel from any two of the three attachment sites, leaving the third attachment to be made afterward.

Another key consideration in the development of panel attachment procedures is that the risk of damage to the panels due to handling or contact with adjacent panels must be minimized. Once attached to the truss, adjacent panels are designed to have an edge clearance of less than 0.25 in (0.6 cm). To allow such a close fit and effectively eliminate the risk of damage to the panel edges, all panel edges are beveled such that the edge clearance between adjacent panels is substantially greater (on the order of inches) until the panel is drawn into the truss for final capture. Installing each panel with no more than two adjacent panels in place reduces further the risk of damaging panels. Thus, only two close-fitting panel edges are of concern during EVA installation of a panel. Previous tests (ref. 10) have shown that the panel alignment guides provided on the truss nodes are adequate for insuring that these two close-fitting panel edges will clear during assembly.

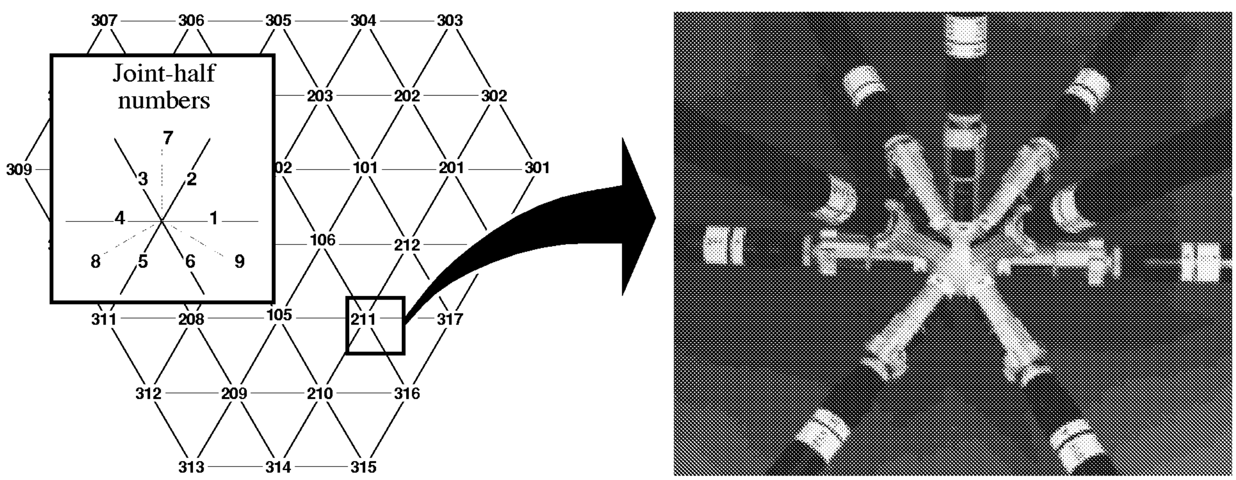
Hardware identification numbers. To ensure proper identification and facilitate efficient EVA assembly, each strut, node, and reflector panel is labeled according to its location in the reflector (see Fig. 14). The labeling sequence is designed to follow the assembly procedure and provide the EVA astronauts with the necessary information to preclude the need for additional written or oral instructions that might slow down the assembly process.

The panels are labeled 1 through 7 to identify the order in which they are attached to the truss (fig. 14(a)). Nodes in the concave surface of the truss are labeled with white three-digit numbers on a black background (fig. 14(a)). Nodes in the convex surface of the truss are identified by black three-digit numbers on a white background (fig. 14(b)). The first digit of the node number identifies which "ring" in the truss surface contains the node (ring 1 is nearest the center of the truss). The last two digits of the node number discriminate between nodes in a given ring.

Finally, each node joint-half on each node is labeled with a single-digit number as indicated in the insets of fig. 14. Numbers 1 through 6 are assigned to joint-halves connecting struts in either the concave or convex surface of the truss (solid lines in insets of fig. 14), and 7 through 9 are assigned to joint-halves connecting core struts (dashed lines in insets of fig. 14).



(a) Concave-surface node numbers and reflector panel numbers.



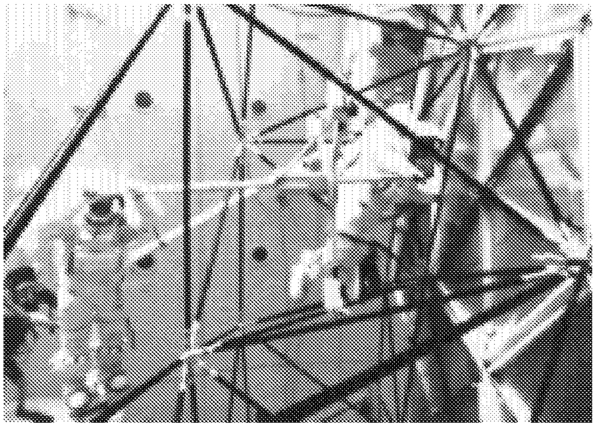
(b) Convex-surface node numbers.

Figure 14. Reflector hardware identification numbers.

Panel-Replacement Tool

After a reflector has been completely assembled, one of its reflector panels could become damaged and thus require replacement. Although the panel alignment guides located on the truss nodes are adequate to prevent panel damage during panel attachment, the guides do not align the panel precisely enough to prevent contact between adjacent panels during removal of a panel. To provide the capability for removing and replacing a damaged panel without the risk of damaging adjacent panels, or without requiring the disassembly of a significant part of the reflector, it is necessary to use a special-purpose tool. The basic requirements for this tool are to: 1) accommodate hexagonal panels of slightly different sizes; 2) maintain panel alignment during removal and replacement; and 3) insure that the replacement panel is positioned in the same rotational orientation as the damaged panel it replaces.

Figure 15 shows a photograph and sketch of the panel-replacement tool evaluated in the present tests. The tool includes two major components: the hub assembly and the sliding guide pole. The hub assembly is aligned and attached to the truss, and provides the necessary alignment constraints for removal and replacement of a panel. The sliding guide pole is attached to the reflector panel and includes machined surfaces that engage bearings within the hub assembly.



Photograph of test subjects attaching panel-replacement tool to panel in neutral buoyancy.

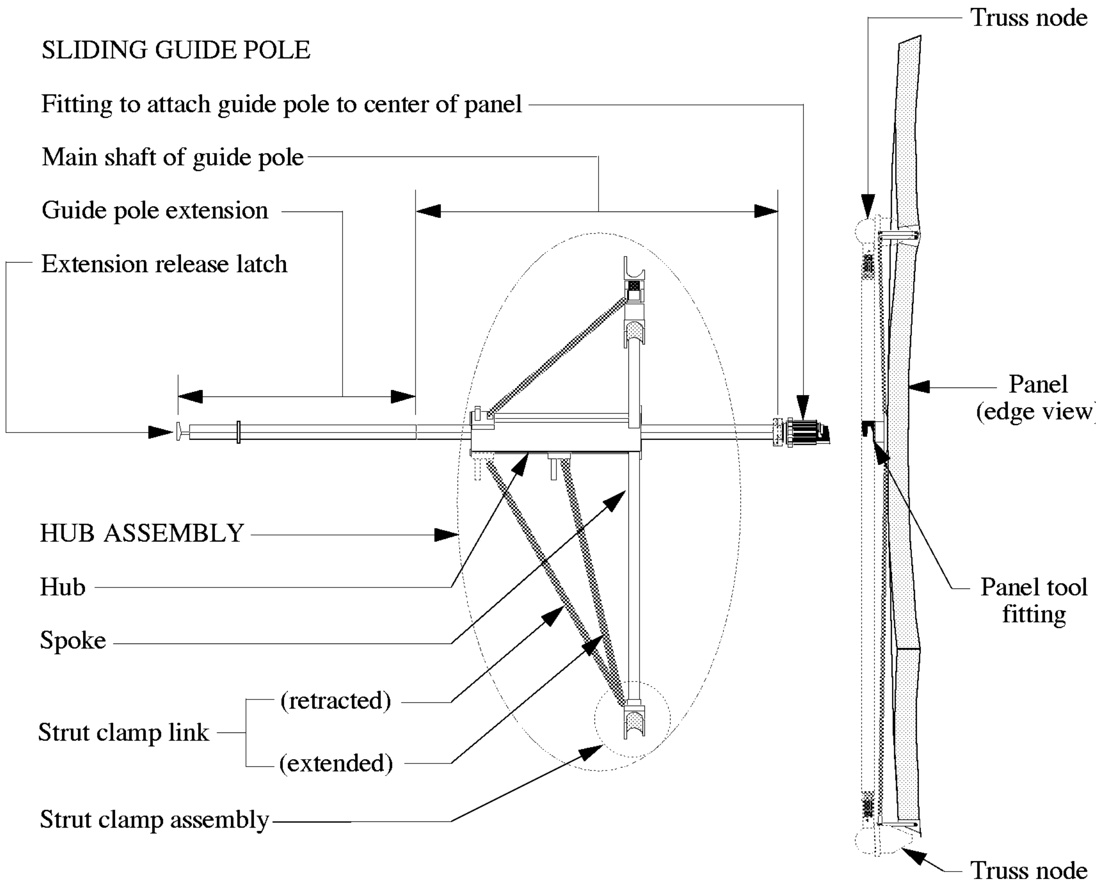
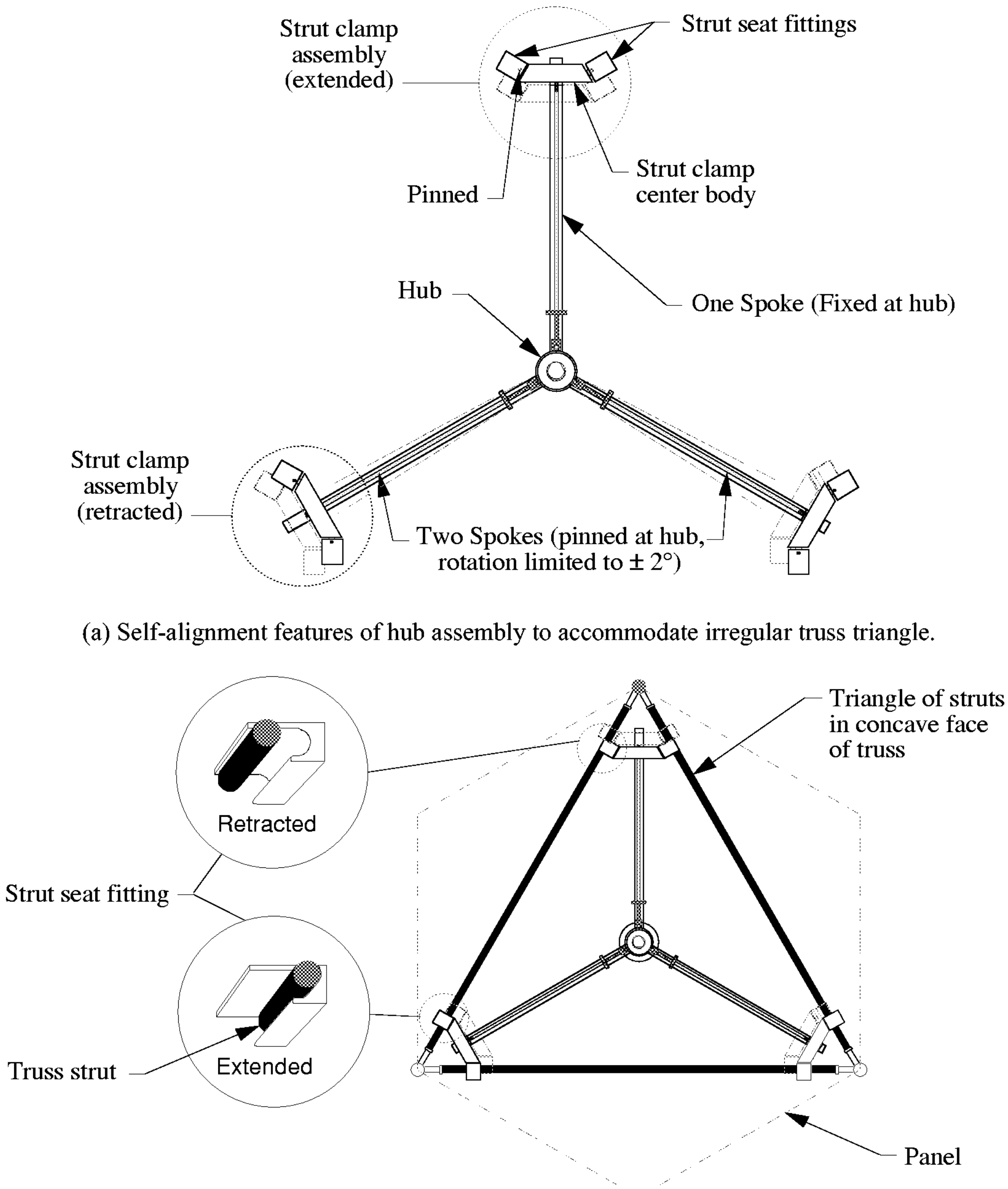


Figure 15 Panel-replacement tool.

The hub assembly is locked to the triangle of truss struts behind the panel with three strut clamp assemblies as shown in fig. 16(a). The three strut clamp assemblies are mounted on three spokes that emanate from the hub. Two of the spokes are pinned at the hub to allow several degrees of rotation, and accommodate dimensional differences between truss triangles. Each strut clamp assembly slides along its spoke and is locked into position by a strut clamp link (see lower diagram in fig. 15). As the strut clamp assembly is extended, two fittings with encircle and wedge tightly against the truss struts as shown in fig. 16(b). Wedging all three strut clamp assemblies into the truss, aligns and fixes the hub assembly to the truss.



(a) Self-alignment features of hub assembly to accommodate irregular truss triangle.

(b) Method for locking hub assembly to truss struts.

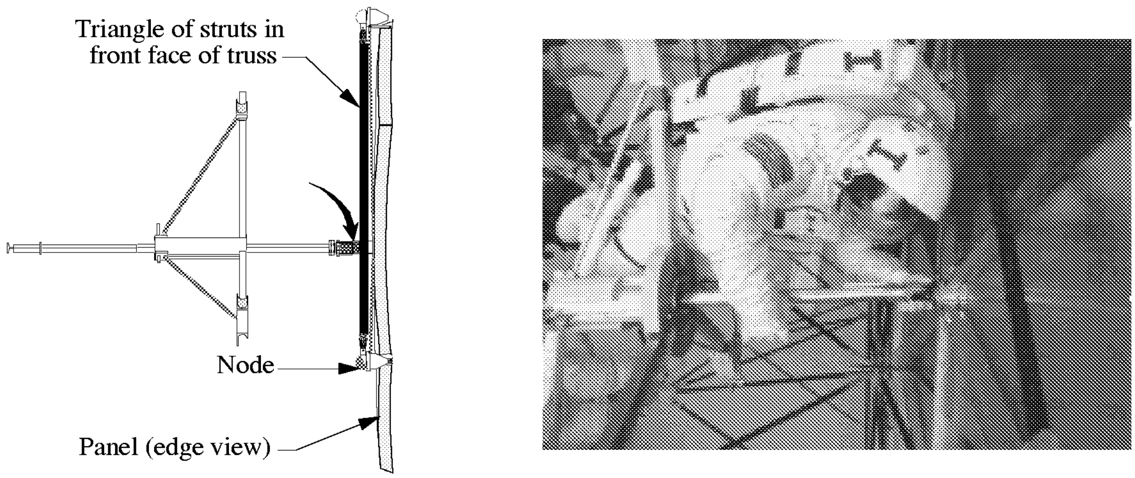
Figure 16. Details of hub assembly to lock it to truss struts.

The sliding guide pole is split into a main shaft and an extension that can be detached from the main shaft by actuating a release latch on the end of the extension (see Fig. 15). The main shaft of the guide pole is equipped with a fitting that mates to a similar fitting on the back (non-reflective) side of the panel. Since these fittings are the only connection between the panel and the panel-replacement tool, they are designed to mate precisely in one orientation, thus preserving the alignment of the panel during removal and replacement.

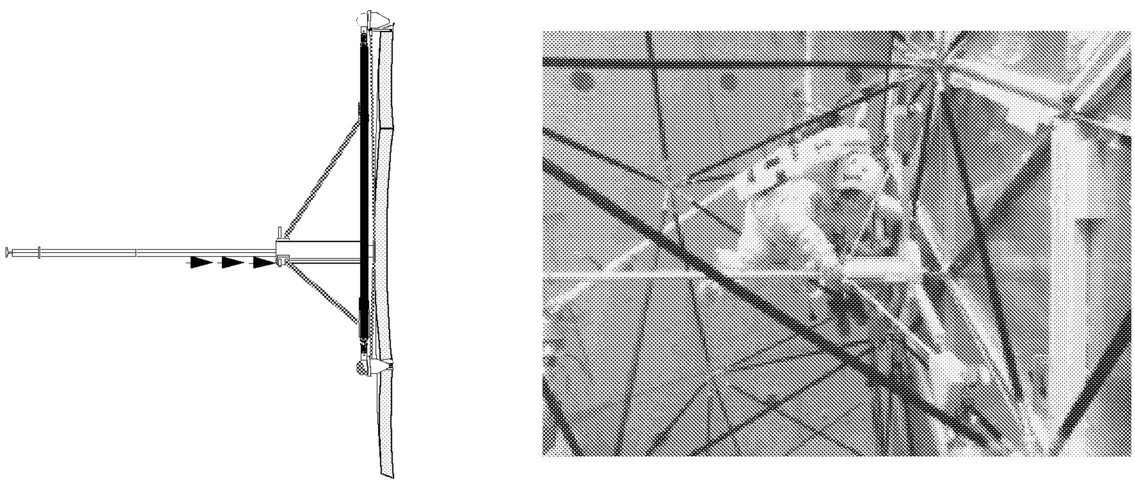
The panel removal operation is depicted in fig. 17 with a combination of sketches and photographs from neutral buoyancy testing. For removal and replacement of a damaged panel, one of the EVA astronauts free floats inside the truss to operate the panel-replacement tool while the other astronaut is positioned in front of the reflector on a moving foot restraint. Although the EVA guidelines presented previously recommend against free floating, the replacement of a damaged panel is a contingency operation that would only be performed infrequently. Hence, it is reasonable to allow the astronauts to perform these tasks while free floating and thus eliminate the need for mounting a portable foot restraint inside the reflector structure. During the present tests, the Manipulator Foot Restraint (MFR) attached to the Remote Manipulator System (RMS) was used to position the astronaut in front of the reflector surface.

As depicted in Figure 17, the guide pole is first attached to the center fitting on the back of the panel (fig. 17 (a)) by the free-floating astronaut. Second, with the strut clamp assemblies retracted, the free-floating astronaut slides the hub assembly along the guide pole until guides on the strut seat fittings contact the triangle of truss struts immediately behind the panel (fig. 17(b)). Third, the free-floating astronaut extends the strut clamp assemblies, one at a time, along their respective spokes to seat and lock the strut clamps onto the truss struts, thus aligning and locking the panel removal tool to the reflector structure (fig. 17(c)). Fourth, the free-floating astronaut unlatches the damaged panel from the three truss nodes and slides the guide pole and damaged panel at least one meter out from the reflector surface (fig. 17(d)). Fifth, the astronaut positioned behind the damaged panel on the MFR, grips the main shaft of the guide pole and removes the panel and attached guide pole after the free-floating astronaut actuates the guide pole release latch (fig. 17(e)).

To complete the sequence, the main shaft of the guide pole is removed from the damaged panel and attached to a replacement panel, which is installed by reversing the removal sequence.

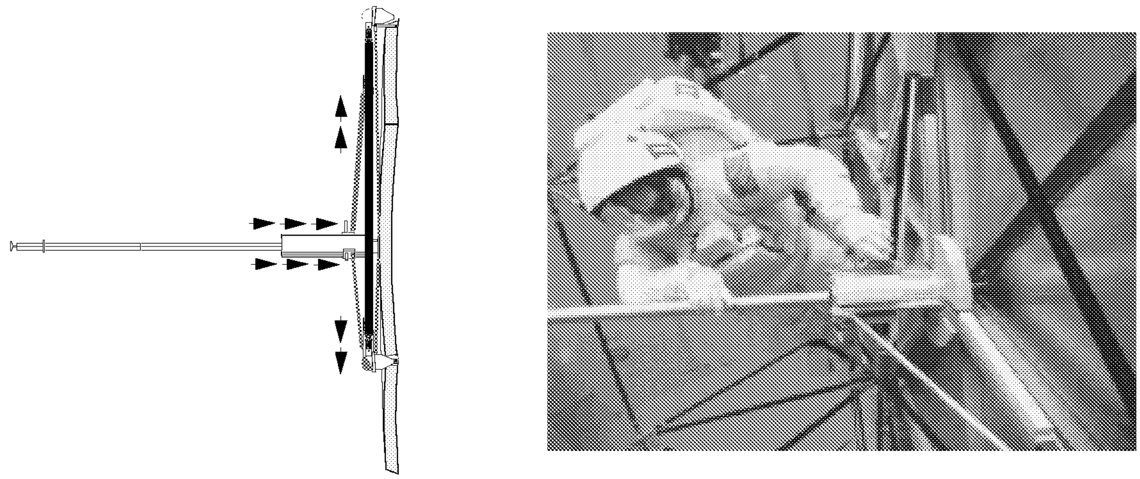


(a) Attach guide pole to center of panel.

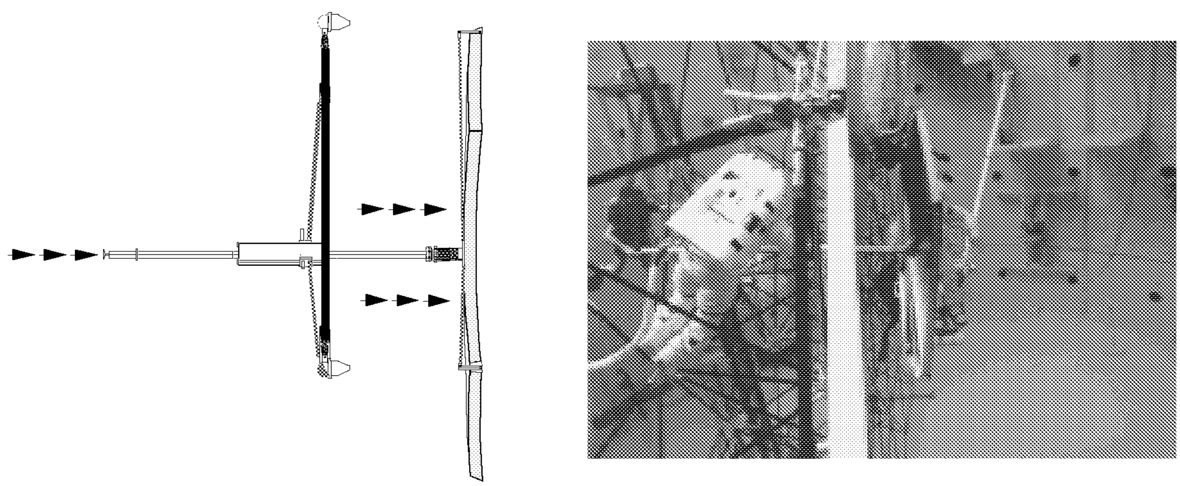


(b) Slide hub assembly along guide pole until strut seat fittings contact struts.

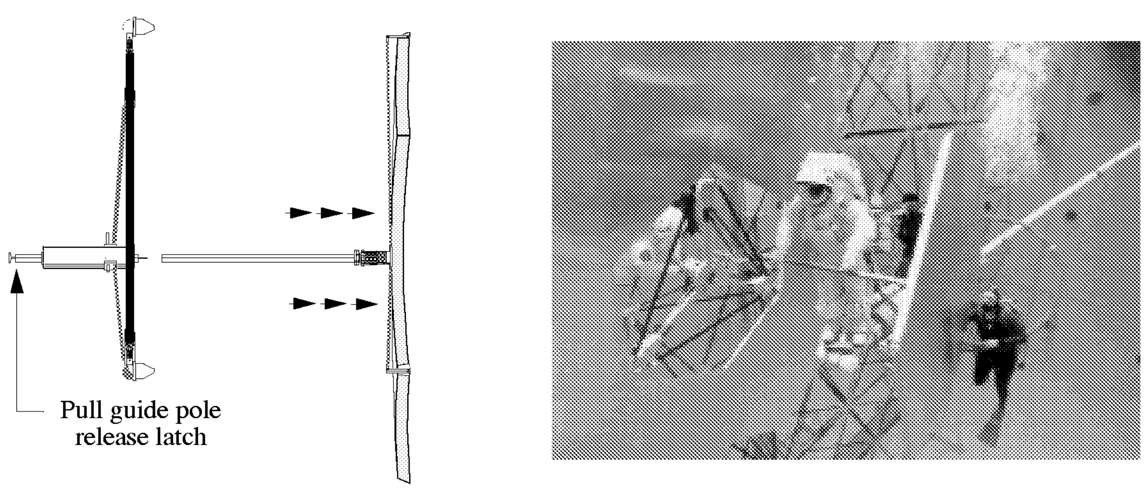
Figure 17. Panel removal sequence.



