JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 31, No. 4, July–August 1994

Neutral Buoyancy Evaluation of Extravehicular Activity Assembly of a Large Precision Reflector

Walter L. Heard Jr.* and Mark S. Lake†
NASA Langley Research Center, Hampton, Virginia 23681

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 0-*g* (neutral buoyancy) assembly tests of a 14-m-diam precision reflector mockup. The test article represents a precision reflector having a reflective surface that 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 3 h and 7 min by two pressure-suited test subjects. The average time to attach a panel was 2 min and 3 s. These efficient assembly times were achieved because all hardware and assembly procedures were designed to be compatible with EVA assembly capabilities.

Introduction

TO improve our understanding of the environment and the natural and man-made hazards that threaten it, NASA has begun numerous Earth science initiatives such as the Mission to Planet Earth program. Through these initiatives, new remote-sensing requirements are developing that will drive the design of the next generation of Earth resource surveillance sensors. Studies have already identified a future need for high-resolution sensors that will incorporate solid-surface primary reflectors that are up to 40 m in diameter with surface precisions between 20 and 50 μ rms.[1] One such instrument is the offset-feed scanning microwave radiometer sketched in Fig. 1. The proposed operational sizes of these primary reflectors exceed the payload shroud size of any current or envisioned launch vehicle. Thus, the primary reflector surface must be segmented into panels that are compatible with the size of the launch vehicle. Furthermore, to minimize the use of active shape control, these reflector panels will most likely be supported by a stiff, accurate truss structure.

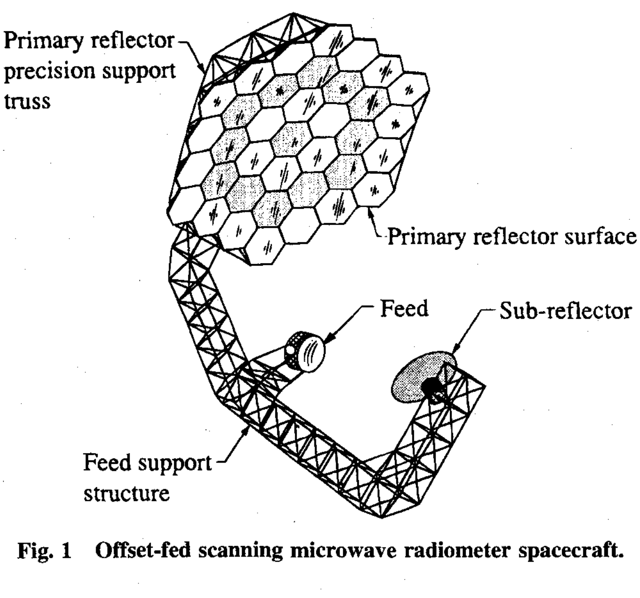


Fig. 1 Offset-fed scanning microwave radiometer spacecraft.

To make large precision reflectors viable, it is necessary to develop and demonstrate high-precision hardware and a reliable method for constructing reflectors on orbit using this hardware. Although methods to deploy precision reflectors on orbit are being studied,[2–4] deployable joints and actuators have not yet been developed that are capable of reliably deploying solid reflector panels and passively maintaining deployed reflector surface accuracies of 20–50 μ rms. Therefore, high-precision deployable solid-surface reflectors are still considered high-risk technology ventures. On the other hand, ground tests have demonstrated that a segmented reflector support truss can be assembled to an accuracy of 20–50 μ rms using high-precision erectable truss hardware developed by NASA.[5] Conceptually, either robotic devices or astronauts in extravehicular activity (EVA) could assemble precision reflectors on orbit using this hardware. Although preliminary studies of a ground-based automated construction system[6] have shown that a reliable, low-cost flight system will take many years of additional research to develop, preliminary simulated EVA tests[7] have indicated that astronauts should be able to efficiently and reliably assemble precision reflectors using currently available EVA technology. Therefore, the lowest development cost and least technically risky construction approach for building precision reflectors on orbit is EVA assembly.

Past simulated 0-*g* structural assembly tests[8–10] and the Assembly Concept for Construction of Erectable Space Structure (ACCESS) space construction experiment[11] have shown that well-trained astronauts who are adept at EVA can rapidly construct beamlike truss structures provided the truss hardware is EVA compatible and simple mechanical crew aids are used to position the astronauts at the work sites and to assure that the building material is readily accessible. However, each of the trusses studied in Refs. 8–11 consisted of struts having no more than 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.

Received July 16, 1993; revision received Sept. 14, 1993; accepted for publication Sept 15, 1993.

*Senior Aerospace Engineer, Structural Mechanics Division, Mail Stop 199. Senior Member AIAA.

