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A 928-M^2 (10 000 FT^2) SOLAR ARRAY

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ABSTRACT

As the power requirements for space vehicles increases, the area of solar arrays that convert solar energy to usable electrical power increases. The requirements for a 928-m^2 (10 000 ft^2) array, its design, and a full-scale demonstration of one quadrant (232 m^2 (2500 ft^2)) deployed in a one-g field are described in this report.

INTRODUCTION

Until the beginning of this program, all operational solar-array systems were designed in small sizes (the largest was 112 m^2 in area per vehicle) and were designed for low structural loadings (0.1-g level or less) in the deployed condition. The space station solar-array requirements were to design a deployable array of silicon solar cells 928 m^2 in area that was to be capable of articulation in two axes for sun tracking; the entire structure was to be packaged for deployment in the space shuttle cargo bay. The entire structure had to be retractable automatically into a 4.27-meter diameter by 15.25-meter length shuttle cargo envelope without recourse to astronaut extravehicular activity (EVA). Furthermore, high-on orbit loads had to be tolerated by the structure in the deployed condition because it was required that the entire space station rotate about a center displaced as much as 13.4 meters from the center of mass of the solar-array system, resulting in nonsymmetric gravity loadings that are an order of magnitude greater than those previously experienced in operational solar arrays.

After an evaluation of state-of-the-art solar-array and extendible-beam technology, design studies were conducted to evaluate several structural configurations, including calculation of weight penalties and assessment of system complexity. A two-boom system was selected that used an Astromast boom as a basic deployable structure. This boom and rigid truss members, which also functioned as ascent supporting members for the stowed solar array, were the main structural elements. A unique variable-tensioning system and an auxiliary guide-wire system were used for deployment of the flexible solar-array strips.

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Full-scale hardware was fabricated and assembled into a 232-m^2 quadrant of the 928-m^2 array. The quadrant components were tested individually for function and were assembled for deployment-capability testing.

DESIGN REQUIREMENTS

The following two ground rules were established at the beginning of the design phase to accommodate the development of a valid component-technology demonstration during a period of requirement definition. Maximum use was to be made of modularity so that changes could be made at the component and subcomponent levels and to facilitate straightforward size scaleup or scaledown. If a requirement conflict occurred, the most difficult requirement was to be adopted so that any subsequent changes or firming up in requirements would result in a less difficult design or fabrication problem and, thereby, not compromising the validity of the technology demonstrated in the program.

The NASA shuttle-launched space station requirements were used as a basis for the design. The shuttle requirements that were developed originally and the requirements derived using the noted ground rules are listed in table I. There were additional assumed requirements, listed in table II, which provided a basis for the solar-array design.

STRUCTURAL DESIGN

Configuration

A model of the space station solar-array baseline 928-m^2 design is shown in figure 1 in relation to a shuttle-launched space station concept. The test quadrant that was fabricated is shown in figures 1 and 2. The quadrant is 10.3 meters wide by 27.4 meters long. The orientation and power-transfer drive is built around a 1.53-meter power-boom section at the center root of the array.

The initial deployment sequence of the solar array, starting with the position of the stowed quadrants that are packaged within the 4.27-meter maximum envelope (a basic requirement of the design), is shown in figure 3. Initial outward deployment of the quadrants is accomplished by means of a jackscrew mechanism. After this phase of the deployment has been accomplished, the upper portion of the structure, the outboard support assembly (OSA), begins the deployment of the major array.

The major structural elements of the solar array and the next step in the deployment sequence are shown in figure 4. The two inboard solar-array strips, on each side of the boom, deploy to provide power for the artificial-gravity mode, which is the initial mode that is assumed to be used in the operational station. The inboard and outboard supports form the upper and lower supports for the packaged array during launch and contain the tensioning mechanisms that are required for proper support of the arrays. Also, these support assemblies provide housings for the guide-wire assembly that is used for solar-array-strip alinement and to provide retraction capability for the strips. After all of the 10 solar-array strips have been deployed, subsequent retractions are completed with all solar-array strips and structures being retracted together, providing replaceability at the array level. An attachment point is provided for the support of the inboard support assembly during ascent and the artificial-gravity mode.

The deployed arrays, with guy tapes in place, are shown in figure 5. The inset shows more details of the packaged array before deployment.

Extendible Truss Beam

The extendible truss beam (ETB) forms the primary structural element of the solar-array system. It is the actuation (deployment and retraction) device and the supporting structure for the flexible-substrate solar array. Because of its characteristics of high strength and stiffness as well as low weight and thermal bending, a truss beam was selected for this application. Although other truss-beam designs that have significantly lower parts counts and higher strength-to-weight ratios are available, the Astromast beam (figure 6) develops full strength and rigidity at any stage of deployment, is fully retractable, and represents the minimum developmental cost. In addition, this type of boom is versatile in that the deployed length and structural properties may be varied with little change to the basic design and hardware.

In the launch mode, the entire beam is stowed within a canister 0.61 meter in diameter and 1.32 meters in height. The upper external portion of this canister is a rotatable nut that has three sets of inward-facing rectangular threads. The internal (stationary) part of the canister supports the three vertical guideslots. The rollers extending from the beam-batten corners are guided by tracks and are engaged simultaneously between the vertical guideslots and the lands of the threaded nut. The beam deploys from or retracts into the canister when the nut is rotated by means of electric motors. Cams for latching and unlatching the diagonal linkages of the beam are fixed to the inner canister wall just below the rotating nut. The ETB is shown deployed in figure 7.

When extended to its full length (25.6 meters), the beam is composed of 66 bays (including two bays that remain inside the canister). A single bay consists of two fixed (upper and lower) tubular triangles (battens) joined at each of the vertices by vertical tubular compression members and by diagonal cable-tension members. Three of the six tension cables terminate at one end (bottom of the bay) in an "over-center" toggle-joint locking mechanism. The longerons and tubular batten members are deformed locally to minimize the stowed-package height. These deformations reduce the overall stowed height by approximately 30 percent, and reduce the strength of the members by approximately 25 percent.

The ETB was subjected to basic structural testing in the vertical position. Compression loads of as much as 19 670 newtons (2400 pounds) combined with a 271 meter-newtons (200 foot-pounds) bending moment were sustained without failure. Also, during testing, more than 2000 bays were extended and retracted successfully. The only major failure occurred when a pivot pin in the latching mechanism sheared after 882 bays had been extended.