(c) Extend strut clamps by sliding clamp actuators along hub. Lock in place when struts are seated in fittings.



(d) Unlatch panel corners from truss nodes and slide guide pole and panel out of hub assembly.



(e) Pull guide pole release latch. Remove panel and main shaft of guide pole.

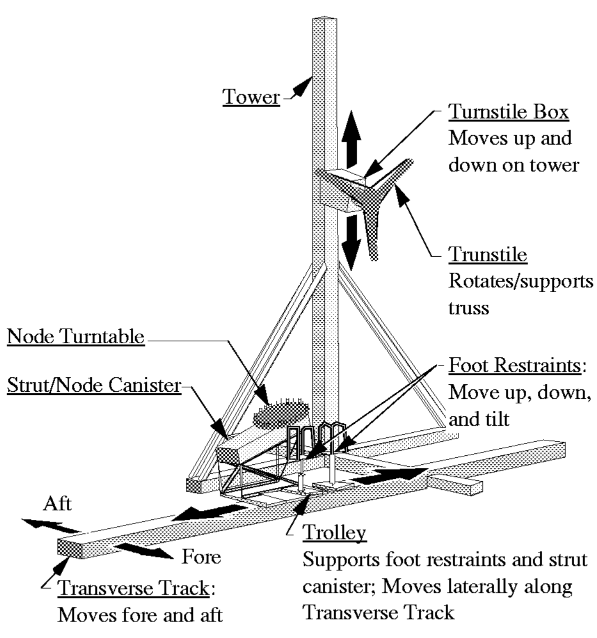
Figure 17. Panel removal sequence (concluded).

Assembly Fixture and Mobile Foot Restraints

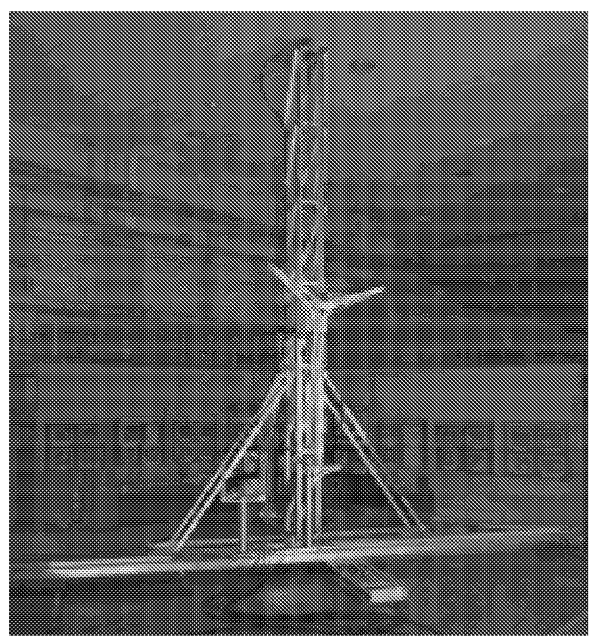
During assembly of the reflector, the astronauts are positioned with mobile foot restraints while the reflector test article is oriented and held in position with an assembly fixture. Figure 18 shows the assembly fixture and mobile foot restraints used in the present tests. The assembly fixture consists of a 10.4-m vertical tower, turnstile box, and turnstile. The three center nodes in the convex surface of the reflector truss are attached to the three legs of the turnstile. As the reflector is assembled, the turnstile rotates the reflector to orient it and the turnstile box is moved upward on the tower to keep the bottom edge of the reflector at a convenient height for the EVA test subjects.

Prior to assembly, the truss struts and nodes are stowed in the order of assembly in five strut/node canisters. Each canister contains 63 struts and between 12 and 21 nodes, which are stowed on a turntable attached to the canister. Only one strut/node canister is used at a time in the work area. When the material is depleted, the strut/node canister is replaced with a full canister by scuba divers simulating the function of the RMS (or some other automated positioning device). Two test subjects retrieve stowed hardware and assemble the test article from mobile foot restraints positioned at the base of the assembly fixture (fig. 18(c)). Each foot restraint has two handrails to facilitate ingress and egress, a foot pedal for manual yaw control, and a hydraulic cylinder that allows about one meter of vertical travel. Since the current test setup requires one test subject to be reclined while assembling the truss, the higher of the two foot restraints incorporates a kinematic linkage, which causes that test subject to be reclined as the foot restraint is raised.

The foot restraints and strut/node canister are attached to a trolley that moves transversely along a 15-m track (fig. 18(a)). The transverse track and trolley also move fore and aft along a 2-m track. These two motions allow the foot restraints and the strut/node canister to be positioned at all work sites necessary for assembly of the reflector. The turnstile, foot restraints, trolley and transverse track are hydraulically powered and controlled by a remote operator stationed at a console located outside the water tank (fig. 18(d)). All motions are directed by the test subjects through voice commands to the console operator, who can view the operations through a porthole in the tank wall. For on-orbit operations the foot restraints and turnstile could be controlled by a pre-programmed computer, thus eliminating the need for a remote operator.

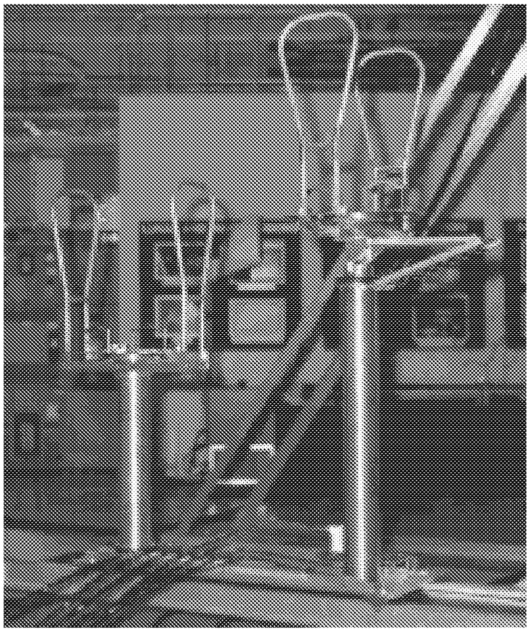


(a) Schematic of Components

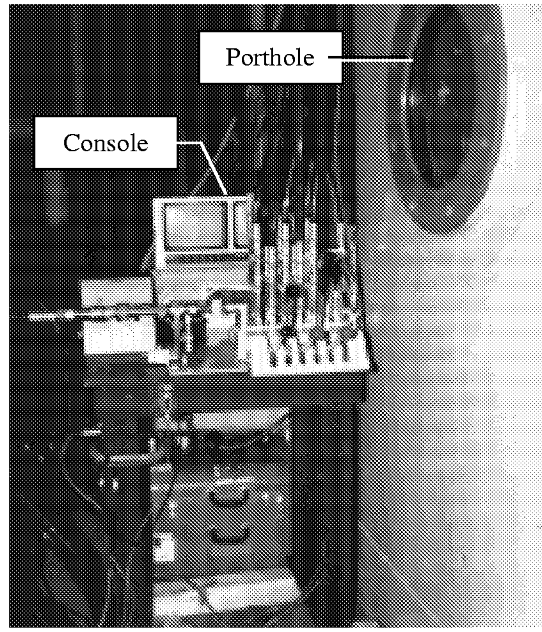


(b) Photograph of test hardware

Figure 18. Assembly fixture and mobile foot restraints.



(c) Mobile foot restraints



(d) Control console and tank porthole.

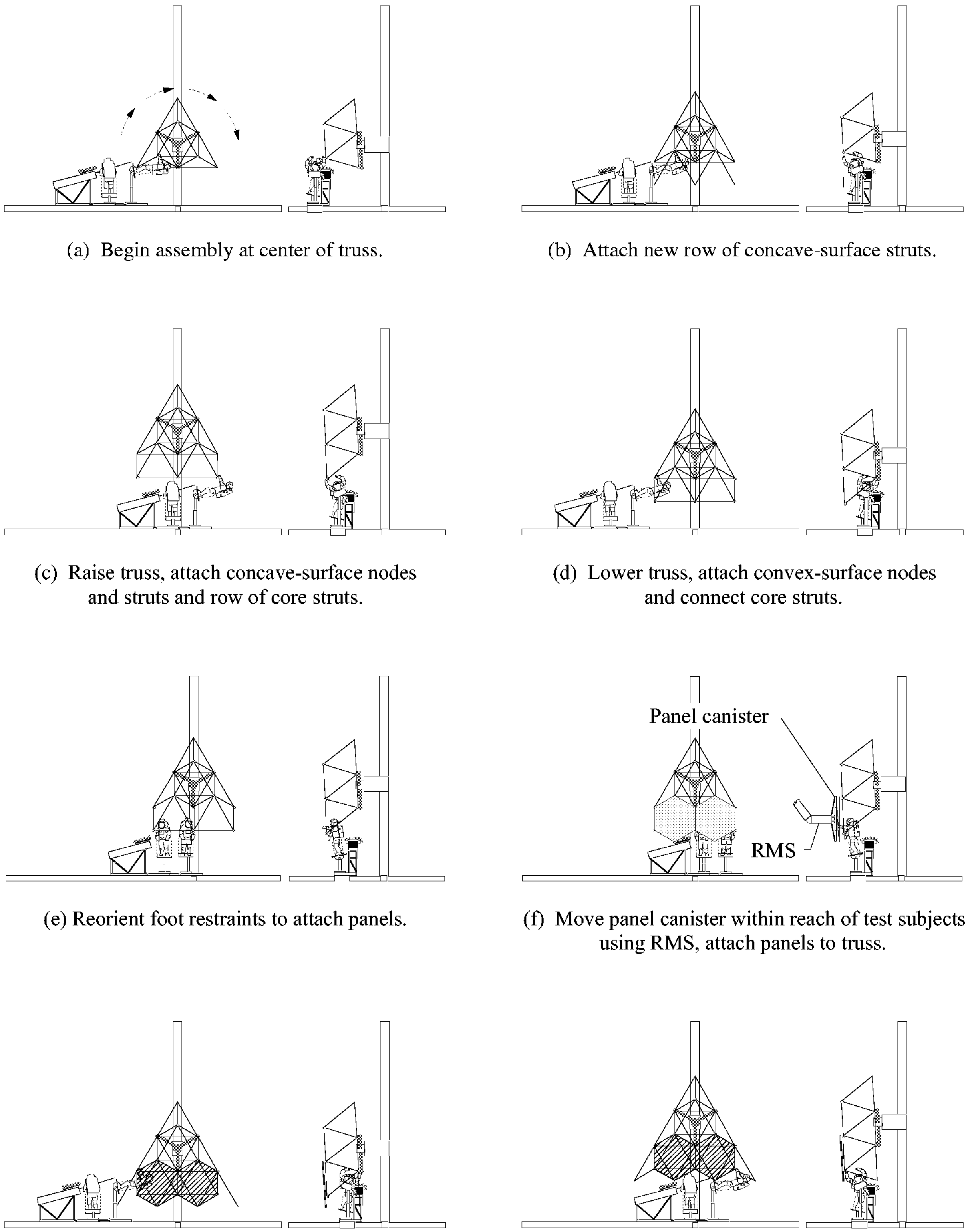
Figure 18. Assembly fixture and mobile foot restraints (concluded).

The assembly fixture is sized with large factors of safety and driven with hydraulics for 1-g operation and simplicity. An assembly fixture for use on-orbit could be functionally similar, but much lighter in weight. It could be supported on one of the standard pallets used in the cargo bay of the Shuttle or on the truss structure of the International Space Station. Although the tower and transverse track could be pre-assembled for launch, they may have to be hinged and folded, depending on the diameter of the reflector to be assembled. The tower could be automatically raised to an upright position after orbit is achieved. For on-orbit application, the transverse track would be stationary and the necessary fore and aft motion provided through an additional direction of motion in the trolley.

Reflector Assembly Procedure

The complete reflector assembly procedure is comprised of 261 steps with successive steps separated by repositioning of either the foot restraints or the truss. The sequence of steps is a simple repetition of a few basic operations that are easily memorized. Therefore, despite the large number of steps, there is no need for written or verbal prompting of the EVA astronauts. Prior to the present tests, each step in the assembly procedure was planned in detail to aid in evaluating test-subject and truss-positioning requirements and determine estimates for the completion times. The first 54 steps of the assembly procedure are detailed in the Appendix. The remaining 207 steps follow the pattern established in the first 54 steps, and these remaining steps are not detailed herein.

The reflector is assembled in concentric rings starting at the center (fig. 19(a)). Each ring forms a triangle of three reflector-panel strips separated by 120° rotations of the assembly fixture turnstile. Assembly of a strip begins by attaching a new row of concave-surface struts to the existing row of concave-surface nodes (fig. 19(b)). Next, the truss is raised, a new row of concave-surface nodes are attached to the free ends of the newly installed struts, followed by the remaining concave-surface struts and a row of core struts (fig. 19(c)). Then, the core struts are connected to already-existing convex-surface nodes (fig. 19(d)). At this point, the astronauts are reoriented and the row of reflector panels is attached using the RMS to position the panel canister (figs. 19(e) and (f)). After panel installation, the astronauts are repositioned to attach a new row of convex-surface struts (fig. 19(g)). The truss is then raised and the astronauts attach a new row of core struts. Finally, the row of convex-surface nodes along with the remaining convex-surface struts are attached (fig. 19(i)). After each strip is assembled, the reflector is rotated 120° and the sequence of operations is repeated until the reflector is complete (fig. 19(j)).



(a) Begin assembly at center of truss.

(b) Attach new row of concave-surface struts.

(c) Raise truss, attach concave-surface nodes and struts and row of core struts.

(d) Lower truss, attach convex-surface nodes and connect core struts.

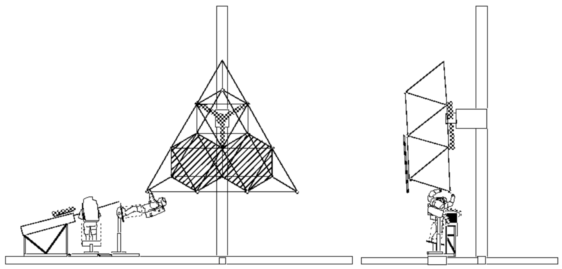
(e) Reorient foot restraints to attach panels.

(f) Move panel canister within reach of test subjects using RMS, attach panels to truss.

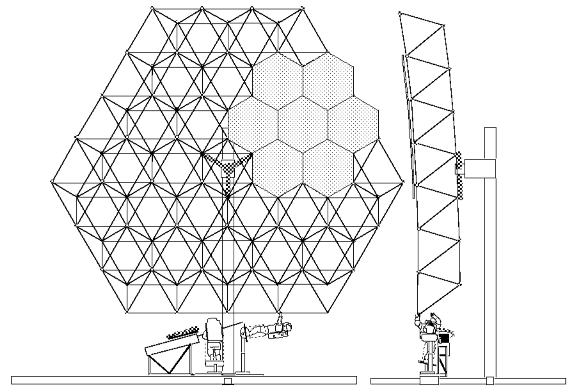
(g) Reorient foot restraints and attach row of convex-surface struts.

(h) Attach core struts to concave-surface nodes.

Figure 19. Assembly procedure.



(i) Attach convex-surface nodes and horizontal struts to complete strip.

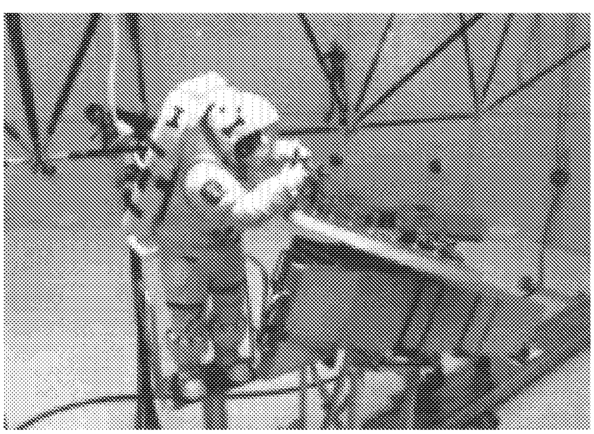


(j) Rotate 120°, assemble a row of truss, attach panels, repeat until reflector is complete.

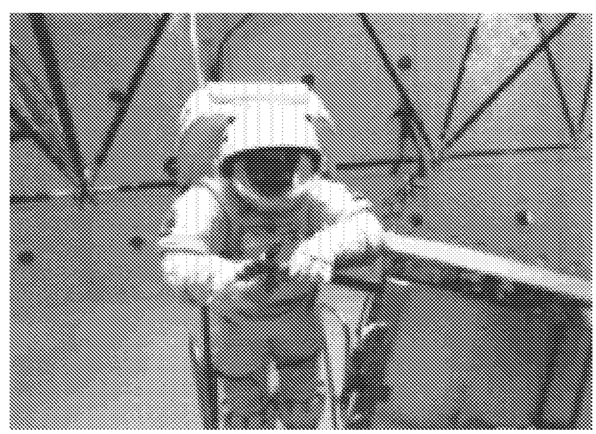
Figure 19. Assembly procedure (concluded).

Techniques for Efficient Truss Assembly

To maximize the test subjects' efficiency, the present procedure reduces the diversity of tasks for which each test subject is responsible by restricting the upright test subject to unstowing and managing the truss hardware while the reclined test subject is restricted to making the structural connections (fig. 20). This approach limits the number of tasks that each test subject must learn, thus accelerating their rate of learning and decreasing assembly times. Passing the struts is relatively easy since they are neutrally buoyant and the strut/node canister is oriented such that as the struts are extracted, they are automatically directed to the reclined test subject. However, as explained before, the nodes are not neutrally buoyant. Thus, to assist in passing the nodes, the upright test subject pre-attaches each node to a strut scheduled for installation at the same time (figs. 20(a) and (b)), then the strut/node pair is passed to the reclined test subject (fig. 20(c)) for attachment into the truss (fig. 20(d)). If no strut is scheduled to be attached simultaneously with a given node, the node is passed between test subjects using an extra strut fitted with a quick-attachment strut-end joint. The struts and nodes are stowed in the order of assembly to minimize the risk of interchanging parts and eliminate the potential for wasting time searching for the proper component at each step of the assembly procedure. Furthermore, to minimize foot restraint positioning time, each test subject is maintained in these orientations for all truss assembly tasks, and the reclined test subject makes all structural connections at a given node with the foot restraints in one position.

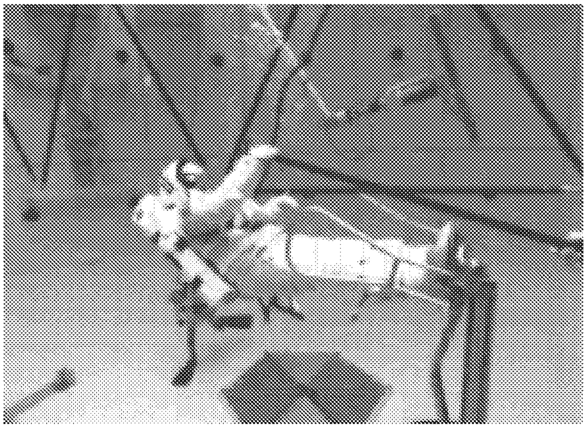


(a) Node is unstowed from strut/node canister.

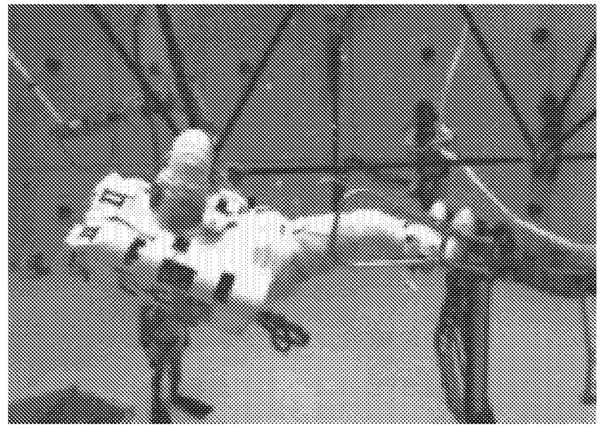


(b) Strut is selected from canister and attached to node.

Figure 20. Truss hardware management during assembly.



(c) Strut and node are passed to the reclined test subject.

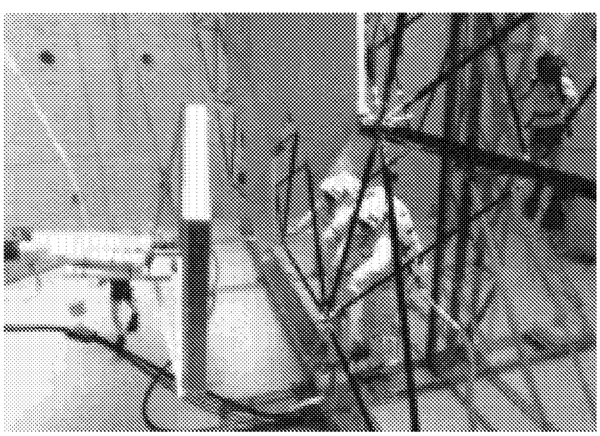


(d) Strut and node are connected into truss.

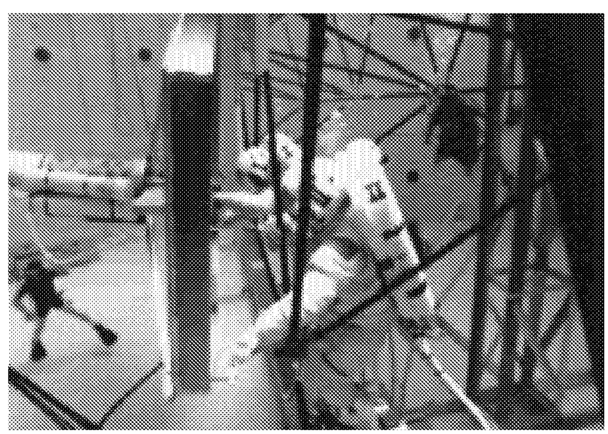
Figure 20. Truss hardware management during assembly (concluded).

Techniques for Efficient Reflector-Panel Installation

During panel attachment activities, the test subjects are reoriented so that they stand shoulder-to-shoulder facing out from behind the reflector surface (fig. 21). This orientation allows each test subject good visibility of his personal work area and his partner's work area, which helps the test subjects coordinate their actions to align and attach the reflector panels. Each reflector panel is kept in a protective canister that is maneuvered by the RMS to within reach of the test subjects (fig. 21(a)). For the present tests, the panel canister was sized to hold only one panel. However, a dispenser canister capable of holding multiple panels would probably be used on-orbit to reduce the number of RMS maneuvers required for panel attachment operations. After the panel canister is in position, the test subjects release latches that hold the panel in the canister, and slowly remove the panel taking care not to damage the panel edges by contact with the canister (fig. 21(b)). Once the panel has been removed from the canister, the test subjects align and attach the two lower panel-corner joints with latches on the truss nodes (fig. 21(c)). After the two lower panel-corner joints are locked, one of the test subjects egresses his foot restraints and manually translates a few feet to lock the upper panel-corner joint (fig. 21(d)). This free-floating operation is allowed because it requires less time than repositioning the foot restraints.

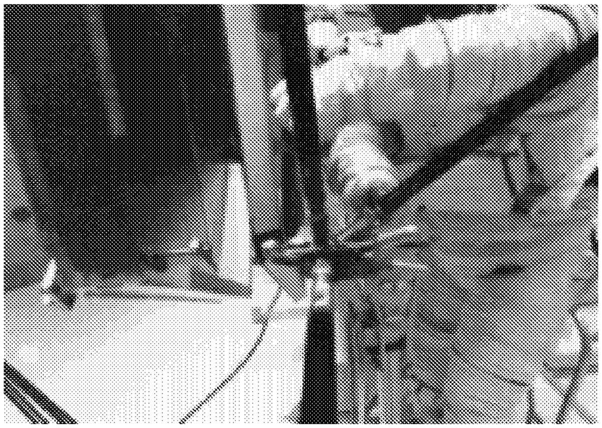


(a) Panel canister is positioned within arms reach of test subjects with RMS.

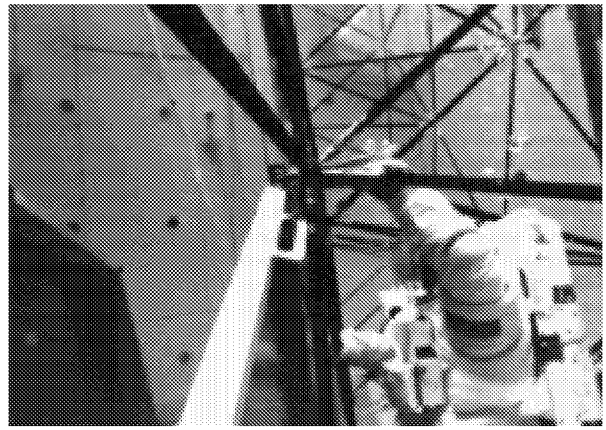


(b) Test subjects release latches which hold panel in canister and remove panel from canister.

Figure 21. Reflector panel installation.