†Aerospace Engineer, Structural Mechanics Division, Mail Stop 199. Senior Member AIAA.

In contrast, a doubly curved precision reflector such as that shown in Fig. 1 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.[7] Therefore it is important to understand how this complication affects the efficiency with which astronauts can assemble precision reflectors in EVA. 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 is minimized. The purpose of the present research is to apply the lessons learned in past EVA structural assembly tests to the development of hardware and procedures that enable efficient EVA assembly of precision reflectors and to verify these hardware and procedures through simulated 0-*g* assembly testing.

With the development and verification of an efficient and reliable EVA assembly procedure and the availability of high-precision erectable truss hardware, large precision reflectors could be assembled on orbit to support a variety of scientific missions. In the near future the Space Shuttle could be used as a construction base to assemble reflectors up to about 15 m in diameter. The diameter of the reflector panels could range between 2 and 4 m, which would enable efficient assembly in the Space Shuttle cargo bay. Further into the future, reflectors up to 50 m in diameter could be constructed at Space Station Freedom if it becomes available for use as a construction base.

14-m-Diam Reflector

The present study focuses on the construction of the radiometer primary reflector shown in Fig. 1 using procedures and EVA crew aids that could be designed for use on the Shuttle or Space Station Freedom. This reflector is an offset-focus paraboloid with an 11.8-m-diam aperture, supported on a doubly curved 14-m-diam tetrahedral truss. The reflector surface is partitioned into 37 hexagonal panels, each of which is attached at three corners to truss nodes. The truss is comprised of 84 nodes and 315 struts. The struts are approximately 2 m in length, but because of the curvature of the reflector, the struts differ slightly in length. In addition, the strut and panel attachment ports on the truss nodes differ slightly in orientation, and the reflector panels differ slightly in curvature and planform shape.

The design of the 14-m-diam reflector represents a compromise between structural performance, ease of fabrication, launch vehicle packaging, and EVA assembly considerations, and a key variable in this design trade is the size of the reflector panels. Large reflector panels can be packaged more efficiently in a launch vehicle than small reflector panels. Furthermore, the supporting truss structure for 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 supporting truss structure for 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 reflector panels. Therefore, as a reasonable compromise for the present tests, the 14-m-diam reflector is partitioned into 37 hexagonal panels that are approximately 2.3 m in diameter. However, as precision panel fabrication technology progresses, and if packaging and EVA handling requirements permit, it may become desirable to consider larger panels in the future.

EVA Assembly Procedure Guidelines

The assembly procedure is based on experience gained from many neutral buoyancy structural assembly tests performed over the last decade in which the 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 and EVA crew aids. 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.

1) 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 astronauts would not warrant the additional complexity required of the EVA crew aids, the assembly procedure, and the extra life support systems.

2) Perform most tasks from foot restraints. 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 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 with one hand and with minimal applied force or torque.

3) Improve efficiency through automated crew aids. Space construction by EVA methods is efficient when the astronauts are used solely to assemble the structure. Other tasks, such as translating between work sites and retrieving building material canisters, can be time consuming as well as fatiguing for the EVA crew to perform unaided. Thus, the EVA crew should be translated between work sites using mobile foot restraints, and strut/node and panel canisters should be positioned using an automated device such as the remote manipulator system (RMS). Furthermore, to minimize wasted time, it is important to maneuver the RMS in parallel with the astronauts' assembly tasks when possible because RMS motions are characteristically slow and could retard assembly time by creating long idle periods for the EVA crew.

4) Use an assembly fixture. To reduce the range of motion, to simplify the design of the mobile foot restraint system, and to enhance positioning efficiency, the reflector should be held by an assembly fixture that provides additional 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.

5) Use one astronaut to assemble the truss and one to manage the material. In previous simulated EVA assembly tests[8,10] and in the ACCESS flight experiment,[11] beamlike trusses were efficiently assembled by two people, each with access to separate strut canisters. However, a new approach was devised to assemble curved reflector support trusses using only one astronaut to assemble the truss and one to manage the building material. This strategy reduces the diversity of 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 space. However, if fatigue becomes a problem, astronauts could trade positions at an appropriate point during the assembly. A change of positions would require thorough cross training so that the astronauts learn the different assembly tasks associated with each position, but such training has historically been standard operating procedure for all EVA activities.

6) Handle panels only from the back (nonreflective) side. 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 devised confines the astronauts to working behind the reflector panels at all times.

7) 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.

8) Attach panels to a stable structure. The panels should always be attached to nodes that are kinematically stable, i.e., nodes that have been "rigidized" by connected struts. This rule minimizes the risk of damaging panels during assembly by insuring that they are firmly held in position relative to one another at all times.