Guy-Tape Assembly

The guy-tape system minimizes the beam-bending loads and prevents cross-wrinkling of the substrates strips by limiting the inplane deflections of the truss beam to less than 25 centimeters. These deflections of the beam tip are caused by external loading on the array from station-docking, attitude-control, and artificial-gravity operation.

The guy-tape assembly consists of a 27.10-meter (1068 inch) winding tape and a reel motor for stowage and release of the tape. The reel motor (one for each quadrant of the array wing), to which one end of each tape is attached, is mounted near the outer end of its inboard-support assembly. The other end of each tape is fixed to the cap at the upper end of the truss beam by means of a pair of 0.294-centimeter-diameter stainless-steel-cable assemblies, each of which straddles the cap assembly. As the truss beam is deployed, the tapes unreel until a fixed position of the array wing is reached. The guy-stowage mechanism is shown in figure 8 installed on the inboard support assembly (ISA).

Strip Tensioning and Deployment Mechanism

As was mentioned, the three outer strips of each solar-array quadrant are deployed after artificial-gravity operation has been completed and are tensioned to a constant value of 29.2 N/m (2 lb/ft) throughout the entire mission life. To accomplish this task, a simple motor-clutch system is mounted on the OSA (fig. 9) and is combined with a Negator reel-tensioning system on the inboard supports in order to provide a simple combined deployment drive and tensioning system for the zero-g strips. The two strips closest to the beam in each quadrant require much higher tensions during operation in artificial gravity. These strips are tensioned through the use of a pneumatic bellows system. During ascent, the unpressurized bellows are left open to the outboard atmosphere to prevent inadvertent actuation of the mechanism. After extension and before artificial-gravity operation, the bellows are pressurized to provide the increase in tension for the strips; tension is maintained until the station returns to a zero-g mode. Assuming the strip modulus of elasticity is constant with load, the tension during artificial-gravity operation will vary from 1220 newtons (275 pounds) to 1265 newtons (285 pounds) because of length changes that result from orbital temperature variations in the extendable beam and the strip (fig. 10). After the artificial-gravity mode, the bellows are depressurized and the system becomes a completely spring-loaded system for the remainder of the mission.

Array Packaging and Deployment Assembly

Details of one array-strip packaging assembly, 20 of which are required for the solar-array baseline design, are shown in figure 11. The cover plate (top) and the base plate (bottom) of the strip package are honeycomb pallets that are lined on the inside with polyurethane foam. The plates are used to provide support normal to the stored modules and to provide contamination control during ground-based handling ascent and descent phases of the station mission. The sheet-metal sides on the packaging assembly are formed to deflect the retracting strip modules into the container for orderly stacking during the ground-based test. Also, the sides are used to control contamination and to contain the retracted strip during resupply operations.

Each strip cover plate has six adjustable preload screws (three near the front edge and three near the rear edge) to prevent slippage between stowed strip-module joints during launch and ascent. Separation-nut assemblies, at the front and rear center edges of the cover and base plate, form the tie points of the ISA and OSA, thereby supporting the container. These assemblies are detonated on command to release the preload screws and to permit system deployment.

Cushioning pads between alternate module layers (cell to cell surfaces) of a strip prevent possible cell damage during ground-based handling and ascent vibration. The pads are hinged, at the front edge of the ISA, to a spring-loaded double-hinge system to facilitate removal of the pads during deployment. A pair of guide wires, tensioned by negator motors and reels and passing through slots in alternate module joints, maintain control of the strips during deployment and retraction of the array. During extension and retraction tests, the simulated OSA was offset as much as 10° and the strip was extended and retracted successfully several times.

GROUND-BASED TESTING

To demonstrate quadrant operation it was necessary to counterbalance all deployed fixed and variable weights and to balance the system tensions with an applied (but variable) moment at the beam cap. This setup was accomplished as shown in figure 12.

A 12.2-meter I-beam was supported from the test area ceiling 33.6 meters (110 feet) above the floor and was stabilized by means of a cable on each end tied to the floor. The beam was used to support the pulley systems for the deployed variable and fixed weights. A chain of various weights per meter was used in combination with fixed weights as the variable counterbalances.

A moment-reaction beam was used in conjunction with a cable to balance the quadrant tensions. The cable was attached to the overhead beam, passed around a pulley near the external beam support ETB cap, and over another pulley at the reaction beam tip, and then attached to a hydraulic cylinder at floor level. A leveling accelerometer was attached to the ETB cap and the reading was used to manually increase or decrease the tension in the cable, thereby maintaining the cap within 0.5° of level. Normally, after the tension was adjusted for a deployment cycle, no further adjustment was required in order to maintain a level cap.

Ten complete deployment cycles involving numerous short extensions and retractions were accomplished successfully. In addition, two cycles were accomplished that demonstrated the ability of the array system to extend and retract a single strip for replacement or additional power. During extensions or retractions, the air conditioning was shut down to ensure that no external loads were imparted to the array.

CONCLUDING REMARKS

The following conclusions were formulated during the study program and the hardware demonstration. It is feasible to design, fabricate, and test solar arrays 928 m^2 in area that will withstand the loads of a spinning spacecraft. The design must be modular from the solar-cell strip to structural components to permit configuration versatility, component handling, and maintenance. The Astromast extendible truss beam is an excellent choice if high strength, low thermal bending, configuration versatility, and retraction are required of a beam. Vertical testing of large-area flexible-substrate arrays is a practical method of ground-based testing if adequate indoor facilities are available.