(c) Lower panel-corner joints are aligned with truss-node fittings, then captured and locked in place.



(d) One test subject free translates vertically to capture and lock upper panel-corner joint onto truss node.

Figure 21. Reflector panel installation (concluded).

Predicted Assembly Times

As discussed at the beginning of the present section, the complete reflector assembly procedure is comprised of 261 steps. The Appendix presents detailed drawings for each of the first 54 steps of the assembly procedure. The illustrations in the Appendix depict the configuration of the reflector, assembly fixture, and test subjects at the completion of each of the assembly steps. Also listed within each illustration are the tasks to be performed during that step and estimates for the times to complete these tasks. There are only 11 different tasks performed throughout the assembly procedure. These tasks are listed in Table I along with estimated completion times. The tasks fall within the following three general categories: foot restraint and truss positioning tasks; truss construction tasks; and panel installation tasks. The following few paragraphs present estimates that were made prior to the present tests for the completion times of each of the tasks.

Foot restraint and truss positioning tasks. Estimates for foot restraint and truss positioning times were derived from rates-of-motion designed into these devices. The mobile foot restraints and the turnstile box were assumed to translate at their design speed of 0.3 m/s (1.0 ft/s). Similarly, the turnstile was assumed to rotate the truss at its design rate of 2.0 degrees/s. To account for the time required to communicate truss and foot restraint positioning commands between the test subjects and the console operator, five seconds was added to the estimated time of completion of each of positioning task.

Truss assembly tasks. During truss construction, one test subject is dedicated to unstowing the truss hardware, while the other test subject is dedicated to installing the hardware. The present procedures are designed to allow unstowage to occur concurrently with installation. Therefore, the unstowage tasks were not identified separately for estimating assembly times. Only three different truss assembly tasks were identified explicitly for estimation of completion times: installation of a strut (one end), installation of a node, and connection of the free end of a pre-installed strut to a pre-installed node.

The installation time for a single strut was derived from previous simulated EVA assembly tests using similar strut and node hardware (ref. 10). These previous tests resulted in an average time of approximately 40 seconds to unstow a strut and connect one end to a pre-installed node. However, these previous tests were performed in one day, thus the test subjects had little training time to perfect their techniques, and the foot restraint system was inadequate and imposed many awkward working positions on the test subjects. Allowing for a factor of two improvement in the previously documented assembly rate (with appropriate training and foot restraint systems), a more reasonable estimate for unstowage and installation of a single strut is 20 sec. Therefore, assuming that unstowage and installation of a strut take approximately the same amount of time, it was estimated that each strut in the present tests could be installed in approximately 10 sec. Similarly, it was estimated that the free end of a pre-installed strut could be connected to a pre-installed node in 5 sec., and each node could be installed in 20 sec., regardless of whether or not a strut was pre-attached.

The last row in Table I under "Truss Construction Tasks" identifies 100 seconds as the completion time for replacement of strut/node stowage canisters by the utility divers. Although this task was a necessary part of the underwater assembly simulations, obviously it would not be performed in a like manner on-orbit. Thus the time to complete this task is of little interest in the present study. Nevertheless, for the purpose of planning, 100 seconds was allowed in the assembly procedure for each strut/node canister replacement.

Reflector panel installation tasks. To estimate panel installation times, it is necessary to understand not only the rates at which the test subjects can manually align and attach a panel to the truss, but also the rates at which the foot restraints, truss, and RMS can be positioned. The foot restraint and truss positioning rates are easily estimated as already discussed. However the RMS positioning rates are more difficult to estimate. Two factors which complicate this are: 1) the RMS does not translate at a fixed rate, and 2) prior to neutral buoyancy testing, it is hard to accurately estimate the distance the RMS will have to travel to affect final positioning of the panel canister. Somewhat arbitrarily, 15 seconds was estimated for final positioning of the panel canister (in addition to 5 seconds for communication of these positioning commands by the test subjects).

During the reflector assembly tests reported in reference 10, three mockup reflector panels were installed on a precision truss structure using the same type of panel attachment joints as those used in the present tests. An average time of 48 seconds was required for two test subjects to align and attach the lower two panel-corner joints of each panel to the truss after the panel was brought within reach of the test subjects. However, the design and installation procedure for the panels used in the present test are improved over those used in the earlier tests. Due to these discrepancies and the fact that only three panel installations were performed during the earlier tests, only 40 seconds was estimated for completion of this task in the present tests.

The final task in the panel installation procedure is capture and locking of the third panel-corner joint by one of the test subjects free floating out of his foot restraints. During the earlier tests (ref. 10), an average of 16 seconds was required for the test subject to egress his foot restraints, free translate to the joint, and lock the joint. In the present tests, the test subject must also free translate back to and ingress his foot restraints after making this panel connection. Since it is more difficult and time consuming to ingress rather than egress EVA foot restraints, 40 seconds was estimated for completion of the entire task in the present tests.

Test Results

The reflector test article was assembled three times during nine neutral-buoyancy tests. Multiple tests were required to complete each build because tests were limited to two and one-half hours in length to insure the safety of the test subjects in neutral buoyancy. In addition, many tests were terminated early due to logistical problems such as electrical storms in the vicinity, life support system malfunctions, and test apparatus malfunctions. The procedures and a tool for removal and replacement of a damaged reflector panel were evaluated during tests 5 and 9 after the reflector assembly had been completed. These evaluations were intended to be qualitative in nature and are summarized at the end of this section.

Because of the limited available training and test time, the same pair of test subjects and the same control station operator was used for all but one test. The test subjects were both involved in the development of the test hardware, and thus very experienced in its operation prior to the tests. In addition both test subjects had substantial prior experience in neutral buoyancy simulation of EVA structural assembly. Furthermore, to reduce the number of tasks that they needed to learn, and thus accelerate their learning times, the test subjects did not interchange positions during reflector assembly (the test subjects did interchange positions while evaluating the removal and replacement of a damaged panel). The only exception to this practice was made during the third test when a highly EVA-experienced astronaut served as the reclined test subject. Although the astronaut had very little training time to develop optimal techniques, he was able to perform the assembly procedure with little difficulty and had no trouble manipulating the truss components or operating the joint hardware.

Reflector Assembly Time Histories

Table II presents the measured elapsed time at the completion of each assembly step during the three assemblies (denoted Build 1, Build 2, and Build 3) of the reflector. Table II also presents the elapsed times predicted using the task time estimates from Table I. For ease of comparison, these data are plotted in fig. 22. Superimposed over these time history plots are labels and hash mark used to delimit data from the nine neutral-buoyancy tests. Five tests were expended on Build 1. Since the number of available tests days was limited, Build 1 was terminated at the end of test five, after completing only 224 steps, to conserve test days for the remaining builds. Build 2 was completed during tests 6 and 7, and Build 3 was completed during tests 8 and 9. The time history plots are not smooth because the assembly steps do not necessarily consist of identical tasks, thus the elapsed time per step varies considerably.

From the data in Table II and fig. 22 it is apparent that the assembly times decrease significantly as the test subjects gain experience. Furthermore, during the last two tests these times were very close to the predicted values. Most of the improvement in the measured assembly time is attributed to the performance of the reclined test subject who makes all of the structural connections during truss assembly. The other test subject, although constantly unstowing struts and nodes and passing them to the reclined test subject, has no difficult hand or body positions to learn, thus he is typically able to keep up with the pace established by the reclined test subject.

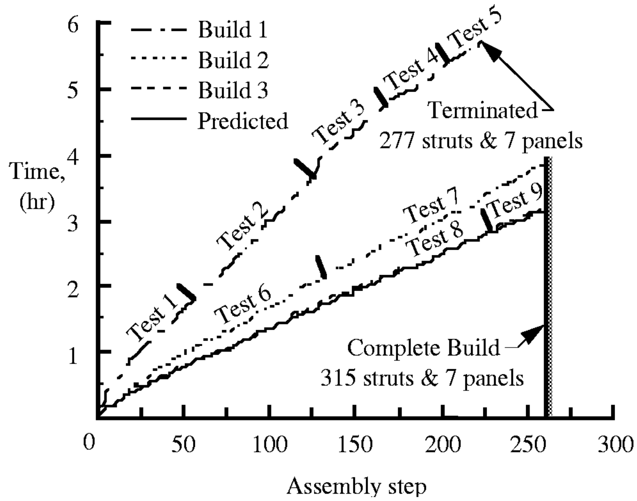


Figure 22. Time history for simulated EVA assembly of 14-m reflector.

An important observation that should be made from the data in fig. 22 is that *conclusions drawn from early tests can be misleading since performance can improve dramatically with training.* For example, if the test program had been halted after the first five tests, unrealistically high estimates would have been made for the time necessary to assemble this precision reflector on orbit. Similarly, if EVA hardware compatibility assessments had been made after only the first few tests, the test subjects might have judged the hardware negatively since they had not learned the most efficient techniques for operating it.

In general, it is important for the EVA planner and hardware designer to realize that with extended training the EVA test subject invariably becomes more familiar with the characteristics of the hardware, and learns how to work more effectively with it. This learning process can manifest itself in reduced fatigue, increased proficiency, and a significant improvement in the perceived "EVA-compatibility" of the hardware. Thus, it is important to allow adequate time for training of the EVA subjects before critical evaluations are made of procedures and hardware. In the present tests, both test subjects felt that their skills had developed and their performance had virtually peaked by the end of Build 2. Therefore, conclusions based on the data from Build 3 are considered to be realistic and representative of the performance that could be expected out of a well-trained EVA crew.

Breakdown of Reflector Assembly Task Times

Figure 23 presents the total time for each build and the predicted time broken down into the following five major task groups: 1) strut/node canister replacement (replacement by scuba divers of an empty canister with a full canister--performed four times per Build); 2) panel attachment (removal by test subjects of a panel from the panel canister and attachment to three truss nodes--performed seven times per Build); 3) positioning for panel attachment (reorientation and translation of test subjects' foot restraints and RMS maneuvering of the panel canister to within the reach envelope of the test subjects); 4) truss assembly (installation of struts and nodes by the reclined test subject); and 5) positioning for truss assembly (translation of test subjects' foot restraints and translation and rotation of assembly fixture turnstile). Since Build 1 was terminated after assembly of only 277 truss struts, the truss assembly times in fig. 23 are extrapolations of the actual times to times for assembly of the complete truss.

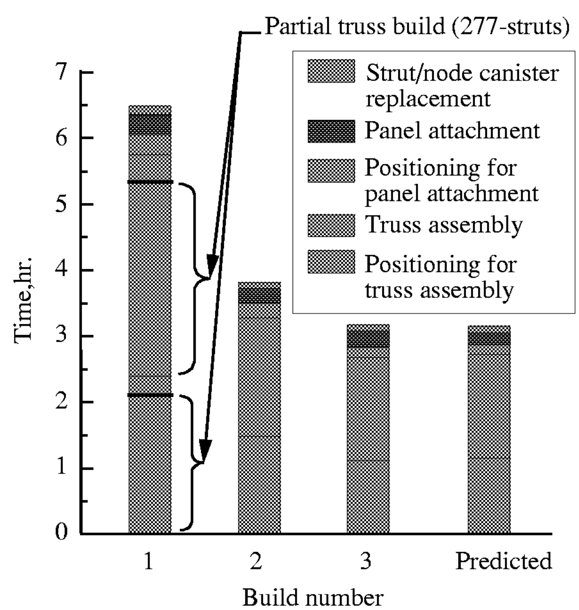


Figure 23. Breakdown of task times for assembly of 14-m reflector (only seven reflector panels).

Similar to fig. 22, fig. 23 clearly illustrates that significant improvement in assembly and positioning times was realized after thorough training. Furthermore, this training resulted in excellent agreement between the actual times measured during Build 3 and the times predicted from previous EVA truss assembly experience. The positioning time for truss assembly measured between 41 and 45% of the total truss assembly time for all builds as compared to the predicted value of 42%. This indicates that, as training progressed, foot restraint positioning and truss assembly times improved at about the same rate. Although, not as dramatic, some improvement can also be seen in both the time required to maneuver into position for panel attachment and the time to attach the panels.

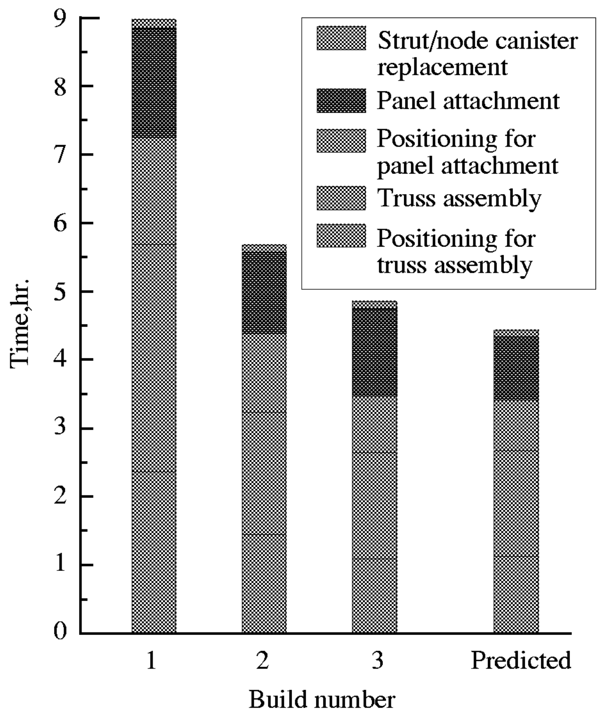


Figure 24. Projection of task times for assembly of 14-m reflector with all 37 panels.

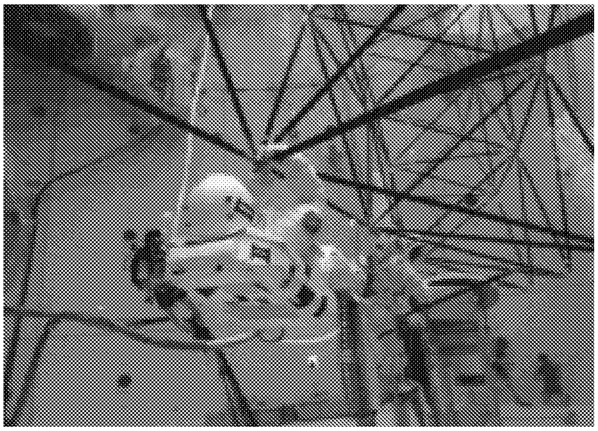
The panel attachment task times from Build 3 appear to be in good agreement with predictions. However, since only seven panels were attached, the discrepancies are not obvious in the scale shown. In fact, the panel attachment task in Build 3 actually took about 37% longer than predicted while panel positioning took 12.5% longer. However, the panel attachment task time predictions were based on little historical data, thus it is not surprising that discrepancies exist. This discrepancy between the Build 3 and the predicted panel attachment times is more clearly shown in fig. 24 where the times to assemble the complete reflector and install all 37 reflector panels are projected from the data in fig. 23. Nevertheless, these data indicate that a complete reflector could be assembled by two astronauts in EVA in less than 5 hours! *Hence, it is reasonable to predict that a 14m-diameter reflector like this could be assembled on-orbit in one EVA!*

Qualitative Assessments of Reflector Assembly Procedure

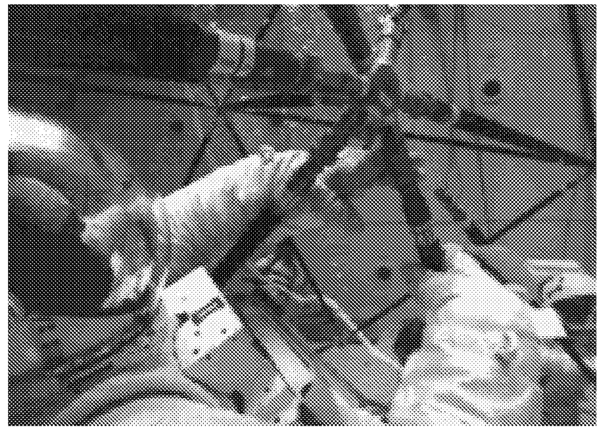
General. The multiple tests executed by the engineer test subjects during Builds 1 and 2 afforded them enough training time to refine their techniques and assemble the reflector within the predicted time estimates. During Build 3, the division of tasks was found to be very equitable resulting in essentially no idle time for either test subject except during RMS maneuvering of the panel canisters. The upright test subject had no difficulty seeing, reaching, unstowing, or passing the hardware components, and both test subjects found the assembly procedure simple to learn. The reclined subject felt that having the upright subject unstow and pass the struts and nodes to him, conserved his energy and was also beneficial in allowing him to concentrate solely on making the structural connections. Both subjects agreed that requiring every piece of hardware to be handled by each of them virtually eliminates the risk of assembling components out of order or in the wrong location, and indeed this never occurred during the present tests.

The most challenging aspect of the truss assembly tasks executed by the reclined test subject was making all strut attachments at a given node from a single foot restraint position. This practice was adopted to decrease assembly times by eliminating unnecessary repositioning of the foot restraints. However, it required the reclined test subject to make many strut-to-node attachments in locations or at orientations which precluded him from applying a firm palm grip to the joint locking collar (see fig. 25). During the first six tests, the reclined test subjects experimented with the height of the test article above the foot restraints and their body position relative to the reflector to determine the least fatiguing and fastest technique for constructing the reflector. By the end of Build 2, the test subjects and the control station operator had learned the most efficient techniques and foot restraint positions for each task. Consequently, the assembly times for Build 3 were significantly lower than the previous builds and these times agreed well with the predicted values.

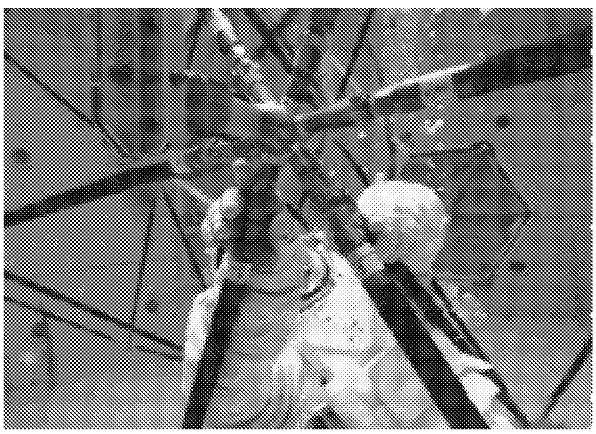
In general, the reflector panels were attached quickly with few difficulties encountered. The moderate physical exertion required was judged by the test subjects to result, primarily, from overcoming the water resistance of the panels. The EVA handles provided on the back of the panels enabled the test subjects to use only one hand to maneuver the panels onto the guides located on the truss nodes. The spring-loaded capture feature of the panel-to-truss attachment joints provided a quick, and easily made, interim connection to the truss. Often, as the test subjects aligned two corners of the panel and drew the panel in along the capture guides, all three corners would capture simultaneously. Finally, the locking handles were easily rotated to the locked position to effect the final structural connection.



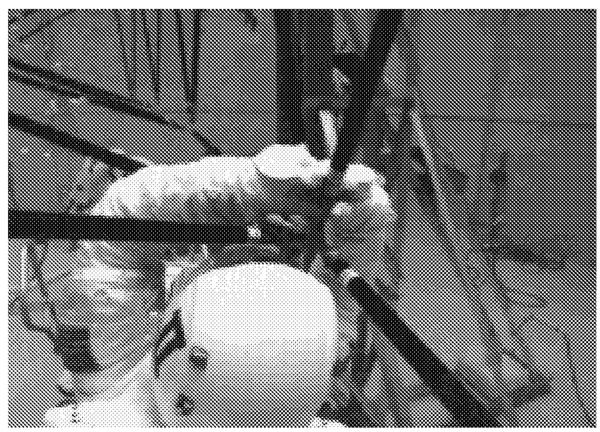
(a) Test subject's chest is positioned about one ft. below the node for optimal reach and visibility during truss assembly.



(b) Reaching a strut with two hands for efficient alignment and capture is occasionally difficult due to interference between the suit and the truss.



(c) Occasionally, reach and vision limitations dictate a single-handed strut alignment and capture.



(d) Although it is easier to lock a joint using a firm palm grip, the joint can be locked using two fingers if necessary.

Figure 25. Test subject position and orientation is selected to minimize reach and visibility limitations.

There were only two significant sources of time delays during panel attachment operations. One was the slow translation rate of the RMS caused by the water resistance during positioning of the panel canister. The other was a restriction on the test subjects' vertical translation rate, imposed by underwater diving rules for safety reasons. The panel attachment procedure required one test subject to exit his foot restraints and ascend to lock the third panel corner to a node and then descend back to the foot restraints. Although this was a simple task to execute, the speed of ascent and descent were restricted to eliminate pressure spikes in the EVA pressure suit.

Although all tasks required of the control station operator and the upright test subject are as important to the efficiency of the assembly procedure as those required of the reclined test subject, their tasks were simpler and less physically demanding than those of the reclined test subject. Therefore, the rate of improvement in assembly times during Builds 1 and 2 was primarily determined by the rate at which the reclined test subject learned his tasks. Furthermore the rate of execution of the assembly procedure during Build 3 was primarily determined by the rate at which the reclined test subject executed his tasks, despite the fact that both test subjects worked continuously with little idle time during this build. As stated previously, the same engineer served as the reclined test subject for all tests except test 3, during which an astronaut participated as the reclined test subject. The following specific comments reflect the views of these two reclined test subjects:

Astronaut test subject. 1. Vernier positioning of the foot restraints and the truss is time consuming and should be avoided. Following coarse positioning, the test subject should use the flexibility of his body to make the necessary fine adjustments for strut attachment.

2. Experience both on orbit and in neutral buoyancy has proven that the dexterity of the EVA crew member is improved and the onset of fatigue delayed with a tight fitting space suit (extravehicular mobility unit (EMU)). The hard upper torso (HUT) and the gloves should be very close fitting, and that the arm length should be adjusted to keep the astronaut's fingertips touching the glove fingertips.

3. Working upright in neutral buoyancy tests is probably the preferred orientation, and working in front of, as well as behind the truss probably affords a less obstructed work site. *[Author's note: It was considered impractical to construct the test article with both test subjects upright, because the Neutral Buoyancy Simulator is not deep enough to orient the foot restraint trolley and track vertically instead of horizontally. Also during the first four tests, departures were made from the original assembly procedure to evaluate working in front of as well as behind the truss. However it was found that any advantages gained by a less obstructed work site were offset by extra time spent in additional foot restraint positioning.]*

4. The node spacing of the test article truss (approximately two meters) provides adequate room for the astronaut in a free-floating mode to maneuver through the truss if necessary.

5. Strut alignment is generally easy. The preferable orientation of the joint-halves would allow strut entry from the node side facing away from the test subject. This makes it easier to place the strut end into the receptacle and pull into place with the thumb and forefinger.

6. In many instances, the strut joint-half locking collar is hard to grasp with a palm grip and the joint must be locked using only the fingertips. This problem results from crowding at the node by adjacent struts, and could be relieved by a longer locking collar on the strut joint-half.

7. Assembling a full ring of truss before attaching a full ring of panels may be beneficial because it would reduce the number of times foot restraints would be repositioned.

Engineer test subject. 1. The hardware numbering scheme and labels (see figs. 5 and 14) were easily visible throughout the test, precluded misplacement of any hardware, and facilitated easy memorization of the assembly procedure – eliminating the need for verbal prompting of the assembly steps.

2. The reclined test subject can significantly improve assembly times with little added fatigue by allowing foot restraint positioning errors of ±30 to ±60 cm and manually compensating for these errors with upper body positioning using leg and lower torso muscles.

3. The strut-to-node capture feature is indispensable for this type of assembly activity. It allows single-handed alignment and capture of the struts, thus extending the test subject's functional reach envelope, and enabling him to make connections which would otherwise be impossible without foot restraint repositioning. However, aligning and capturing a strut with one hand is usually more fatiguing and time-consuming than two-handed techniques and should only be used when reach restrictions dictate. The least fatiguing and most time-efficient alignment and capture technique requires the thumb and forefinger of one hand to apply a light closing force to the joint halves while the other hand effects final strut alignment with a very light grip. Alternatively if reach is slightly limited, a single thumb or finger tip pressing against the strut joint-half can be nearly as effective for capturing the joint-halves.

4. Although it is probably preferable to work upright in neutral buoyancy whenever possible, test subjects can work effectively from a reclined position if they have a close fitting HUT and suit arms.

5. The strut joint locking collars were often inadvertently knocked out of the capture position during strut manipulation. Hence, a stronger detent should be designed into the joint to avoid this problem.

6. Difficult strut connections, which are often encountered when many struts are being connected to a single node, are the most significant source of test subject fatigue. Significant training and practice is required for the test subject to learn the most efficient body positions for making multiple strut-to-node connections at a given node. However, extending the length of the strut-to-node joint locking collars would probably simplify this task and reduce training times.