Test Apparatus

Test Article

A test article representing the 14-m-diam radiometer primary reflector was fabricated for the present tests using near-flight-quality strut and panel attachment joints[7] and mockup reflector panels made of sheet metal. A sketch of the test article attached to an assembly fixture and installed in the Marshall Space Flight Center (MSFC) Neutral Buoyancy Simulator (NBS) water tank is shown in Fig. 2. The test article is about the largest practical size that can be accommodated in the 12.2-m-deep NBS water tank. To reduce costs, only seven mockup reflector panels were fabricated. These panels were arranged in a single cluster with six of the panels surrounding a central panel so that removal and replacement of an interior panel could be investigated.

Truss

The test article truss is composed of 84 nodes and 315 struts. Each end of a strut has an aluminum joint-half (Fig. 3a) that mates to a matching joint-half located on a node. A spring-loaded capture feature is designed into the strut joint-half to allow the EVA astronaut to make a quick temporary attachment with one hand. The astronaut then completes the strut-to-node connection by rotating a locking collar on the strut joint-half 45 deg. To best simulate weightless behavior in the underwater environment, each strut is equipped with internal buoyancy compensators at both ends. The buoyancy compensators allow the struts to be neutrally buoyed and trimmed to maintain any depth and any given orientation underwater without altering the external appearance of the struts. The nodes could not be made neutrally buoyant without adding external floatation that would alter their external appearance and impede handling. Therefore, no attempt was made to neutrally buoy the nodes. Additional details of the design and operation of the truss hardware is presented in Refs. 5 and 7.

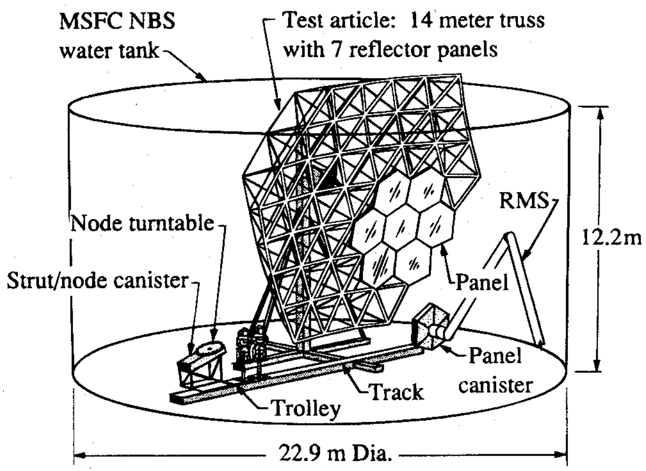


Fig. 2 Test article attached to the assembly fixture installed in the Neutral Buoyancy Simulator.

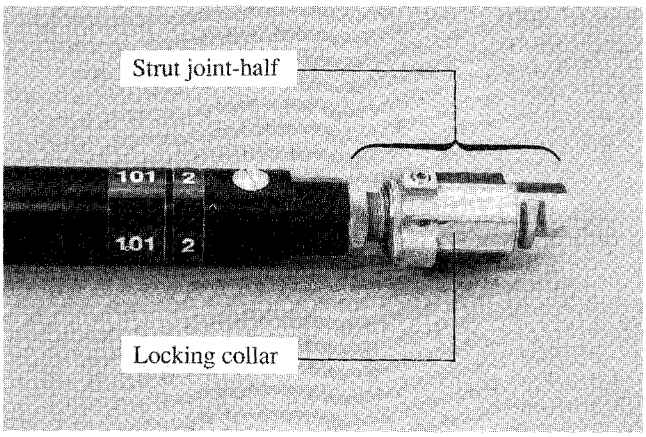


Fig. 3a Typical truss strut.

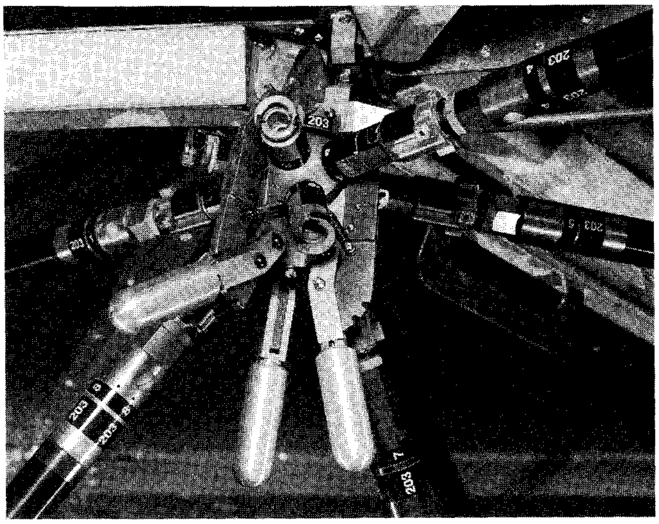


Fig. 3b Typical node in concave surface of truss.