TABLE I. - BASELINE REQUIREMENTS FOR FIRST-LEVEL DESIGN

Requirement	Cargo	Module size, m	Artificial-g mode	Power level, kW	Module weight, kg	Launch mode	Resupply launch	Inclination, deg	Altitude, km
MSC-03696 (ground rule)	--	4.27 by 17.7	Not on first station	15 average, minimum	908	Shuttle	--	55	445 to 500
Derived	--	4.27 by 11.6	Capability for all stations	25 average, 100 maximum	--	--	Complete power module, no EVA	--	--
Assumed	--	--	At start of flight only	--	--	--	Replace strip by EVA	--	--

TABLE II. - BASELINE REQUIREMENTS FOR SECOND-LEVEL DESIGN

Item	Assumed requirement
Resupply accommodation	Main structure retractable (array strips retractable)
Artificial-g mode	Main structure fully deployable to 25.6 m with 4 strips/wing
Artificial-g mode	Maximum artificial-g radius of rotation displacement = 13.4 m
Array orientation	2-axis tracking $\pm$ 12° point accuracy
Lowest possible level of resupply	Array strip (1.83 by 25.3 m) EVA required
Maintainability	Shirt-sleeve maintenance

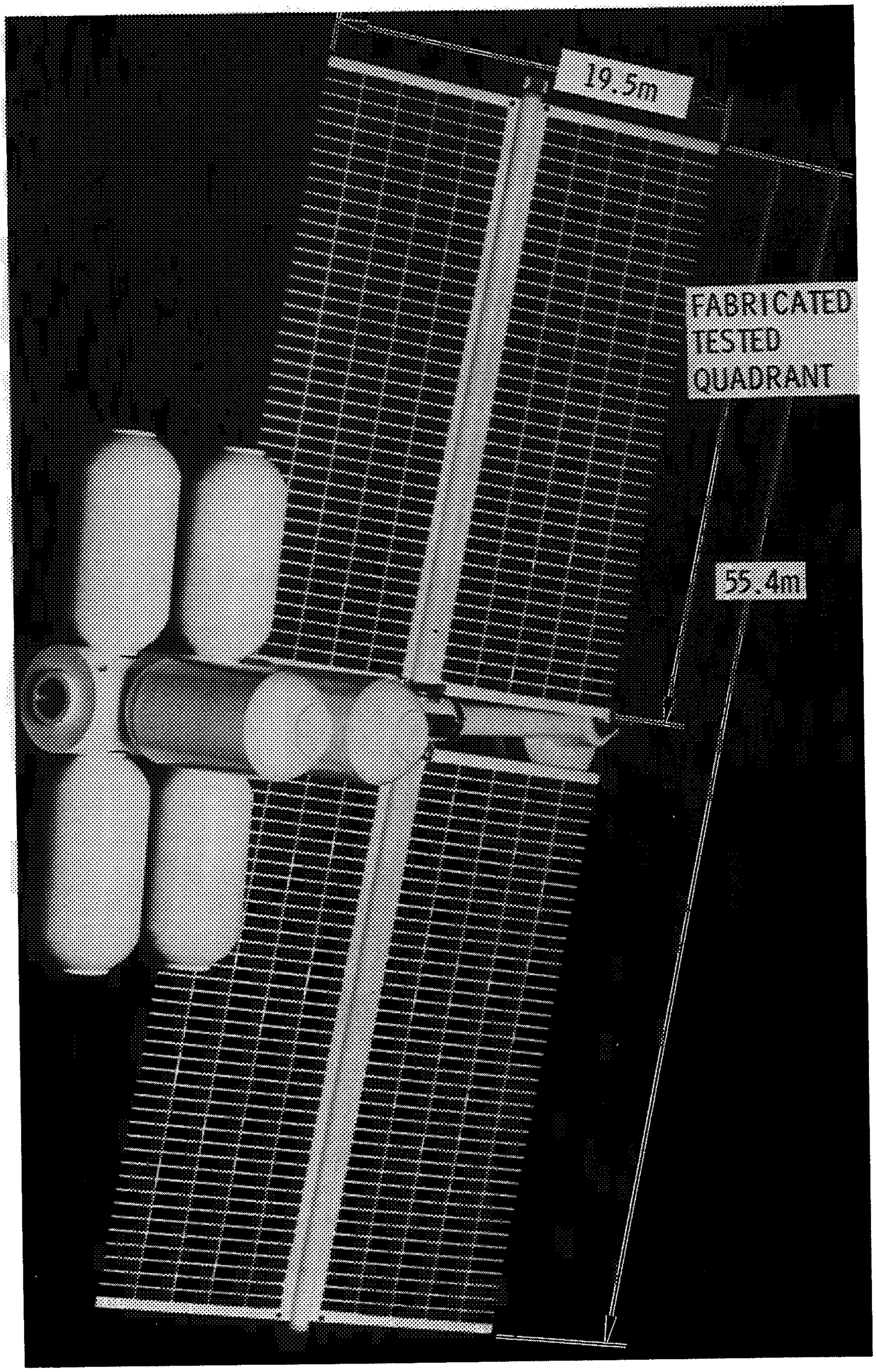

Figure 1. - Shuttle-launched station concept.

