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Neutral Buoyancy Test Evaluation of Hardware and Extravehicular Activity Procedures for On-Orbit Assembly of a 14 Meter Precision Reflector

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Summary

A procedure that enables astronauts in extravehicular activity (EVA) to perform efficient on-orbit assembly of large paraboloidal precision reflectors is presented. The procedure and associated hardware are verified in simulated 0g (neutral buoyancy) assembly tests of a 14 m diameter precision reflector mockup. The test article represents a precision reflector having a reflective surface which is segmented into 37 individual panels. The panels are supported on a doubly curved tetrahedral truss consisting of 315 struts. The entire truss and seven reflector panels were assembled in three hours and seven minutes by two pressure-suited test subjects. The average time to attach a panel was two minutes and three seconds. These efficient assembly times were achieved because all hardware and assembly procedures were designed to be compatible with EVA assembly capabilities.

Introduction

NASA is developing the technology to build precision reflector spacecraft for future Earth-observation missions. Such spacecraft may be vital to NASA's Mission to Planet Earth program. Figure 1 is a sketch of an offset-feed scanning microwave radiometer (ref. 1), a large aperture Earth-observation instrument with a segmented reflector made up of closely-spaced hexagonal precision panels that are supported on a precision truss structure. If the maximum dimension of each reflector panel does not exceed about four meters, this proposed configuration could be packaged for transportation to orbit in the National Space Transportation System (Space Shuttle) or in another launch vehicle of similar diameter. However, a method for on-orbit assembly is required.

Methods to deploy precision reflectors on orbit are being studied (refs. 2-4). However, the technology for designing complex deployment mechanisms that maintain a precision reflective surface after deployment is still in the conceptual, high-risk stage. Likewise, the technology for assembly by robotics (ref. 5), another method that is being studied, is not sufficiently advanced to offer a practical and reliable solution in the near future. However, an assembly method for which the technology is sufficiently advanced is on-orbit assembly by astronauts in extravehicular activity (EVA). Simulated 0g ground tests have shown that EVA, used in combination with relatively simple automated crew aids, provides a reliable and rapid method for the construction of truss structures. Furthermore, the maturity of EVA assembly technology eliminates the expense, risk, and delay associated with new technology development.

Results from simulated EVA structural assembly test programs (refs. 6-8) show that thoroughly trained astronauts who are adept at EVA structural assembly can rapidly and easily construct straight beam-like truss structures using EVA compatible hardware and simple automated crew aids that maintain the astronauts in foot restraints, position the astronauts at the work sites, and assure that the building material is readily accessible. The efficiency of this method of construction was demonstrated on orbit with the ACCESS space construction experiment (ref. 9). However, each of the trusses studied in references 6-9 consisted of struts of no more than two different lengths and nodes of no more than two different geometries. Therefore, all identical struts and nodes were incorporated randomly during the assembly

process. In contrast, a doubly-curved precision reflector such as shown in figure 1 involves packaging of large numbers of unique struts, nodes, and panels, each of which must be presented to the astronauts in the proper sequence during construction for installation in a unique location (ref. 10). The purpose of the present research is to apply the basic methods proven for EVA assembly of beam-like structures to the development of a procedure that enables efficient EVA assembly of precision reflectors and to verify the procedure through simulated 0g assembly testing.

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EVA Assembly Procedure Guidelines and Rationale

The assembly procedure is based on experience gained from many neutral buoyancy structural assembly tests performed over the last decade in which one or both authors of the present report performed as pressure-suited test subjects. The assembly procedure also draws on the lessons learned from the ACCESS structural assembly flight experiment performed on the Shuttle in 1985 for which one of the authors was the Principal Investigator. These tests have shown that even very large truss structures can be assembled predictably and efficiently by EVA astronauts if a well-planned and well-practiced assembly procedure is combined with properly designed structural hardware. The following guidelines, derived from previous EVA truss assembly tests, were used during the development of the precision reflector assembly procedure and hardware to insure the efficient use of EVA astronauts.

Use two EVA astronauts. It is standard NASA policy to use two astronauts to perform EVA tasks. It was felt that any reduction in assembly time that might be realized from the use of more than two would not warrant the additional complexity required of the assembly fixture, the assembly procedure, and the extra life support systems.

Work from foot restraints for all significant tasks. Space construction by EVA methods is efficient when the astronauts are used solely to assemble structure. Other major energy-expending tasks, such as manually moving and retrieving building material and manual translations between work sites, can be time consuming as well as fatiguing. Thus, such tasks should be accomplished using mobile foot restraints and other automated crew aids when they are required on a routine basis.

Use an assembly fixture. 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 which provides some relative movement between the reflector and the astronauts. An assembly fixture of this type is particularly important in the construction of large structures for which large ranges of motion are required.

Handle panels only from the back (non reflective) side. To reduce the chance of damage to the reflector surface, the astronauts should avoid working on the reflective (concave) side of the panels. Thus, the assembly procedure devised confines the astronauts to work behind the concave side of the truss at all times.

Integrate the installation of the panels with the truss assembly. The panels should be installed on the support 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 a fully assembled truss

Attach panels to stable structure. The panels should always be attached to nodes which are kinematically stable. (For example, no panel attachments should be made to a node at the free end of a cantilevered strut).

Use one astronaut to assemble the truss and one to manage the material. In previous simulated EVA assembly tests (refs. 6 and 8), and in the ACCESS flight experiment (ref. 9), beam-like trusses were efficiently assembled by two people, each with access to separate strut canisters. However, to assemble curved areal-type trusses with attached reflective panels, a new approach is devised that uses only one astronaut to attach the struts and nodes, and one to manage the building material. This strategy reduces the number of assembly tasks required of each astronaut. An additional advantage is that only one of the EVA astronauts requires access to a strut/node canister, thus reducing clutter by eliminating the need for a second canister in the confined work envelope.

Use automated means to maneuver component stowage canisters. To reduce the astronauts' workload, the Remote Manipulator System (RMS) is used to change out the strut/node canisters and to coarsely position the panel canisters. However, it is important to maneuver the RMS in parallel with the astronauts' assembly tasks where possible because RMS motions are characteristically slow and could retard assembly time by creating long idle periods for the EVA crew.

Test Apparatus

Test Article

The test article represents the radiometer primary reflector shown in figure 1. This reflector is an offset paraboloid with an 11.8 m diameter aperture. Its reflective surface is partitioned into 37 hexagonal panels, each of which is attached at three of its corners to truss nodes. A sketch of the test article attached to the assembly fixture and installed in the Marshall Space Flight Center (MSFC) Neutral Buoyancy Simulator (NBS) water tank is shown in figure 2. The test article consists of the doubly curved tetrahedral truss and seven mockup reflector panels. Because of the double curvature, there are 107 different lengths of truss struts, each of the truss nodes is unique, and each of the reflector panels is a unique, irregularly-shaped hexagon.

The node spacing of the test article is on the order of two meters, about the minimum spacing that could be used without overly confining the work space of the EVA crew. This spacing was chosen because the nominal 2.3 m diameter panels it accommodates are much easier to fabricate than four-meter panels (the maximum size panels that would fit in the Space Shuttle) and may be easier to package as well as manipulate by EVA astronauts on orbit. However, as precision panel fabrication technology progresses, it may become desirable to consider larger panels because a support truss consisting of longer struts is stiffer and has a lower part count.

Truss. Photographs of the test article truss hardware are shown in figure 3. The centers of the nodes lying in the concave side of the truss are 12 cm behind the reflective surface. The truss consists of 315 straight, tubular, aluminum struts interconnected at 84 nodes. To produce the curvature, the node spacing ranges from a minimum of 2.03 m to a maximum of 2.21 m. The maximum diameter of the truss is 14 m. The test article is about the largest practical size that can be accommodated for full assembly testing in the 12.2 m deep NBS water tank.