Figure 3b shows a typical "interior" node on the concave truss surface (truss surface that supports the reflector panels). All interior concave- and convex-surface nodes are fitted with nine joint-halves for strut attachments, whereas perimeter nodes (those lying around the edge of the truss) are fitted with four to seven joint-halves. The center of each concave-surface node is 12 cm behind the reflector surface to allow room for the reflector panel attachment hardware.

To produce the desired curvature in the truss, the distances between the centers of adjacent nodes range from a minimum of 2.038 m to a maximum of 2.206 m. Since all joint hardware is identical, the node-center to node-center distance is varied by adjusting the lengths of the struts between 1.777 and 1.944 m. This variation in strut lengths (and, consequently, the variation in node-center to node-center distance) was 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) If all struts in the concave side of the truss have approximately the same length, the reflector panels have approximately the same size and shape, thus simplifying the design of reflector panel stowage canisters. 3) During fabrication, struts were set to length using a laser interferometer fixture that accommodates only a limited range of strut lengths.

There are 107 different node-center to node-center dimensions for the 315 struts. Thus, many struts should have the same lengths. However, due to the extreme surface precision requirements of this type of reflector, all struts are set to unique lengths to compensate for manufacturing tolerances in the truss nodes.[5] Therefore each strut occupies a unique location in the reflector truss, and no interchanging is allowed during assembly. The procedure and fixture for setting the struts to length are described in Ref. 5 (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. 5).

Panels

Each reflector panel is attached to three concave-surface truss nodes using latch hardware that is described in detail in Ref. 7 (referred to there as the "Design 1" concept). The corners of three adjacent panels are attached to each interior node in the concave surface; thus three panel latches are incorporated into these nodes as shown in Fig. 3b. Nodes located along the edges on the concave surface of the truss accommodate the corners of only one or two panels; thus only one or two panel latches are incorporated into these "boundary" nodes. Normally all concave surface nodes would incorporate panel attachment hardware. However, 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.

Figure 4 shows the seven mockup panels attached to a segment of the truss (see also Fig. 2). To reduce the fabrication costs, each mockup panel is 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 are designed to lie in the paraboloidal reflector surface. 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. EVA handles are provided on the back (nonreflective) side of each panel to facilitate handling and maneuvering by the EVA crew. Rigid closed-cell foam is bonded around the panel edges for floatation, and three ballast chambers are attached to the panel frame to allow trimming for neutral buoyancy. More details of the mockup panel construction and the panel attachment hardware may be found in Ref. 7.

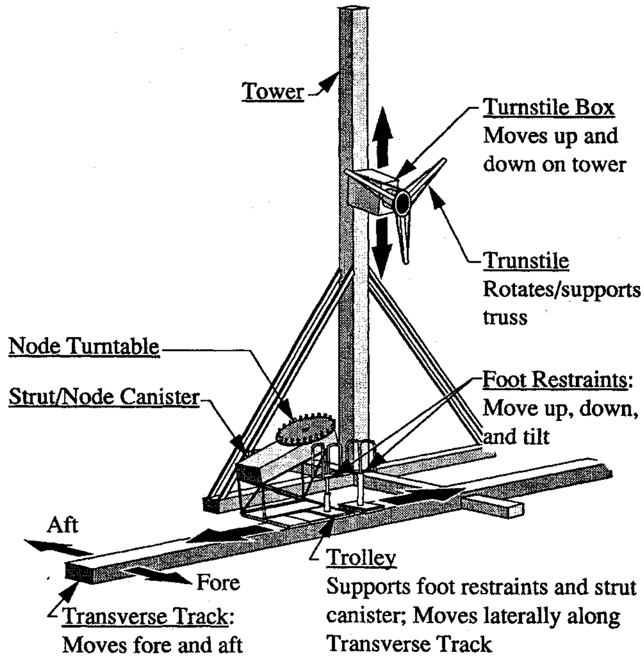


Fig. 5 Assembly fixture and mobile foot restraints.

Assembly Fixture, Mobile Foot Restraints, and On-Orbit Scenario

Figure 5 is a schematic showing the various components of 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 that supports and positions the reflector test article during assembly, thereby reducing the range of motion requirements of the mobile foot restraints. The test article is attached to the turnstile at the center ring of three nodes lying in the convex side of the truss. As the test article is assembled, its diameter increases and the turnstile box is moved upwards on the tower to keep the bottom edge of the test article at a convenient height for the test subjects.