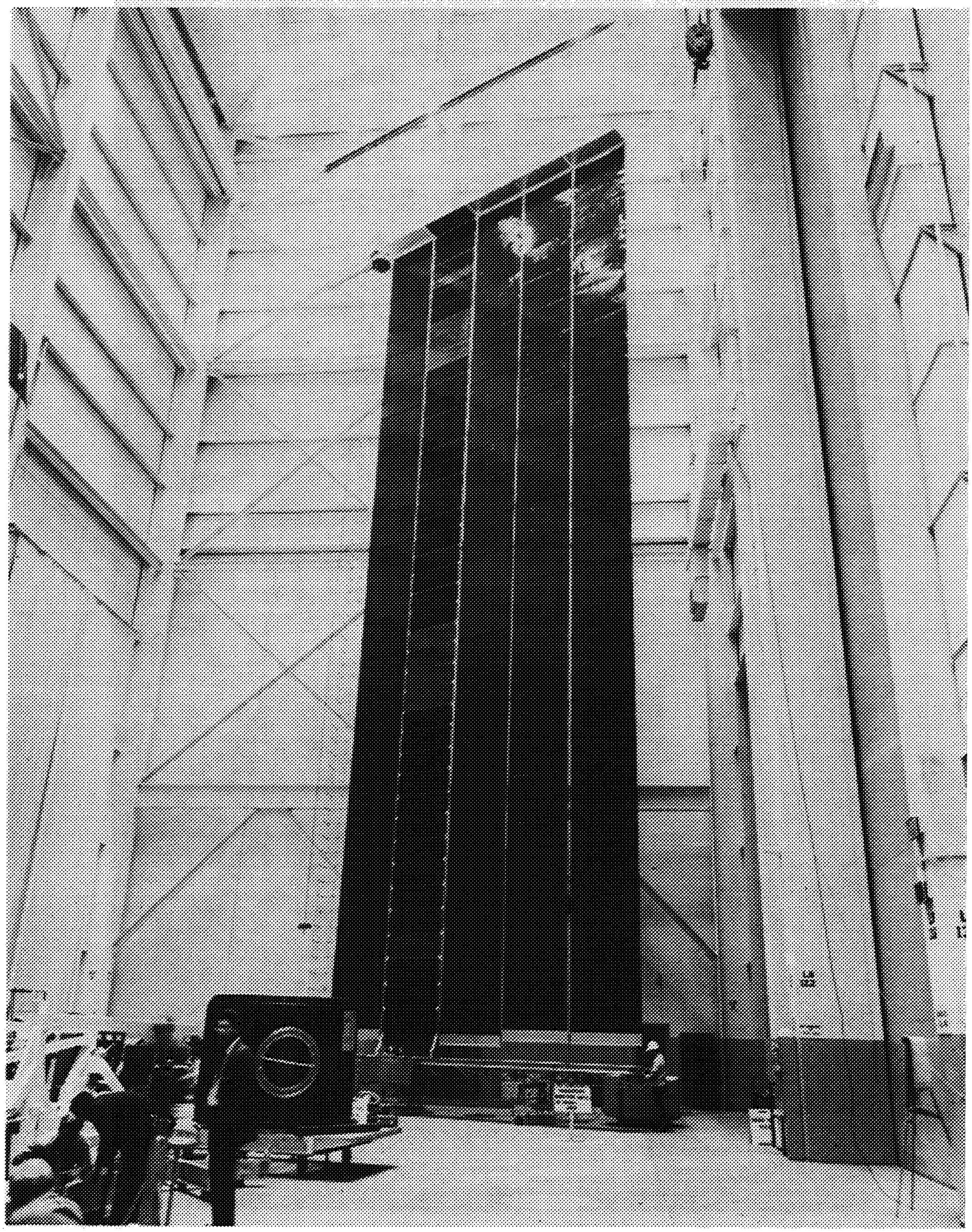

Figure 2. - Deployment-test quadrant.

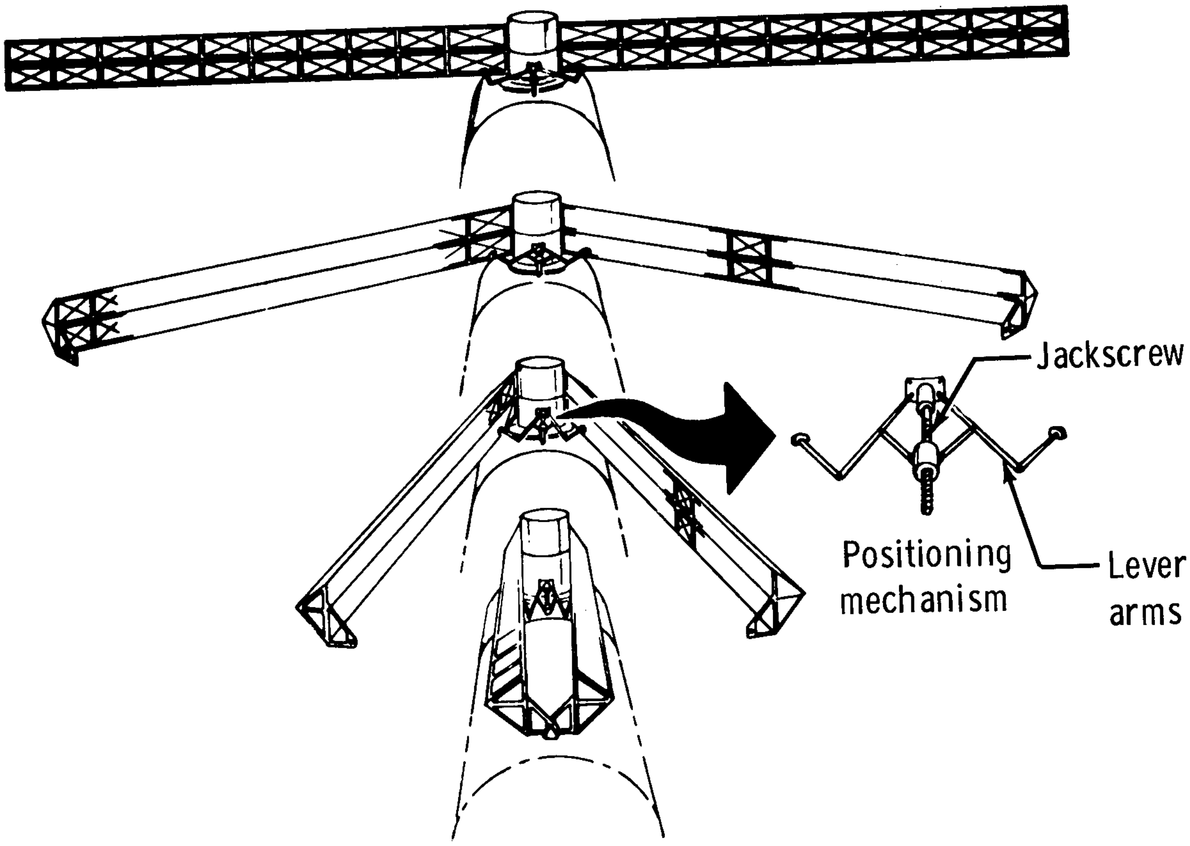

Figure 3. - Initial positioning of stowed quadrants.