Struts. A photograph of a typical strut is shown in figure 3(b). Each end of a strut has an aluminum joint-half by which it can be attached to a matching joint-half located at a port on a node. A spring-loaded capture feature is designed into the joint hardware which facilitates a quick temporary attachment by an EVA astronaut. The astronaut must then rotate a locking collar on the strut joint-half 45° to complete the structural attachment. Additional details of the joint operation and the strut fabrication are presented in refs. 10 and 11.

The differences in strut lengths were minimized during design of the truss for the following reasons:

(1) Strut stowage canisters are simpler to design when there are no wide variations in the strut lengths.

(2) When all struts in the concave side of the truss have approximately the same length, the reflector panels will have approximately the same size and shape. Reflector panel stowage canisters are simpler to design when all panels are approximately the same size and shape.

(3) During fabrication, struts were set to length using a laser interferometer fixture which accommodates only a limited range of strut lengths.

The procedure and fixture for setting the struts to length are described in ref. 11 (note that a more liberal length tolerance was allowed in the neutral buoyancy test article than that presented for the high-precision structural test article in ref. 11). The maximum differences in strut lengths are: 3.9 cm in the concave side of the truss, 4.7 cm in the convex side, and 16 cm in the entire truss. All core struts (those struts connecting the nodes in the concave side to the nodes in the convex side) were of equal length, 1.94 m, and were the longest struts in the truss. The shortest strut occurs in the concave side and is 1.78 m long. Each strut is 3.18 cm in diameter and is equipped with an internal buoyancy compensator at each end. The buoyancy compensators (ref. 10) allow the struts to be neutrally buoyed and trimmed to maintain any depth and any given orientation underwater to best simulate weightless behavior.

Nodes. Figure 3(c) shows a typical "interior" node on the convex side of the truss, and figure 3(d) shows a typical "interior" node on the concave side. Nodes on the concave side of the truss are provided with panel attachment hardware for supporting the panels. The panel attachment hardware is described in detail in ref. 10 where it is referred to as the "Design 1" concept. The interior nodes on the concave side must accommodate the corners of three panels, thus all the panel attachment hardware required to make the connections (three latches, three locking handles, etc.) is incorporated into an interior node. Nodes located along the edges on the concave side of the truss need to accommodate the corners of only one or two panels. The panel attachment hardware incorporated into these "boundary" nodes is reduced accordingly. Normally all nodes on the concave side would incorporate panel attachment hardware. However, since only seven panels are used in the present tests (fig. 2), the panel attachment hardware is incorporated on only 12 nodes. The nodes could not be made neutrally buoyant without adding external floatation which would alter their external appearance and impede handling, therefore, no attempt was made to neutrally buoy the nodes.

Panels. Figures 4(a) and (c) show different views of the panels attached to a segment of the truss, and figure 4(b) shows the locations of the EVA handles provided on the back (non reflective) side of a typical panel. The handles are provided to facilitate handling and maneuvering by the EVA crew. Seven unique mockup panels were fabricated. To reduce the fabrication costs, each mockup panel was made from six flat, aluminum, triangular sheets attached to an aluminum frame. To approximate the curvature of the reflector surface, the six corner points and the center point of each mockup panel were designed to lie in the paraboloidal reflector surface. Hardware used to attach the mockup panels to the truss nodes is provided at three of the panel corners (every other corner). The gaps between the edges of adjacent panels are approximately 0.3 cm. The panel edges are beveled to provide adequate clearance for installation purposes. More details of the mockup panel construction and the panel attachment hardware may be found in ref. 10, in which a similar panel fabrication method and similar panel attachment hardware are described.

Hardware connectivity identification. Each strut, node, and panel is labeled to identify the specific location it must occupy in the reflector. The labels on the struts and nodes can be seen in figure 3. The labels are used by the test subjects during assembly. The labeling system adopted involves a three-digit number that identifies the node and a single digit number that identifies one of the nine ports to which struts can be attached to the node. The nodes in the concave side and those in the convex side lie in concentric rings. The first digit of the node number indicates the ring number (with ring 1 nearest the center of the truss) and the last two digits of the node number discriminate between nodes in a given ring. Thus, node 101 refers to node 1 in ring 1. The ends of the struts are labeled with the three-digit node number followed by a space and the single digit port number. Thus, the strut end labeled 101 2 in figure 3 (b) should be attached to node 101 at port 2. White numbers on a black background indicate components which lie in the concave side of the truss, and black numbers on a white background indicate components which lie in the convex side of the truss.

Assembly Fixture and Mobile Foot Restraints

Figure 5(a) is a photograph of the assembly fixture and mobile foot restraints used in the present tests. Figure 5(b) is a schematic showing the various components. The assembly fixture consists of a vertical tower, turnstile box, and turnstile which supports and positions the test article during assembly, thereby reducing the complexity of the mobile foot restraints. Two test subjects working from the foot restraints on the trolley assemble the test article by adding rings of struts, nodes, and panels. The foot restraints and strut/node canister move as a unit with the trolley. As the diameter of the truss increases with each ring of new structure, the turnstile box is moved upwards on the tower. The transverse track and trolley are moved as needed to position the test subjects and the strut/node canister at the appropriate work sites. The tower is 10.4 m tall; the transverse track is 15 m long.

The truss struts are stowed in their order of assembly in five canisters. There are 63 struts per canister. The nodes are stowed in their order of assembly on five turntables. There is one turntable attached to each of the strut canisters. 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.

Remote control station. The turnstile, foot restraints, trolley and transverse track are hydraulically powered and controlled by a remote operator (engineer) stationed at a console located outside the water tank, as shown in figure 6. All motions are directed by the test subjects through voice communications with the console engineer who can view the assembly operations through a porthole in the tank wall.

On-orbit scenario. The assembly fixture is sized for 1g operation and large factors of safety were used for the design. Hydraulics are used for convenience. An assembly fixture designed for use with the Shuttle as the construction base could be functionally similar, but of much lighter weight design. It could be supported on one or two of any of the standard pallets used in the Shuttle. Although the tower and transverse track can be preassembled 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. All motions of the foot restraints, and turnstile could be electronically controlled by a preprogrammed computer so that the need for a remote operator could be eliminated. For on-orbit application, the transverse track would be stationary and the necessary fore and aft motion provided through an additional degree of freedom designed into the trolley.

Assembly Procedure

Because the assembly of an areal structure having double curvature is more complex than the assembly of beam-like structures, the present procedure uses an approach that reduces the diversity of tasks for which each astronaut is responsible. Thus, one astronaut is restricted to unstowing and managing the truss hardware while the other is restricted to making the structural connections. This approach enhances the astronauts' ability to assemble the reflector without written instructions or verbal prompting. To streamline truss assembly activities, the assembly procedure maintains each astronaut in a predetermined orientation at both the front and back sides of the truss. However, the astronauts are reoriented for panel attachment activities.

The assembly procedure consists of 261 steps. A detailed computer-aided drawing of each step of the procedure (summarized in figure 7) was developed to estimate assembly time. During assembly of truss components (figs. 7(a), (b), (d), (g), and (h)), the astronaut in the upright orientation removes the struts and nodes from the strut/node canister and passes them to the astronaut in the reclined (horizontal) orientation who makes the structural connections. Figures 7(c), (e), and (f) show the astronauts reoriented for attachment of panels. Each panel is kept in a protective canister that is maneuvered by the RMS into a position within reach of the astronauts (fig. 7(f)). The astronauts then remove the panel from the canister and make the final attachment to the truss. The panels are always handled from the back side to reduce the risk of damage to the reflective surface. For the present tests, the panel canister was sized to hold only one panel. On orbit, a dispenser type canister capable of stowing multiple panels would probably be used on reduce the number of RMS maneuvers required for panel attachment operations.

Test Results

Test Article Assembly Times

Photographs of the fully assembled test article are shown in figures 8(a) and 8(b). The top part of the test article protrudes through the surface of the water and, thus, is not visible in the photographs. Figure 9 shows the time history for three assemblies (denoted Build 1, Build 2, and Build 3) of the test article. The elapsed time at the completion of each of the 261 steps are plotted. The steps do not necessarily consist of identical tasks, thus the curves are not smooth. Multiple tests were required to complete each build because the underwater depth at which the test subjects worked imposed a time limit that was shorter than the predicted build time. Only one test was allowed per day, and the number of available tests days was limited. Factors which shortened or canceled some tests were electrical storms in the vicinity, life support system malfunctions, and test hardware malfunctions. Where possible, life support and hardware

malfunctions were corrected during the first five tests comprising Build 1. Build 1 was terminated early to conserve test days for Builds 2 and 3.