Qualitative Assessments of Damaged Reflector Panel Removal and Replacement

An additional goal of the present tests is to verify that EVA astronauts can remove and replace a damaged reflector panel if they are provided with a tool that accurately maintains panel alignment during removal and replacement. One concept for such a tool was presented in fig. 15 and evaluated during tests 5 and 9 after the reflector assembly had been completed. The removal and replacement procedure outlined in fig. 17 was executed three times on the center panel (panel 4 in fig. 5(a)) of the seven-panel cluster. These tests verified that an interior panel in a segmented reflector could be removed and replaced in a reasonable time with one test subject free floating and one test subject positioned in a mobile foot restraint (the RMS MFR). The two engineer test subjects performed all panel removal tests. Unlike the reflector assembly tests, the engineer test subjects interchanged positions during the panel removal tests to allow both to evaluate all panel removal tasks.

1. Positioning and operating the panel removal tool behind the damaged panel was challenging for the free-floating test subject to perform unaided. Due to its size, the tool was difficult for the free-floating test subject to manipulate efficiently inside of the reflector support truss. Therefore, the test subject in the MFR was positioned behind the reflector at the beginning of the activity to aid the free-floating test subject in positioning the tool. Once the tool was aligned and positioned for attachment to the damaged panel, it was relatively easy for the free-floating test subject to attach the tool guide pole to the fitting on the back of the panel.

2. The remaining tasks required to align and attach the tool sliding hub assembly to the reflector support truss, and to release the damaged panel from the truss, were accomplished with little difficulty by the free-floating test subject. Sliding the damaged reflector panel away from the reflector surface using the guide pole was difficult for the free-floating test subject due to the substantial amount of water drag induced by the panel as it was moved. Nevertheless, it was judged that this task would be easily accomplished on-orbit in the absence of water drag.

3. The test subject in the MFR easily removed the panel from the tool by separating the main shaft of the guide pole from the guide pole extension while the free-floating test subject actuated the release latch on the back of the guide pole extension. Due to the fact that the panel and guide pole were neutrally buoyant, the test subject on the MFR also had no trouble manipulating the removed panel other than difficulties associated with the excessive water drag on the panel.

4. The only significant problem encountered at any point during the removal and replacement procedure was the reattachment of the main shaft of the guide pole (with the replacement panel installed) to the guide pole extension (which was still in the sliding hub assembly of the tool). This interface incorporated a pip pin that was difficult for the test subject on the MFR to accurately align due to limited visibility. Nevertheless, the test subjects agreed that this problem could be easily resolved in a flight version of the removal tool by incorporating a tapered mechanism which would aid the EVA astronaut in affecting final alignment and capture of the two guide pole halves.

5. Of great significance it was found that, with the replacement panel reattached, the tool provided adequate alignment to preclude any significant contact between the replacement panel and adjacent panels as the replacement panel was drawn into position on the reflector surface by the free-floating test subject.

6. Finally, although positioning and operating the panel-replacement tool would be easier from foot restraints, it was generally felt that these tasks were easy enough to accomplish while free-floating inside the reflector structure. This conclusion is further reinforced by the observation that replacement of a damaged panel is a contingency operation that would be performed only infrequently, thus the efficiency with which the operation can be carried out may not be of paramount importance.

Conclusions

A procedure that enables astronauts in EVA to perform efficient on-orbit assembly of large, truss-supported, segmented, reflectors is presented. The procedure and associated hardware are verified in simulated 0*g* (neutral buoyancy) assembly tests of a 14m-diameter reflector test article. The test article includes a doubly curved tetrahedral truss consisting of 315 struts and 84 nodes, supporting a reflective surface. The complete reflective surface would consist of 37 hexagonal panels, but only seven panels were fabricated for use in these tests.

The test article was built three times over the course of nine simulated EVA's. Each simulated EVA was planned for a duration of approximately three hours, but several were cut short due to complications. Engineer test subjects performed all but the third EVA simulation. To streamline the learning process, each engineer test subject learned and executed only the tasks for one of the EVA crew positions (i.e., the engineer test subjects did not interchange roles during the test series). During the third test an astronaut served as the test subject who performed all the structural connections. Procedures and a tool for the removal and replacement of a damaged panel were qualitatively evaluated during two of the neutral-buoyancy tests. The following conclusions can be drawn:

1. These data indicate that it is reasonable for two astronauts to assemble a 14m, truss-supported, segmented reflector on-orbit in ONLY ONE EVA!

2. Relatively simple mechanical crew aids and properly designed structural hardware reduce EVA crew members' work loads to an acceptable level enabling a rapid and reliable method for on-orbit assembly of precision reflectors and taking advantage of the dexterity, adaptability, and flexibility available only with human involvement. Furthermore, mechanically assisted EVA requires no new, high-risk, technology development. Thus, these operations are not only efficient, but also technically less risky than automated operations.

3. By simplifying the reflector assembly procedure to a repetition of a few basic operations, which are easily memorized, and including easily identifiable numbers on all hardware components, it is possible to virtually eliminate the need for prompting the astronauts. Not only does this approach streamline the procedure by minimizing idle time, but it also has the additional benefit of increasing the likelihood that all steps will be executed in the proper order since simplicity implies reliability.

4. Learning the assembly procedure involves not only learning the assembly sequence, but also learning the most efficient body position and technique to use in executing each task in the sequence. Although, the assembly sequence was easily memorized without neutral buoyancy training, efficient techniques and body positions could be learned only after considerable practice and training during neutral buoyancy testing.

5. The excellent agreement between the predicted assembly time and the test assembly time from Build 3 demonstrates that the assembly procedure is EVA compatible and task times (after the test subjects were well-trained) can be reliably predicted.

6. The significant drop in assembly times and test subject fatigue from Build 1 to Build 3, and the corresponding improvement in perceived EVA-compatibility of the hardware, demonstrates the importance of training EVA test subjects adequately before conducting procedure and hardware evaluations.

7. Although the strut-to-node connections were made in the predicted time, awkward hand positions were sometimes required to rotate the locking collars to complete the structural connections. It was generally agreed that the length of the locking collars should be extended so that they may be more easily grasped without interference from surrounding structure.

8. The strut-to-node capture feature is convenient for making all attachments and indispensable in allowing the test subjects to use one hand to attach struts in hard-to-reach locations. However, the locking collar detent was inadequate for maintaining the capture position and should be modified or redesigned.

9. The spring-loaded capture feature of the panel-to-truss attachment joints provided a quick and easily made interim connection to the truss. Often, as the test subjects aligned two corners of the panel and drew the panel in along the capture guides, all three corners would capture simultaneously. The locking handles were easily rotated to the locked position to effect the final structural connection. In general, the panels were attached quickly with few difficulties encountered.

10. The panel removal and replacement tool was relatively easy to operate while free floating, and it provided adequate alignment to preclude any significant contact between the replacement panel and adjacent panels as the replacement panel was drawn into position on the reflector surface.

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August, 21 2000

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Table I. Pre-Test Estimates for Completion Times of Reflector Assembly Tasks

Task	Estimated completion time
Foot Restraint and Truss Positioning Tasks	
Communicate foot restraint, truss, or RMS positioning command	5 sec
Foot restraint translation	1 ft/sec
Truss vertical translation	1 ft/sec
Truss rotation	2 deg/sec
Truss Construction Tasks	
Install node (with or without strut pre-attached)	20 sec
Install strut (one end of strut connected to pre-installed node)	10 sec
Connect free end of pre-installed strut to pre-installed node	5 sec
Replacement of strut/node canister by utility divers	100 sec
Panel Installation Tasks	
Final positioning of reflector panel canister by RMS	15 sec
Align and attach two lower panel-corner joints to the truss	40 sec
Egress foot restraint, attach upper panel-corner joint, ingress foot restraint	40 sec

Table II. Measured and Predicted Elapsed Times for Reflector Assembly

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
1	0:00:00	0:00:00	0:00:00	0:00:00
2	0:04:27	0:01:56	0:01:33	0:01:10
3	0:08:17	0:03:36	0:02:59	0:03:10
4	0:11:21	0:04:56	0:04:21	0:05:05
5	0:14:40	0:06:32	0:06:03	0:06:41
6	0:16:34	0:07:44	0:07:00	0:08:31
7	0:22:37	0:08:41	0:07:57	0:10:16
8	0:24:49	0:09:58	0:09:25	0:10:54
9	0:27:11	0:10:45	0:09:56	0:11:25
10	0:29:31	0:11:41	0:11:01	0:12:19
11	0:32:18	0:13:06	0:11:54	0:13:15
12	0:33:49	0:13:51	0:12:51	0:13:56
13	0:35:23	0:14:59	0:13:52	0:14:53
14	0:35:57	0:15:19	0:14:04	0:15:09
15	0:39:57	0:16:15	0:14:54	0:16:00
16	0:41:05	0:18:25	0:16:51	0:17:16
17	0:43:34	0:19:42	0:18:18	0:18:46
18	0:44:08	0:20:13	0:18:44	0:19:13
19	0:48:23	0:22:57	0:22:10	0:21:03
20	0:51:38	0:24:51	0:24:02	0:22:13
21	0:52:33	0:26:38	0:24:43	0:22:44
22	0:53:36	0:28:20	0:25:21	0:23:15
23	0:55:42	0:29:21	0:26:21	0:23:52
24	0:57:37	0:30:31	0:26:57	0:24:23
25	0:58:47	0:31:13	0:27:30	0:24:54
26	1:00:08	0:31:52	0:28:00	0:25:47
27	1:01:58	0:32:42	0:28:48	0:26:43
28	1:03:35	0:33:43	0:29:29	0:27:39
29	1:04:46	0:34:12	0:29:54	0:28:25
30	1:05:53	0:35:32	0:30:38	0:29:39
31	1:07:13	0:37:47	0:31:37	0:30:42
32	1:08:08	0:38:58	0:32:03	0:31:13
33	1:08:54	0:39:56	0:32:38	0:31:44
34	1:10:43	0:41:03	0:33:29	0:32:38
35	1:13:13	0:42:04	0:34:10	0:33:34
36	1:14:51	0:43:05	0:35:11	0:34:30
37	1:15:57	0:43:50	0:35:34	0:35:11
38	1:17:57	0:45:05	0:36:43	0:36:18
39	1:18:38	0:45:29	0:36:59	0:36:24
40	1:19:03	0:45:47	0:37:03	0:36:40
41	1:19:23	0:46:09	0:37:30	0:36:56
42	1:21:50	0:47:15	0:38:24	0:37:41
43	1:23:03	0:48:20	0:39:08	0:38:12
44	1:25:32	0:50:42	0:41:07	0:40:23
45	1:26:42	0:51:21	0:41:46	0:40:54
46	1:28:46	0:53:12	0:42:30	0:41:31
47	1:29:49	0:54:25	0:43:12	0:42:02
48	1:31:41	0:55:02	0:43:43	0:42:33
49	1:33:06	0:55:37	0:44:16	0:43:04
50	1:34:08	0:56:20	0:44:50	0:43:57

Table II. Continued

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
51	1:36:34	0:57:11	0:45:28	0:44:53
52	1:38:07	0:58:00	0:46:06	0:45:49
53	1:40:06	0:58:57	0:46:39	0:46:45
54	1:41:55	0:59:30	0:47:09	0:47:31
55	1:43:20	1:00:29	0:48:18	0:48:36
56	1:45:47	1:01:55	0:49:57	0:49:52
57	1:47:05	1:02:41	0:50:30	0:50:23
58	1:48:25	1:03:26	0:51:00	0:50:54
59	1:49:34	1:04:00	0:51:31	0:51:25
60	1:51:23	1:05:01	0:52:38	0:52:19
61	1:53:32	1:05:46	0:53:36	0:53:15
62	1:55:15	1:06:36	0:54:16	0:54:11
63	1:57:30	1:07:20	0:55:06	0:55:07
64	1:59:03	1:07:53	0:55:43	0:55:48
65	1:59:52	1:08:52	0:55:57	0:56:10
66	2:00:42	1:09:05	0:55:09	0:56:26
67	2:01:14	1:09:18	0:56:17	0:56:42
68	2:01:48	1:09:28	0:56:35	0:56:58
69	2:02:15	1:09:49	0:56:46	0:57:14
70	2:05:04	1:11:24	0:57:41	0:58:06
71	2:06:36	1:12:17	0:58:30	0:58:37
72	2:08:01	1:13:12	0:59:16	0:59:08
73	2:09:04	1:13:50	0:59:59	0:59:39
74	2:10:02	1:14:55	1:00:36	1:00:10
75	2:12:01	1:15:51	1:01:13	1:00:47
76	2:14:34	1:16:35	1:01:50	1:01:18
77	2:15:57	1:17:15	1:02:22	1:01:49
78	2:17:11	1:18:03	1:03:13	1:02:20
79	2:18:23	1:18:38	1:03:43	1:02:51
80	2:19:47	1:19:35	1:04:26	1:03:44
81	2:21:15	1:20:29	1:05:06	1:04:40
82	2:22:58	1:21:13	1:05:44	1:05:36
83	2:25:22	1:22:00	1:06:20	1:06:32
84	2:26:34	1:22:58	1:07:04	1:07:28
85	2:27:53	1:23:36	1:07:40	1:08:14
86	2:28:34	1:24:04	1:07:50	1:08:30
87	2:30:21	1:25:17	1:08:47	1:09:35
88	2:32:21	1:26:36	1:10:12	1:10:40
89	2:33:39	1:27:46	1:10:47	1:11:11
90	2:34:42	1:28:32	1:11:26	1:11:42
91	2:38:41	1:30:19	1:12:50	1:13:53
92	2:39:33	1:31:03	1:13:25	1:14:24
93	2:41:19	1:32:00	1:14:17	1:15:18
94	2:44:43	1:33:34	1:15:04	1:16:14
95	2:47:45	1:34:26	1:16:08	1:17:10
96	2:49:55	1:35:53	1:17:22	1:18:06
97	2:51:45	1:37:04	1:18:05	1:19:02
98	2:53:12	1:37:31	1:18:36	1:19:43
99	2:55:05	1:37:59	1:19:12	1:20:05
100	2:55:45	1:38:25	1:19:24	1:20:21

Table II. Continued

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
101	2:56:20	1:38:40	1:19:36	1:20:37
102	2:56:49	1:38:54	1:19:48	1:20:53
103	2:57:15	1:39:06	1:19:57	1:21:09
104	2:57:45	1:39:14	1:20:06	1:21:25
105	3:01:13	1:40:09	1:21:12	1:22:12
106	3:02:58	1:41:29	1:21:52	1:22:48
107	3:05:13	1:43:15	1:23:42	1:24:18
108	3:05:48	1:43:59	1:24:03	1:24:37
109	3:07:44	1:44:29	1:25:10	1:25:05
110	3:09:54	1:45:42	1:26:52	1:26:35
111	3:10:14	1:46:07	1:27:11	1:26:54
112	3:11:12	1:47:28	1:27:37	1:27:22
113	3:13:35	1:48:59	1:29:55	1:28:52
114	3:15:30	1:50:07	1:31:17	1:29:41
115	3:16:59	1:51:28	1:32:03	1:30:12
116	3:18:34	1:53:19	1:32:46	1:30:43
117	3:19:31	1:54:08	1:33:30	1:31:14
118	3:20:41	1:55:12	1:34:15	1:31:45
119	3:21:41	1:55:36	1:34:39	1:32:06
120	3:23:40	1:56:22	1:35:13	1:32:33
121	3:26:28	1:57:15	1:35:50	1:33:04
122	3:28:49	1:58:05	1:36:20	1:33:35
123	3:30:34	1:58:50	1:37:10	1:34:06
124	3:32:10	1:59:33	1:37:41	1:34:37
125	3:33:10	2:00:05	1:38:01	1:34:58
126	3:37:13	2:01:02	1:38:54	1:36:01
127	3:39:08	2:01:45	1:39:28	1:36:57
128	3:42:37	2:02:27	1:40:13	1:37:53
129	3:47:55	2:03:21	1:40:47	1:38:49
130	3:49:48	2:04:08	1:41:16	1:39:45
131	3:52:04	2:05:57	1:42:42	1:40:58
132	3:55:54	2:07:17	1:44:23	1:42:14
133	3:57:16	2:08:01	1:44:51	1:42:45
134	3:58:33	2:08:31	1:45:16	1:43:16
135	3:59:43	2:08:59	1:45:53	1:43:47
136	4:00:46	2:09:45	1:46:30	1:44:18
137	4:01:38	2:10:17	1:47:09	1:44:39
138	4:03:52	2:11:28	1:48:05	1:45:38
139	4:05:16	2:12:26	1:48:49	1:46:34
140	4:06:49	2:13:19	1:49:32	1:47:30
141	4:08:10	2:14:04	1:50:18	1:48:26
142	4:09:26	2:15:05	1:51:10	1:49:22
143	4:10:39	2:15:40	1:51:48	1:50:03
144	4:12:07	2:16:23	1:52:21	1:50:25
145	4:12:33	2:16:42	1:52:31	1:50:41
146	4:12:47	2:16:50	1:52:39	1:50:57
147	4:13:01	2:16:58	1:52:47	1:51:13
148	4:13:12	2:17:09	1:52:54	1:51:29
149	4:13:22	2:17:26	1:53:00	1:51:45
150	4:15:26	2:18:35	1:53:48	1:52:34

Table II. Continued

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
151	4:19:45	2:21:05	1:56:05	1:54:45
152	4:20:39	2:21:52	1:56:37	1:55:16
153	4:21:22	2:23:01	1:57:07	1:55:47
154	4:22:10	2:23:42	1:57:53	1:56:18
155	4:23:34	2:24:13	1:58:33	1:56:39
156	4:25:52	2:24:52	1:58:57	1:57:06
157	4:27:33	2:25:39	1:59:39	1:57:37
158	4:28:38	2:26:32	2:00:14	1:58:08
159	4:29:30	2:27:10	2:00:41	1:58:39
160	4:30:19	2:27:55	2:01:17	1:59:10
161	4:30:53	2:28:25	2:01:38	1:59:31
162	4:32:22	2:29:16	2:02:22	2:00:34
163	4:33:10	2:30:03	2:03:01	2:01:30
164	4:34:32	2:30:56	2:03:34	2:02:26
165	4:35:48	2:32:00	2:04:10	2:03:22
166	4:36:58	2:32:48	2:04:48	2:04:18
167	4:38:38	2:34:22	2:05:59	2:05:39
168	4:41:59	2:36:10	2:07:13	2:05:53
169	4:42:49	2:36:47	2:07:44	2:07:14
170	4:44:25	2:37:23	2:08:16	2:07:45
171	4:45:17	2:37:56	2:08:47	2:08:16
172	4:46:18	2:38:26	2:09:19	2:08:47
173	4:47:08	2:39:00	2:09:52	2:09:18
174	4:47:37	2:39:31	2:10:31	2:09:39
175	4:49:11	2:40:22	2:11:29	2:10:38
176	4:50:18	2:41:16	2:12:29	2:11:34
177	4:51:20	2:42:12	2:13:21	2:12:30
178	4:52:05	2:43:05	2:13:58	2:13:26
179	4:53:11	2:43:51	2:14:43	2:14:22
180	4:54:34	2:44:30	2:15:19	2:15:08
181	4:54:55	2:45:03	2:15:48	2:15:30
182	4:55:34	2:45:17	2:16:00	2:15:46
183	4:55:46	2:45:26	2:16:08	2:16:02
184	4:56:05	2:45:55	2:16:18	2:16:18
185	4:56:19	2:46:15	2:16:35	2:16:34
186	4:56:28	2:46:27	2:16:51	2:16:50
187	4:58:19	2:47:27	2:17:33	2:17:39
188	4:58:55	2:48:05	2:18:09	2:18:10
189	4:59:36	2:49:04	2:18:51	2:18:41
190	5:00:11	2:49:49	2:19:34	2:19:12
191	5:00:44	2:50:58	2:20:10	2:19:43
192	5:01:30	2:51:19	2:20:26	2:20:04
193	5:03:11	2:51:47	2:20:54	2:20:31
194	5:04:26	2:52:23	2:21:22	2:21:02
195	5:05:31	2:52:54	2:21:51	2:21:33
196	5:06:40	2:53:30	2:22:18	2:22:04
197	5:10:30	2:55:15	2:24:44	2:24:15
198	5:10:53	2:55:32	2:25:10	2:24:36
199	5:12:11	2:56:43	2:25:59	2:25:39
200	5:13:56	2:57:30	2:26:32	2:26:35

Table II. Continued

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
201	5:15:31	2:58:01	2:27:08	2:27:31
202	5:16:16	2:58:40	2:27:47	2:28:27
203	5:16:51	2:59:37	2:28:43	2:29:23
204	5:18:17	3:00:57	2:30:09	2:30:44
205	5:20:29	3:02:40	2:30:56	2:31:40
206	5:21:36	3:03:12	2:31:31	2:32:11
207	5:22:24	3:03:40	2:31:57	2:32:42
208	5:23:09	3:04:13	2:32:20	2:33:13
209	5:23:46	3:04:45	2:32:47	2:33:44
210	5:24:14	3:05:16	2:33:06	2:34:05
211	5:25:22	3:06:01	2:34:08	2:35:04
212	5:27:04	3:06:49	2:34:53	2:36:00
213	5:28:16	3:08:03	2:36:07	2:36:56
214	5:29:05	3:08:59	2:37:01	2:37:52
215	5:29:53	3:09:24	2:37:37	2:38:38
216	5:30:38	3:09:52	2:37:57	2:39:00
217	5:31:01	3:10:05	2:38:07	2:39:16
218	5:31:27	3:10:16	2:38:19	2:39:32
219	5:31:50	3:10:27	2:38:30	2:39:49
220	5:32:07	3:10:40	2:38:39	2:40:04
221	5:33:16	3:11:40	2:39:35	2:40:51
222	5:35:37	3:13:34	2:39:59	2:41:27
223	5:37:17	3:15:19	2:41:57	2:42:57
224	5:38:08	3:15:53	2:42:29	2:43:16
225	5:40:46	3:16:34	2:42:44	2:43:44
226	5:43:37	3:19:36	2:44:25	2:45:14
227		3:20:37	2:45:17	2:45:45
228		3:22:34	2:47:42	2:46:50
229		3:23:20	2:49:08	2:47:32
230		3:24:11	2:49:45	2:48:03
231		3:24:50	2:50:16	2:48:34
232		3:25:27	2:50:39	2:49:05
233		3:26:17	2:51:11	2:49:36
234		3:26:43	2:51:33	2:49:57
235		3:28:16	2:52:54	2:50:56
236		3:29:32	2:53:31	2:51:52
237		3:30:16	2:54:16	2:52:48
238		3:31:02	2:55:07	2:53:44
239		3:31:34	2:55:33	2:54:30
240		3:31:53	2:56:01	2:54:52
241		3:32:05	2:56:13	2:55:08
242		3:32:16	2:56:29	2:55:24
243		3:32:30	2:56:43	2:55:40
244		3:32:39	2:56:52	2:55:56
245		3:35:36	2:59:14	2:57:01
246		3:36:32	3:00:27	2:58:01
247		3:37:20	3:00:55	2:58:32
248		3:38:08	3:01:17	2:59:03
249		3:39:28	3:01:45	2:59:34
250		3:40:02	3:02:16	3:00:05

Table II. Concluded

	Elapsed Time (hr:min:sec)			
Step	Measured (Build 1)	Measured (Build 2)	Measured (Build 3)	Predicted
251		3:40:30	3:02:42	3:00:26
252		3:41:33	3:03:36	3:01:25
253		3:42:48	3:04:19	3:02:11
254		3:43:25	3:05:05	3:03:17
255		3:44:17	3:05:46	3:04:13
256		3:44:59	3:06:20	3:04:59
257		3:45:12	3:06:40	3:05:21
258		3:45:27	3:07:00	3:05:37
259		3:45:39	3:07:11	3:05:53
260		3:45:51	3:07:23	3:06:09
261		3:45:59	3:07:32	3:06:25

Appendix: Detailed Assembly Procedure

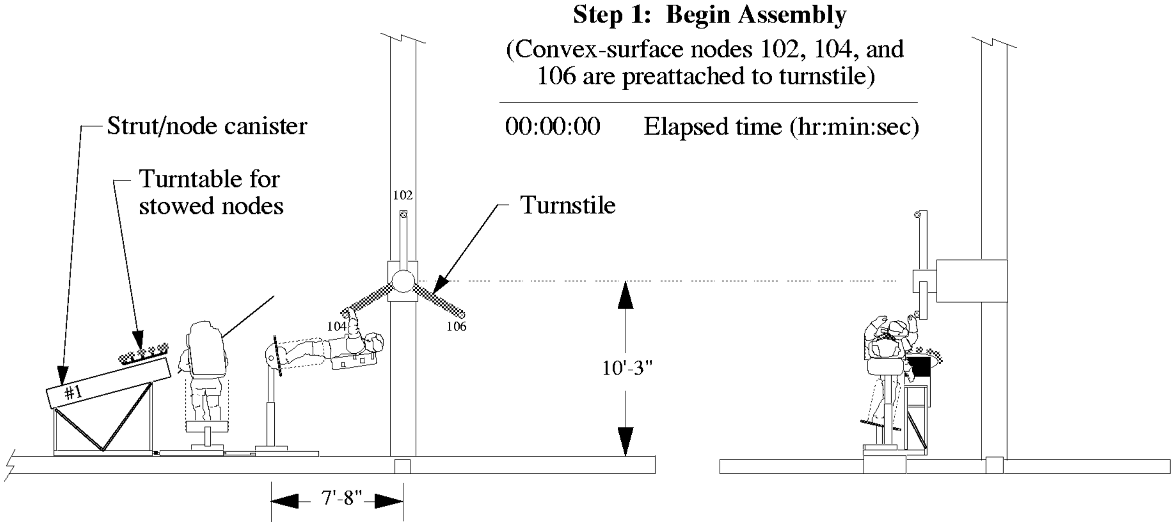
The complete reflector assembly procedure is comprised of 1,006 individual tasks, divided into the 11 general categories identified in Table I. The tasks are grouped into a series of 261 steps with successive steps separated by repositioning of either the foot restraints or the truss. A detailed computer-generated drawing was made for each step to aid in evaluating test subject and truss positioning requirements. Estimates for the completion time of each step were assembled from estimates for the completion time of each task. To illustrate this planning process the first 54 steps of the assembly procedure are detailed in fig. A-1.