Two test subjects retrieve stowed hardware and assemble the test article from mobile foot restraints positioned at the base of the assembly fixture. 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 1 of vertical travel. Since the current test setup requires one test subject to be reclined while assembling the truss, one foot restraint incorporates a kinematic linkage that allows the 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. 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 truss struts and nodes are stowed in their order of assembly in five strut/node canisters. Each canister contains 63 struts and from 12 to 21 nodes that are stowed on a turntable attached to the canister. Only one 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).

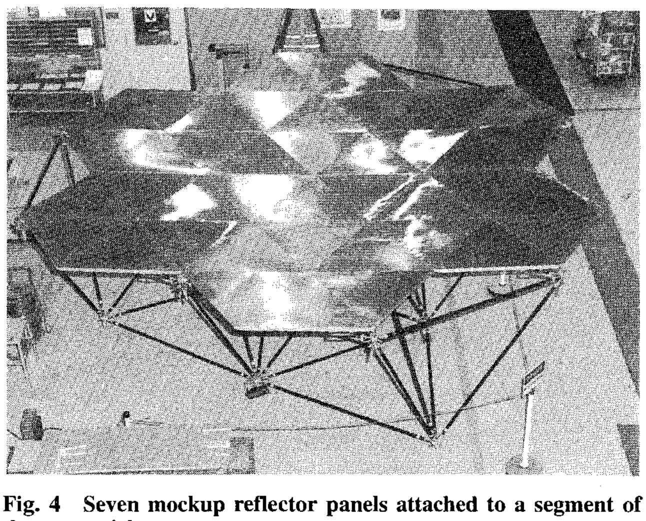


Fig. 4 Seven mockup reflector panels attached to a segment of the test article truss.

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. All motions are directed by the test subjects through voice communications with the console operator who can view the assembly operations through a porthole in the tank wall.

The assembly fixture is sized with large factors of safety for 1-*g* operation. Hydraulics are used for convenience. An assembly fixture designed for use on orbit 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 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. The transverse track would be stationary and the necessary fore and aft motion provided through an additional degree of freedom designed into the trolley. If vernier-positioning motions can be minimized, all coarse-positioning motions of the foot restraints and turnstile could be preprogrammed and controlled by the EVA astronauts using relatively few commands from a simple controller mounted to the foot restraint. Thus the need for a remote operator could be eliminated.

Assembly Procedure

An areal structure having double curvature is more complex to assemble than a beamlike structure due to the large number of unique parts that must be handled. The present procedure compensates for this complexity by reducing the diversity of tasks for which each test subject is responsible. This procedure allows the test subjects to easily assemble the reflector without written instructions or verbal prompting by restricting one test subject to unstowing and managing the truss hardware while the other is restricted to making the structural connections. Furthermore, to minimize foot restraint positioning time, each test subject is maintained in a predetermined orientation for all truss assembly tasks. However, the test subjects are reoriented for panel attachment activities.

The assembly procedure consists of 261 steps. A detailed computer-generated drawing was developed for each step to estimate assembly time and to evaluate test subject and truss positioning requirements. This procedure is summarized in Fig. 6. During truss assembly (Fig. 6a), the test subject in the upright orientation removes the struts and nodes from the strut/node canister and passes them to the test subject in the reclined (horizontal) orientation who makes the structural connections. After a row of truss is completed, the test subjects are reoriented for attachment of panels to that row of truss (Fig. 6b).

Each panel is kept in a protective canister that is maneuvered by the RMS into a position within reach of the test subjects (Fig. 6c). For the present tests, the panel canister was sized to hold only one panel. However, a dispenser-type canister capable of stowing multiple panels would probably be used on orbit to reduce the number of RMS maneuvers required for panel attachment operations. After the panel is in position, the test subjects remove it from the canister and attach it to the truss. After the two lower panel attachment joints are locked, one of the test subjects egresses his foot restraints and manually translates a few feet to lock the upper panel attachment joint. This free-floating operation is allowed because it requires less time than repositioning the foot restraints. The panels are always handled from the back side to reduce the risk of damage to the reflective surface. After each row of truss and panels is assembled, the reflector is rotated 120 deg, and assembly is begun on the next row. This process is repeated until the reflector is completed (Fig. 6d).

Each step of the assembly procedure was divided up into individual tasks such as translating to a new work site, unstowing a piece of hardware, or connecting the piece of hardware to the reflector. Then each task was evaluated based on previous truss assembly test data, estimates were made for the time necessary to complete each task, and these estimates were compiled into the predicted assembly times presented in the following section. The foot restraint trolley was designed and estimated to translate at 1 ft/s, which is believed to be reasonable for a flight version. Likewise, due to flight data, the RMS translation rates were assumed to be much less (actual rates varied depending on the task). However, the assembly procedure was designed with minimal RMS translations, and EVA tasks were conducted in parallel with the RMS whenever possible to minimize the effect slow RMS operations would have on the total assembly time.