Because of the limited available training and test time, the same pair of test subjects (the authors of the present paper) were used for all but one test. Furthermore, to reduce the number of tasks which they needed to learn and, thus, accelerate their learning times, the test subjects did not interchange positions. The only exception to this procedure was made during test 3 of Build 1 when a highly EVA-experienced astronaut served as the reclined test subject. Although the astronaut had very little training time to learn to the assembly procedure and develop optimal techniques, he had no trouble manipulating the truss components or operating the joint hardware. Furthermore, his participation in the tests provided the engineers with many valuable insights which ultimately led to greatly improved assembly times. It is important to realize that learning the assembly procedure involves not only learning the proper order of assembly tasks, but also learning the most efficient body position and technique to use in executing each task. Although, the order of tasks was easily memorized before neutral buoyancy testing began, efficient techniques and body positions could only be learned during neutral buoyancy testing.

Due to experience in previous EVA truss assembly tests, the engineer and astronaut test subjects all agreed that during truss assembly the reclined test subject should make all strut attachments at a given node from a single foot restraint position. This guideline increases the rate at which assembly tasks can be completed because it eliminates foot restraint repositioning time. However, by maintaining a fixed foot restraint position at a given node, many strut-to-node attachments must be made in locations or at orientations which preclude the reclined test subject from applying a firm palm grip to the joint locking collar. Consequently, during tests 1, 2 and 3 of Build 1 the engineer and astronaut test subjects experimented with such factors as the most beneficial height of the test article above the foot restraints, the best angular orientation of the reclined test subject, and the optimum body positions and assembly techniques for constructing the test article. Thus during the first three tests the reclined test subject was attempting to find the optimum (least fatiguing) positions affordable during nearly every step of the assembly procedure. Even though these extraneous positioning motions were reduced during tests 4 and 5, they are the major contributor to the excessive (more than twice the prediction) time taken to assemble the test article during Build 1. Build 2, which was accomplished during tests 6 and 7, is a marked improvement over Build 1. However, during the early part of test 6, the reclined test subject was still refining his techniques, thus, test times are longer than predicted. For Build 3 (tests 8 and 9), the test subjects and control console engineer were well trained and confident of their prescribed tasks. The results corroborate the predicted time shown by the unbroken line in figure 9.

Most of the improvement exhibited in the data can be attributed to learning by the reclined test subject who makes all of the structural connections associated with the truss assembly. The other test subject, although constantly removing struts and nodes from stowage and passing them to the reclined test subject, has no difficult hand or body positions to learn, thus his tasks usually do not impact the assembly time. It is recognized that the ability of the hydraulic control station operator to quickly position the test subjects and truss also improves with experience. Thus, the same control station operator was used for all tests and the training he received during Build 1 allowed him to efficiently execute all positioning commands as predicted during Builds 2 and 3.

A comparison of the Build 3 data with the data from Builds 1 and 2 in figure 9 demonstrates that adequate training can be time-consuming, thus, conclusions drawn from early tests can be misleading. If the test program had been halted after the first five tests, erroneous conclusions would have been drawn that would have resulted in unrealistically high estimates of the on-orbit assembly time. Sometimes, EVA time estimates and hardware compatibility assessments are based on "quick-look" tests. One problem with such tests is that they allow the astronauts only a relatively short period of time to work with the hardware. Therefore, the

astronauts are forced to make assessments before they have had the opportunity to become fully trained. It is important for the EVA planner and hardware designer to realize that the real or perceived negative aspects of the operation of a piece of hardware usually become obvious to an EVA subject much quicker than the positive aspects of its operation. However, experience has shown that with extended training the test subject invariably becomes more familiar with the characteristics of the hardware, and learns how to work effectively with it. This learning process manifests itself in reduced fatigue, increased proficiency, and a significant improvement in the perceived "EVA-compatibility" of the hardware. Thus unnecessary procedure modifications and costly hardware modifications that usually lead to increased complexity can be avoided.

Breakdown of Assembly Task Times

The total time for each build and the predicted time are presented in figure 10 and 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), 2. panel attachment (removal by test subjects of a panel from the panel canister and attachment to three truss nodes--performed seven times), 3. positioning for panel attachment (reorientations and translations of test subjects' foot restraints and RMS maneuvering of the panel canister to within the reach envelope of the test subjects), 4. strut assembly (attachment of struts to nodes by the reclined test subject), and 5. positioning for strut attachment (translation of test subjects' foot restraints and translation and rotation of assembly fixture turnstile). Although Build 1 was terminated after the assembly of only 277 struts, the assembly time has been extrapolated in figure 10 to estimate the strut assembly and positioning times for the 315 struts of the complete truss. Also, the positioning and assembly times for seven reflector panels presented in figure 10 were extrapolated to estimate the panel positioning and assembly times for a complete, 37-panel reflector, and the data is presented in figure 11.

A comparison of the Build 3 strut assembly time with the predicted time in figure 10 shows excellent agreement, and comparison with the data from Builds 1 and 2 shows that significant improvement can be realized with thorough training. The positioning time for strut assembly was between 41 and 45% of the total truss assembly time for all builds and this compares with 42% from the predicted time. This indicates that as the reclined test subject learned optimum body positions and techniques for truss assembly, foot restraint positioning and strut attachment times decreased 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. The panel attachment task times from Build 3, figure 10, appear to be in good agreement with predictions. However, since only seven panels were attached, the discrepancies are not obvious in the scale shown. The panel attachment task in Build 3, for example, actually took about 37% longer than predicted while panel positioning took 12.5% longer. The discrepancies are more discernible in figure 11 where the task times are extrapolated to a complete 37-panel reflector. The panel attachment task time predictions, however, were based on little historical data, thus it is not surprising that discrepancies exist. Usually, before each panel was attached, the test subjects were idle while positioning operations involving maneuvering of the panel canister by the RMS operator, and positioning of the test subjects' foot restraints were carried out. The total amount of time expended on these operations, however, decreased significantly with each build. The trend indicates how these task times dramatically improve with training.

Test Subjects' Assessment and Comments

General. The multiple tests available to the engineer test subjects afforded them enough practice time to develop their techniques for execution of the preplanned assembly procedure during the latter tests. In general, these two subjects found that the assembly procedure could be executed as planned and within predicted times during the Build 3 tests. The division of tasks

was found to be very efficient with essentially no idle time (other than during RMS maneuvering of the panel canisters) for either test subject. The upright test subject had no difficulty seeing, reaching, unstowing, or passing the hardware components, and both test subjects found the order of steps in the assembly procedure simple to learn. The reclined subject felt that having the other 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 forcing every piece of hardware to be handled by each of them reduces the risk of assembling components out of order or in the wrong location.

The handles provided on the back side 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. 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. The moderate physical exertion required was judged by the test subjects to result, primarily, from overcoming the water resistance of the panels. There were only two significant sources of time delays during panel attachment operations. One was the slow translational 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 the ascent and descent were restricted by the test conductor to eliminate pressure spikes in the test subject's pressure suit.

Although all tasks required of the control console 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 was primarily a function of the rate at which the reclined test subject learned his tasks. As stated previously, the same engineer served as the reclined test subject for all tests except test 3, and an astronaut participated as the reclined test subject during test 3. The following comments reflect the views of these two 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. The dexterity of the astronaut is improved and the onset of fatigue delayed with a tight fitting space suit (extravehicular mobility unit (EMU)). Experience both on orbit and in neutral buoyancy has proven that the hard upper torso (HUT) and the gloves should be very close fitting, and that the arm length should be adjusted to keep the finger tips touching the glove finger tips.