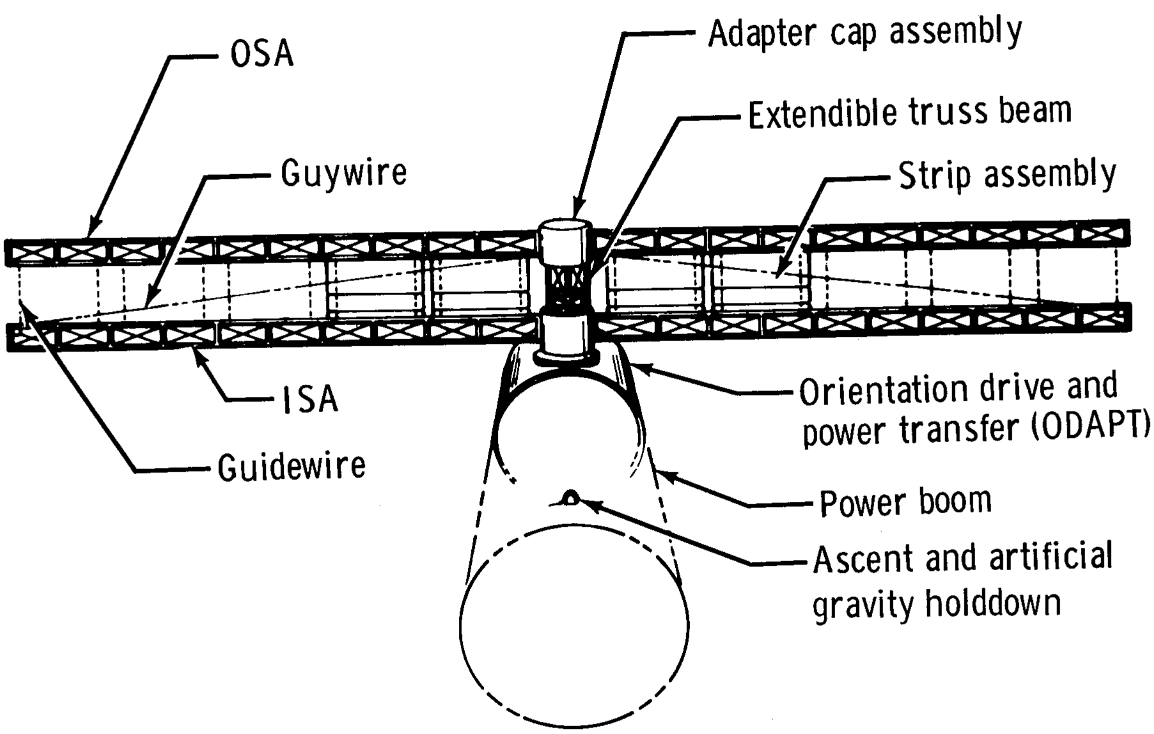

Figure 4. - Baseline structural elements.

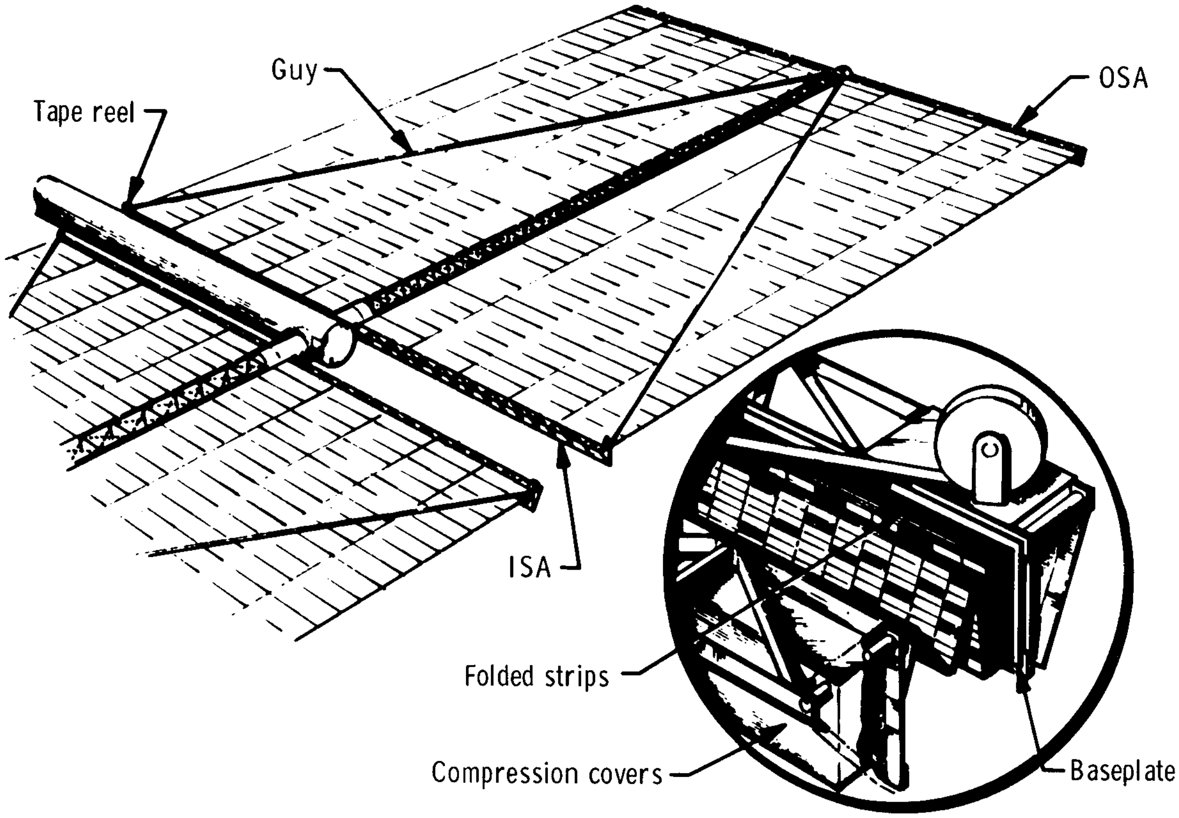

Figure 5. - Array wing.