The illustrations in fig. A-1 depict the test apparatus at the end of each assembly step. Also listed are the tasks performed during that step and estimates, derived from Table I, for the times to complete these tasks. Steps 1 through 7 define the assembly sequence for the center section of the reflector. Steps 8 through 30 define the assembly sequence for the first row of truss and panels. Finally, steps 31 through 54 define the assembly sequence for the second complete row of truss (panels are not included on this row). The remainder of the assembly procedure is comprised of identical steps, grouped in similar but progressively longer sequences, to assemble each ring of truss structure and install each ring of reflector panels.

Step 1: Begin Assembly

(Convex-surface nodes 102, 104, and 106 are preattached to turnstile)

00:00:00 Elapsed time (hr:min:sec)



Step 2

Time (sec)	Task
10*	Unstow 104-3
10	Install 104-3
10	Install 104-2
10	Install 104-7
10	Install 104-1
10	Install 104-9
10	Install 104-6
00:01:10	Elapsed time

*Note: 10 seconds is assumed for unstowage of the first strut, all subsequent hardware unstowage is performed in parallel with assembly tasks.

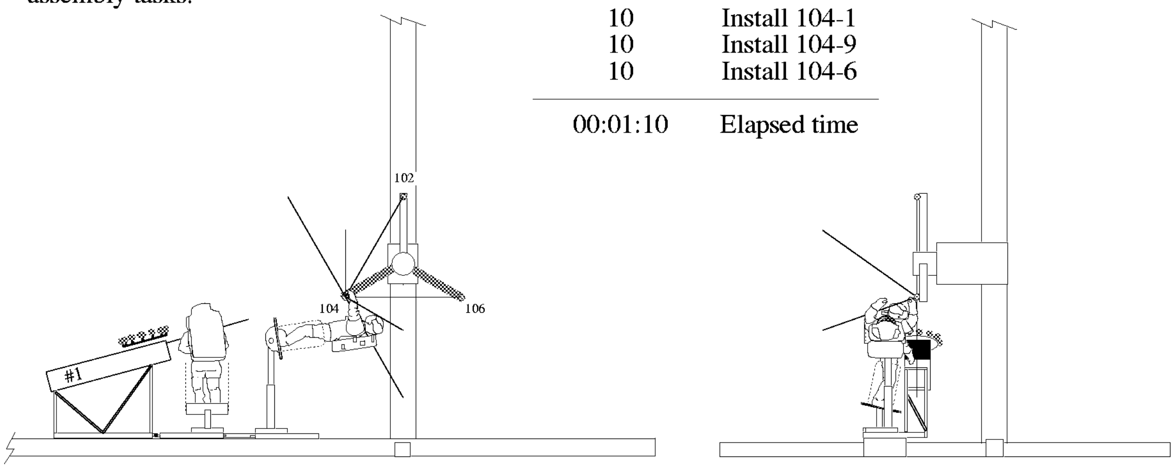
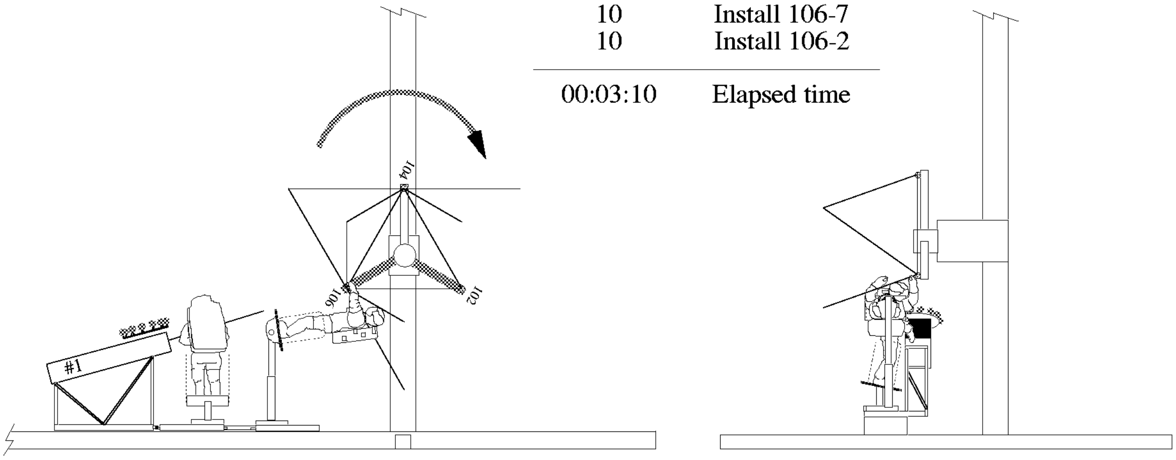


Figure A-1. Detailed reflector assembly procedure and estimated elapsed time.

Step 3

Time (sec)	Task
60+5	Rotate truss 120° (+ communicate)
5	Lock 106-4
10	Install 106-5
10	Install 106-8
10	Install 106-3
10	Install 106-7
10	Install 106-2
00:03:10	Elapsed time



Step 4

Time (sec)	Task
60+5	Rotate truss 120°
5	Lock 102-6
5	Lock 102-5
10	Install 102-1
10	Install 102-9
10	Install 102-8
10	Install 102-4
00:05:05	Elapsed time

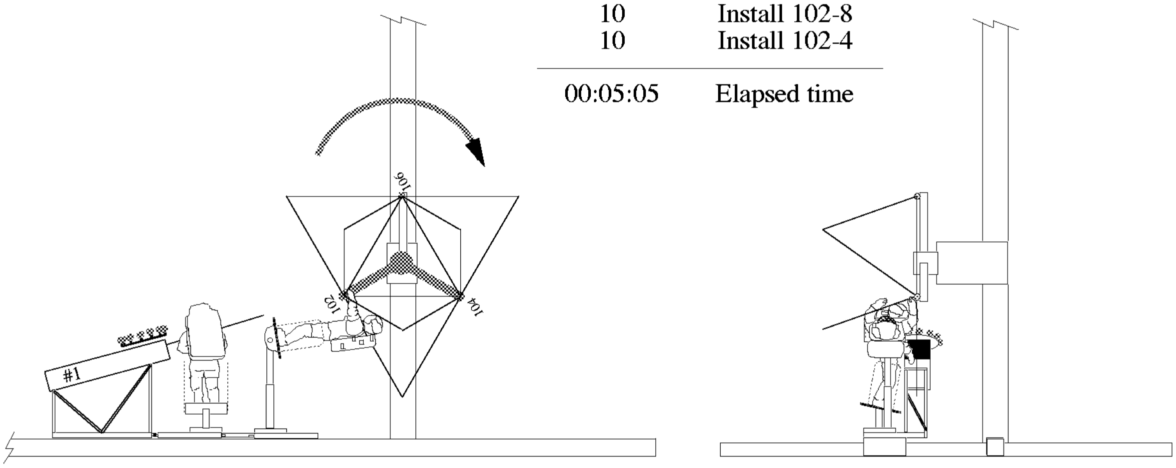
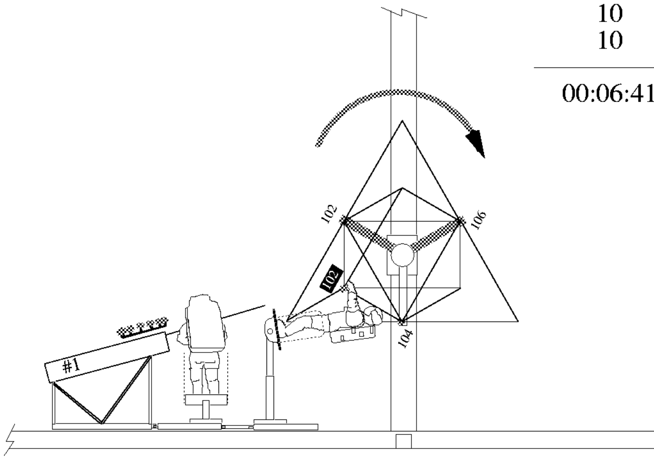
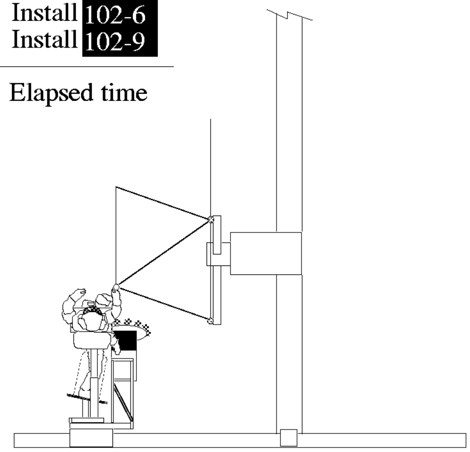


Figure A-1. Continued.

Step 5

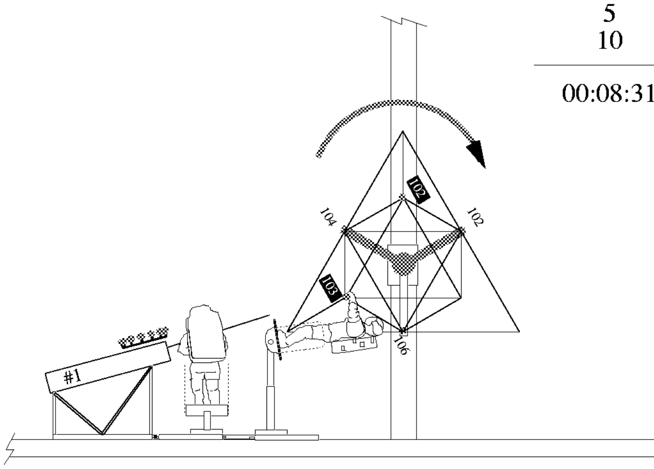
Time (sec)	Task
6+5	Move forward 2 m
30+5	Rotate truss 60°
20	Install node 102 with 102-1 attached
5	Lock 102-7
5	Lock 102-8
10	Install 102-6
10	Install 102-9
00:06:41	Elapsed time





Step 6

Time (sec)	Task
60+5	Rotate truss 120°
20	Install node 103 with 103-2 attached
5	Lock 103-9
5	Lock 103-8
5	Lock 103-3
10	Install 103-7
00:08:31	Elapsed time



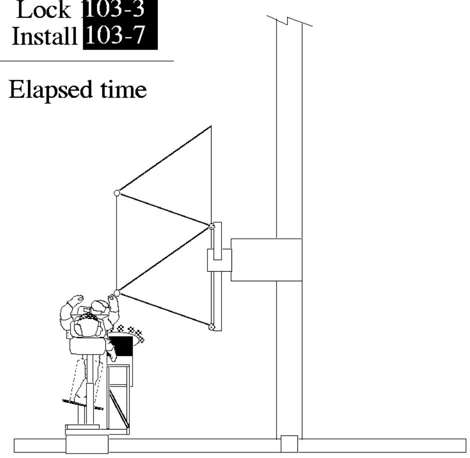
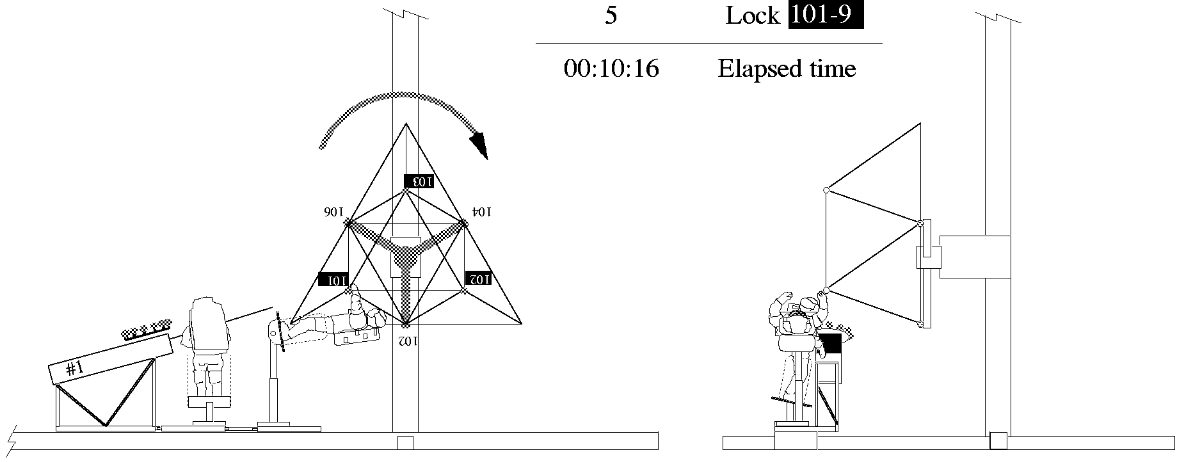


Figure A-1. Continued.

If the reflector surface was to be fully populated, one panel would be installed at the end of this step.

Step 7

Time (sec)	Task
60+5	Rotate truss 60˚
20	Install node 101 with 101-8 attached
5	Lock 101-7
5	Lock 101-5
5	Lock 101-4
5	Lock 101-9
00:10:16	Elapsed time



Step 8

Time (sec)	Task
6+5	Move right 2 m
2+5	Move back 2/3 m
10	Install 102-2
10	Install 102-3
00:10:54	Elapsed time

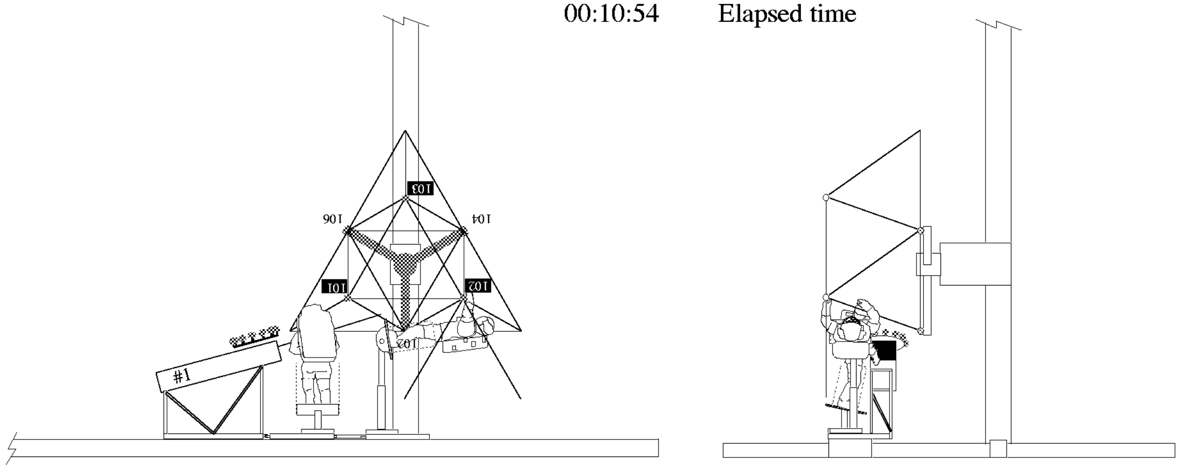
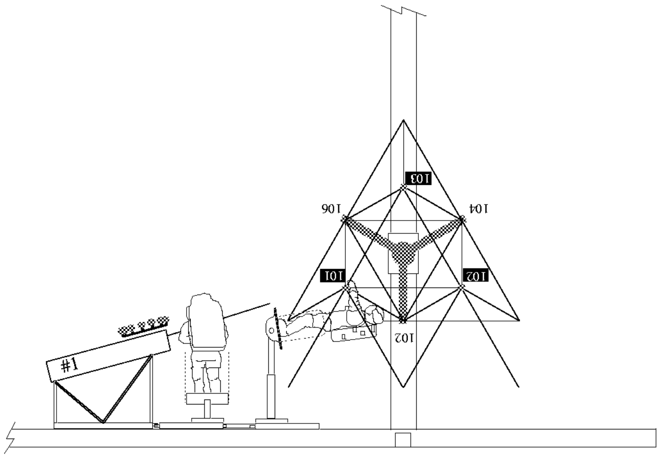
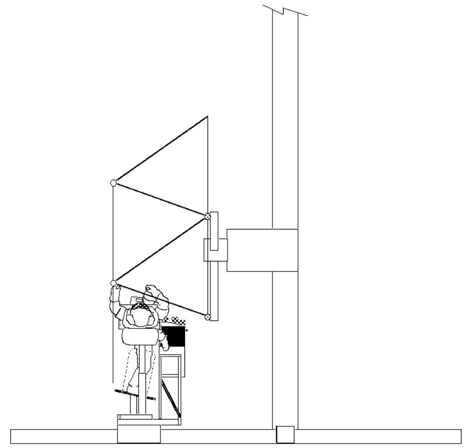


Figure A-1. Continued.

Step 9

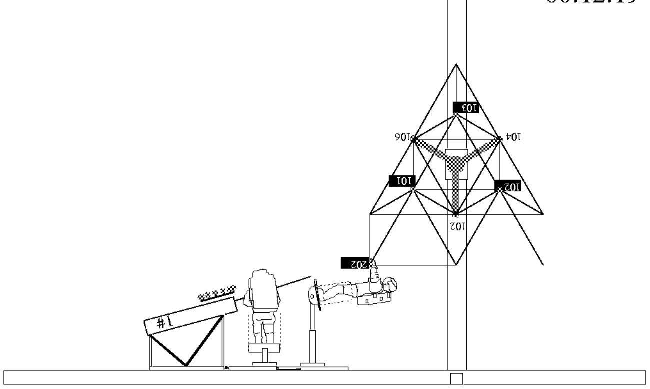
Time (sec)	Task
6+5	Move left 2 m
10	Install 101-2
10	Install 101-3
00:11:25	Elapsed time





Step 10

Time (sec)	Task
3+5	Move left 1 m
6+5	Raise truss 2 m
20	Install node 202 with 202-7 attached
5	Lock 202-5
10	Install 202-4
00:12:19	Elapsed time



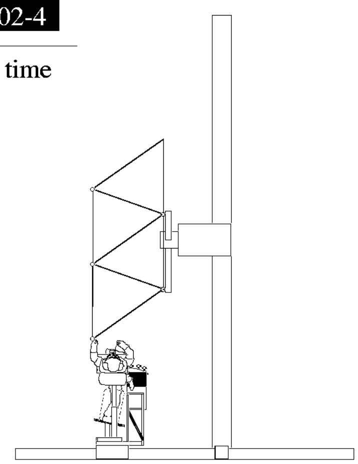
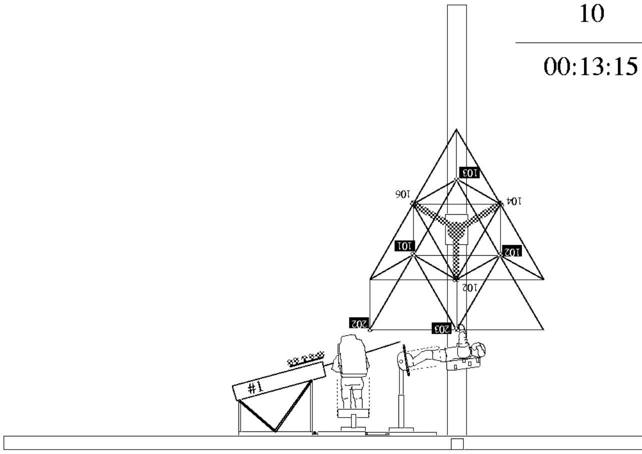
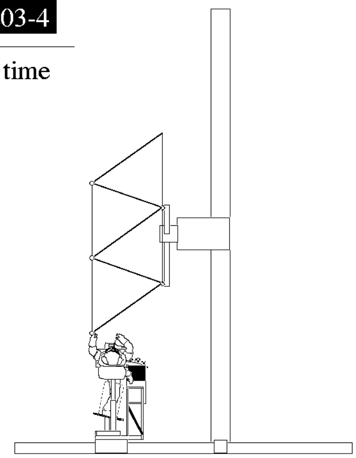


Figure A-1. Continued.

Step 11

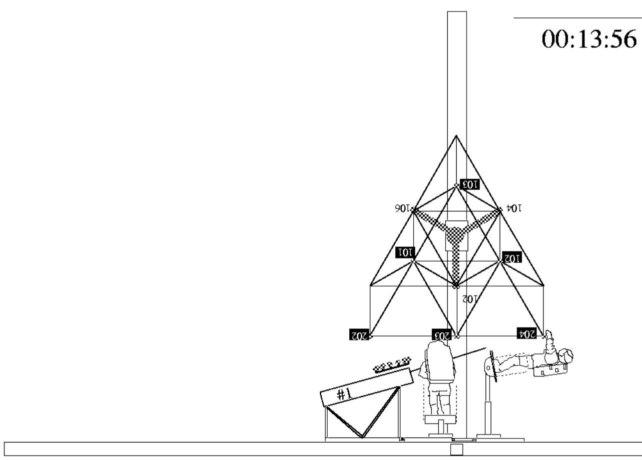
Time (sec)	Task
6+5	Move right 2 m
20	Install node 203 with 203-7 attached
5	Lock 203-1
5	Lock 203-6
5	Lock 203-5
10	Install 203-4
00:13:15	Elapsed time





Step 12

Time (sec)	Task
6+5	Move right 2 m
20	Install node 204 with 204-7 attached
5	Lock 204-1
5	Lock 204-6
00:13:56	Elapsed time



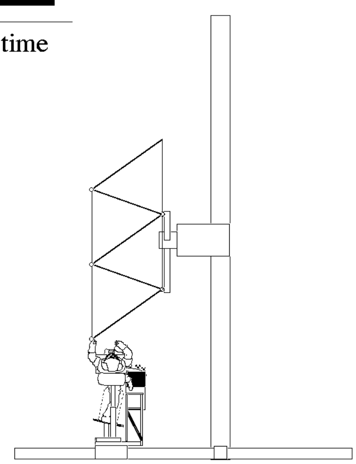
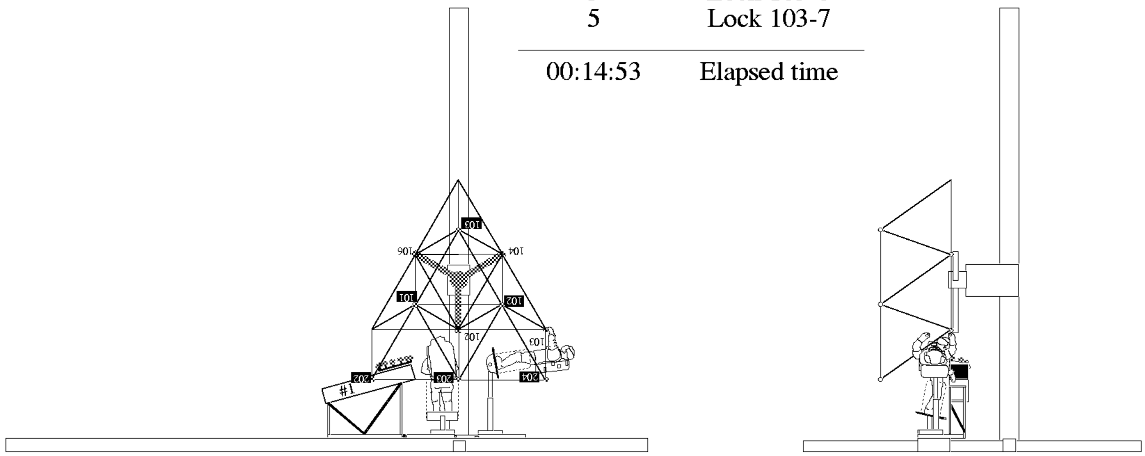


Figure A-1. Continued.