Test Results

Test Article Assembly Times

A photograph of the fully assembled test article is shown in Fig. 7. The top of the test article protrudes out of the water; thus it is not visible in the photographs. Figure 8 shows the elapsed time at the completion of each assembly step during the three assemblies (denoted Build 1, Build 2, and Build 3) of the test article. Since the assembly steps do not necessarily consist of identical tasks, the elapsed time per step varies considerably, and the elapsed-time curves in Fig. 8 are not smooth. Multiple tests were required to complete each build because test durations were limited to 2½ h to insure the safety of the

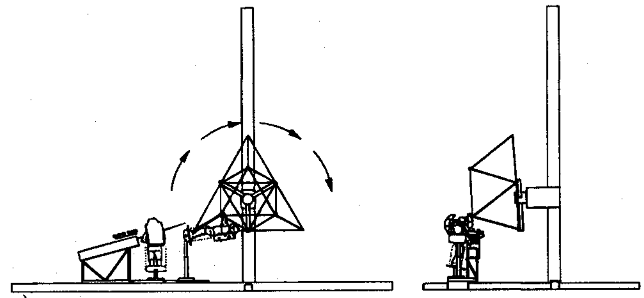

a)

Fig. 6a Begin assembly at center of truss rotating turnstile in 120-deg increments.

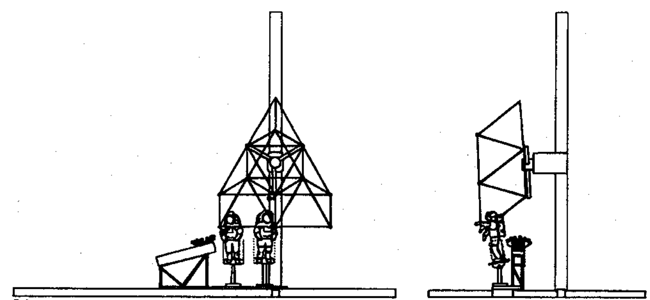
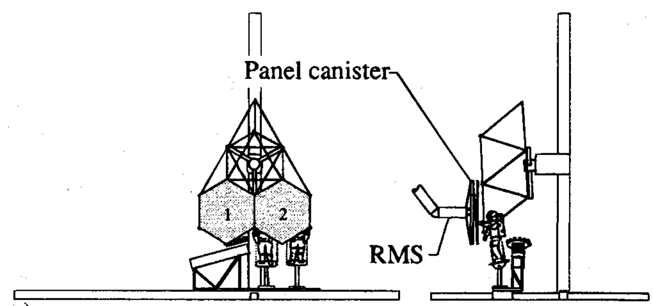

b)

Fig. 6b Reorient foot restraints to attach panels.



c)

Fig. 6c Move panel canisters within reach of test subjects using RMS; attach panels to truss.

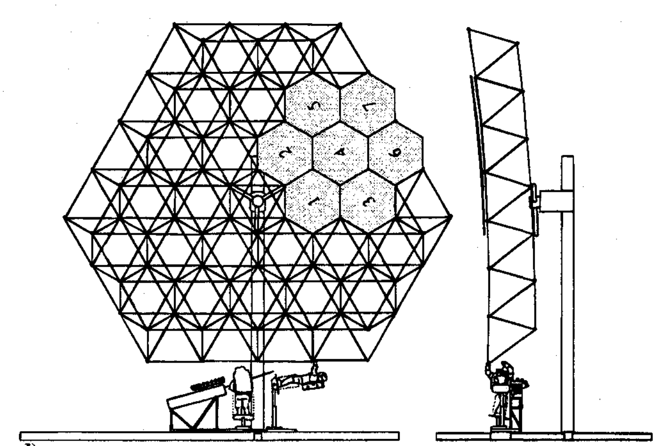

d)

Fig. 6d Rotate turnstile 120 deg, assemble a row of truss, attach panels, repeat until reflector is complete.

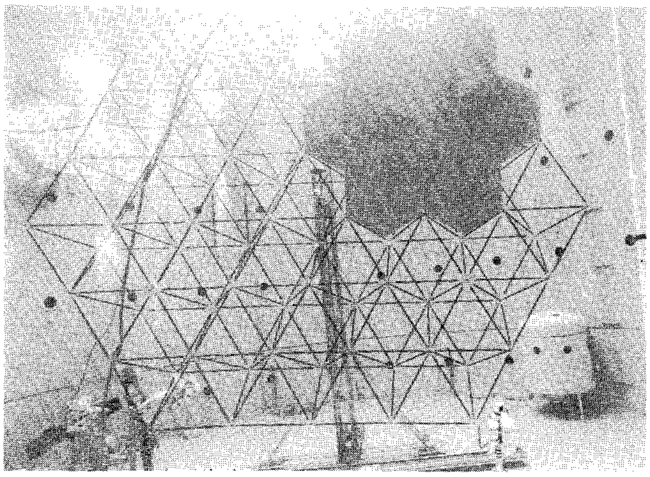


Fig. 7 Photograph of assembled test article in Neutral Buoyancy Simulator.