3. If the test subject is allowed to work in front of the reflective surface, more fore and aft travel of the foot restraints might be beneficial. 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.

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. Using both test subjects to assemble the truss components might be more productive.

6. Strut alignment is easy. The preferable orientation of the receptacles attached to the nodes (node ports) is with the entry 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.

7. The locking collar, in many instances, is hard to grasp with the full hand because other struts entering the joint are in the way, thus the finger tips have to be used to lock the joint. A longer locking collar would be easier to grasp and should benefit this situation.

8. Assembling a full ring of truss before attaching a full ring of panels may be beneficial and should be considered.

Engineer test subject . 1. A significant amount of time is spent requesting and waiting for accurate foot restraint positioning. Much time can be saved if the reclined test subject allows foot restraint positioning errors of ± 30 -60 cm and compensates for these errors by swinging his upper body into final position using leg and lower torso muscles. This approach significantly improves assembly times while adding only slightly to the fatigue level.

2. The strut-to-node capture feature allows single-handed alignment and capture of the struts. This attribute extends his functional reach envelop, and enables him to make connections which would otherwise be extremely difficult or impossible without repositioning the foot restraints. However, the least fatiguing and most time-efficient alignment and capture technique requires both hands with the thumb and forefinger of one hand applying a light closing force to the joint halves while the other hand effects final strut alignment with a very light grip. If there is inadequate reach for the test subject to pinch the joint halves with thumb and forefinger, a single thumb or finger tip pressing against the strut-end joint can be nearly as effective for capturing the joint halves. Although aligning and capturing a strut with one hand is possible, it is usually more fatiguing and time-consuming than the two-handed techniques and should only be used when reach restrictions dictate.

3. The locking collars were often inadvertently knocked out of the capture position during manipulation of the strut. A better and more positive detent should be designed to avoid this problem.

4. Difficult structural connections, which are the most significant source of test subject fatigue, are often encountered when many struts are being connected to a single node. In such instances, the struts physically interfere with the test subject's hand so that a firm palm grip cannot be used to rotate the locking collar. Thus, the locking collars had to be rotated with two and sometimes only one finger. Nevertheless, with sufficient training and practice, the test subject can become efficient at making all strut-to-node connections required in the assembly procedure. Extending the length of the locking collars would probably enable the test subject to lock the joint farther away from the node where there is more room for his hand.

Conclusions

A procedure that enables astronauts in EVA to perform efficient on-orbit assembly of large, precision, primary reflectors is presented. The procedure and associated hardware are verified in simulated 0g (neutral buoyancy) assembly tests of a 14 m diameter reflector mockup. The test article is a doubly-curved tetrahedral truss consisting of 315 struts (107 different lengths) and 84 unique nodes, supporting a reflective surface. The complete reflective surface would consist of 37 closely-spaced, near hexagonal-shaped segments called panels. However, only seven panels were fabricated for use in these tests.

Nine tests were performed to build the test article three times. Engineer test subjects performed all but the third test. To streamline the learning process, the test subjects did not interchange positions. During the third test an astronaut served as the test subject who performed all the structural connections. The following conclusions can be drawn from these tests:

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

2. The precision reflector assembly procedure is built around a few basic steps which are performed in sequence. The sequence is repetitive and, thus, is quickly learned. The numbering system used on the truss components clearly defines their unique locations in the test article, thus written instructions or verbal prompting is not required.

3. 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 only be learned during neutral buoyancy testing.

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

5. 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 requiring adequate training for EVA test subjects before conducting procedure and hardware evaluations.

6. 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 is a consensus of the test subjects that the length of the locking collars should be extended so that they may be more easily grasped without interference from surrounding structure.

7. 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.

8. 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.

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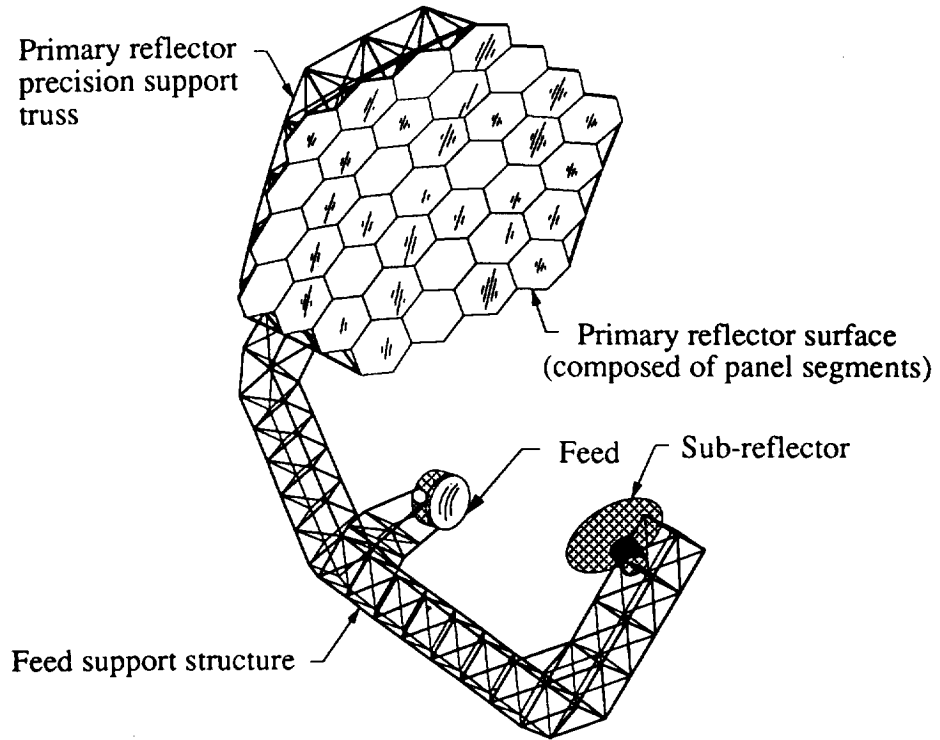


Figure 1. Precision reflector used as the primary reflector for an offset-feed scanning microwave radiometer spacecraft.