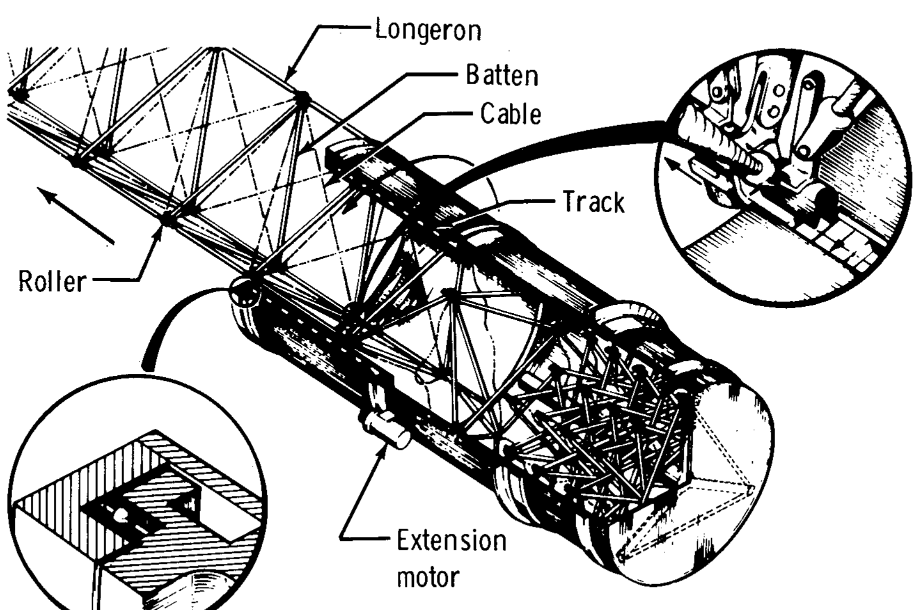

Figure 6. - Cutaway of the Astromast.

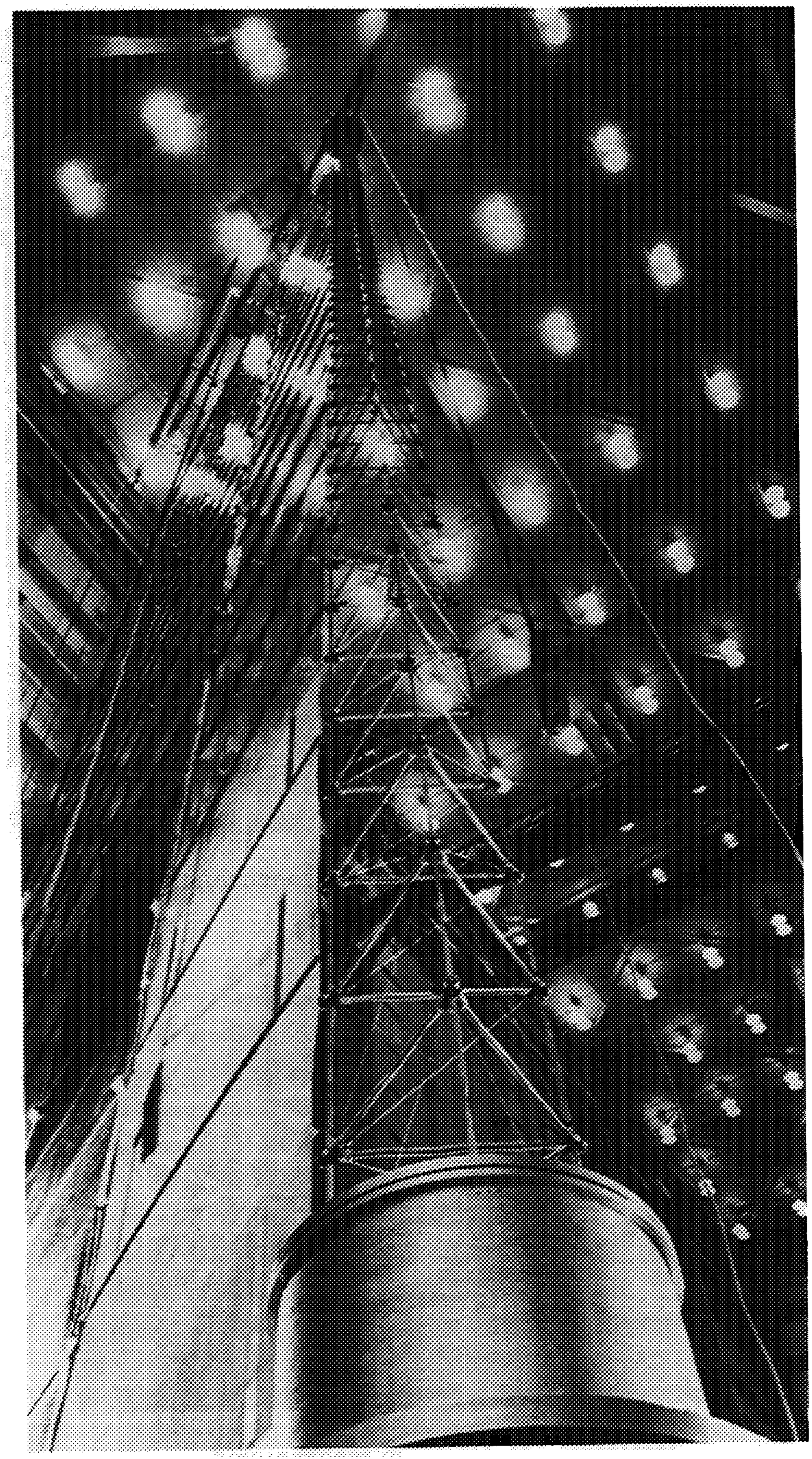

Figure 7. - Extendible truss beam.