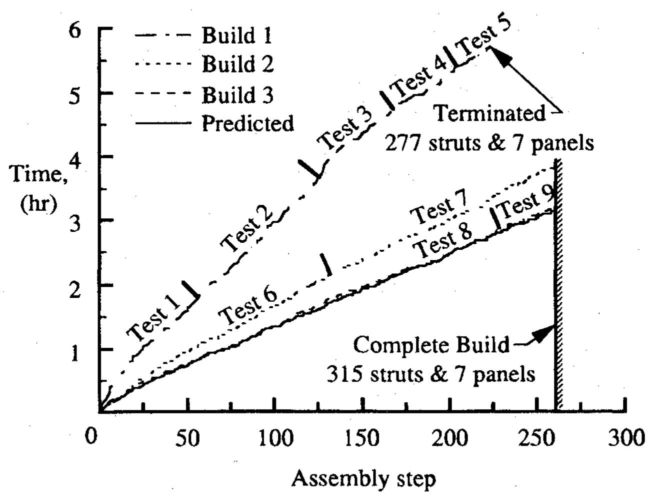


Fig. 8 Time history for simulated EVA assembly of test article.

test subjects, and many tests were terminated early due to logistical problems such as electrical storms in the vicinity, life support system malfunctions, and test hardware malfunctions. Most life support system and hardware problems occurred and were corrected during the first five tests composing Build 1. Nevertheless, since only one test was allowed per day, and the number of available tests days was limited, Build 1 was terminated after completing only 226 steps 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 that they needed to learn and, thus, to 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 the assembly procedure and to 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 that 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.

Because of 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 that preclude the reclined test subject from applying a firm palm grip to the joint locking collar. Consequently, during the first three tests of Build 1 the engineer and astronaut test subjects experimented with factors such as the height of the test article above the foot restraints and the body position of the reclined test subject to determine the optimum techniques (least fatiguing and fastest) for constructing the test article. This learning process is the major contributor to the excessive time (more than twice the prediction) taken to assemble the test article during Build 1 (Fig. 8). Build 2, which was accomplished during tests 6 and 7, shows 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. Consequently, the assembly times for Build 3 corroborate the predicted time shown by the unbroken line in Fig. 8.

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 Fig. 8 demonstrates that adequate training can be time consuming, and conclusions drawn from early tests can be misleading. For example, if the test program had been halted after the first five tests, unrealistically high estimates would have been made of the time necessary for on-orbit assembly of this precision reflector. Unfortunately, in many EVA development programs, EVA time estimates and hardware compatibility assessments are based on a very limited number of tests. One problem with this approach is that when the astronauts are allowed only a short period of time to work with the hardware, they are forced to make assessments before they have had the opportunity to become completely familiar with its operation. This problem is particularly significant if the EVA hardware being evaluated is complex. Therefore, 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 usually manifests itself in reduced fatigue, increased proficiency, and a significant improvement in the perceived "EVA compatibility" of the hardware. Therefore, it is important to plan a generous amount of EVA training time before evaluating developmental hardware so that design revisions are based on accurate evaluations.

Breakdown of Assembly Task Times

Figure 9 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 (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) truss assembly (attachment of struts to 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 only 277 truss struts were assembled, the truss assembly and positioning times have been extrapolated in Fig. 9 to estimate the times for assembly of the complete truss with 315 struts.

Similar to Fig. 8, Fig. 9 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 with 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. 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, whereas 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.

Test Subjects' Assessment and Comments

General

The multiple tests available to the engineer test subjects afforded them enough training time to develop their techniques for execution of the assembly procedure as planned and within