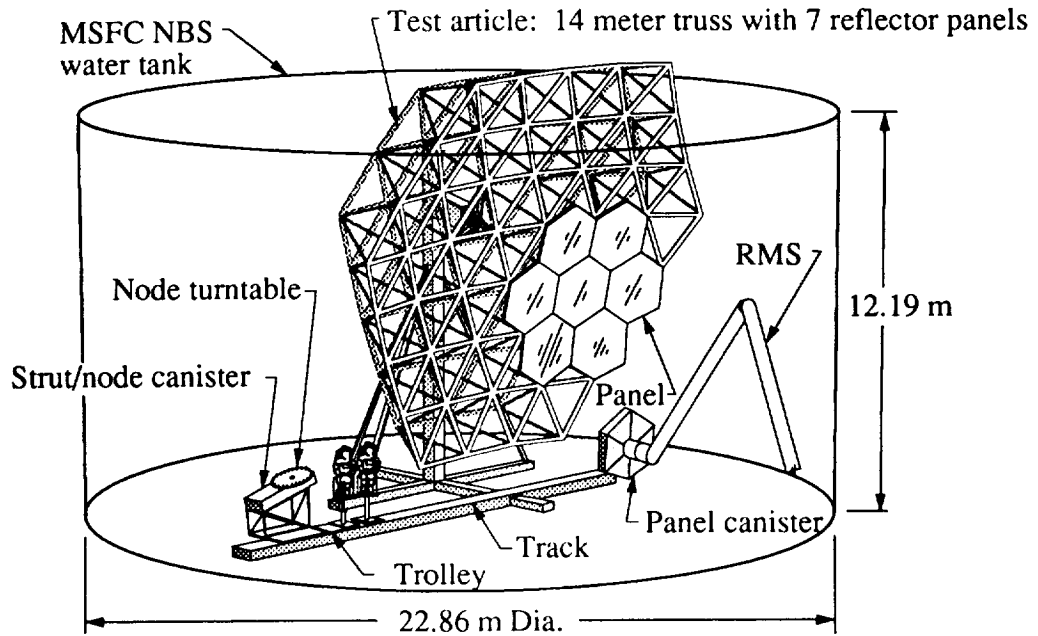
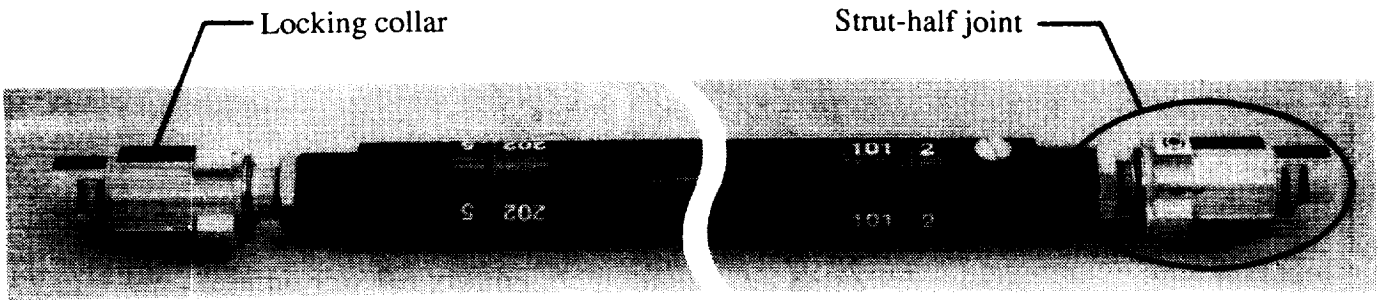
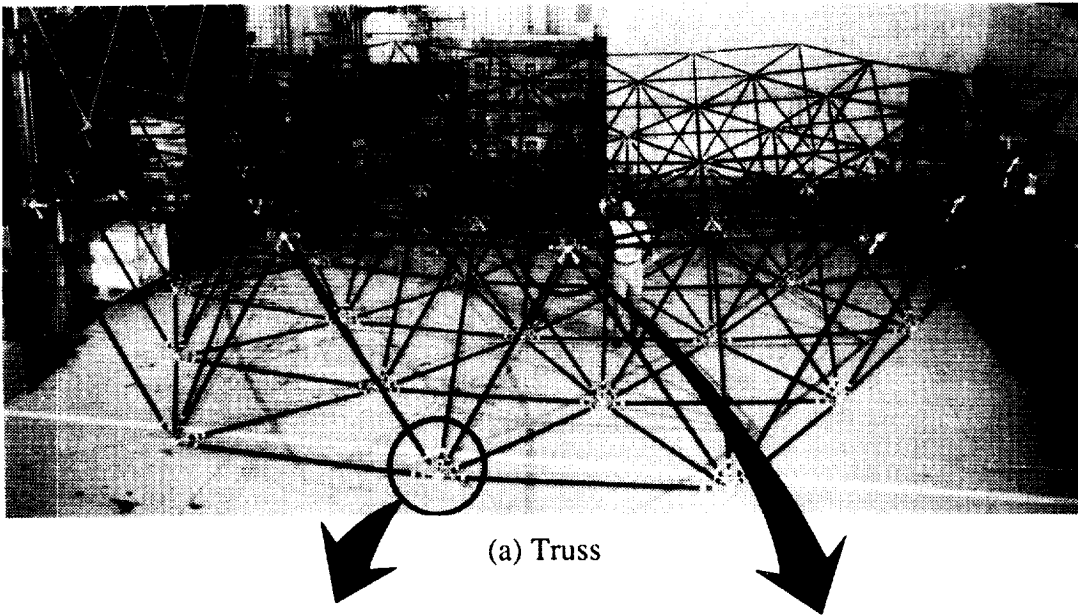


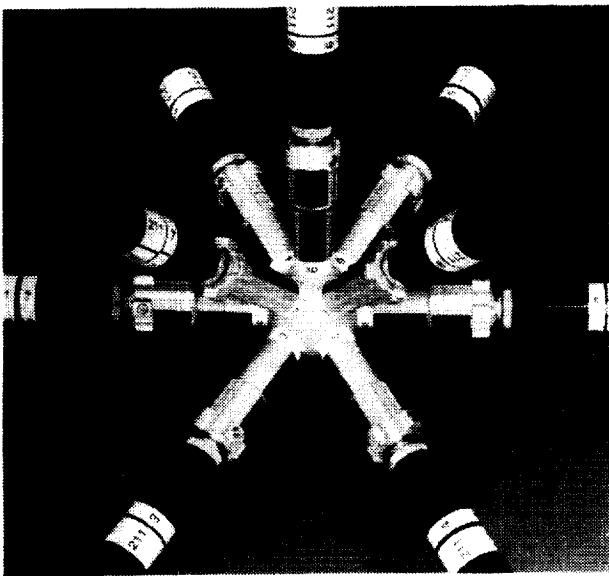
Figure 2. Sketch of the test article attached to the assembly fixture installed in the Neutral Buoyancy Simulator water tank.