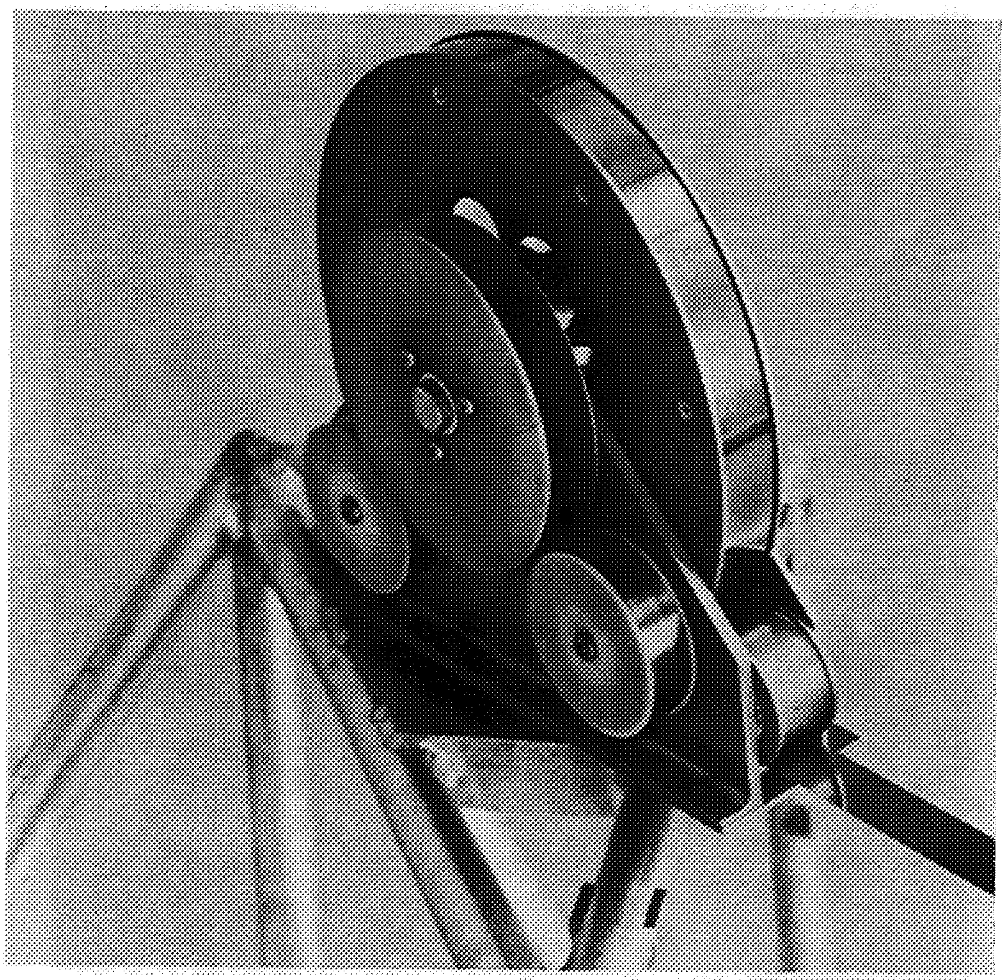

Figure 8. - Guy-tape stowage mechanism.

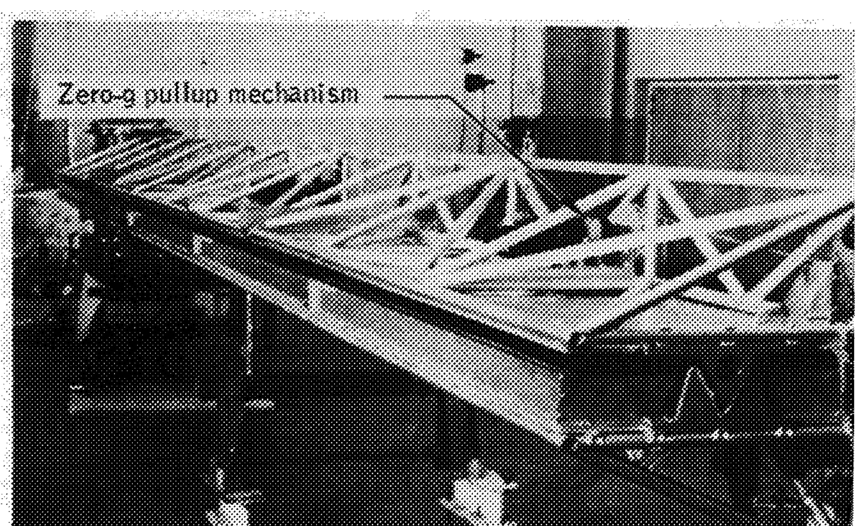

Figure 9. - Strip pullup mechanisms.

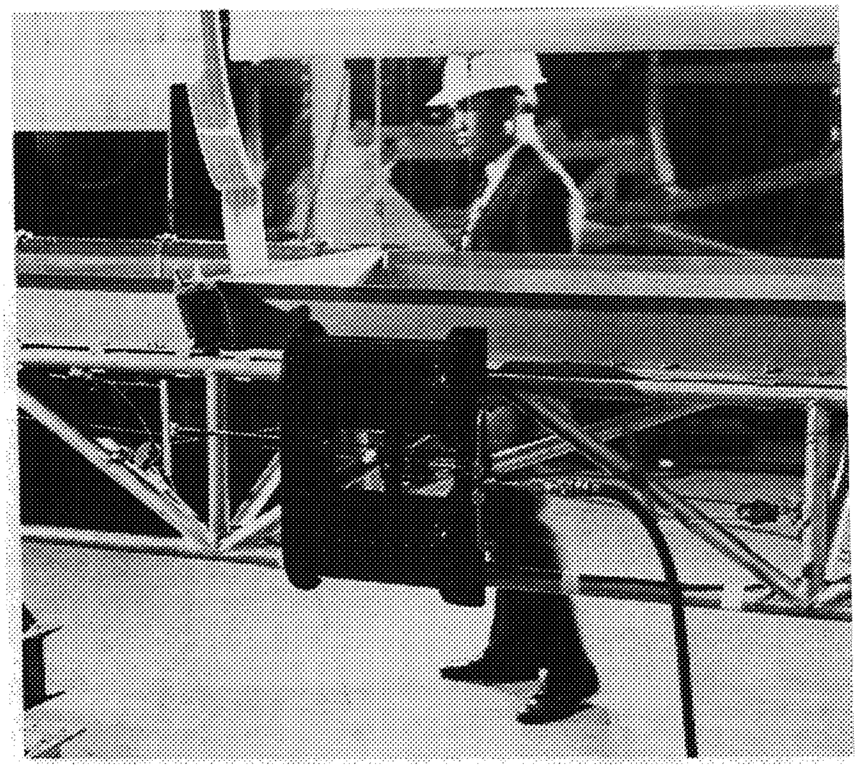

Figure 10. - Artificial-gravity tension mechanism.