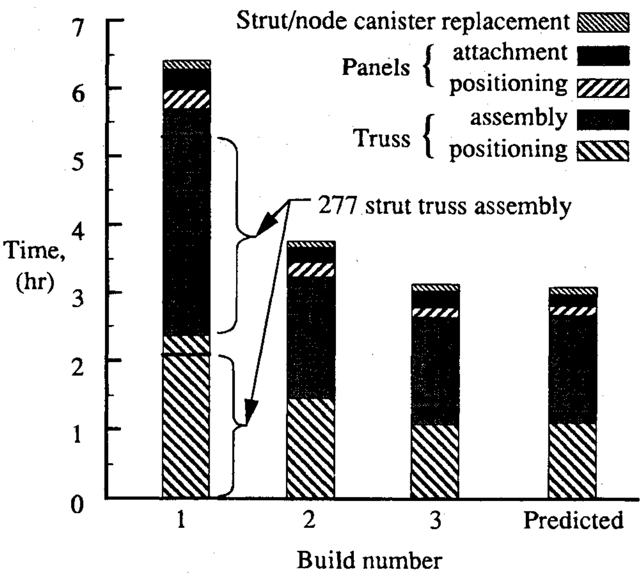


Fig. 9 Breakdown of task times for assembly of test article.

predicted times during the Build 3 tests. 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 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 virtually eliminates the risk of assembling components out of order or in the wrong location.

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. 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. Finally, the locking handles were easily rotated to the locked position to effect the final structural connection.

There were only two significant sources of time delays during panel attachment of 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, 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 to less than 0.5 ft/s 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, 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 the arm length should be adjusted to keep the 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 NBS 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 2 m) 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 reclined test subjects 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.

2) The strut-to-node capture feature allows single-handed alignment and capture of the struts, thus extending the test subject's functional reach envelope and enabling him to make connections that 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 fingertip pressing against the strut joint-half can be nearly as effective for capturing the joint-halves.

3) 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.

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

5) 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.

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 0-*g* (neutral buoyancy) assembly tests of a 14-m-diam reflector mockup. The test article is a doubly curved tetrahedral truss consisting of 315 struts and 84 nodes, supporting a reflective surface. The complete reflective surface would consist of 37 closely spaced, hexagonal panels, but only seven panels were fabricated fur 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 of the structural connections. The following conclusions can be drawn from these tests.

1) 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.

2) The precision reflector assembly procedure is built around a few basic steps that 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 are 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 be learned only after considerable practice and training 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 demonstrate 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 the 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.

References

[1] Campbell, T. G., Lawrence, R. W., Schroeder, L. C., Kendall, B. M., and Harrington, R. F., "Development of Microwave Radiometer Sensor Technology for Geostationary Earth Science Platforms," Inst. of Electrical and Electronics Engineers, IEEE Catalog No. 91CH2971-0, June 1991.

[2] Mahoney, M. J., and Ibbott, A. C., "A Large Deployable Reflector Assembly Scenario, A Space Station Utilization Study," NASA JPL D-5942, Nov. 1988.

[3] Miller, R. K., Thomson, M., and Hedgepeth, J. M., "Concepts, Analysis and Development for Precision Deployable Space Structures," NASA CR 187622, July 1991.

[4] Mikulas, M. M., Jr., Freeland, R. F., and Taylor, R. M., "One-Ring Deployable High Precision Segmented Reflector Concept," NASA JPL

D-9845, June 1992.

[5]Bush, H. G., Herstrom, C. L., Heard, W. L., Jr., Collins, T. J., Fichter, W. B., Wallsom, R. E., and Phelps, J. E., "Design and Fabrication of an Erectable Truss for Precision Segmented Reflector Application," *Journal of Spacecraft and Rockets,* Vol. 28, No. 2, 1991, pp. 251–257.

[6]Desrochers, A. A., ed., *Intelligent Robotic Systems for Space Exploration,* 1st ed., Kluwer Academic Publishers, Norwell, MA, 1992, pp. 100, 101.

[7]Heard, W. L., Jr., Lake, M. S., Bush, H. G., Jensen, J. K., Phelps, J., E., and Wallsom, R. E., "Extravehicular Activity Compatibility Evaluation of Developmental Hardware for Assembly and Repair of Precision Reflectors," NASA TP 3246, Sept. 1992.

[8]Heard, W. L., Jr., Bush, H. G., Wallsom, R. E., and Jensen, J. K., "A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Spaces Trusses," NASA TP 2108, March 1983.

[9]Watson, J. J., Heard, W. L., Jr., and Jensen, J. K., "Swing-Arm Beam Erector (SABER) Concept for Single Astronaut Assembly of Space Structure," NASA TP 2379, March 1985.

[10]Heard, W. L., Jr., Watson, J. J., Lake, M. S., Bush, H. G., Jensen, J. K., Wallsom, R. E., and Phelps, J. E., "Tests of an Alternate Mobile Transporter and EVA Assembly Procedure for the Space Station Freedom Truss," NASA TP 3245, Oct. 1992.

[11]Heard, W. L., Jr., Watson, J. J., Ross, J. L., Spring, S. C., and Cleave, M. L., "Results of the ACCESS Space Construction Shuttle Flight Experiment," AIAA Paper 86-1186, June 1986.