Step 13

Time (sec)	Task
3+5	Move back 1 m
4+5	Lower truss 4/3 m
20	Install node 103
5	Lock 103-1
5	Lock 103-9
5	Lock 103-6
5	Lock 103-7
00:14:53	Elapsed time



Step 14

Time (sec)	Task
6+5	Move left 2 m
5	Lock 102-7
00:15:09	Elapsed time

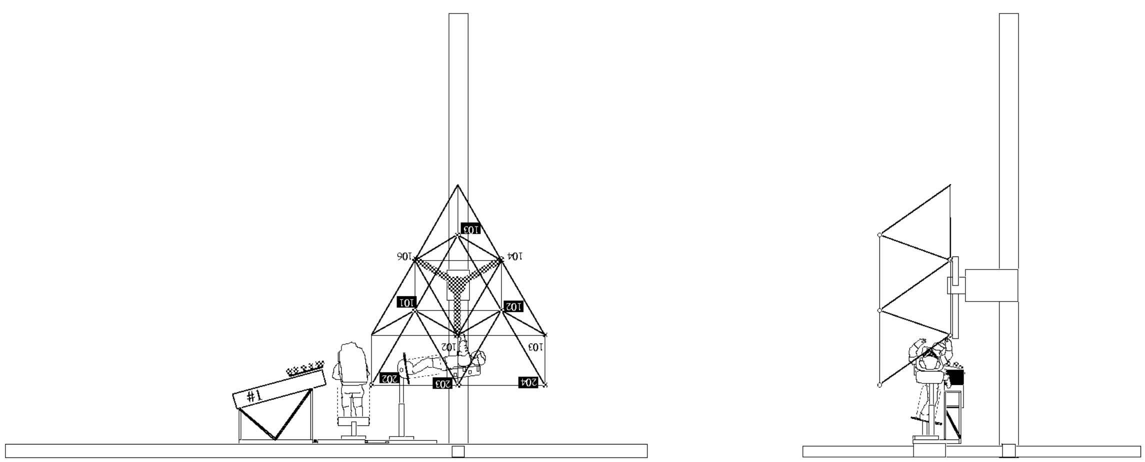
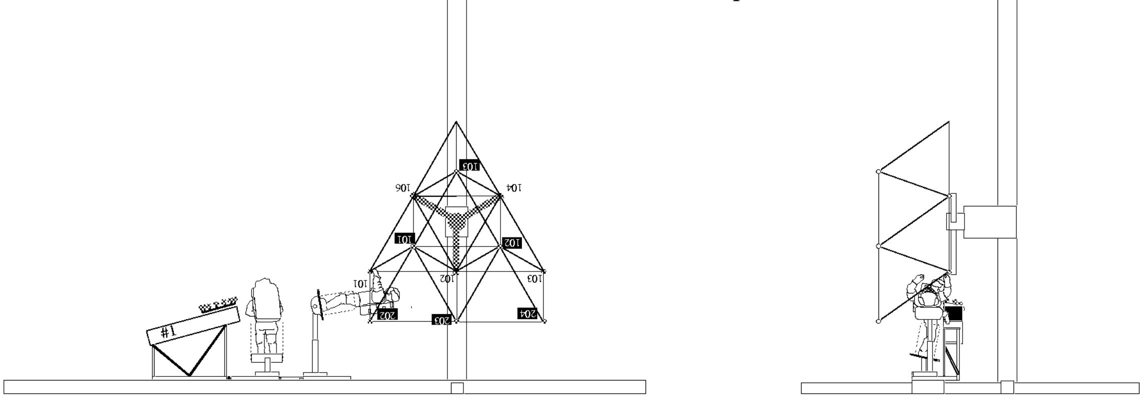


Figure A-1. Continued.

Step 15

Time (sec)	Task
6+5	Move left 2 m
20	Install node 101
5	Lock 101-5
5	Lock 101-8
5	Lock 101-7
5	Lock 101-4
00:16:00	Elapsed time



Step 16

Time (sec)	Task
6+5	Raise truss 2 m
10+5	Reorient test subjects
9+5	Move right 3 m
3+5	Lower truss 1 m
3+5	Move forward 1 m
15+5	Position panel canister with RMS
00:17:16	Elapsed time

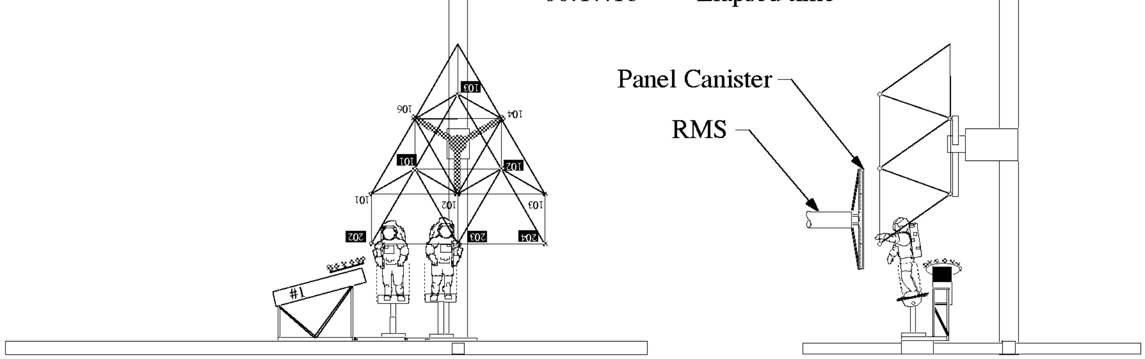
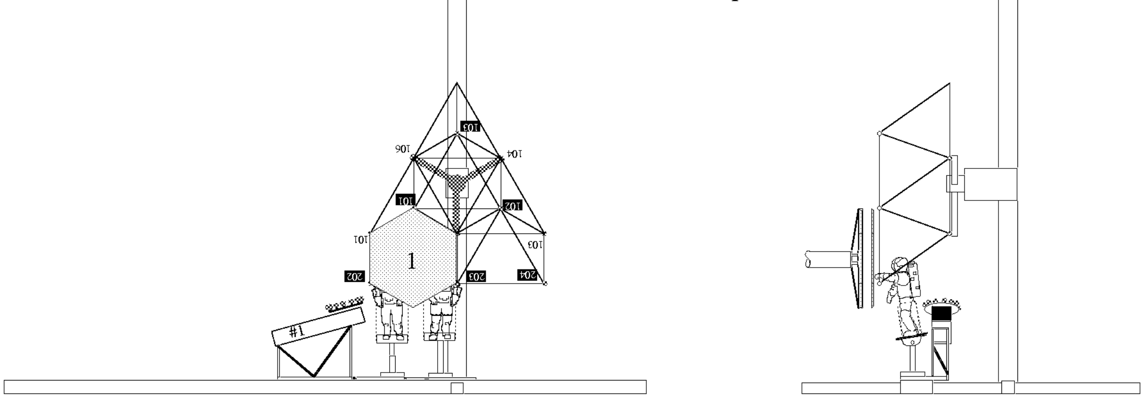


Figure A-1. Continued.

Step 17

Time (sec)	Task
10	Remove panel from canister
40	Attach panel to nodes 202 & 203
40	EV-1 attach panel to node 101 free floating
00:18:46	Elapsed time



Step 18

Time (sec)	Task
3+5	Raise truss 1 m
6+5	Move right 2 m
3+5	Lower truss 1 m
00:19:13	Elapsed time

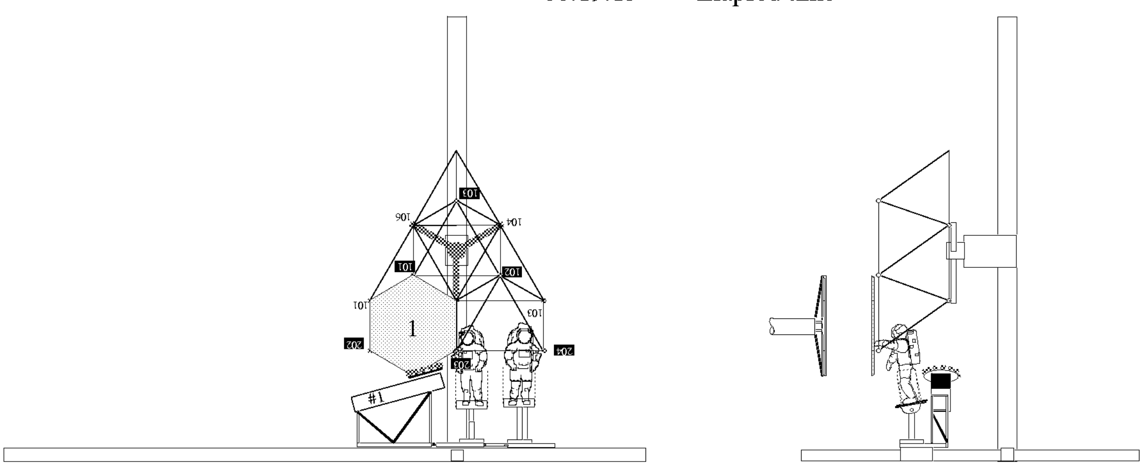
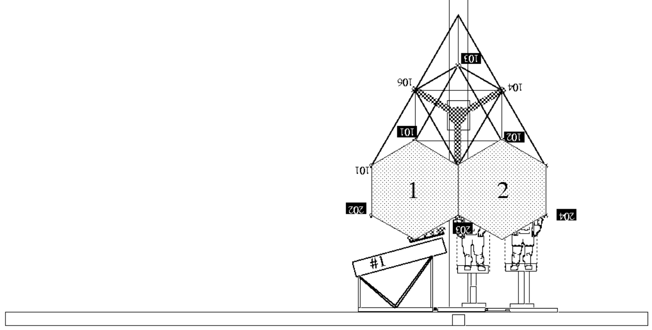
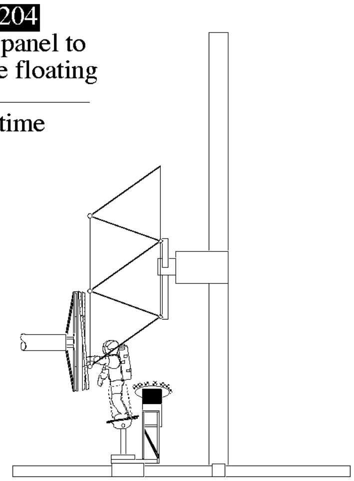


Figure A-1. Continued.

Step 19

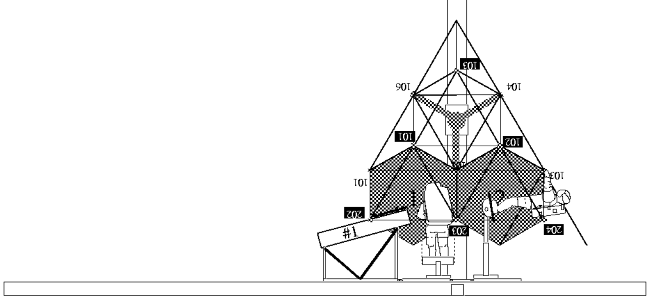
Time (sec)	Task
15+5	Position panel canister with RMS
10	Remove panel from canister
40	Attach panel to nodes 203 & 204
40	EV-1 attach panel to node 102 free floating
00:21:03	Elapsed time





Step 20

Time (sec)	Task
3+5	Raise truss 1 m
10+5	Reorient test subjects
3+5	Move left 1 m
3+5	Move back 1 m
6+5	Lower truss 2 m
10	Install 103-2
10	Install 103-3
00:22:13	Elapsed time



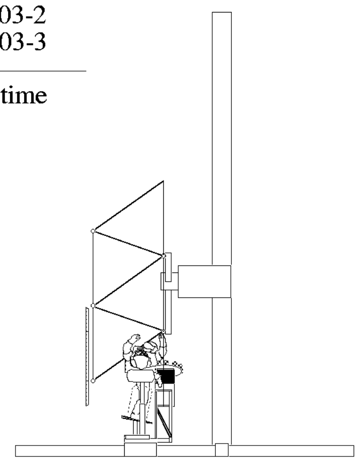
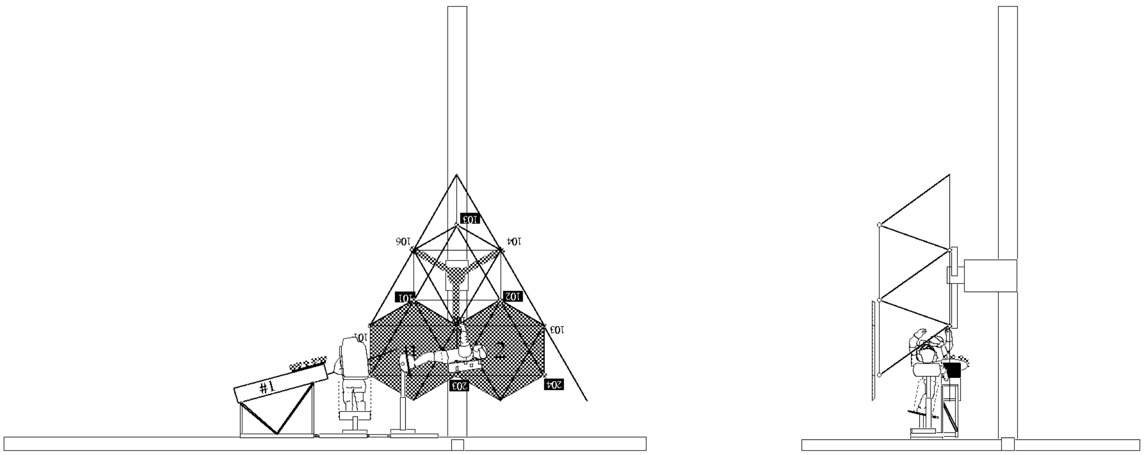


Figure A-1. Continued.

Step 21

Time (sec)	Task
6+5	Move left 2 m
10	Install 102-2
10	Install 102-3
00:22:44	Elapsed time



Step 22

Time (sec)	Task
6+5	Move left 2 m
10	Install 101-2
10	Install 101-3
00:23:15	Elapsed time

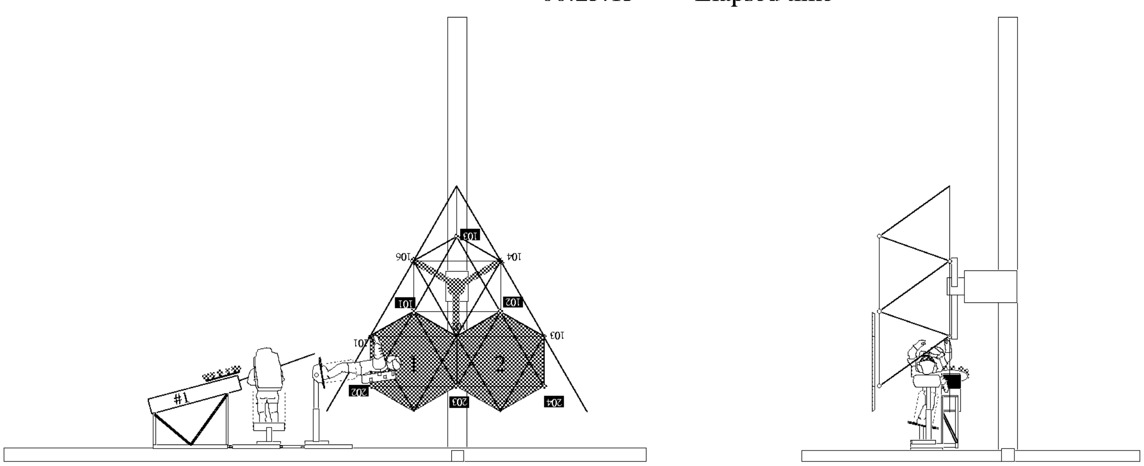
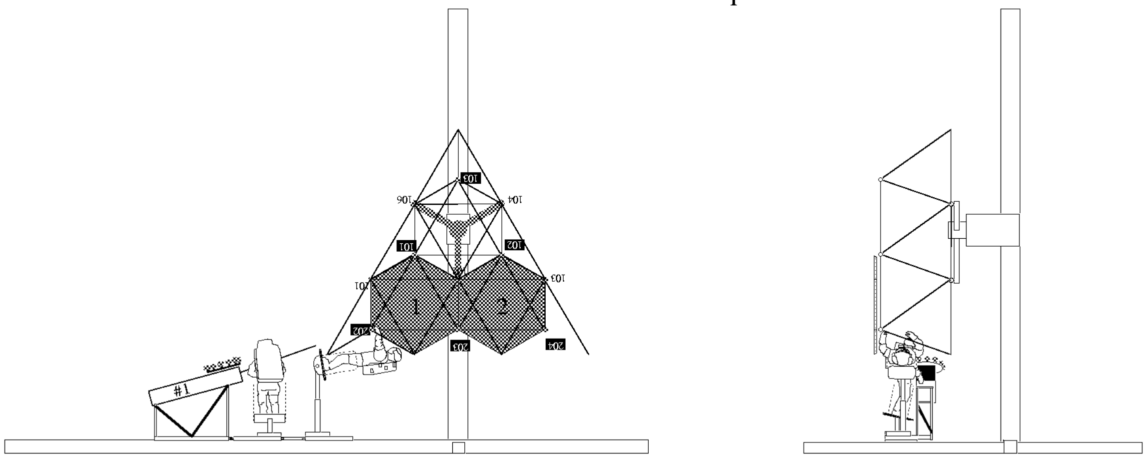


Figure A-1. Continued.

Step 23

Time (sec)	Task
4+5	Raise truss 4/3 m
3+5	Move forward 1 m
10	Install 202-8
10	Install 202-9
00:23:52	Elapsed time



Step 24

Time (sec)	Task
6+5	Move right 2 m
10	Install 203-8
10	Install 203-9
00:24:23	Elapsed time

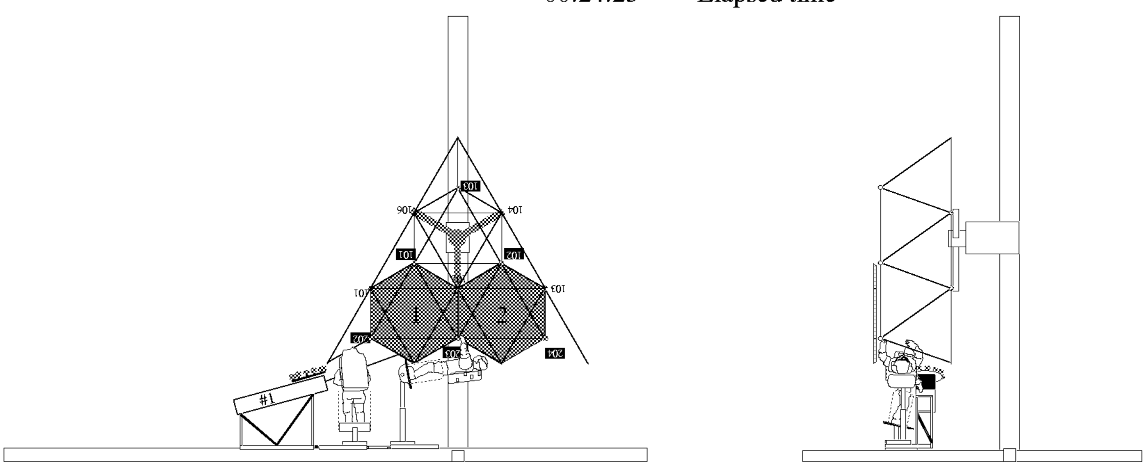
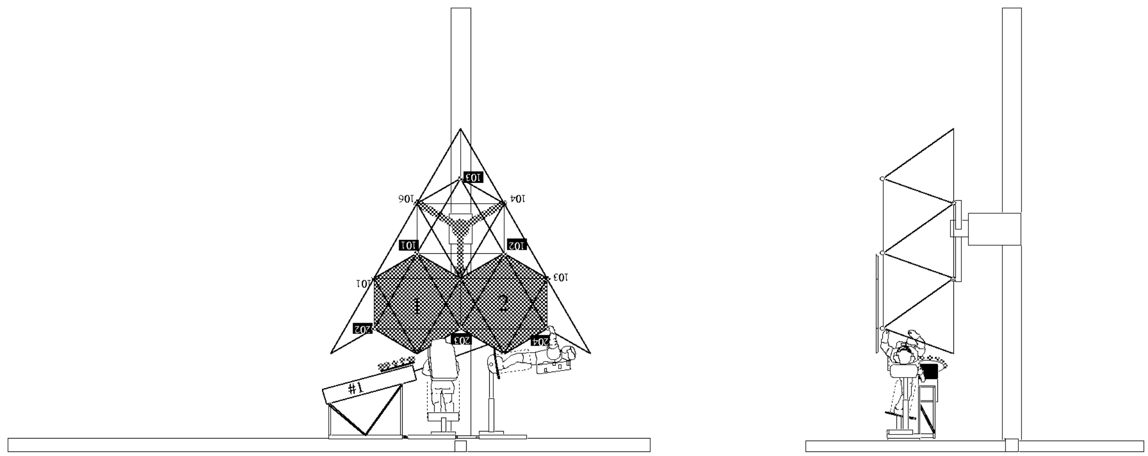


Figure A-1. Continued.

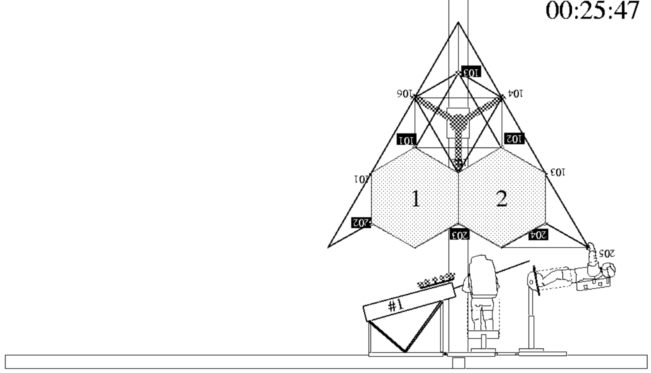
Step 25

Time (sec)	Task
6+5	Move right 2 m
10	Install 204-8
10	Install 204-9
00:24:54	Elapsed time



Step 26

Time (sec)	Task
2+5	Raise truss 2/3 m
3+5	Move right 1 m
3+5	Move back 1 m
20	Install node 205 with 205-1 attached
5	Lock 205-9
5	Lock 205-6
00:25:47	Elapsed time



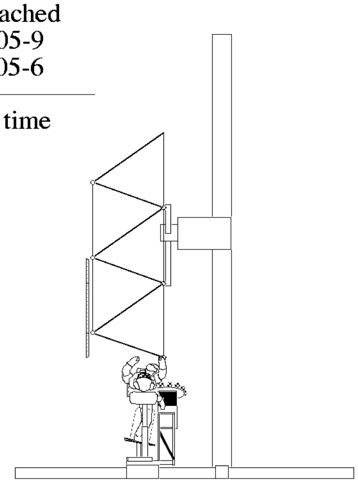
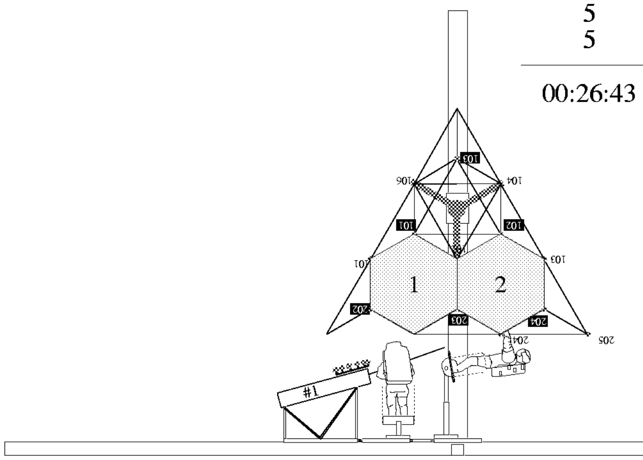
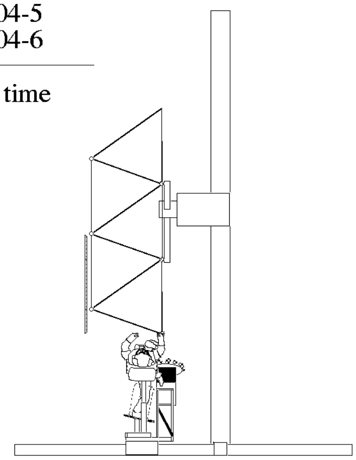


Figure A-1. Continued.