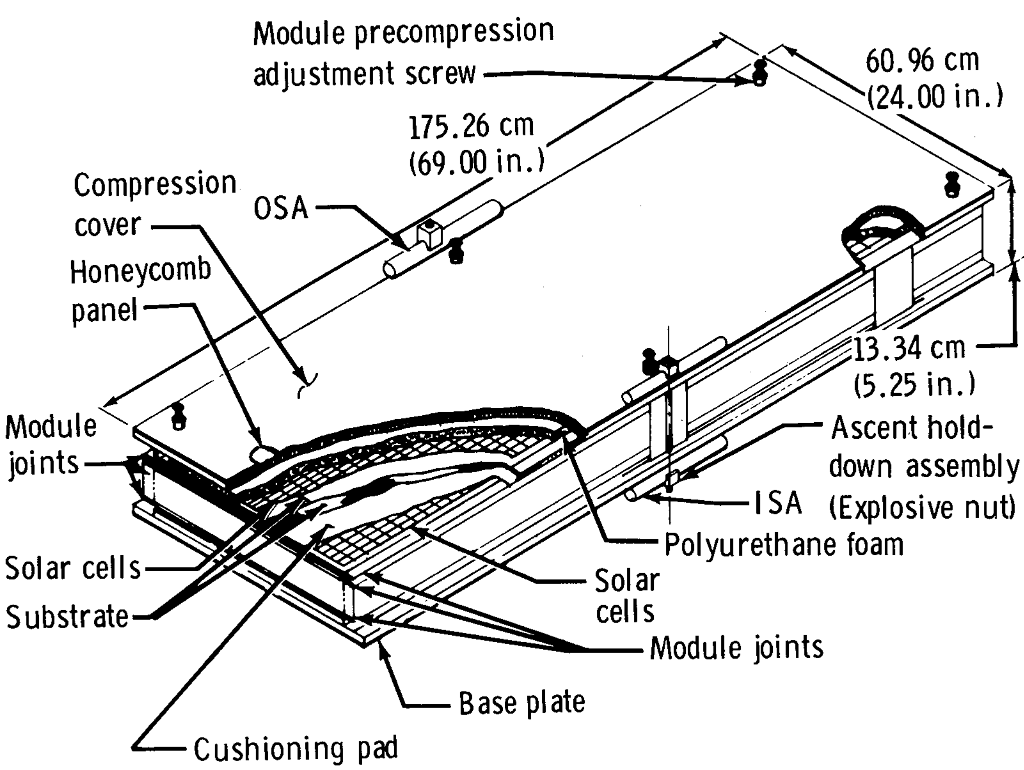

Figure 11. - Array packaging assembly.

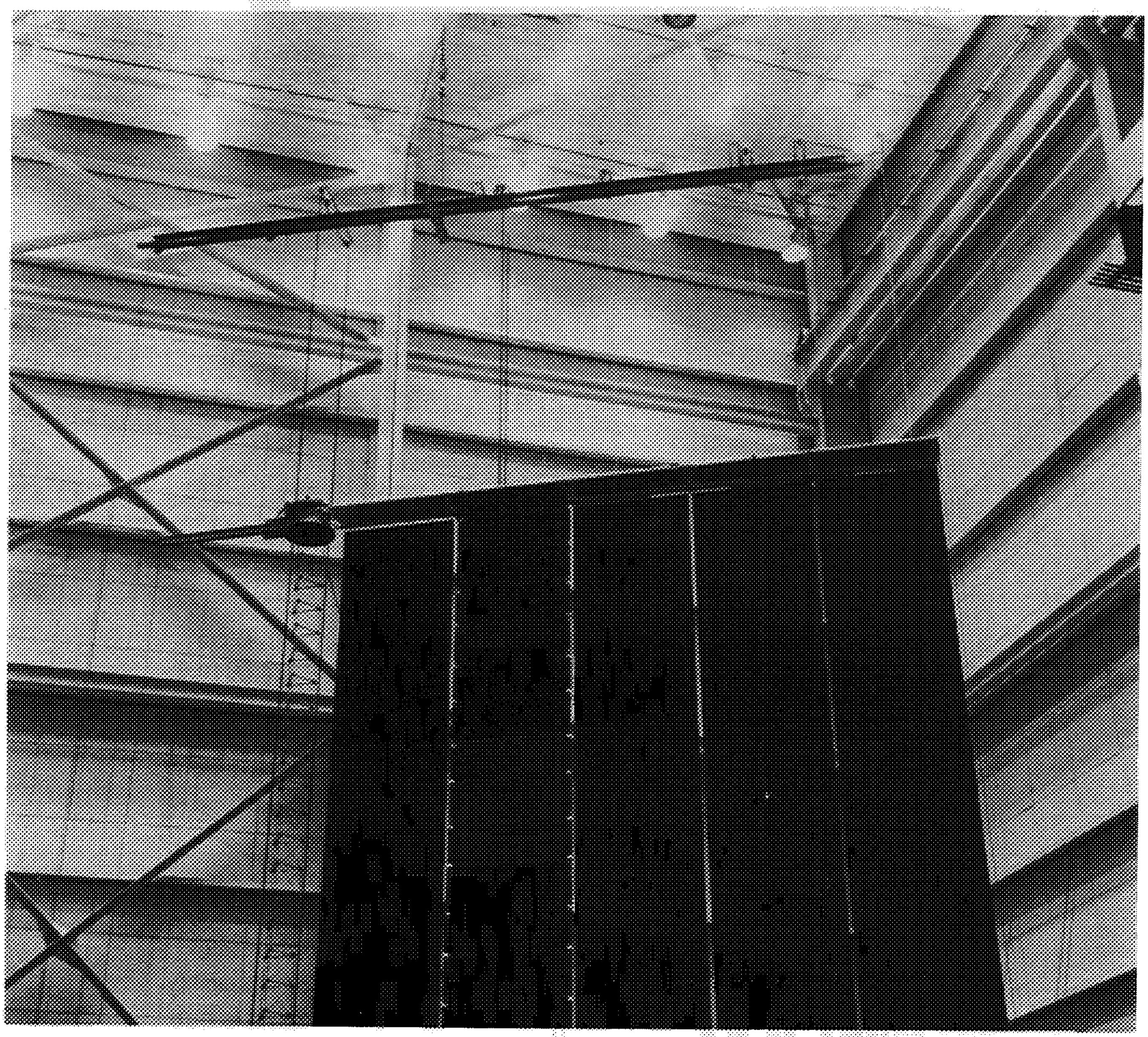

Figure 12. - Counterbalance support beam.

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