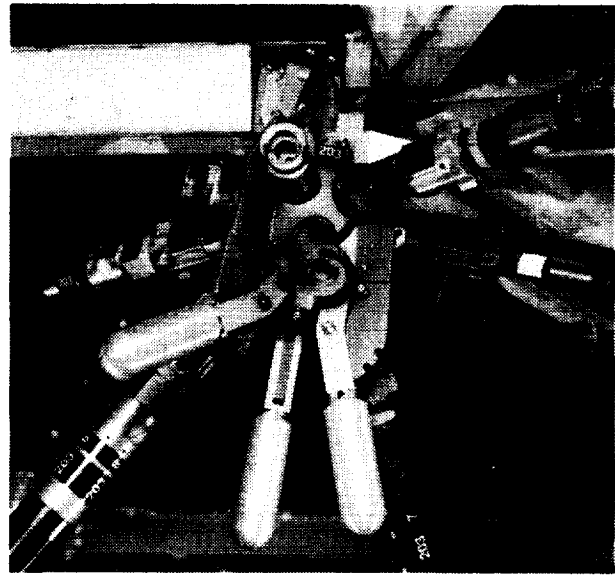
(b) Typical strut



(a) Truss

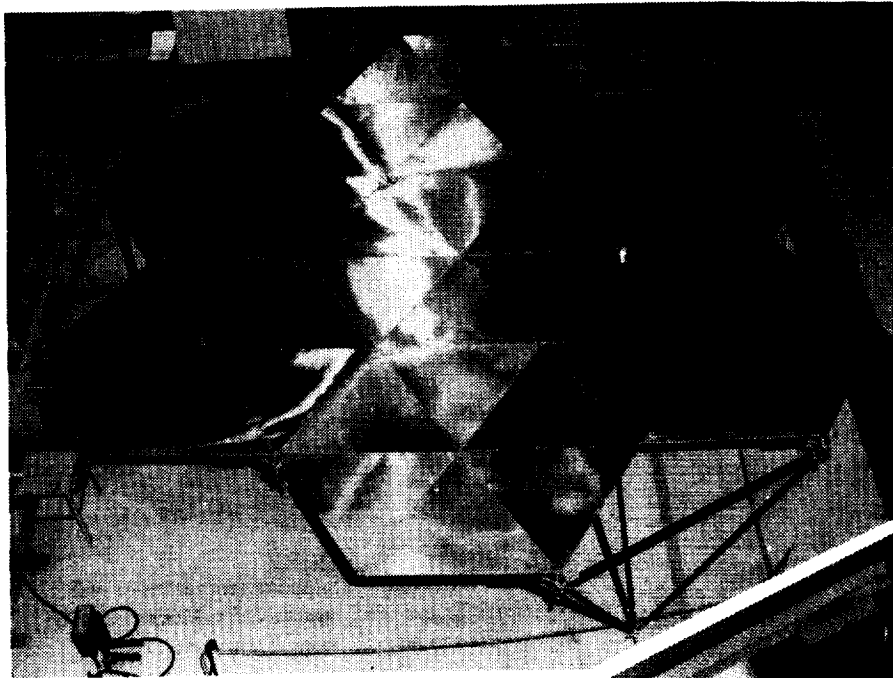


(c) Typical node in convex surface of truss

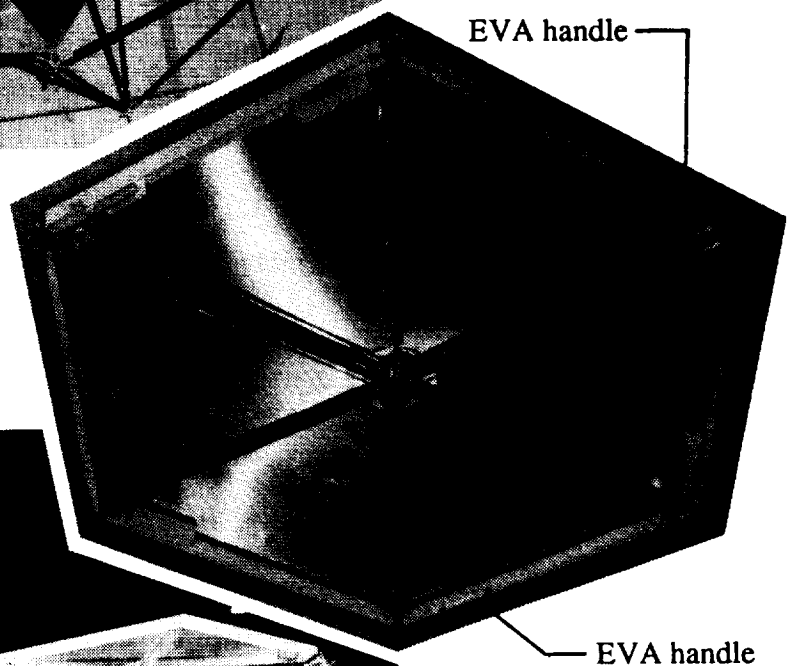


(d) Typical node in concave surface of truss

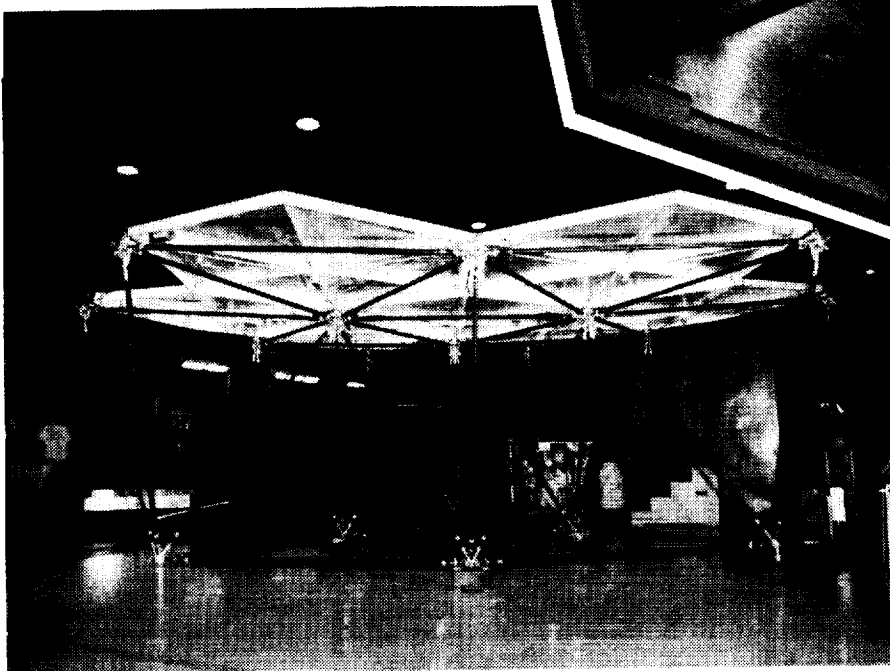
Figure 3.- Test article truss hardware.



(a) Top view.

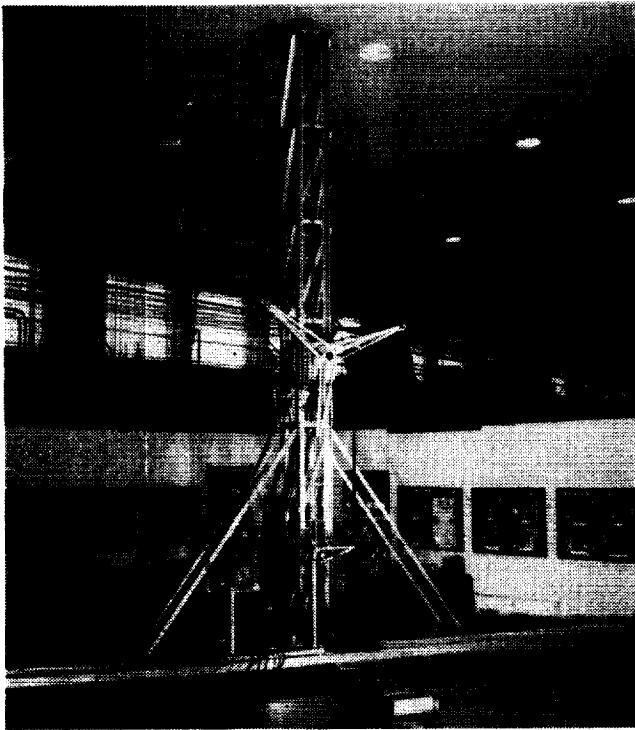


(b) Convex side of panel.

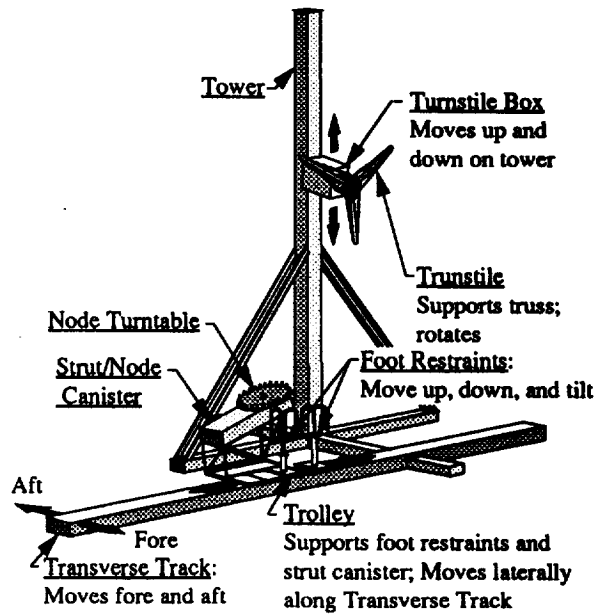


(c) Side view

Figure 4.- Seven mockup reflector panels attached to a segment of the test article truss.



a) Photograph of test hardware.



b) Schematic of components.

Figure 5.-Assembly fixture and mobile foot restraints.



Figure 6.- Remote Control Station.

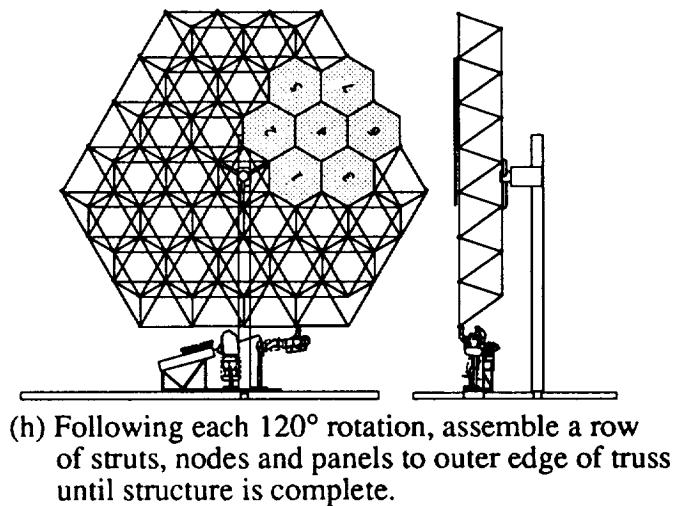
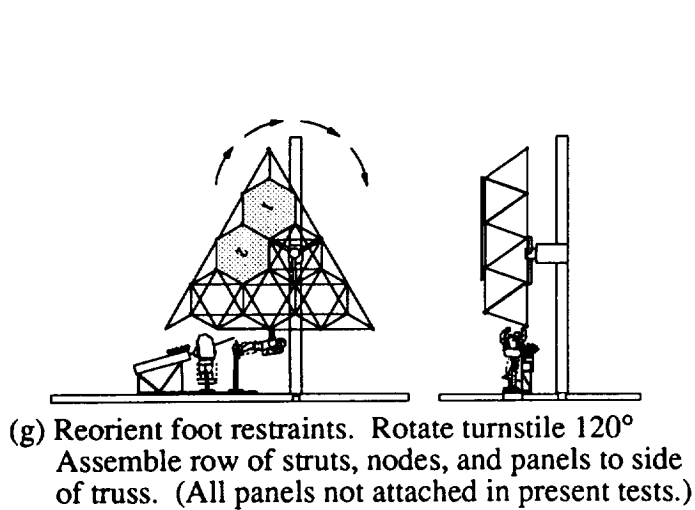
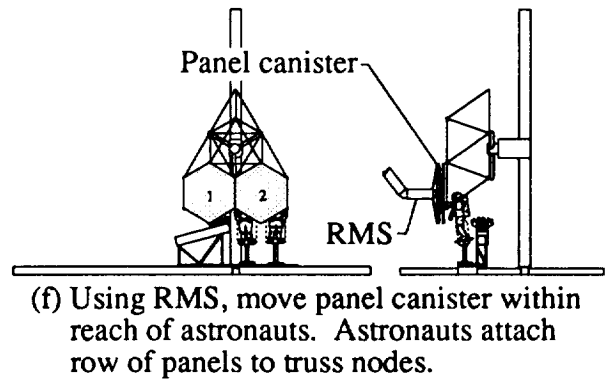
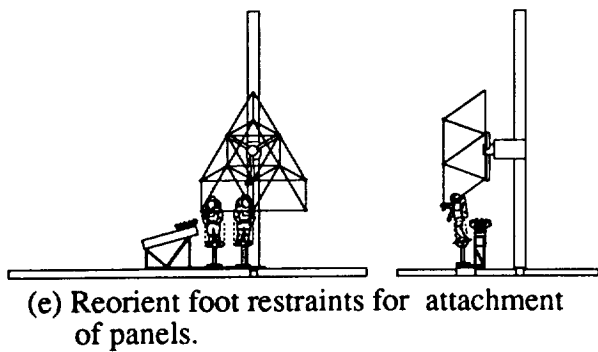
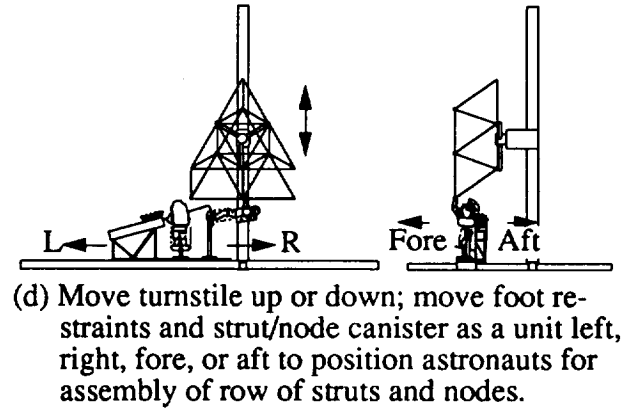
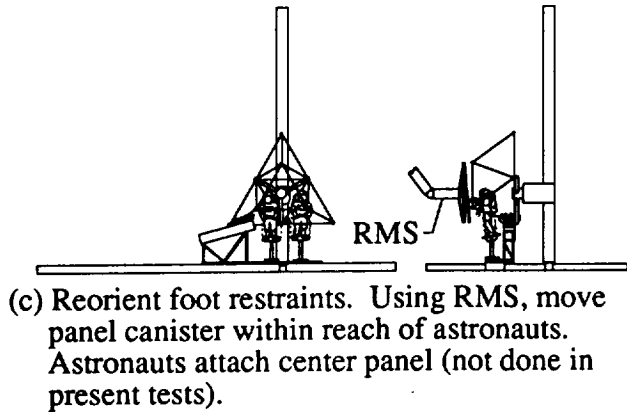
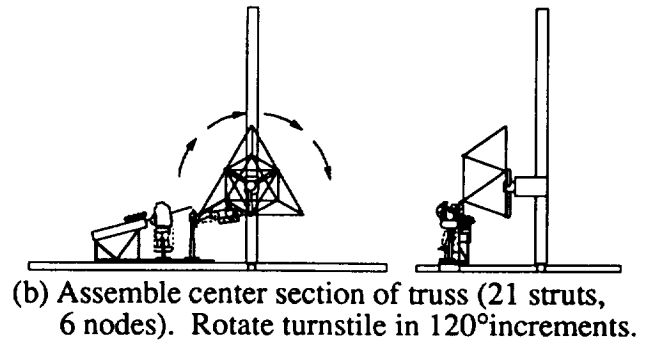
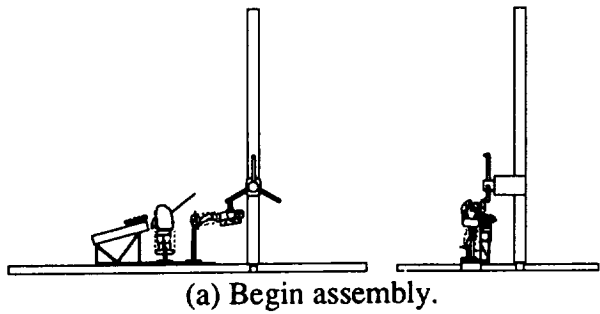
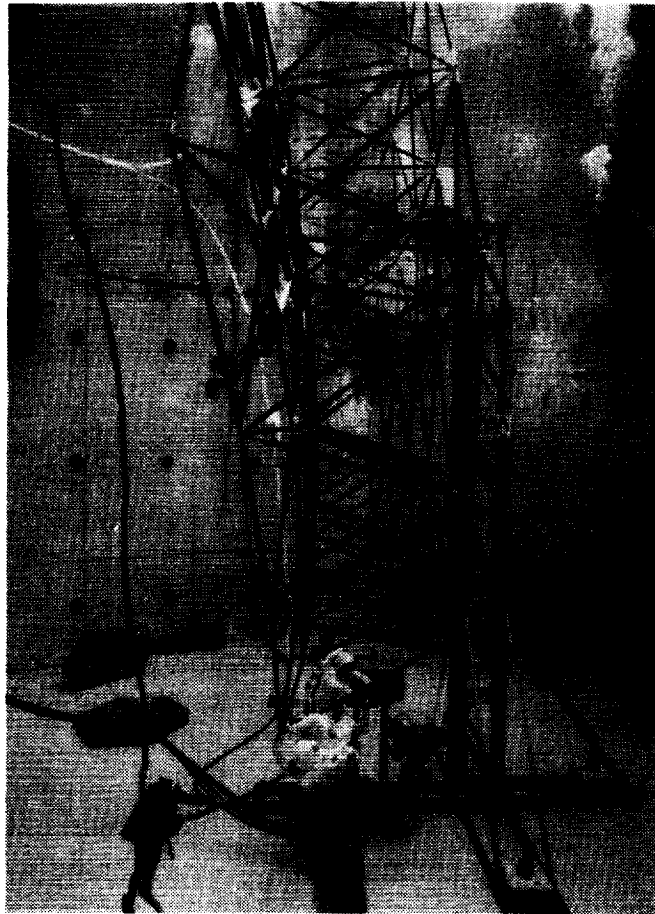
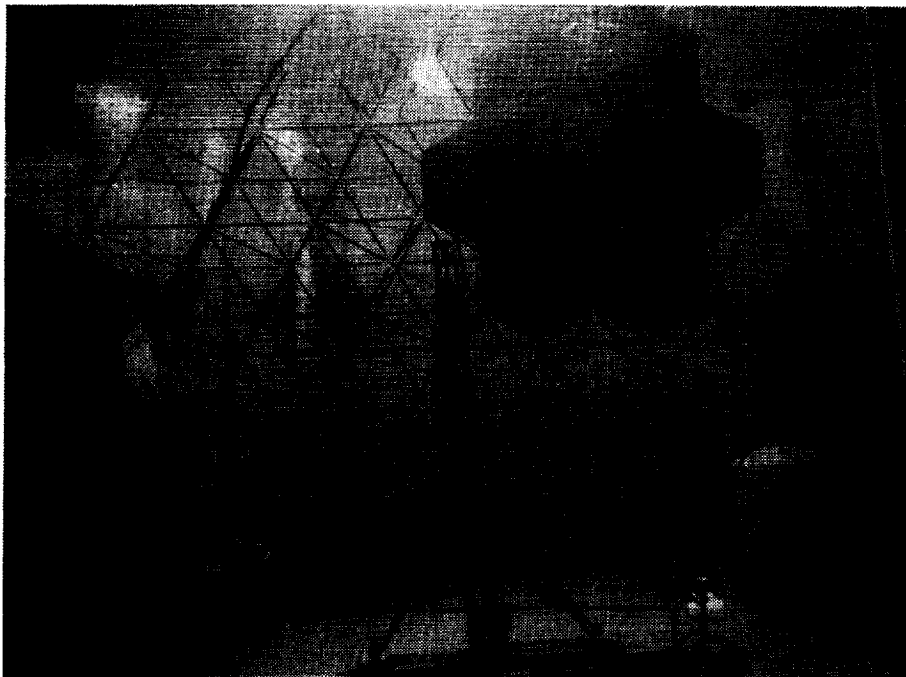


Fig. 7.-General assembly procedure.



(a) Side view



(b) Front view

Figure 8.- Completed reflector.

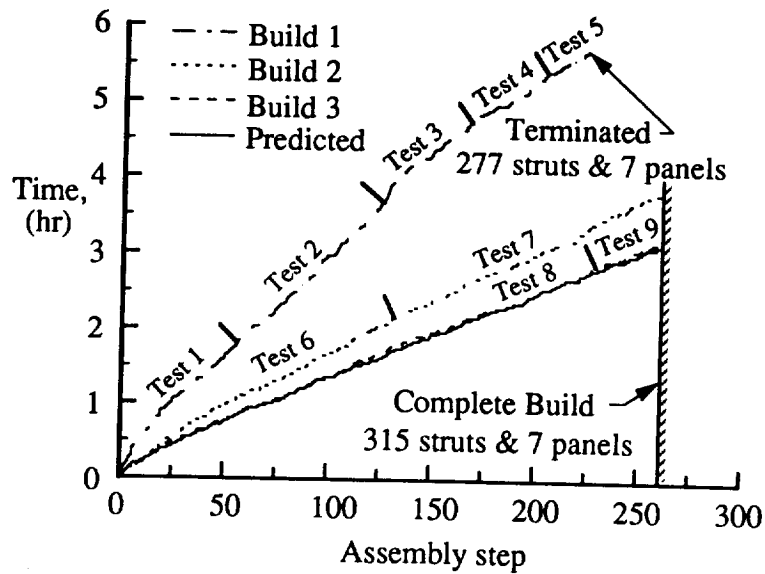


Fig. 9.-Time history for EVA assembly of test article.

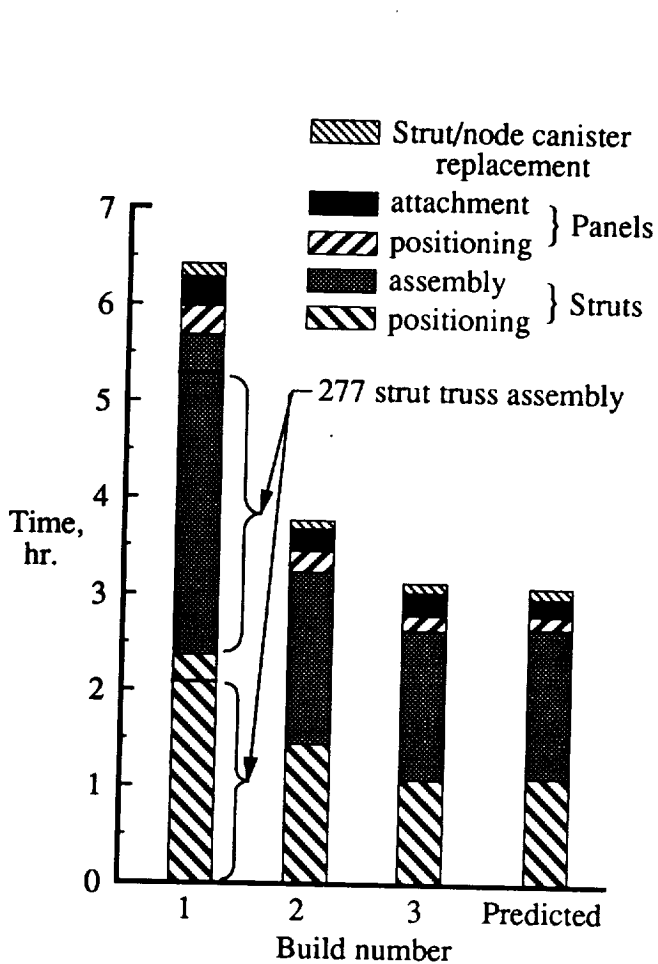


Figure 10.-Breakdown of task times for assembly of test article (7 panels).

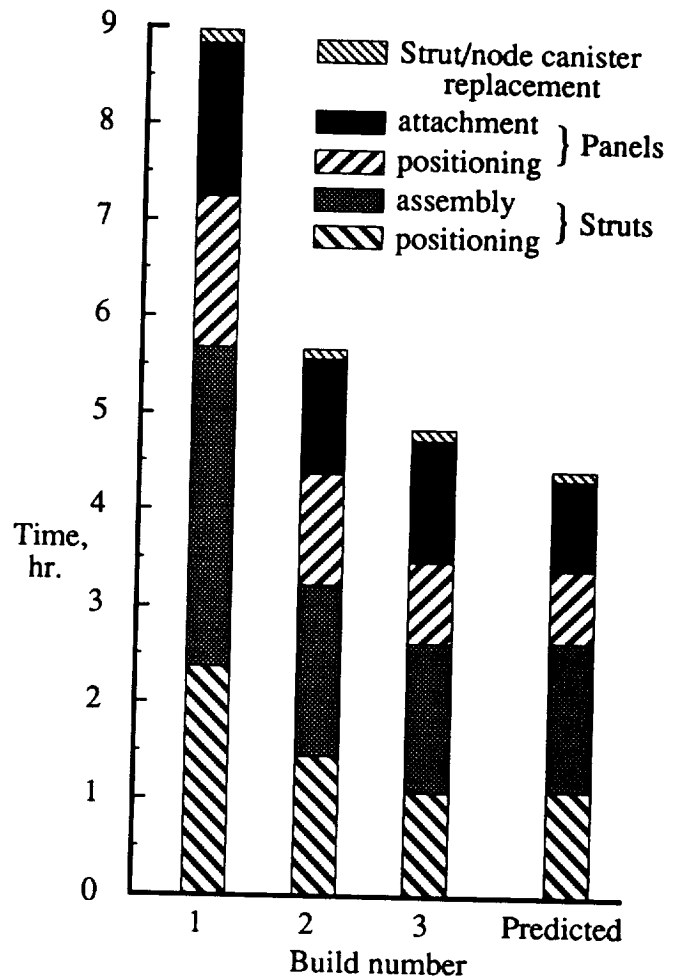


Figure 11.-Breakdown of task times projected for assembly of reflector with 37 panels.

REPORT DOCUMENTATION PAGE

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