Step 27

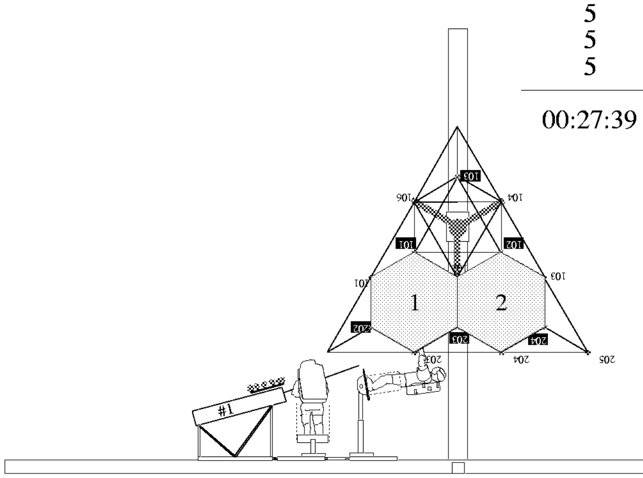
Time (sec)	Task
6+5	Move left 2 m
20	Install node 204 with 204-1 attached
5	Lock 204-9
5	Lock 204-8
5	Lock 204-4
5	Lock 204-5
5	Lock 204-6
00:26:43	Elapsed time





Step 28

Time (sec)	Task
6+5	Move left 2 m
20	Install node 203 with 203-1 attached
5	Lock 203-9
5	Lock 203-8
5	Lock 203-4
5	Lock 203-5
5	Lock 203-6
00:27:39	Elapsed time



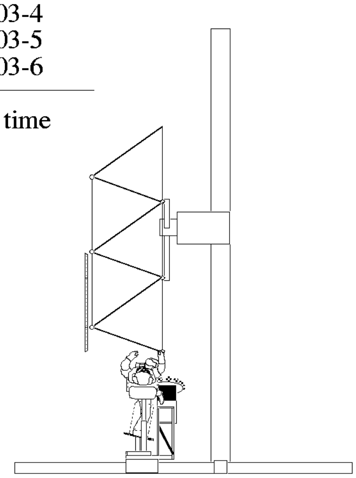
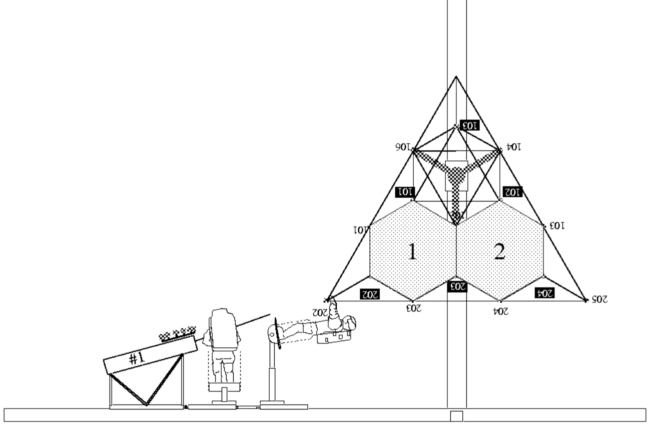
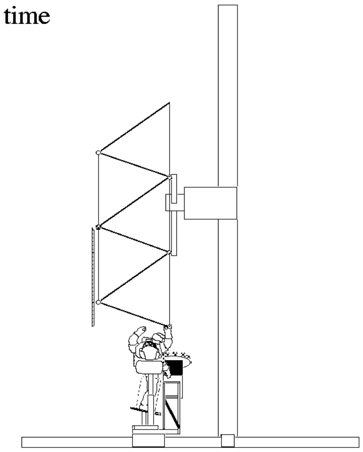


Figure A-1. Continued.

Step 29

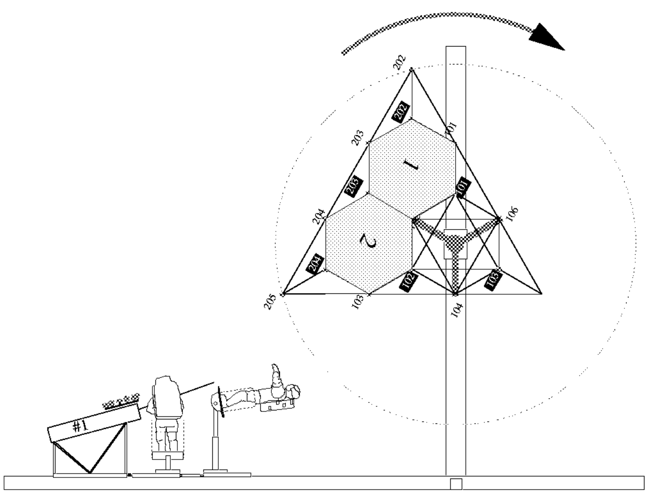
Time (sec)	Task
6+5	Move left 2 m
20	Install node 202
5	Lock 202-5
5	Lock 202-8
5	Lock 202-4
00:28:25	Elapsed time





Step 30

Time (sec)	Task
4+5	Move left 4/3 m
60+5	Rotate truss 120°
00:29:39	Elapsed time



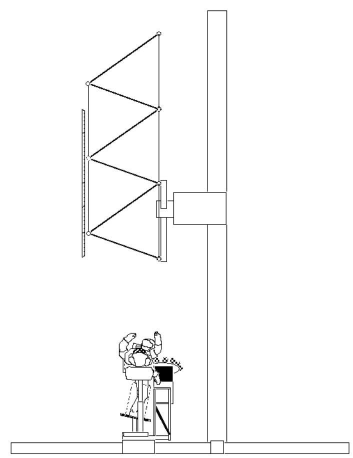
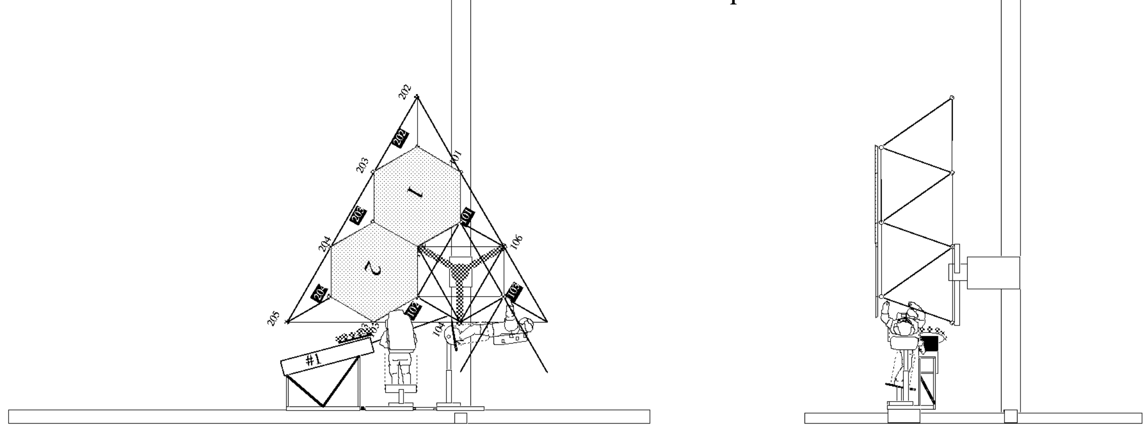


Figure A-1. Continued.

Step 31

Time (sec)	Task
3+5	Move forward 1 m
7+5	Lower truss 2 1/3 m
18+5	Move right 6 m
10	Install 103-4
10	Install 103-5
00:30:42	Elapsed time



Step 32

Time (sec)	Task
6+5	Move left 2 m
10	Install 102-4
10	Install 102-5
00:31:13	Elapsed time

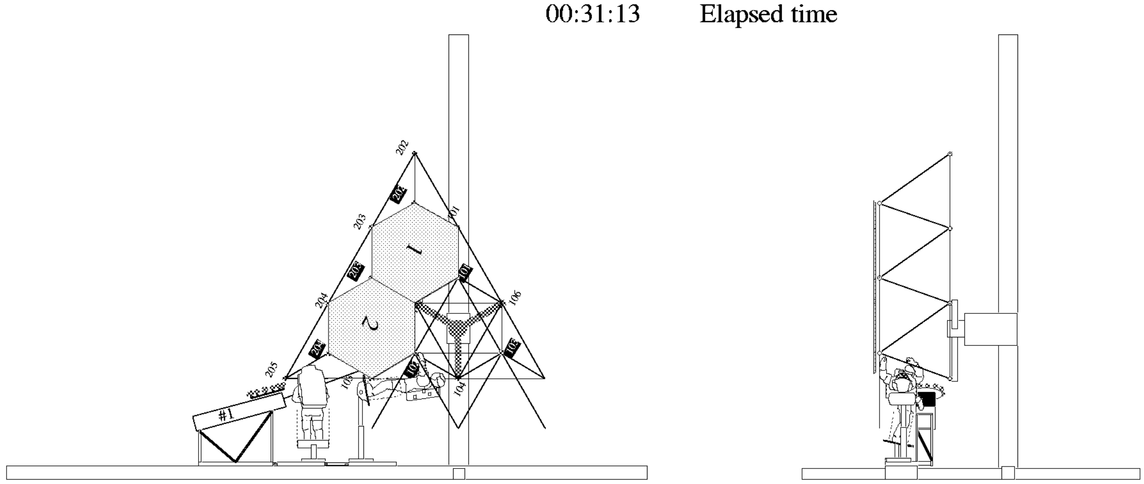
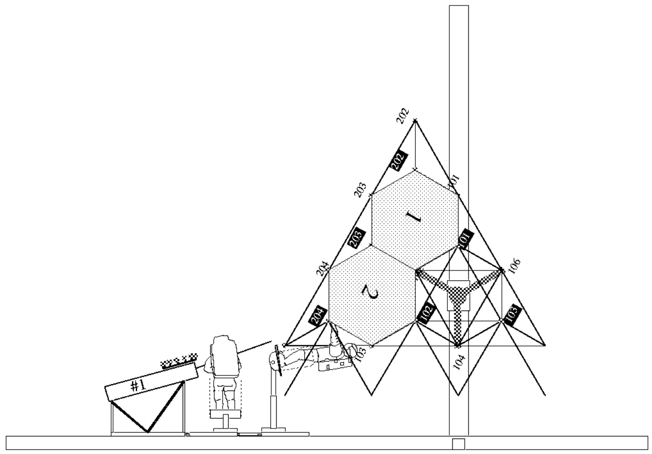
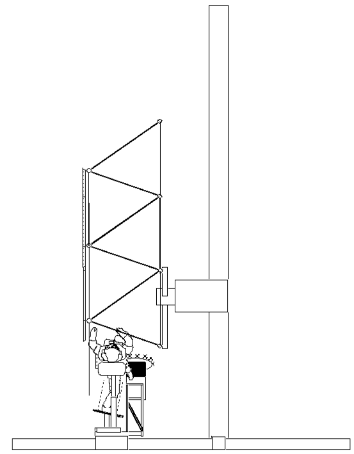


Figure A-1. Continued.

Step 33

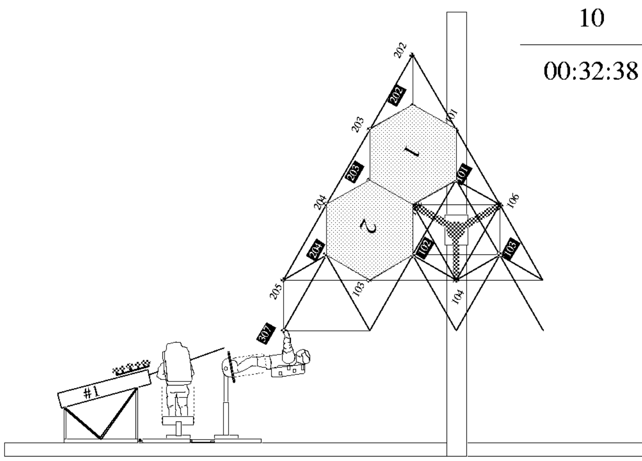
Time (sec)	Task
6+5	Move left 2 m
10	Install 204-4
10	Install 204-5
00:31:44	Elapsed time





Step 34

Time (sec)	Task
3+5	Move left 1 m
6+5	Raise truss 2 m
20	Install node 307 with 307-8 attached
5	Lock 307-1
10	Install 307-6
00:32:38	Elapsed time



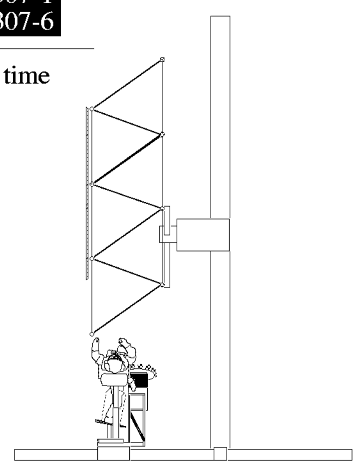
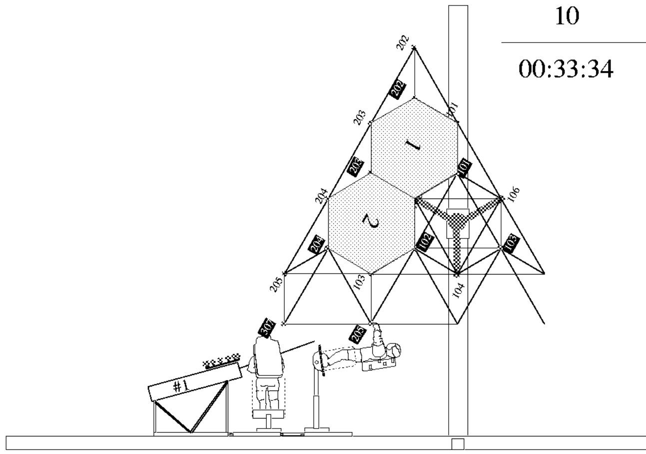
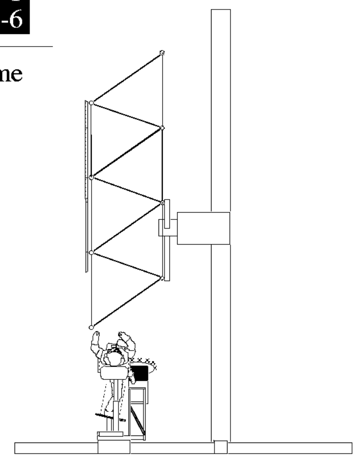


Figure A-1. Continued.

Step 35

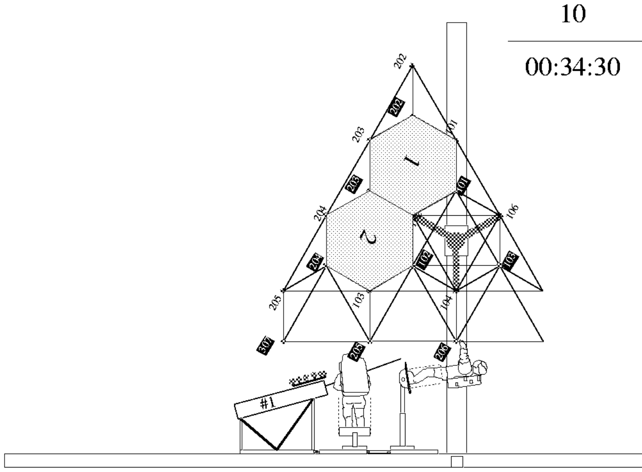
Time (sec)	Task
6+5	Move right 2 m
20	Install node 205 with 205-8 attached
5	Lock 205-3
5	Lock 205-2
5	Lock 205-1
10	Install 205-6
00:33:34	Elapsed time





Step 36

Time (sec)	Task
6+5	Move right 2 m
20	Install node 206 with 206-8 attached
5	Lock 206-3
5	Lock 206-2
5	Lock 206-1
10	Install 206-6
00:34:30	Elapsed time



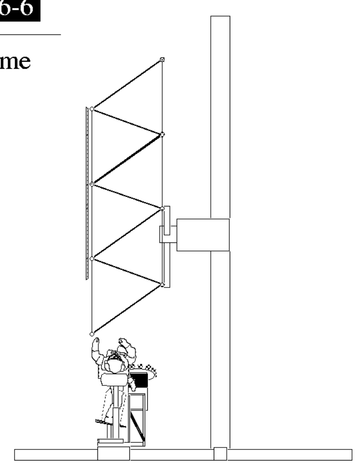
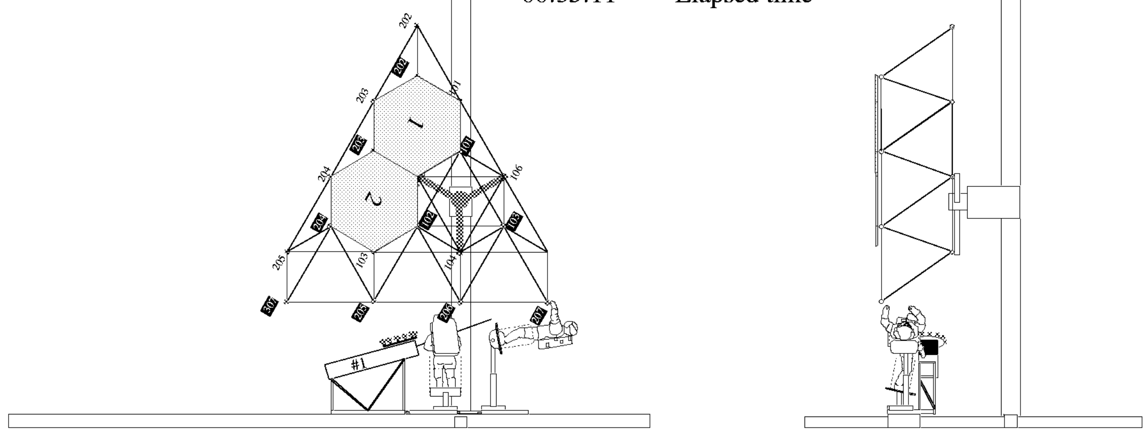


Figure A-1. Continued.

Step 37

Time (sec)	Task
6+5	Move right 2 m
20	Install node 207 with 207-8 attached
5	Lock 207-3
5	Lock 207-2
00:35:11	Elapsed time



Step 38

Time (sec)	Task
3+5	Move back 1 m
4+5	Lower truss 4/3 m
20	Install node 105
5	Lock 105-3
5	Lock 105-7
5	Lock 105-2
5	Lock 105-8
00:36:08	Elapsed time

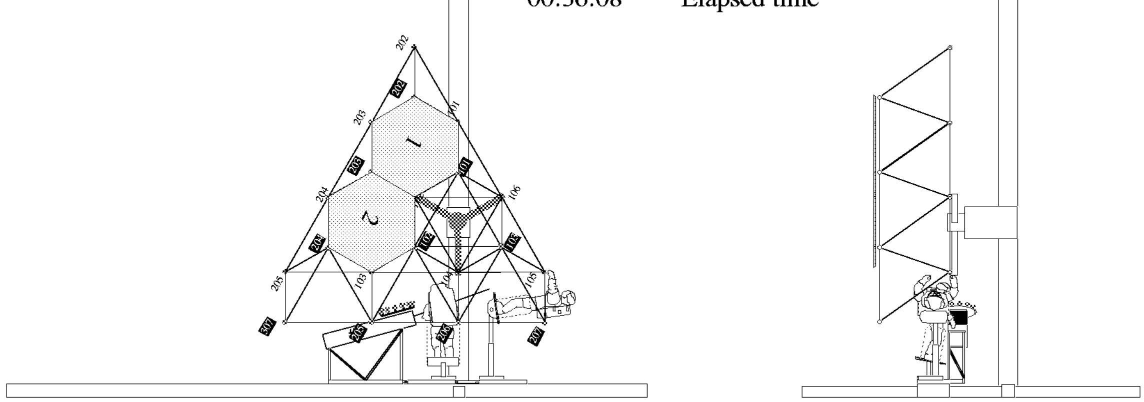
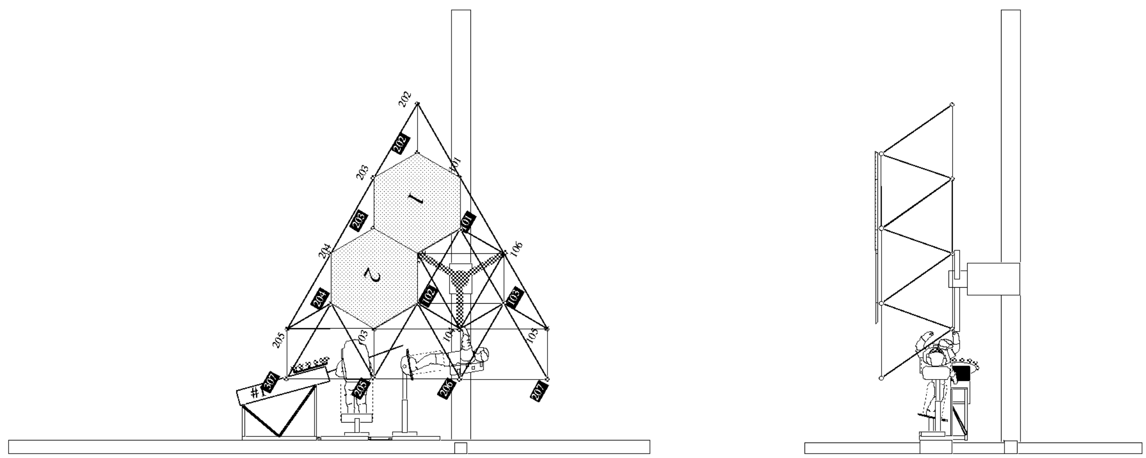


Figure A-1. Continued.

Step 39

Time (sec)	Task
6+5	Move left 2 m
5	Lock 104-8
00:36:24	Elapsed time



Step 40

Time (sec)	Task
6+5	Move left 2 m
5	Lock 103-8
00:36:40	Elapsed time

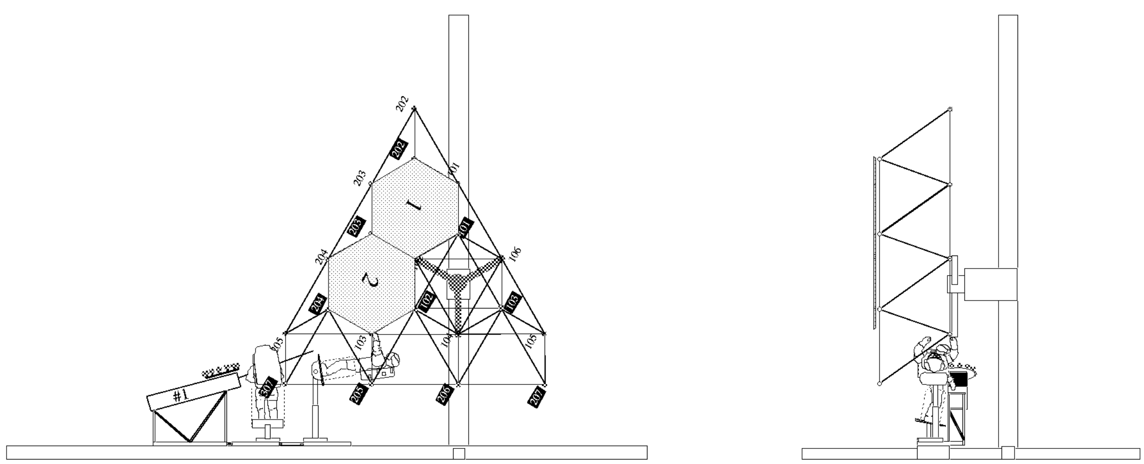
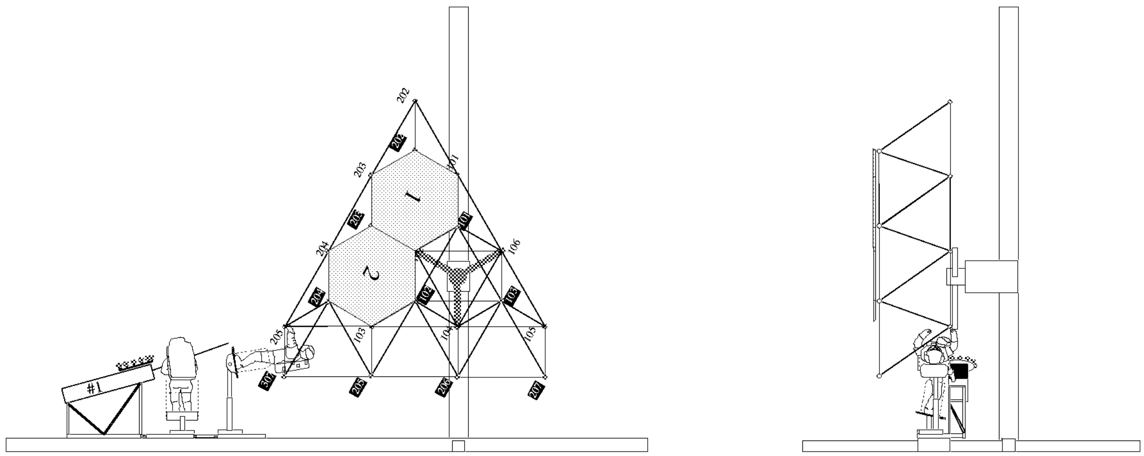


Figure A-1. Continued.

If the reflector surface were to be fully populated, three panels would be installed at the end of this step.

Step 41

Time (sec)	Task
6+5	Move left 2 m
5	Lock 205-8
00:36:56	Elapsed time



Step 42

Time (sec)	Task
20+5	Move right 6 2/3 m
10	Install 105-4
10	Install 105-5
00:37:41	Elapsed time

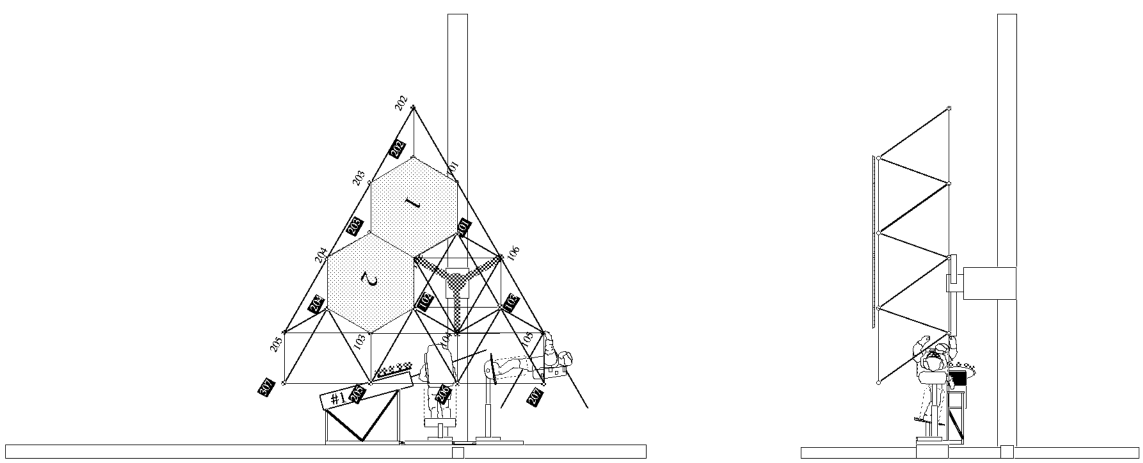
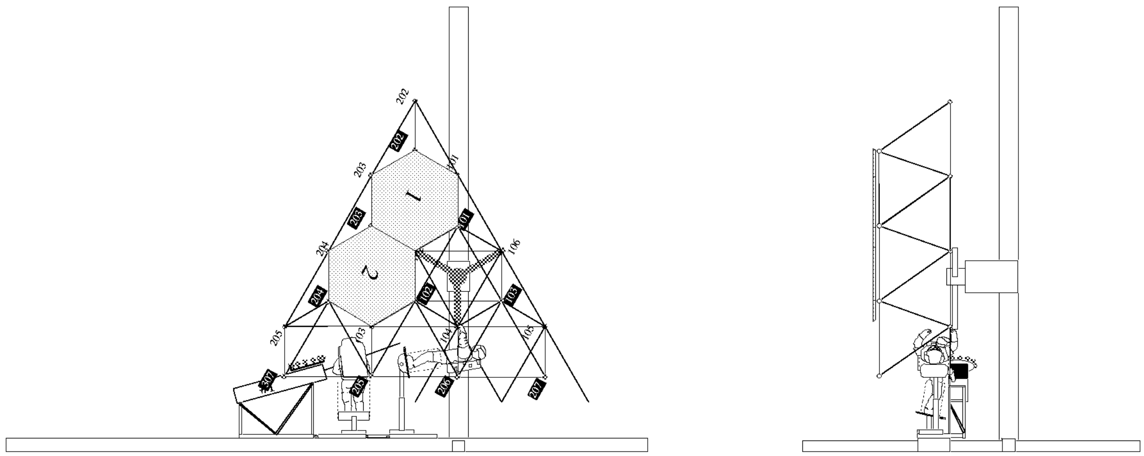


Figure A-1. Continued.

Step 43

Time (sec)	Task
6+5	Move left 2 m
10	Install 104-4
10	Install 104-5
00:38:12	Elapsed time



Step 44

Time (sec)	Task
6+5	Move left 2 m
10	Install 103-4
95+5	Utility divers replace strut/node canister
10	Install 103-5
00:40:23	Elapsed time

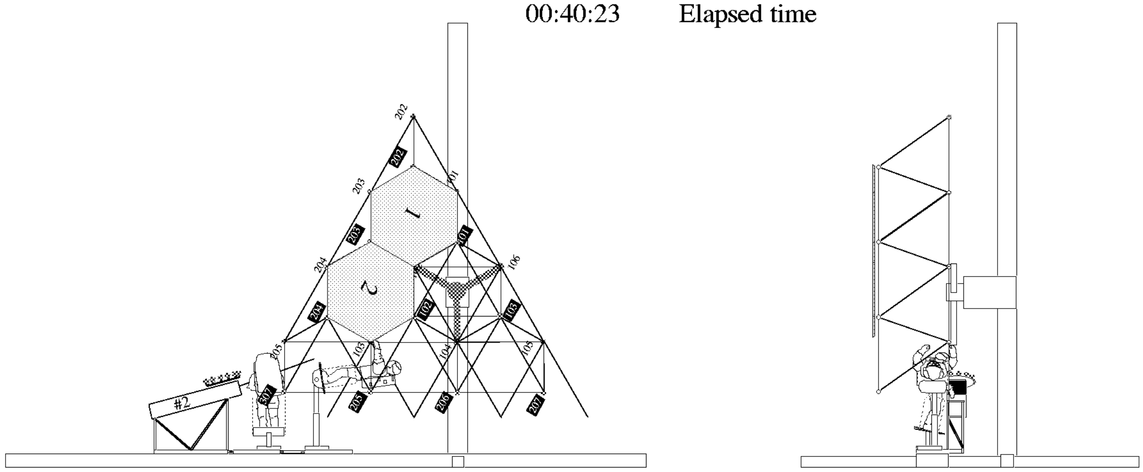
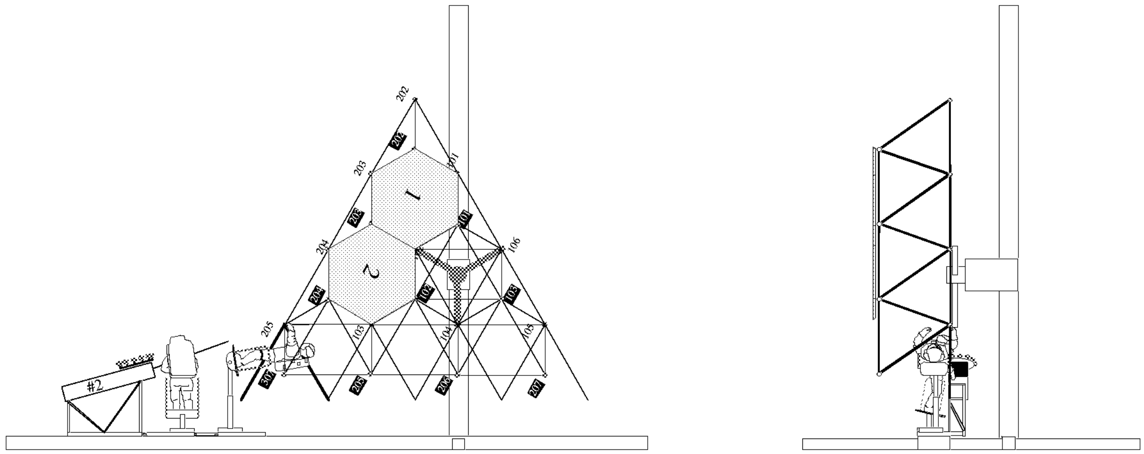


Figure A-1. Continued.

Step 45

Time (sec)	Task
6+5	Move left 2 m
10	Install 205-4
10	Install 205-5
00:40:54	Elapsed time



Step 46

Time (sec)	Task
4+5	Raise truss 4/3 m
3+5	Move forward 1 m
10	Install 307-9
10	Install 307-7
00:41:31	Elapsed time

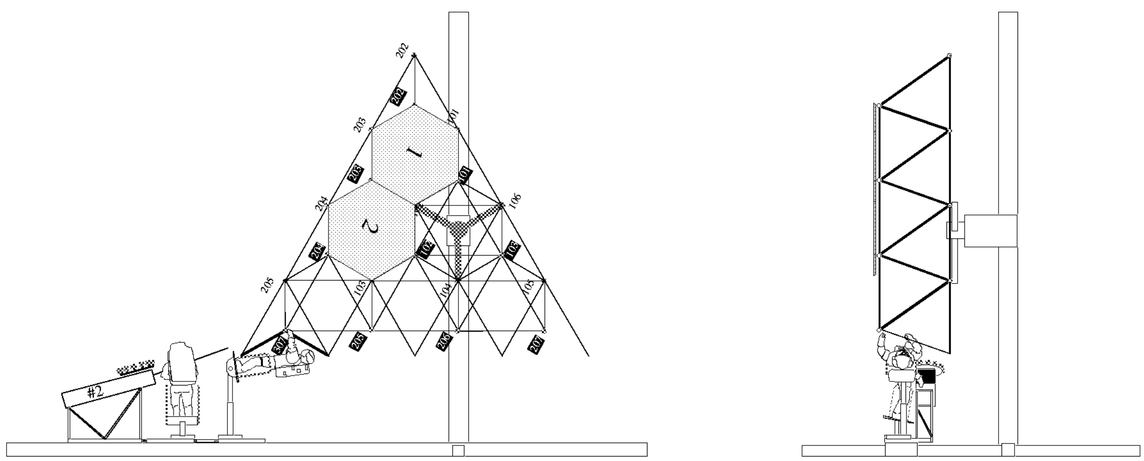
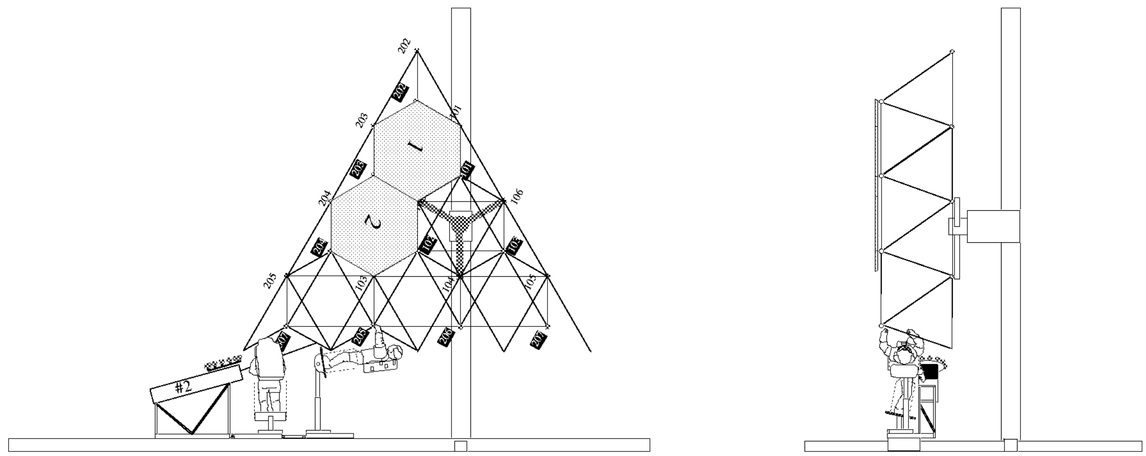


Figure A-1. Continued.

Step 47

Time (sec)	Task
6+5	Move right 2 m
10	Install 205-9
10	Install 205-7
00:42:02	Elapsed time



Step 48

Time (sec)	Task
6+5	Move right 2 m
10	Install 206-9
10	Install 206-7
00:42:33	Elapsed time

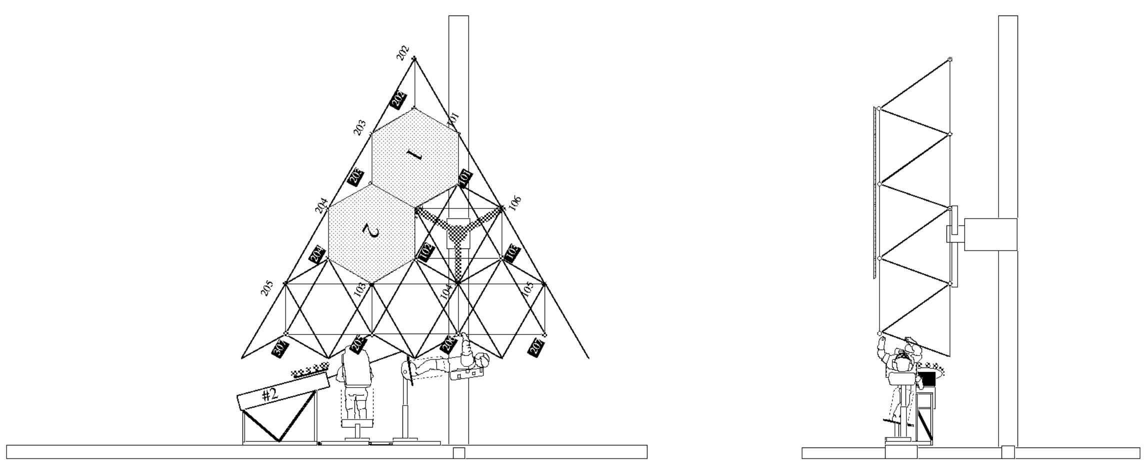
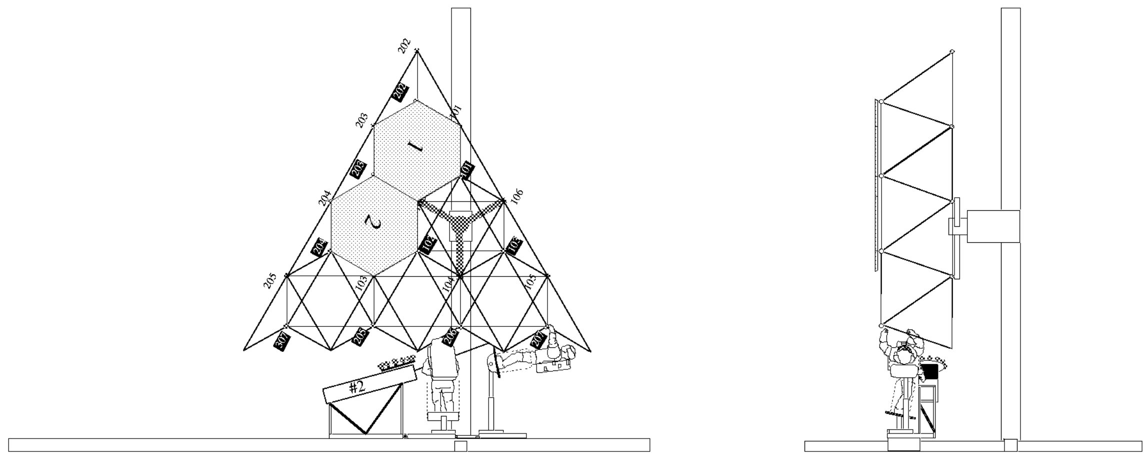


Figure A-1. Continued.

Step 49

Time (sec)	Task
6+5	Move right 2 m
10	Install 207-9
10	Install 207-7
00:43:04	Elapsed time



Step 50

Time (sec)	Task
2+5	Raise truss 2/3 m
3+5	Move right 1 m
3+5	Move back 1 m
20	Install node 209 with 209-3 attached
5	Lock 209-7
5	Lock 209-2
00:43:57	Elapsed time

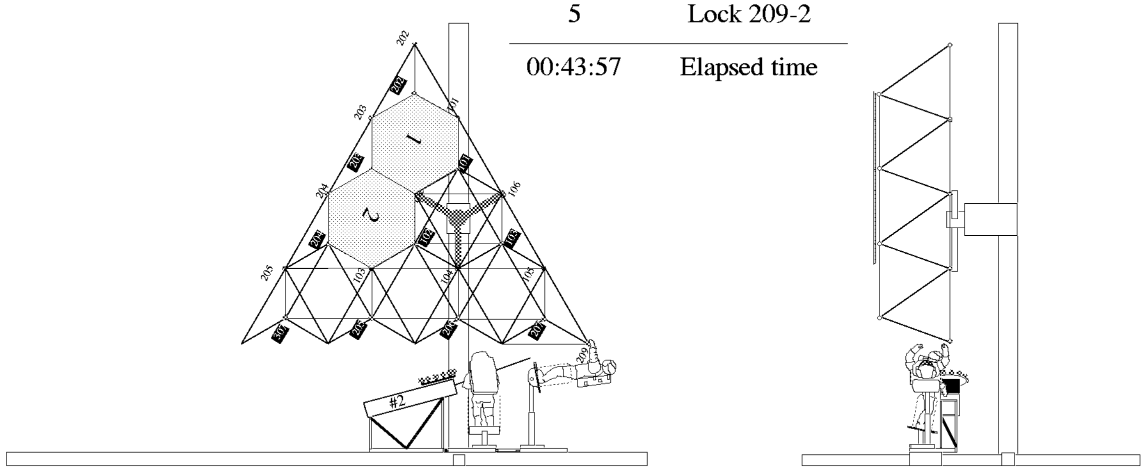
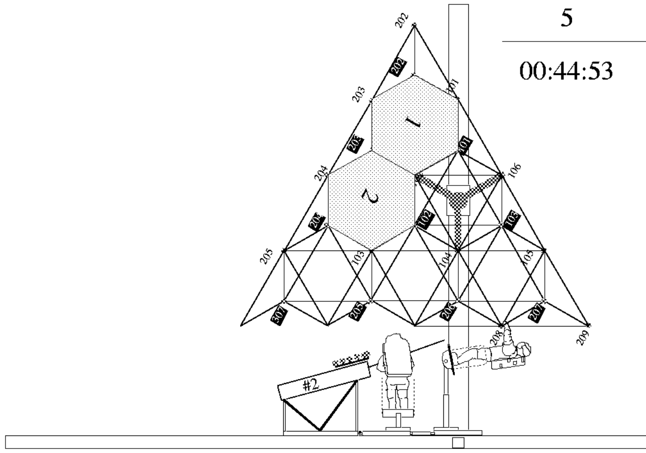
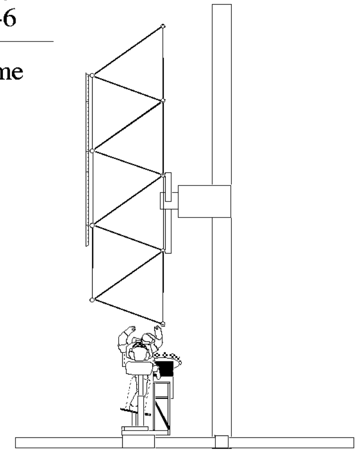


Figure A-1. Continued.

Step 51

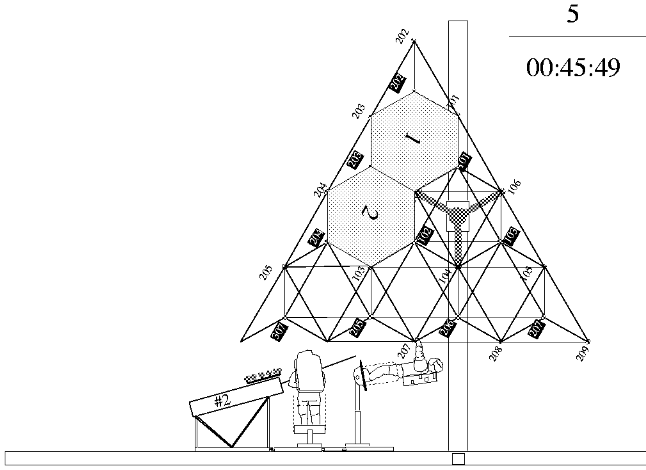
Time (sec)	Task
6+5	Move left 2 m
20	Install node 208 with 208-3 attached
5	Lock 208-7
5	Lock 208-2
5	Lock 208-1
5	Lock 208-9
5	Lock 208-6
00:44:53	Elapsed time





Step 52

Time (sec)	Task
6+5	Move left 2 m
20	Install node 207 with 207-3 attached
5	Lock 207-7
5	Lock 207-2
5	Lock 207-1
5	Lock 207-9
5	Lock 207-6
00:45:49	Elapsed time



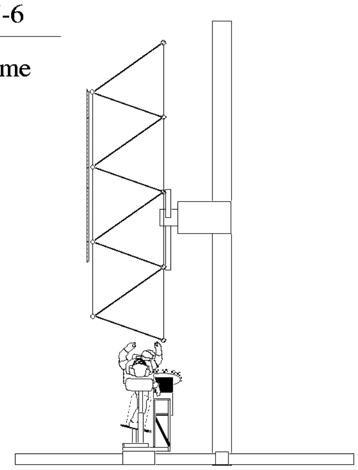
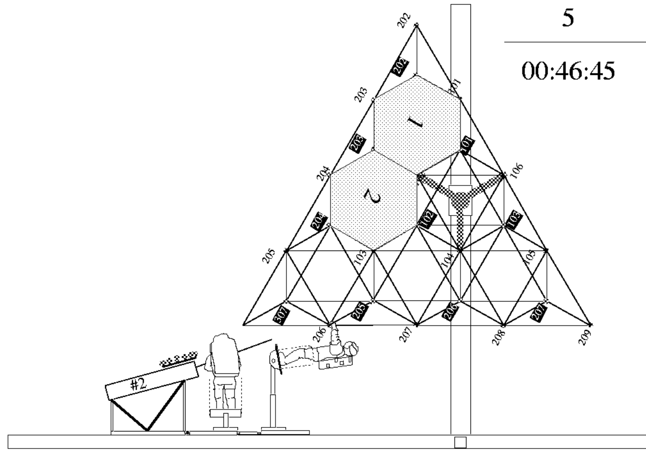
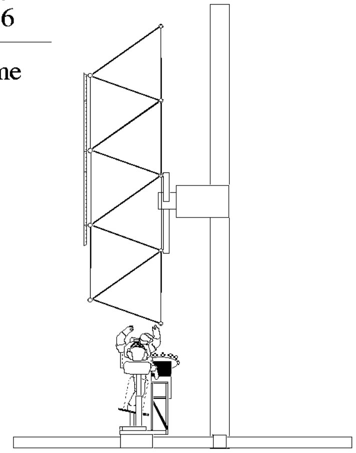


Figure A-1. Continued.

Step 53

Time (sec)	Task
6+5	Move left 2 m
20	Install node 206 with 206-3 attached
5	Lock 206-7
5	Lock 206-2
5	Lock 206-1
5	Lock 206-9
5	Lock 206-6
00:46:45	Elapsed time

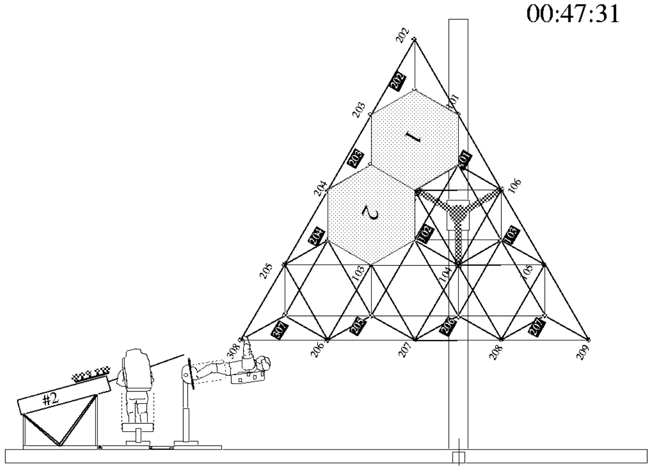




After completion of Step 54, rotate truss 120° and continue assembly.

Step 54

Time (sec)	Task
6+5	Move left 2 m
20	Install node 308
5	Lock 308-1
5	Lock 308-9
5	Lock 308-6
00:47:31	Elapsed time



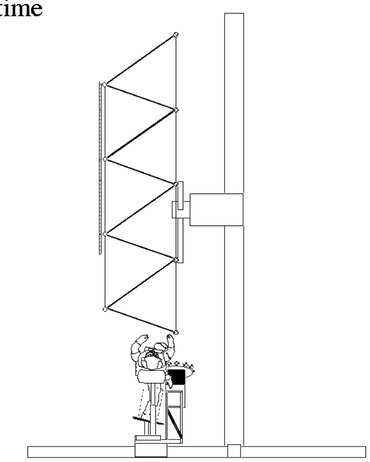


Figure A-1. Concluded.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2000	Technical Publication

4. TITLE AND SUBTITLE
Evaluation of Hardware and Procedures for Astronaut Assembly and Repair of Large Precision Reflectors

5. FUNDING NUMBERS
WU 242-90-19-10

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-18019

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/TP-2000-210317

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category 18 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A detailed procedure is presented that enables astronauts in extravehicular activity (EVA) to efficiently assemble and repair large (i.e., greater than 10m-diameter) segmented reflectors, supported by a truss, for space-based optical or radio-frequency science instruments. The procedure, estimated timelines, and reflector hardware performance are verified in simulated 0-g (neutral buoyancy) assembly tests of a 14m-diameter, offset-focus, reflector test article. The test article includes a near-flight-quality, 315-member, doubly curved support truss and 7 mockup reflector panels (roughly 2m in diameter) representing a portion of the 37 total panels needed to fully populate the reflector. Data from the tests indicate that a flight version of the design (including all reflector panels) could be assembled in less than 5 hours – less than the 6 hours normally permitted for a single EVA. This assembly rate essentially matches pre-test predictions that were based on a vast amount of historical data on EVA assembly of structures produced by NASA Langley Research Center. Furthermore, procedures and a tool for the removal and replacement of a damaged reflector panel were evaluated, and it was shown that EVA repair of this type of reflector is feasible with the use of appropriate EVA crew aids.

14. SUBJECT TERMS
EVA assembly; Astronaut assembly; Truss assembly; EVA compatibility; Precision reflectors; Neutral buoyancy assembly

15. NUMBER OF PAGES
70

16. PRICE CODE
A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL