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A Definition Study of the On-orbit Assembly Operations for the Outboard Photovoltaic Power Modules for Space Station Freedom

Thomas J. Sours
Lewis Research Center
Cleveland, Ohio

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Glossary

Assembly Operations	Assembly procedures that are carried out on one flight increment or NSTS mission.
Assembly Procedure	The process that each piece of the station goes through to get from its launch packaged configuration to its on-orbit configuration.
Assembly Sequence	The order in which all of the pieces of the station are delivered to orbit and assembled into their on-orbit configuration.
Inboard	Refers to locations nearer to the center-of-mass of the station.
Launch Manifest	The total of items on a given NSTS launch that are payload items. This includes items in the cargo bay, located within the pressurized environment of the orbiter vehicle and also any additional consummables that must be carried aloft to support the mission.
Neutral Buoyancy Testing	Underwater testing that simulates the microgravity environment of EVA operations. Used for hardware development, operations verification and training.

Outboard	Refers to locations farther from the center-of-mass of the station.
PV Launch Package	PV module equipment and its associated flight support hardware in its launch configuration. This will probably include more then one item in the orbiter cargo bay.
PV Module	One unit of power generation and storage. There are four PV modules included in the EPS. Each PV module is rated at 18.75 kw for a station power of 75 kw net to the users.

Acronym List

APD	Astronaut Positioning Device
AWP	Assembly Work Platform
BG/SA	Beta Gimbal/Solar Array
CAD	Computer Aided Design
CADAM	Computer/Graphics Augmented Design and Manufacturing
CETA	Crew and Equipment Translation Aid
EPS	Electric Power System
EVA	Extravehicular Activity
FTS	Flight Telerobotic Servicer
GF	Grapple Fixture
IB	Inboard
IEA	Integrated Equipment Assembly
IVA	Intravehicular Activity
JSC	Johnson Space Center
LC	Launch Cradle
LeRC	Lewis Research Center
MB	Manned Base
MSC	Mobile Servicing System
MT	Mobile Transporter
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OB	Outboard
ORU	Orbital Replacement Unit
PFR	Portable Foot Restraint
PMC	Permanently Manned Configuration
PMAD	Power Management and Distribution
PV	Photovoltaic
SRAD	Space Radiator Assembly Demonstration
SRMS	Shuttle Remote Manipulator System
SSRMS	Space Station Remote Manipulator System

I. Introduction

This study is the most complete work to date describing the assembly of the outboard PV modules for Space Station Freedom. The results of this study will be used as design input to help define assembly equipment that is being developed to support station assembly.

This assembly equipment includes the Assembly Work Platform (AWP), the Mobile Servicing Center (MSC), The Space Station Remote Manipulator System (SSRMS), the Extravehicular Activity System (EVAS) and the Flight Telerobotic Servicer (FTS). These systems are all vital to the assembly operations that construct the outboard PV modules. This study defines a scenario by which these various items of assembly equipment will be used to assemble the outboard PV modules.

One of the largest challenges of the space station program is to assemble the space station on-orbit. As currently planned, this assembly will take roughly the same number of space shuttle missions as have been conducted to date. Nothing of this magnitude has ever been attempted on-orbit. This assembly work will require extensive use of EVA astronauts and telerobotic devices. To date the United States space program has accumulated approximately 400 man-hours of EVA experience. This experience is from the Gemini, Apollo, Skylab and Shuttle programs. The assembly of Space Station Freedom will require an estimated 500 man-hours of EVA.

Since the Space Station Freedom Program is still in a definition phase, the concepts for the various systems are still in a state of flux. This study is therefore highly conceptual in nature. This work is part of ongoing activities in the area of on-orbit assembly planning. As the design process progresses this work will be continuously refined to ensure that the various systems on the station will be operationally compatible with each other. Extensive computer simulation will be used during this process. This will be complemented by neutral buoyancy testing of selected hardware. Neutral buoyancy testing is performed in a water tank with neutrally buoyed mock-ups and test conductors. It serves as a good approximation to the microgravity environment on-orbit. Shuttle flight demonstrations will be used prior to the start of the space station assembly process to verify the performance of the telerobotic systems.

A. Space Station Freedom Program

Space Station Freedom will be assembled on-orbit beginning in 1995. When completed the station will be multifunctional. It will serve as a manufacturing facility, a research facility, an Earth viewing platform, a satellite repair depot and as a staging area for missions to the Earth's moon, the planet Mars and beyond.

The space station will be delivered to and assembled on-orbit over approximately 20 National Space Transportation System (NSTS) missions. Ref. 1 The assembly sequence is in the process of being optimized to meet the myriad of requirements that it must satisfy. The optimization of the assembly sequence is a multivariable problem. In optimizing the assembly sequence, it is necessary to study the assembly requirements of the various systems on the station and to select an assembly method that is compatible with each system. In order to ensure that the station can be successfully assembled on-orbit, the assembly operations requirements must be considered early in the design phase of the flight hardware.

After each and every mission a fully functional, survivable spacecraft must be left on-orbit. The effect of failed equipment on-orbit and the subsequent required maintenance and logistics during the assembly phase must also be considered. The assembly sequence must also support contingency and abort operations of the NSTS. The launch manifest for each mission must meet all of the orbiter constraints on volume, mass, center-of-mass, physical clearances, safety, structural integrity and a host of other conditions. The on-orbit operations must not exceed the available EVA, IVA, power, pointing capability and other resources available during the assembly phase.

The finished configuration of Space Station Freedom is illustrated in Figure 1 The station is arranged along the transverse boom which is an erected structure with each truss bay being a five meter cube. The space station equipment and payloads will be attached to this structure. At the center of the transverse boom will be the living quarters for the crew as well as laboratory space. The European Space Agency and the Japanese will each supply one laboratory module for the station.

The solar power modules are located on either end of the boom. They are separated from the rest of the station by alpha gimbals. The purpose of this gimbal is to provide sun tracking of the solar arrays. The alpha gimbals must make one complete revolution for each orbit of the Earth. The station will be in a circular orbit, 220 nautical miles above the Earth surface with a 28.5 degree inclination to the equator. In this orbit a satellite will take ninety minutes to circle the globe. The solar arrays are mounted on beta gimbals which will rotate plus or minus fifty-two degrees to account for the seasonal variation in the Earths orbit plane.

Position designation and nomenclature on the station are described in Figure 2 and Figure 3 The face of each truss bay is given a designation. The truss bays that contain the port outboard PV module are PA3 through PA6. The truss bays that contain the starboard outboard PV module are SA3 through SA6. These illustrations include designation of the locations of attached payloads and space station systems.

B. Electric Power System

The NASA Lewis Research Center has the responsibility to produce the electrical power system for Space Station Freedom. The

Rocketdyne division of Rockwell International Corporation in Canoga Park, California is the prime contractor for this effort. This includes the design, development, manufacturing, assembly planning and maintenance planning for the end-to-end system architecture.

The two main parts of the power system are the Solar Power Modules for power generation and energy storage and the Power Management and Distribution System which will control and deliver the power generated by the Solar Power Modules.

The space station will be powered by two solar power modules. Each of these will consist of one inboard and one outboard solar photovoltaic (PV) module. Each PV module is sized for 18.75 kw power generation and energy storage for a solar power module total of 37.5 kw. The port and starboard solar power modules on the station will be interchangeable.

C. Outboard PV Module

The Lewis Research Center will be the prime mission integrator of the flight that delivers the two outboard PV modules to the station. Other work package equipment will not be manifested on this flight. There are a total of four PV modules on the station to provide for power generation and energy storage. The current plan is for the first of these to go to orbit on MB–1, The second on MB–5 and the last two on MB–11. The first and second to be delivered are referred to as the inboard PV modules and the last two as the outboard PV modules. This convention is derived from their respective positions in relation to the center of the station.

The components of a PV module are illustrated in Figure 4. The PV Modules will be built up Orbital Replacement Units (ORU). The approach to maintenance will be for these ORU's to be removed and replaced on orbit. The PV module consists of three large components that have to be installed into the space station truss. These are the Integrated Equipment Assembly (IEA) and two Beta Gimbal/Solar Array (BG/SA) assemblies.

The Integrated Equipment Assembly will be preintegrated on the ground during ground processing. It will contain the battery and PMAD ORU's for one PV module. On-orbit the IEA will be attached to the truss, the electrical connections mated and then the nine heat pipe radiator fins will be installed using the station's robotic arm. The thermal cooling loop will not require any fluid connections to be made on-orbit.

The beta gimbal and the solar array will also be preintegrated on the ground. On-orbit they will be installed in the truss and their respective electrical connections mated. There will not be any active cooling of these devices required as there is in the case of the IEA.

The outboard PV module will include four bays of space station truss, cable trays, EVA System hardware as well as the components mentioned above.

The launch package configuration of the PV modules will be the same for all four modules. This is illustrated in Figure 5 PV Module Launch Packaging. The only significant difference between the inboard and outboard PV modules from a launch packaging and assembly viewpoint is that the outboard modules will each have two additional bays of truss. The procedure by which a particular PV module gets assembled is dependent on when in the assembly sequence it gets delivered to the station. The launch package design must be compatible with each of these different assembly procedures and launch manifest constraints.

The PV module launch package consists of the Integrated Equipment Assembly, two Beta Gimbal / Solar Array Assemblies, Truss, Utilities and a launch cradle to support these items during the launch phase of the NSTS mission that delivers them to the station. The launch cradle will be returned to Earth after it is unloaded at the station.

II. On-orbit Assembly Resources

Careful planning is being done to ensure that the station can be assembled on-orbit. The on-orbit assembly of the station will require many resources. Crew time, equipment, data, power and other resources all must be utilized to perform the on-orbit assembly. One of the scarcest resources will be the availability of EVA crew time. One of the goals of the assembly planning is to minimize the amount of EVA time that is required to assemble the station. This will be accomplished by designing the flight hardware such that it is easily assembled on-orbit and through the use of telerobotic devices to aid the astronauts in their tasks.

The first PV module will be assembled using the cargo bay of a shuttle orbiter as a working platform. These activities will take place within the reach envelop of the SRMS. The SRMS will be used to retrieve the various PV module equipment from the cargo bay and to position it so that EVA astronauts, aided by the Assembly Work Platform, can attach it to the truss structure.

The second PV module will be delivered to orbit on MB-5. Ref. 1 At this time in the assembly sequence there will be a mantended station on-orbit to serve as a base of operations. This assembly operation will be carried out away from the cargo bay using the Space Station Remote Manipulator System to serve the function that the Shuttle Remote Manipulator System provided during the assembly of the first PV module. In this second PV module assembly mission the launch packaged PV module must be removed from the cargo bay and attached to the MSC for transportation to the assembly operations site. After the Second PV module is assembled the launch cradle will be returned to the cargo bay of the orbiter for return to earth.

The third and forth PV modules will be delivered to the station after Permanently Manned Capability (PMC) is reached. They will be assembled in similar fashion as the second PV module, but there will be more assembly resources available to support these operations. The station EVA System will be able to supply the required EVA astronauts and the telerobotic devices will have IVA control stations within the station.

The Assembly Work Platform (AWP), illustrated in Figure 6. will be used to assemble the space station truss and install the PV module equipment onto the truss. Ref. 3, Ref. 5 The AWP will provide the EVA astronauts with mobility while they assemble the station. The Astronaut Positioning Device (APD) will move the astronauts so that they can efficiently use their time assembling the station rather then translating from place to place. This item of flight support equipment is being developed by the Johnson Space Center (JSC). It will be included on the manifest for the first assembly flight, Mission Based-1 (MB-1), and will be used to position the EVA astronauts while they assemble the truss and install most of the space station equipment onto the truss. The AWP will be mounted on the Mobile Transporter (MT) which provide it mobility on the space station truss. It will operate independently of the MSC which will also be mounted on the MT.

The EVA System (EVAS) includes all of the support equipment for the EVA astronauts. EVA life support equipment, airlocks, translation and positioning aids, tools, tethers, and other equipment fall into the category of the EVA System. The capability of the EVA System will be dependent on which flight in the assembly sequence is being considered. The assembly of the outboard PV modules is scheduled for Flight MB-11. At this time in the assembly sequence the station will have achieved its Permanently Manned Configuration (PMC) the implication of this is that the assembly resources needed can be supplied by the station. This means that there will not need to be an orbiter present during the assembly of the outboard PV modules. During the assembly of the first two PV modules, on flights

MB-1 and MB-5, the EVA astronauts are supplied from the orbiter. This leads to a limit of two six hour long EVA periods that can be utilized to perform the necessary EVA assembly operations. Since the EVA astronauts are being supplied from the station it is not necessary that the complete assembly of both outboard PV modules be accomplished while the orbiter that delivered them to the station is present.

EVA astronauts will perform the majority of the assembly tasks on the station. The reach envelop of an EVA suited crewperson is shown in Figure 7. This illustration represents where an EVA astronaut will be able to do useful work while in a foot restraint. The astronaut's foot restraints will be located on the Astronaut Positioning Device of the Assembly Work Platform. The IVA crew will be able to manipulate the EVA astronauts such that the assembly operations that need to be performed will be easily within their reach capability. During the initial period of station assembly the EVA astronauts will be supplied by a space shuttle orbiter vehicle. After the station becomes permanently manned the EVA astronauts will be supplied by the space station. Since the assembly of the outboard PV module is after the station is permanently manned, the EVA resource will be supplied by the station EVA System. For the purpose of outboard PV module assembly it will not matter which system provides the EVA astronauts.

Translation of crew and equipment is one of the most difficult and time consuming tasks that EVA requires. Though the use of remotely operated manipulators and astronaut positioning aids a portion of the assembly work load will be shifted from the EVA crew to the IVA crew. The function of equipment retrieval and crew positioning will be performed by IVA astronauts operating the robotic systems on the station and shuttle. The EVA astronauts will be able to more effectively use their time to perform those tasks that require the dexterous capability that only humans can supply.

IVA astronauts will be used during assembly operations to control the various telerobotic equipment that will support the assembly activities being conducted external to the pressurized environment of the station. This activity will be conducted both while EVA astronauts are working and while no EVA astronaut activity is taking place.

The IVA crew will command the automated deployment systems such as the solar arrays. The IVA crew will also be responsible to control the start-up of the PV modules after they are assembled.

The Shuttle Remote Manipulator System (SRMS) will be used to remove equipment from the cargo bay of the orbiters. The equipment will then be handed off to the SSRMS or stowed on the truss in the vicinity of the pressurized modules.

The Space Station Remote Manipulator System (SSRMS) is the station version of the shuttle arm. Ref.4 It will be used to retrieve and position EVA crew and equipment. The SSRMS will be capable of being operated from within the pressurized living environment of the station, from an orbiter, or from an EVA control station.

The Flight Telerobotic Servicer (FTS) will be available to support the assembly of the outboard PV modules. Ref.6 It will probably be mounted onto the SSRMS for most of its tasks during these assembly operations. It will be used to release the PV module components from the launch cradle. It will also serve as an alignment and stabilization aid for the EVA astronauts as they install the transition structures between the PV components and the space station truss.

III. Procedure

A. Data Input

To produce this assembly scenario, fairly detailed dimensional information on the various items was needed. This was often difficult to obtain. These devices are being designed and produced by different organizations in the United States and Canada. Most of the assembly equipment programs are in a conceptual/preliminary design phase. Consequently, much of the information needed to generate CADAM models was not readily available in the Space Station Freedom Program documentation and had to be obtained informally through contacts in the various organizations. From July through November 1988 meetings were held with representatives of the various organizations involved with the assembly equipment.

Information on the PV modules was obtained from the Rocketdyne Division of Rockwell International Corporation and from the Photovoltaic Division of NASA Lewis Research Center. This information represents the baseline concept that was proposed by Rocketdyne in the spring of 1988. The configuration of the PV module is currently under study. As these programs progress, the assembly operations for the PV modules will have to be studied to insure that the designs of the assembly equipment and the PV module components are compatible.

The solar power module coordinate system is found in Figure 8. This coordinate system is a right-handed orthogonal system and is fixed to the solar power module. This means that it does not rotate with respect to the sun vector, unlike the space station coordinate system which does not rotate with respect to the earth vector. The +X axis is toward the sun. The +Y axis is along the center line of the truss away from the alpha gimbal or joint. The origin is at the center of the first batten frame outboard of the alpha gimbal. This coordinate system is the same for both the port and starboard solar power modules. Individual truss struts are designated by type and by position on the truss. This is illustrated in Figure 9. Each strut is identified by the truss bay it is located in, the face on that bay and the type of strut that it is (ie. batten, longeron, diagonal). The truss bay location nomenclature is illustrated in Figure 2 and Figure 3 These conventions are used to identify positions on the station for the purpose of this study.

B. Assembly Operations Assumptions

To produce this assembly scenario, many assumptions had to be made about the NSTS and Station capabilities. These assumptions are consistent with the current program guidelines.

By MB-11 the station will have achieved a Permanently Manned Configuration. The implication of this is that all of the Environmental Control and Life Support Systems and other safety critical systems must be kept operating in order to insure the safety of the crew and the integrity of the Station. There must be sufficient power left over to operate the MSC. The alpha gimbal will be restarted after the EVA crew begins assembly operations. When the alpha gimbal is stopped there is a resultant loss in power output of the effected PV module. The sun tracking will have to be resumed in order to assure sufficient power to perform the PV module assembly operations.

For those EPS elements requiring automated deployment (solar array blankets) the deployment sequence will be controlled by IVA crew. A backup deployment method via EVA must be available for each automated deployment sequence.

There will be a fully functioning FTS, AWP, MSC and SSRMS on-orbit to support these assembly activities. These will be operated IVA from the pressurized environment of the station or from a shuttle.

No EVA crew will be needed to remove items from the cargo bay and stow them onto the MT or AWP. The Truss strut/node packages and the transition structure packages will be temporarily stowed onto the AWP for transportation to the assembly operations site. The utility tray deployment wheels will be mounted on the AWP. The radiator fin packages can be transported to orbit on the same flight as the two outboard PV modules. The radiator fin package can be temporally stowed on the PV module launch cradle for transport to the assembly operations site. The EPS radiator fins can be inserted into the heat exchanger via the MSC SSRMS. This concept is being verified by the SRAD (Space Radiator Assembly Demonstration) project. This project is a flight demonstration that will verify the concept of installing the heat pipe fins using a manipulator arm.

Assembly operations continue during eclipse portion of orbit. Lighting will be provided by the EVA System. IVA support will be required for all EVA activities

C. Assembly Operations Computer Simulation

Assembly operations for the outboard PV module were simulated on the Lewis Research Center's Computer/Graphics Augmented Design and Manufacturing, CADAM system (Version 20.2). This system produces three dimensional wire-frame graphics. This system does not have animation capability. Still frames were produced that represent steps in the process of assembly. A series of fourteen frames were produced that describe the assembly operations. These illustrations of the assembly process can be found in Figure 10 through Figure 23.

Using CADAM the kinematics of the various manipulators can be simulated. Translation paths for the movement of the PV components from their launch cradle to there final operating location on the truss can be planned. Interferences between manipulators, truss struts, and other equipment can be anticipated and the assembly scenario changed in order to ensure a successful mission.

The development of the assembly scenario presented in this study is the result of a six month iterative effort. As the CADAM simulations progressed the assembly procedure was changed in order to be consistent with the constraints of the robotic systems that support the assembly operations and with the launch package configuration. The outboard PV module assembly scenario presented in this study has been accepted as the new program baseline. The baseline assembly scenarios for all of the PV modules can be found in Reference 3.

The computer simulations do not illustrate the utility deployment equipment, stowed truss struts and nodes or other items attached to the Assembly Work Platform. As these items are better defined they will be incorporated into these computer simulations.

IV. Results

The results of this assembly operations study are presented in three ways. The Assembly Operations Narrative describes the assembly process in words. The Assembly Operations Data can be found in Tables 1 through Table 3 which list the steps involved in the assembly and present information on the manipulations that must be made, the resources used and the time required to perform the operations. The Assembly Operations Illustrations in Figure 10 through Figure 23. illustrate the on-orbit configuration as the assembly operations are carried out.

A. Assembly Operations Narrative

After the orbiter has docked to the station the PV modules will be transferred to the Mobile Servicing Center. To do this the orbiter SRMS will grasp a grapple fitting located on the PV module cradle. The IVA orbiter crew at the aft flight deck console will command the release of the longeron fittings that secure the launch cradle to the orbiter structure. The SRMS will then remove the PV module launch package from the cargo bay and position it so that the station's SSRMS can grasp a second grapple fitting. After this is accomplished the SRMS will release its grapple fitting so that the SSRMS will be free to position the PV Launch Package onto the Mobile Servicing Center base unit. The PV launch package is secured onto the MSC by a third grapple fitting on the launch cradle with a corresponding capture mechanism located on the body of the MSC.

This process will be repeated for the radiator fin package which gets removed from the orbiter sill and stowed onto the structure of the launch cradle. The truss structure package, the transition structure package and the utility tray package will similarly be removed from the cargo bay and stowed onto the Assembly Work Platform.

This process of removing the PV module from the cargo bay and stowing it onto the MSC and AWP will be done without the use of EVA astronauts. This will require dexterous manipulation capability and close coordination between the station and orbiter IVA crew members. The Flight Telerobotic Servicer will be available during this assembly mission. This device can be used on the end of an orbiter SRMS or the station SSRMS. It can provide the dexterous manipulation capability that is required to remove hardware from its launch support structure. The hand off from the SRMS to the SSRMS is required by the NSTS program. As the design of the space station systems matures, it may be possible to eliminate this extra step and provide for the SSRMS to retrieve equipment directly from the orbiter bay.

When all of the items required to build one outboard PV module have been removed from the orbiter and stowed for transport the Mobile Transporter will then begin its slow journey to the outboard end of the inboard PV module that was assembled on an earlier flight. The Mobile Transporter speed is estimated at roughly one foot per minute when fully loaded. The inboard PV module as it appears prior to this mission is illustrated in Figure 10.

The Mobile Transporter will stop when in reaches truss face PB7F. This is the first truss bay inboard of the alpha gimbal. At this time the station IVA crew will command the alpha gimbal to stop and align itself so that the Mobile Transporter can make the alpha gimbal crossing. Since the alpha gimbal and its transition structures take the place of one of the bays of truss on the transverse boom, the MT will be able to cross the alpha gimbal like any other bay of truss. This is illustrated in Figure 11.

The Mobile Transporter then indexes out to truss face PA1F. This is the first truss bay outboard of the alpha gimbal. The position of the Mobile Transporter is shown in Figure 12. At this time the assembly of the outboard PV module begins with the arrival of the EVA crew. The EVA crew is transported from the airlock to the assembly operations site by the Crew and Equipment Translation Aid.

The EVA crew will ingress the Astronaut Positioning Devices located on the Assembly Work Platform. These devices provide mobility to the EVA crew to aid them in their assembly tasks. EVA A and B will prepare the utility deployment device and attach the utility tray end to the outboard end of the trays that are part of the inboard PV module.

Since stopping the alpha gimbal results in non sun tracking of the solar arrays, there is a sharp drop in power generation capability. For this reason the alpha gimbal will be restarted at this time. The inboard PV module beta gimbal will be maintained at zero orientation (parallel to the truss axis) while the MT is outboard of the alpha gimbal in order to allow sufficient clearance between the assembly equipment and the solar arrays.

The Mobile Transporter will then index to truss face PA2F, this is the second outboard bay of truss. As it indexes the utility deployer will deploy five meters of utility tray. EVA A and B will begin assembly of the first of four bays of truss that are part of the outboard PV module. This is shown in Figure 13. After the truss struts are put in place the EVA astronauts will secure the utility trays to the truss structure. The AWP will position the EVA astronauts where they need to be in order to make the needed connections. The second, third, and forth bay of the outboard PV module will be constructed in a similar fashion. These are illustrated in Figure 14, Figure 15 and Figure 16. The fourth bay of truss will not have diagonals on the upper and lower faces in order to allow the beta gimbals to be placed in the center of these truss faces.

After the truss structure has been assembled, the PV module components will then be installed onto it. The SSRMS will grapple the upper beta gimbal/solar array package located on the PV launch cradle. The FTS will detach it from the launch cradle. The SSRMS will then reposition the beta gimbal/solar array into the center of the truss face PA6U were it is to be installed. EVA A will attach the transition struts to the corners of the truss face while EVA B, egresses the APD and relocates himself onto a portable foot restraint located on the beta gimbal in order to aid in the installation of the eight transition struts. After the beta gimbal/solar array is securely fastened to the truss structure, EVA A will retrieve the transition utility tray and install it between the beta gimbal and the utility tray. The lower beta gimbal/solar array will be installed in a similar fashion. Figure 17 Lower Beta Gimbal/Solar Array Installation and Figure 18 Beta Gimbal/Solar Array Installation Complete illustrate these steps.

The diagonal truss strut PA5L-D will then be removed and temporarily stowed to allow for the installation of the Integrated Equipment Assembly. The SSRMS will grapple the IEA The FTS will release the IEA from the launch cradle. The IEA will be removed from the launch cradle and positioned in the center of truss bay PA5. This is shown in Figure 19 Integrated Equipment Assembly Installation. The FTS will be used to align and stabilize the large IEA so that EVA A and B can install the transition structure that secures it to the space station truss. The EVA astronauts will deploy the condenser section of the thermal control system by rotating it ninety degrees and preparing it to accept the heat pipe radiator fins. The transition utility tray will then be installed by the EVA astronauts. The installed IEA is shown in Figure 20.

After the installation of the IEA, EVA A and B will make a visual inspection of the outboard PV module and then return to the airlock via the CETA. The radiator heat pipe fins will then be inserted using the FTS on the end of the SSRMS. This operation will not require the use of EVA astronauts. This procedure is illustrated in Figure 21.

The SSRMS and FTS cameras will be used to make a through inspection of the outboard PV module. When this is completed the deployment of the solar arrays can begin. The solar array blanket boxes will rotate ninety degrees into their final position. The solar array can then deploy to unfold the Photovoltaic panels in the blanket boxes. The mobile transporter and other equipment will remain at the outboard PV module to provide monitoring through its cameras. The FTS will be available to provide a means for back up deployment of the solar arrays should the primary deployment devices fail. The deployment of the solar arrays is illustrated in Figure 22.

The Mobile Transporter will translate to truss face PA1F and wait for the alpha gimbal to stop and align for crossing. It will cross the alpha gimbal and return the launch cradle to the shuttle for its return trip to earth. The unloading, transportation and assembly of the fourth PV module will then commence. The completed solar power module is shown in Figure 23.

B. Assembly Operations Data

Table 1 identifies what resources will be used to perform the steps in the assembly operations. This information was generated based on the definitions of the various assembly resources available. This study takes a conservative approach hence, EVA astronauts are relied on to perform many functions that my be accomplished using robotic devices. As the design of the robotic systems matures, it may be possible to shift more of the assembly work load to these devices. This would allow for more EVA astronaut time to perform repairs, maintenance and other tasks that the robotics cannot accomplish.

The timeline estimates presented in Table 2 are "Best Guesses" based upon program experience in the area of EVA techniques. The EVA procedures and timelines will be verified through the use of computer simulation and neutral buoyancy simulation.

Table 3 quantifies the manipulations required during the assembly operations. This table was generated from orthogonal views of Figure 10 through Figure 23. This table is in terms of the solar power module coordinate system that can be found in Figure 8. This table will serve as quantitative input to the design process of the assembly equipment that is being produced. The Canadian's Space Station Remote Manipulator System and the Goddard Space Flight Center's Flight Telerobotic Servicer are probably the programs that will use this information the most. Since the assembly equipment is still being defined, this study attempts to use conservative assumptions with regard to the capability of this equipment. The scenario presented here attempts to operate the various manipulators and positioning equipment well within the defined range-of-motion envelopes.

C. Assembly Operations Illustrations

The assembly of the outboard PV modules is presented in fourteen illustrations. These can be found in Figure 10 through Figure 23. These drawings are one result of the assembly operations computer simulation that was performed.

V. Conclusions

This study establishes that the outboard PV modules can be assembled using the assembly equipment that is planned for the Space Station Freedom Program. These results are based on the configuration of the various systems as of July, 1988. As the design of the PV module and the assembly equipment evolves, studies of this type will have to be performed in great detail in order to ensure that the assembly operations can be performed as planned.

VI. Summary

A scenario for the assembly of the outboard PV modules was produced based upon the available definition for the PV module and the various assembly equipment that is part of the Space Station Freedom Program. These assembly operations were simulated using CADAM.

A table was generated that describes the manipulations that must be performed to assemble the outboard PV module. This table quantifies the manipulations that must be performed in terms of the the solar power module coordinate system. A table that identifies what assembly resources will be required to perform the assembly operations and a table that presents an estimated assembly timeline for the operations were generated.

This study is a part of on going activities in the area of on–orbit assembly planning. Studies of this type will be repeated in ever increasing detail as the design of flight hardware matures. These studies will be complimented by computer simulations, neutral buoyancy testing, and NSTS flight demonstrations.

VII. References

1. Baseline Assembly Sequence; Space Station Freedom Program Change Request CR BB000468 ,October, 1988

2. Watson, Judith J. ; et. al.: Mobile Transporter Test Results - An Assembly Concept for Space Station and Large Space Structures, NASA TM 100661, August 1988.

3. Rockwell International, Rocketdyne Division : Power System Description Document, RI/RD 88-633, 28 October 1988

4. SPAR Aerospace, Presentation to representatives of the NASA Lewis Research Center, Meeting in Toronto,Canada, July, 1988.

5. McDonnel Douglas Aeronautics and Astronautics Corporation, Presentation to the EVA System Working Group, Meeting at Houston,Tx, July, 1988.

6. NASA Goddard Space Flight Center, Presentation at the FTS Implementation Meeting, Meeting at Cleveland, OH, November, 1988.

Table 1. Assembly Operations Resource Utilization

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE STATION EVA A	SPACE STATION EVA B	SPACE STATION IVA	SPACE STATION CETA	SPACE STATION SSRMS	SPACE STATION MSC	SPACE STATION MT	SPACE STATION AWP	SPACE STATION FTS	SHUTTLE SRMS	SHUTTLE BAY	SHUTTLE IVA
	Move PV Launch Package from Shuttle Bay to MSC												
	Grapple GF #1										X		X
	Release Longeroen Fittings											X	X
PV Launch Package	Remove from Cargo Bay										X	X	X
	Grapple GF #2			X		X							
	Release GF #1										X		X
	Position onto POA			X		X							
	Close POA			X			X						
	Release GF #2			X		X							
	Move Radiator Fin Package from Shuttle Bay to Launch Craddle												
	Grapple GF #1										X		X
	Release Retention Fittings									X		X	X
Radiator Fin Package	Remove from Cargo Bay										X	X	X
	Grapple GF #2			X		X							
	Release GF #1										X		X
	Position onto LC			X		X							
	Close Retention Fittings			X			X			X			
	Release GF #2			X		X							
	Move Transition Structure Package from Shuttle Bay to Assembly Work Platform												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED: SPACE STATION									SHUTTLE		
		EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SRMS	BAY	IVA
	Grapple GF #1										X		X
	Release Retention Fittings									X		X	X
Transition Structure Package	Remove from Cargo Bay										X	X	X
	Grapple GF #2			X		X							
	Release GF #1										X		X
	Position onto AWP			X		X			X				
	Close Retention Fittings			X			X			X			
	Release GF #2			X		X							
	Move Truss Structure Package from Shuttle Bay to Assembly Work Platform												
	Grapple GF #1										X		X
	Release Retention Fittings									X		X	X
Truss Structure Package	Remove from Cargo Bay										X	X	X
	Grapple GF #2			X		X							
	Release GF #1										X		X
	Position onto LC			X		X							
	Close Retention Fittings			X			X			X			
	Release GF #2			X		X							
	Move Utility Tray Package from Shuttle Bay to Assembly Work Platform												
	Grapple GF #1										X		X
	Release Retention Fittings									X		X	X
Utility Tray	Remove from Cargo Bay										X	X	X
	Grapple GF #2			X		X							

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE STATION EVA A	SPACE STATION EVA B	SPACE STATION IVA	SPACE STATION CETA	SPACE STATION SSRMS	SPACE STATION MSC	SPACE STATION MT	SPACE STATION AWP	SPACE STATION FTS	SHUTTLE SRMS	SHUTTLE BAY	SHUTTLE IVA
Package	Release GF #1										X		X
	Position onto AWP			X		X			X				
	Close Retention Fittings			X			X			X			
	Release GF #2			X		X							
	See Figure 10.												
	Transport Equipment to work site												
MT	Translate to truss face PB7F			X				X					
Alpha Gimbal	Command to Stop and Align			X									
Beta Gimabl	Command to zero position			X									
	Cross Alpha Gimbal,												
MT	Translate to truss face PA1F			X				X					
	See Figure 11.												
	Crew begins EVA Period												
CREW	Egress Airlock	X	X	X									
	Translate to work site	X	X		X								
	Crew enter CETA APD's	X	X						X				
	See Figure 12.												
	Start of PV Module Assembly												
Upper Utility Tray	Retrieve End of Utility Tray	X		X					X				
	Attach to OB end of IB	X		X					X				
	PV Module Upper Utility Tray												

RESOURCES USED

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE STATION: EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE: SRMS	BAY	IVA
Lower Utility Tray	Retrieve End of Utility Tray		X	X					X				
	Attach to OB end of IB PV Module Lower Utility Tray		X	X					X				
MT	Translate to truss face PA2F (Utilities Deploy) See Figure 13.			X				X					
Alpha Gimbal	Command restart and sun align (Retain IB Beta Angle at zero)			X									
	Assemble Truss Bay #PA3												
Truss Strut	Prepare struts for installation	X	X	X	X	X				X			
Truss Strut	Retrieve and install PA3A-D	X	X	X					X				
Node	Retrieve and install PA3A-N		X	X					X				
Truss Strut	Retrieve and install PA3A-L		X	X					X				
Node	Retrieve and install PA3A-B	X	X	X					X				
Truss Strut	Retrieve and install PA3L-L		X	X					X				
Node	Retrieve and install PA3L-N		X	X					X				
Truss Strut	Retrieve and install PA3L-D		X	X					X				
Truss Strut	Retrieve and install PA3L-B		X	X					X				
Truss Strut	Retrieve and install PA3F-L		X	X					X				
Node	Retrieve and install PA3F-N		X	X					X				
Truss Strut	Retrieve and install PA3F-D	X	X	X					X				
Truss Strut	Retrieve and install PA3F-B	X	X	X					X				
Truss Strut	Retrieve and install PA3U-L	X		X					X				
Node	Retrieve and install PA3U-N	X		X					X				

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE EVA A	SPACE EVA B	SPACE IVA	STATION CETA	STATION SSRMS	STATION MSC	STATION MT	STATION AWP	STATION FTS	SHUTTLE SRMS	SHUTTLE BAY	SHUTTLE IVA
Truss Strut	Retrieve and install PA3U-D	X		X					X				
Truss Strut	Retrieve and install PA3U-B	X		X					X				
Truss Strut	Retrieve and install PA3I-D	X	X	X					X				
Cable Tray	Secure to Truss	X	X	X					X				
MT	Translate to truss face PA3F (Utilities Deploy) See Figure 14.			X				X					
	Assemble Truss Bay #PA4												
Truss Strut	Prepare struts for installation	X	X	X		X				X			
Truss Strut	Retrieve and install PA4A-D	X	X	X					X				
Node	Retrieve and install PA4A-N		X	X					X				
Truss Strut	Retrieve and install PA4A-L		X	X					X				
Truss Strut	Retrieve and install PA4A-B	X	X	X					X				
Truss Strut	Retrieve and install PA4L-L		X	X					X				
Node	Retrieve and install PA4L-N		X	X					X				
Truss Strut	Retrieve and install PA4L-D		X	X					X				
Truss Strut	Retrieve and install PA4L-B		X	X					X				
Truss Strut	Retrieve and install PA4F-L		X	X					X				
Node	Retrieve and install PA4F-N		X	X					X				
Truss Strut	Retrieve and install PA4F-D	X	X	X					X				
Truss Strut	Retrieve and install PA4F-B	X	X	X					X				
Truss Strut	Retrieve and install PA4U-L	X		X					X				
Node	Retrieve and install PA4U-N	X		X					X				
Truss Strut	Retrieve and install PA4U-D	X		X					X				

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
Truss Strut	Retrieve and install PA4U-B	X		X					X				
Truss Strut	Retrieve and install PA4I-D	X	X	X					X				
Cable Tray	Secure to Truss	X	X	X					X				
MT	Translate to truss face PA4F (Utilities Deploy) See Figure 15.			X				X					
	Assemble Truss Bay #PA5												
	Prepare struts for installation	X	X	X	X	X				X			
Truss Strut	Retrieve and install PA5A-D	X	X	X					X				
Node	Retrieve and install PA5A-N		X	X					X				
Truss Strut	Retrieve and install PA5A-L		X	X					X				
Truss Strut	Retrieve and install PA5A-B	X	X	X					X				
Truss Strut	Retrieve and install PA5L-L		X	X					X				
Node	Retrieve and install PA5L-N		X	X					X				
Truss Strut	Retrieve and install PA5L-D		X	X					X				
Truss Strut	Retrieve and install PA5L-B		X	X					X				
Truss Strut	Retrieve and install PA5F-L		X	X					X				
Node	Retrieve and install PA5F-N		X	X					X				
Truss Strut	Retrieve and install PA5F-D		X	X					X				
Truss Strut	Retrieve and install PA5F-B	X	X	X					X				
Truss Strut	Retrieve and install PA5U-L	X		X					X				
Node	Retrieve and install PA5U-N	X		X					X				
Truss Strut	Retrieve and install PA5U-D	X		X					X				
Truss Strut	Retrieve and install PA5U-B	X		X					X				

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE STATION: EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE: SRMS	BAY	IVA
Truss Strut	Retrieve and install PA5I-D	X	X	X					X				
Cable Tray	Secure to Truss	X	X	X					X				
MT	Translate to truss face PA5F (Utilities Deploy) See Figure 16.			X				X					
	Assemble Truss Bay #PA6												
Truss Strut	Prepare struts for installation	X	X	X	X	X				X			
Truss Strut	Delete strut PA6A-D												
Node	Retrieve and install PA6A-N		X	X					X				
Truss Strut	Retrieve and install PA6A-L		X	X					X				
Truss Strut	Retrieve and install PA6A-B	X	X	X					X				
Truss Strut	Retrieve and install PA6L-L		X	X					X				
Node	Retrieve and install PA6L-N		X	X					X				
Truss Strut	Retrieve and install PA6L-D		X	X					X				
Truss Strut	Retrieve and install PA6L-B		X	X					X				
Truss Strut	Retrieve and install PA6F-L		X	X					X				
Node	Retrieve and install PA6F-N		X	X					X				
Truss Strut	Delete strut PA6F-D												
Truss Strut	Retrieve and install PA6F-B	X	X	X					X				
Truss Strut	Retrieve and install PA6U-L	X		X					X				
Node	Retrieve and install PA6U-N	X		X					X				
Truss Strut	Retrieve and install PA6U-D	X		X					X				
Truss Strut	Retrieve and install PA6U-B	X		X					X				
Truss Strut	Retrieve and install PA6I-D	X	X	X					X				

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED: SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
Cable Tray	Secure to Truss	X	X	X					X				
	Install Upper Beta Gimbal/Solar Array												
	Grapple BG/SA			X		X							
	Release from Launch Craddle			X		X				X			
	Remove BG/SA from LC			X		X							
	Position BG/SA to center of PA6U			X		X				X			
EVA B	Egress APD		X										
	Translate to Upper Beta Gimbal		X										
	Position PFR for struts 1 to 4		X										
	retrieve and install #1	X	X	X					X				
	retrieve and install #2	X	X	X					X				
Upper	retrieve and install #3	X	X	X					X				
Beta	retrieve and install #4	X	X	X					X				
Gimbal	Position PFR for struts 5 to 8		X										
Transition	retrieve and install #5	X	X	X					X				
Structure	retrieve and install #6	X	X	X					X				
	retrieve and install #7	X	X	X					X				
	retrieve and install #8	X	X	X					X				
Upper	Retrieve from AWP	X		X					X				
Transition	Attach to Beta Gimbal		X										
Utility Tray	Attach to Utility Tray	X							X				
EVA B	Ingress APD		X										

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED: SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
	Install Lower Beta Gimbal/Solar Array See Figure 17.												
	Grapple BG/SA			X		X							
	Release from Launch Craddle			X		X				X			
	Remove BG/SA from LC			X		X							
	Position BG/SA to center of PA6L			X		X				X			
EVA A	Egress APD	X											
	Translate to Lower Beta Gimbal	X											
	Position PFR for struts 1 to 4	X											
	retrieve and install #1	X	X	X					X				
	retrieve and install #2	X	X	X					X				
Lower	retrieve and install #3	X	X	X					X				
Beta	retrieve and install #4	X	X	X					X				
Gimbal	Position PFR for struts 5 to 8	X											
Transition	retrieve and install #5	X	X	X					X				
Structure	retrieve and install #6	X	X	X					X				
	retrieve and install #7	X	X	X					X				
	retrieve and install #8	X	X	X					X				
Lower	Retrieve from AWP		X	X					X				
Transition	Attach to Beta Gimbal	X											
Utility Tray	Attach to Utility Tray		X						X				
EVA A	Ingress APD See Figure 18.	X											

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
	Install Integrated Equipment Assembly See Figure 19.												
Truss Strut	Remove and stow strut PA5L-D		X	X					X				
IEA	Prepare IEA for removal from LC			X		X				X			
IEA	Grapple IEA with SSRMS			X		X							
IEA	Remove and relocate to center of truss bay PA5			X		X							
Truss Strut	Retrieve and install PA5L-D		X	X					X				
	Install IEA Transition Structure												
	Prepare struts for installation			X		X				X			
	Retrieve and install #1		X	X					X				
IEA	Retrieve and install #2	X		X					X				
Transition	Retrieve and install #3		X	X					X				
Structure	Retrieve and install #4	X		X					X				
	Retrieve and install #5		X	X					X				
	Retrieve and install #6	X		X					X				
	Retrieve and install #7		X	X					X				
	Retrieve and install #8	X		X					X				
Condenser	Deploy-Rotate 90 deg	X	X										
	See Figure 20.												
	Mate Utility Connections												
IEA	Retrieve from AWP		X	X					X				
Transition	Attach to IEA	X											

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	RESOURCES USED SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
Utility Tray	Attach to Utility Tray		X						X				
	End of EVA activities												
CETA	Translate EVA A and EVA B to airlock	X	X		X								
	Install Radiator Fins												
	Prepare Radiator Fins for Insertion			X		X				X			
Rad Fin	Retrieve and install # 1			X		X				X			
Rad Fin	Retrieve and install # 2			X		X				X			
Rad Fin	Retrieve and install # 3			X		X				X			
Rad Fin	Retrieve and install # 4			X		X				X			
Rad Fin	Retrieve and install # 5			X		X				X			
Rad Fin	Retrieve and install # 6			X		X				X			
Rad Fin	Retrieve and install # 7			X		X				X			
Rad Fin	Retrieve and install # 8			X		X				X			
Rad Fin	Retrieve and install # 9			X		X				X			
	See Figure 21.												
Upper Solar Array	Rotate Blanket Boxes			X									
	Deploy Solar Array			X									
Lower Solar Array	Rotate Blanket Boxes			X									
	Deploy Solar Array			X									
	See Figure 22.												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	SPACE STATION EVA A	EVA B	IVA	CETA	SSRMS	MSC	MT	AWP	FTS	SHUTTLE SRMS	BAY	IVA
MT	Translate to truss face PA1F			X				X					
Alpha Gimbal	Command to Stop and Align			X									
MT	Cross Alpha Gimabl, Translate to truss face PB7F			X				X					
Alpha Gimbal	Restart and Sun Align			X									
IB & OB Beta Gimbals	Command to sun align			X									
	See Figure 23.												
	Return Launch Craddle to Shuttle for Return Trip to Earth												
MT	Translate to truss face PB1F			X				X					
SSRMS	Grapple GF #1			X		X							
	Release POA			X			X						
LC	Remove from MSC			X		X							
SRMS	Grapple GF #2										X		X
	Release GF #1			X		X							
	Position LC in Bay										X	X	X
	Command longeroen fittings to closed position											X	X

Table 2. Assembly Timeline Estimates

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
	Move PV Launch Package from Shuttle Bay to MSC						
	Grapple GF #1	5	5			5	0
	Release Longeroen Fittings	2	2			7	0
PV	Remove from Cargo Bay	15	15			22	0
Launch	Grapple GF #2	5	5			27	0
Package	Release GF #1	1	1			28	0
	Position onto POA	15	15			43	0
	Close POA	2	2			45	0
	Release GF #2	1	1	0		46	0
						46	0
						46	0
	Move Radiator Fin Package from					46	0
	Shuttle Bay to Launch Craddle					46	0
						46	0
	Grapple GF #1	5	5			51	0
	Release Retention Fittings	2	2			53	0
Radiator	Remove from Cargo Bay	10	10			63	0
Fin	Grapple GF #2	5	5			68	0
Package	Release GF #1	1	1			69	0
	Position onto LC	10	10			79	0
	Close Retention Fittings	2	2			81	0
	Release GF #2	1	1	0		82	0
						82	0
						82	0
	Move Transition Structure Package from					82	0
	Shuttle Bay to Assembly Work Platform					82	0
						82	0

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
	Grapple GF #1	5	5			87	0
	Release Retention Fittings	2	2			89	0
Transition	Remove from Cargo Bay	10	10			99	0
Structure	Grapple GF #2	5	5			104	0
Package	Release GF #1	1	1			105	0
	Position onto AWP	10	10			115	0
	Close Retention Fittings	2	2			117	0
	Release GF #2	1	1	0		118	0
						118	0
						118	0
	Move Truss Structure Package from					118	0
	Shuttle Bay to Assembly Work Platform					118	0
						118	0
	Grapple GF #1	5	5			123	0
	Release Retention Fittings	2	2			125	0
Truss	Remove from Cargo Bay	10	10			135	0
Structure	Grapple GF #2	5	5			140	0
Package	Release GF #1	1	1			141	0
	Position onto LC	10	10			151	0
	Close Retention Fittings	2	2			153	0
	Release GF #2	1	1	0		154	0
						154	0
						154	0
	Move Utility Tray Package from					154	0
	Shuttle Bay to Assembly Work Platform					154	0
						154	0
	Grapple GF #1	5	5			159	0
	Release Retention Fittings	2	2			161	0
Utility	Remove from Cargo Bay	10	10			171	0
Tray	Grapple GF #2	5	5			176	0

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Package	Release GF #1	1	1			177	0
	Position onto AWP	10	10			187	0
	Close Retention Fittings	2	2			189	0
	Release GF #2	1	1	0		190	0
						190	0
	See Figure 10.					190	0
	Transport Equipment to work site					190	0
						190	0
MT	Translate to truss face PB7F	90	90			280	0
Alpha						280	0
Gimbal	Command to Stop and Align	5	5			285	0
						285	0
Beta	Command to zero position	3	3			288	0
Gimabl						288	0
	Cross Alpha Gimbal,					288	0
MT	Translate to truss face PA1F	30	30			318	0
	See Figure 11.					318	0
						318	0
	Crew begins EVA Period					318	0
						318	0
	Egress Airlock	5	5	5		323	5
CREW	Translate to work site	20		20		323	25
	Crew enter CETA APD's	2		2		323	27
						323	27
	See Figure 12.					323	27
	Start of PV Module Assembly					323	27
						323	27
Upper	Retrieve End of Utility Tray	1	1	1		324	28
Utility	Attach to OB end of IB	2	2	2		326	30
Tray	PV Module Upper Utility Tray					326	30

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
						326	30
Lower	Retrieve End of Utility Tray	1	1		1	327	31
Utility	Attach to OB end of IB	2	2		2	329	33
Tray	PV Module Lower Utility Tray					329	33
						329	33
MT	Translate to truss face PA2F	15	15			344	33
	(Utilities Deploy)					344	33
	See Figure 13.					344	33
						344	33
Alpha	Command restart and sun align	20	20			364	33
Gimbal	(Retain IB Beta Angle at zero)					364	33
						364	33
						364	33
	Assemble Truss Bay #PA3					364	33
						364	33
Truss Strut	Prepare struts for installatio	2	2	2	2	366	35
Truss Strut	Retrieve and install PA3A-D	1	1	1	1	367	36
Node	Retrieve and install PA3A-N	1	1		1	368	37
Truss Strut	Retrieve and install PA3A-L	1	1		1	369	38
Node	Retrieve and install PA3A-B	1	1	1	1	370	39
Truss Strut	Retrieve and install PA3L-L	1	1		1	371	40
Node	Retrieve and install PA3L-N	1	1		1	372	41
Truss Strut	Retrieve and install PA3L-D	1	1		1	373	42
Truss Strut	Retrieve and install PA3L-B	1	1		1	374	43
Truss Strut	Retrieve and install PA3F-L	1	1		1	375	44
Node	Retrieve and install PA3F-N	1	1		1	376	45
Truss Strut	Retrieve and install PA3F-D	1	1	1	1	377	46
Truss Strut	Retrieve and install PA3F-B	1	1	1	1	378	47
Truss Strut	Retrieve and install PA3U-L	1	1	1		379	48
Node	Retrieve and install PA3U-N	1	1	1		360	49

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Truss Strut	Retrieve and install PA3U-D	1	1	1		381	50
Truss Strut	Retrieve and install PA3U-B	1	1	1		382	51
Truss Strut	Retrieve and install PA3I-D	1	1	1	1	383	52
						383	52
Cable Tray	Secure to Truss	3	3	3	3	386	55
						386	55
						386	55
						386	55
MT	Translate to truss face PA3F	15	15			401	55
	(Utilities Deploy)					401	55
	See Figure 14.					401	55
						401	55
	Assemble Truss Bay #PA4					401	55
						401	55
Truss Strut	Prepare struts for installatio	2	2	2	2	403	57
Truss Strut	Retrieve and install PA4A-D	1	1	1	1	404	58
Node	Retrieve and install PA4A-N	1	1		1	405	59
Truss Strut	Retrieve and install PA4A-L	1	1		1	406	60
Truss Strut	Retrieve and install PA4A-B	1	1	1	1	407	61
Truss Strut	Retrieve and install PA4L-L	1	1		1	408	62
Node	Retrieve and install PA4L-N	1	1		1	409	63
Truss Strut	Retrieve and install PA4L-D	1	1		1	410	64
Truss Strut	Retrieve and install PA4L-B	1	1		1	411	65
Truss Strut	Retrieve and install PA4F-L	1	1		1	412	66
Node	Retrieve and install PA4F-N	1	1		1	413	67
Truss Strut	Retrieve and install PA4F-D	1	1	1	1	414	68
Truss Strut	Retrieve and install PA4F-B	1	1	1	1	415	69
Truss Strut	Retrieve and install PA4U-L	1	1	1		416	70
Node	Retrieve and install PA4U-N	1	1	1		417	71
Truss Strut	Retrieve and install PA4U-D	1	1	1		418	72

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Truss Strut	Retrieve and install PA4U-B	1	1	1		419	73
Truss Strut	Retrieve and install PA4I-D	1	1	1	1	420	74
						420	74
Cable Tray	Secure to Truss	3	3	3	3	423	77
						423	77
						423	77
						423	77
MT	Translate to truss face PA4F	15	15			438	77
	(Utilities Deploy)					438	77
	See Figure 15.					438	77
						438	77
	Assemble Truss Bay #PA5					438	77
						438	77
	Prepare struts for installatio	2	2	2	2	440	79
Truss Strut	Retrieve and install PA5A-D	1	1	1	1	441	80
Node	Retrieve and install PA5A-N	1	1		1	442	81
Truss Strut	Retrieve and install PA5A-L	1	1		1	443	82
Truss Strut	Retrieve and install PA5A-B	1	1	1	1	444	83
Truss Strut	Retrieve and install PA5L-L	1	1		1	445	84
Node	Retrieve and install PA5L-N	1	1		1	446	85
Truss Strut	Retrieve and install PA5L-D	1	1		1	447	86
Truss Strut	Retrieve and install PA5L-B	1	1		1	448	87
Truss Strut	Retrieve and install PA5F-L	1	1		1	449	88
Node	Retrieve and install PA5F-N	1	1		1	450	89
Truss Strut	Retrieve and install PA5F-D	1	1		1	451	90
Truss Strut	Retrieve and install PA5F-B	1	1	1	1	452	91
Truss Strut	Retrieve and install PA5U-L	1	1	1		453	92
Node	Retrieve and install PA5U-N	1	1	1		454	93
Truss Strut	Retrieve and install PA5U-D	1	1	1		455	94
Truss Strut	Retrieve and install PA5U-B	1	1	1		456	95

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Truss Strut	Retrieve and install PA5I-D	1	1	1	1	457	96
						457	96
Cable Tray	Secure to Truss	3	3	3	3	460	99
						460	99
						460	99
MT	Translate to truss face PA5F	15	15			475	99
	(Utilities Deploy)					475	99
	See Figure 16.					475	99
						475	99
	Assemble Truss Bay #PA6					475	99
						475	99
Truss Strut	Prepare struts for installatio	2	2	2	2	477	101
Truss Strut	Delete strut PA6A-D					477	101
Node	Retrieve and install PA6A-N	1	1		1	478	102
Truss Strut	Retrieve and install PA6A-L	1	1		1	479	103
Truss Strut	Retrieve and install PA6A-B	1	1	1	1	480	104
Truss Strut	Retrieve and install PA6L-L	1	1		1	481	105
Node	Retrieve and install PA6L-N	1	1		1	482	106
Truss Strut	Retrieve and install PA6L-D	1	1		1	483	107
Truss Strut	Retrieve and install PA6L-B	1	1		1	484	108
Truss Strut	Retrieve and install PA6F-L	1	1		1	485	109
Node	Retrieve and install PA6F-N	1	1		1	486	110
Truss Strut	Delete strut PA6F-D					486	110
Truss Strut	Retrieve and install PA6F-B	1	1	1	1	487	111
Truss Strut	Retrieve and install PA6U-L	1	1	1		488	112
Node	Retrieve and install PA6U-N	1	1	1		489	113
Truss Strut	Retrieve and install PA6U-D	1	1	1		490	114
Truss Strut	Retrieve and install PA6U-B	1	1	1		491	115
Truss Strut	Retrieve and install PA6I-D	1	1	1	1	492	116
						492	116

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Cable Tray	Secure to Truss	3	3	3	3	495	119
						495	119
						495	119
	Install Upper Beta Gimbal/Solar Array					495	119
						495	119
	Grapple BG/SA	5	5			500	119
	Release from Launch Craddle	2	2			502	119
	Remove BG/SA from LC	2	2			504	119
	Position BG/SA to center of PA	5	5			509	119
EVA B	Egress APD	1			1	509	120
	Translate to Upper Beta Gimbal	1			1	509	121
						509	121
	Position PFR for struts 1 to 4	4			4	509	125
	retrieve and install #1	1	1	1	1	510	126
	retrieve and install #2	1	1	1	1	511	127
Upper	retrieve and install #3	1	1	1	1	512	128
Beta	retrieve and install #4	1	1	1	1	513	129
Gimbal	Position PFR for struts 5 to 8	4			4	513	133
Transition	retrieve and install #5	1	1	1	1	514	134
Structure	retrieve and install #6	1	1	1	1	515	135
	retrieve and install #7	1	1	1	1	516	136
	retrieve and install #8	1	1	1	1	517	137
						517	137
Upper	Retrieve from AWP	2	2	2		519	139
Transition	Attach to Beta Gimbal	1	1		1	520	140
Utility	Attach to Utility Tray	1		1		520	141
Tray						520	141
						520	141
EVA B	Ingress APD	2			2	520	143
						520	143

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
						520	143
	Install Lower Beta Gimbal/Solar Array					520	143
	See Figure 17.					520	143
						520	143
	Grapple BG/SA	5	5			525	143
	Release from Launch Craddle	2	2			527	143
	Remove BG/SA from LC	2	2			529	143
	Position BG/SA to center of PA	5	5			534	143
EVA A	Egress APD	1		1		534	144
	Translate to Lower Beta Gimbal	1		1		534	145
						534	145
	Position PFR for struts 1 to 4	4		4		534	149
	retrieve and install #1	1	1	1	1	535	150
	retrieve and install #2	1	1	1	1	536	151
Lower	retrieve and install #3	1	1	1	1	537	152
Beta	retrieve and install #4	1	1	1	1	538	153
Gimbal	Position PFR for struts 5 to 8	4		4		538	157
Transition	retrieve and install #5	1	1	1	1	539	158
Structure	retrieve and install #6	1	1	1	1	540	159
	retrieve and install #7	1	1	1	1	541	160
	retrieve and install #8	1	1	1	1	542	161
						542	161
Lower	Retrieve from AWP	2	2		2	544	163
Transition	Attach to Beta Gimbal	1		1		544	164
Utility	Attach to Utility Tray	1	1		1	545	165
Tray						545	165
						545	165
EVA A	Ingress APD	4		4		545	169
	See Figure 18.					545	169
						545	169

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
						545	169
	Install Integrated Equipment Assembly					545	169
	See Figure 19.					545	169
Truss Strut	Remove and stow strut PA5L-D	3	3		3	548	172
IEA	Prepare IEA for removal from L	4	4			552	172
IEA	Grapple IEA with SSRMS	5	5			557	172
IEA	Remove and relocate to center	10	10			567	172
	truss bay PA5					567	172
Truss Strut	Retrieve and install PA5L-D	2	2		2	569	174
						569	174
	Install IEA Transition Structure					569	174
						569	174
	Prepare struts for installatio	2	2	2	2	571	176
	Retrieve and install #1	1	1		1	572	177
IEA	Retrieve and install #2	1	1	1		573	178
Transition	Retrieve and install #3	1	1		1	574	179
Structure	Retrieve and install #4	1	1	1		575	180
	Retrieve and install #5	1	1		1	576	181
	Retrieve and install #6	1	1	1		577	182
	Retrieve and install #7	1	1		1	578	183
	Retrieve and install #8	1	1	1		579	184
						579	184
Condenser	Deploy-Rotate 90 deg	4	4	4	4	583	188
						583	188
	See Figure 20.					583	188
						583	188
	Mate Utility Connections					583	188
						583	188
IEA	Retrieve from AWP	2	2		2	585	190
Transition	Attach to IEA	1		1		585	191

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
Utility	Attach to Utility Tray	1			1	585	192
Tray						585	192
						585	192
	End of EVA activities					585	192
						585	192
CETA	Translate EVA A and EVA B	20	20	20	20	605	212
	to airlock					605	212
						605	212
	Install Radiator Fins					605	212
						605	212
	Prepare Radiator Fins for Inse	4	4			609	212
Rad Fin	Retrieve and install # 1	15	15			624	212
Rad Fin	Retrieve and install # 2	15	15			639	212
Rad Fin	Retrieve and install # 3	15	15			654	212
Rad Fin	Retrieve and install # 4	15	15			669	212
Rad Fin	Retrieve and install # 5	15	15			684	212
Rad Fin	Retrieve and install # 6	15	15			699	212
Rad Fin	Retrieve and install # 7	15	15			714	212
Rad Fin	Retrieve and install # 8	15	15			729	212
Rad Fin	Retrieve and install # 9	15	15			744	212
	See Figure 21.					744	212
						744	212
Upper						744	212
Solar	Rotate Blanket Boxes	5	5			749	212
Array	Deploy Solar Array	15	15			764	212
						764	212
Lower						764	212
Solar	Rotate Blanket Boxes	5	5			769	212
Array	Deploy Solar Array	15	15			784	212
	See Figure 22.					784	212

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	STEP TIME (Min	IVA TIME (Min	EVA A TIME (Min)	EVA B TIME (Min)	CUMM. IVA TIME (MIN)	CUMM. EVA TIME (MIN)
						784	212
						784	212
MT	Translate to truss face PA1F	60	60			844	212
						844	212
Alpha						844	212
Gimbal	Command to Stop and Align	10	10			854	212
						854	212
	Cross Alpha Gimabl,					854	212
MT	Translate to truss face PB7F	30	30			884	212
						884	212
Alpha						884	212
Gimbal	Restart and Sun Align	10	10			894	212
						894	212
IB & OB						894	212
Beta	Command to sun align	10	10			904	212
Gimbals						904	212
	See Figure 23.					904	212
						904	212
	Return Launch Craddle to Shuttle					904	212
	for Return Trip to Earth					904	212
						904	212
MT	Translate to truss face PB1F	90	90			994	212
SSRMS	Grapple GF #1	10	10			1004	212
	Release POA	5	5			1009	212
LC	Remove from MSC	10	10			1019	212
SRMS	Grapple GF #2	10	10			1029	212
	Release GF #1	2	2			1031	212
	Position LC in Bay	15	15			1046	212
	Command longeroen fittings to	3	3			1049	212
	closed position					1049	212

Table 3. Assembly Operations Manipulation Data

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
	Move PV Launch Package from Shuttle Bay to MSC												
	Grapple GF #1												
	Release Longeroen Fittings												
PV Launch Package	Remove from Cargo Bay	Not Applicable to Solar Power Module Coordinate System											
	Grapple GF #2												
	Release GF #1												
	Position onto POA												
	Close POA												
	Release GF #2												
	Move Radiator Fin Package from Shuttle Bay to Launch Craddle												
	Grapple GF #1												
	Release Retention Fittings												
Radiator Fin Package	Remove from Cargo Bay	Not Applicable to Solar Power Module Coordinate System											
	Grapple GF #2												
	Release GF #1												
	Position onto LC												
	Close Retention Fittings												
	Release GF #2												
	Move Transition Structure Package from Shuttle Bay to Assembly Work Platform												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
	Grapple GF #1												
	Release Retention Fittings												
Transition Structure Package	Remove from Cargo Bay	Not Applicable to Solar Power Module Coordinate System											
	Grapple GF #2												
	Release GF #1												
	Position onto AWP												
	Close Retention Fittings												
	Release GF #2												
	Move Truss Structure Package from Shuttle Bay to Assembly Work Platform												
	Grapple GF #1												
	Release Retention Fittings												
Truss Structure Package	Remove from Cargo Bay	Not Applicable to Solar Power Module Coordinate System											
	Grapple GF #2												
	Release GF #1												
	Position onto LC												
	Close Retention Fittings												
	Release GF #2												
	Move Utility Tray Package from Shuttle Bay to Assembly Work Platform												
	Grapple GF #1												
	Release Retention Fittings												
Utility Tray	Remove from Cargo Bay	Not Applicable to Solar Power Module Coordinate System											
	Grapple GF #2												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Package	Release GF #1 Position onto AWP Close Retention Fittings Release GF #2												
	See Figure 10. Transport Equipment to work site												
MT	Translate to truss face PB7F	3.5	-55	0	3.5	-7.5	0	0	47.5	0	0	0	0
Alpha Gimbal	Command to Stop and Align												
Beta Gimabl	Command to zero position												
MT	Cross Alpha Gimbal, Translate to truss face PA1F See Figure 11.	3.5	-7.5	0	3.5	2.5	0	0	10	0	0	0	0
	Crew begins EVA Period												
CREW	Egress Airlock Translate to work site Crew enter CETA APD's												
	See Figure 12. Start of PV Module Assembly												
Upper Utility Tray	Retrieve End of Utility Tray Attach to OB end of IB PV Module Upper Utility Tray												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Lower Utility Tray	Retrieve End of Utility Tray Attach to OB end of IB PV Module Lower Utility Tray												
MT	Translate to truss face PA2F (Utilities Deploy) See Figure 13.	3.5	2.5	0	3.5	7.5	0	0	5	0	0	0	0
Alpha Gimbal	Command restart and sun align (Retain IB Beta Angle at zero)												
	Assemble Truss Bay #PA3												
Truss Strut	Prepare struts for installation												
Truss Strut	Retrieve and install PA3A-D	3.3	13	-3	-2.5	12.5	0	-5.8	-0.5	3	45	0	0
Node	Retrieve and install PA3A-N	3.3	13	-3	-2.5	15	-2.5	-5.8	2	0.5	0	0	0
Truss Strut	Retrieve and install PA3A-L	3.3	13	-3	-2.5	12.5	-2.5	-5.8	-0.5	0.5	0	0	0
Node	Retrieve and install PA3A-B	3.3	13	-3	-2.5	15	0	-5.8	2	3	0	0	90
Truss Strut	Retrieve and install PA3L-L	3.3	13	-3	2.5	12.5	-2.5	-0.8	-0.5	0.5	0	0	0
Node	Retrieve and install PA3L-N	3.3	13	-3	2.5	12.5	-2.5	-0.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA3L-D	3.3	13	-3	0	12.5	-2.5	-3.3	-0.5	0.5	0	0	45
Truss Strut	Retrieve and install PA3L-B	3.3	13	-3	0	15	-2.5	-3.3	2	0.5	0	0	90
Truss Strut	Retrieve and install PA3F-L	3.3	13	3	2.5	12.5	2.5	-0.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA3F-N	3.3	13	3	2.5	12.5	2.5	-0.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA3F-D	3.3	13	3	2.5	12.5	0	-0.8	-0.5	-3	45	0	0
Truss Strut	Retrieve and install PA3F-B	3.3	13	3	2.5	15	0	-0.8	2	-3	90	0	0
Truss Strut	Retrieve and install PA3U-L	3.3	13	3	-2.5	12.5	2.5	-5.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA3U-N	3.3	13	3	-2.5	12.5	2.5	-5.8	-0.5	-0.5	0	0	0

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Truss Strut	Retrieve and install PA3U-D	3.3	13	3	0	12.5	2.5	-3.3	-0.5	-0.5	0	0	45
Truss Strut	Retrieve and install PA3U-B	3.3	13	3	0	15	2.5	-3.3	2	-0.5	0	0	90
Truss Strut	Retrieve and install PA3I-D	3.3	13	3	0	15	0	-3.3	2	-3	0	45	90
Cable Tray	Secure to Truss												
MT	Translate to truss face PA3F (Utilities Deploy) See Figure 14.	3.5	2.5	0	3.5	12.5	0	0	10	0	0	0	0
	Assemble Truss Bay #PA4												
Truss Strut	Prepare struts for installation												
Truss Strut	Retrieve and install PA4A-D	3.3	18	-3	-2.5	17.5	0	-5.8	-0.5	3	45	0	0
Node	Retrieve and install PA4A-N	3.3	18	-3	-2.5	20	-2.5	-5.8	2	0.5	0	0	0
Truss Strut	Retrieve and install PA4A-L	3.3	18	-3	-2.5	17.5	-2.5	-5.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA4A-B	3.3	18	-3	-2.5	20	0	-5.8	2	3	0	0	90
Truss Strut	Retrieve and install PA4L-L	3.3	18	-3	2.5	17.5	-2.5	-0.8	-0.5	0.5	0	0	0
Node	Retrieve and install PA4L-N	3.3	18	-3	2.5	17.5	-2.5	-0.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA4L-D	3.3	18	-3	0	17.5	-2.5	-3.3	-0.5	0.5	0	0	45
Truss Strut	Retrieve and install PA4L-B	3.3	18	-3	0	20	-2.5	-3.3	2	0.5	0	0	90
Truss Strut	Retrieve and install PA4F-L	3.3	18	3	2.5	17.5	2.5	-0.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA4F-N	3.3	18	3	2.5	17.5	2.5	-0.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA4F-D	3.3	18	3	2.5	17.5	0	-0.8	-0.5	-3	45	0	0
Truss Strut	Retrieve and install PA4F-B	3.3	18	3	2.5	20	0	-0.8	2	-3	90	0	0
Truss Strut	Retrieve and install PA4U-L	3.3	18	3	-2.5	17.5	2.5	-5.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA4U-N	3.3	18	3	-2.5	17.5	2.5	-5.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA4U-D	3.3	18	3	0	17.5	2.5	-3.3	-0.5	-0.5	0	0	45

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Truss Strut	Retrieve and install PA4U-B	3.3	18	3	0	20	2.5	-3.3	2	-0.5	0	0	90
Truss Strut	Retrieve and install PA4I-D	3.3	18	-3	0	20	0	-3.3	2	3	0	45	90
Cable Tray	Secure to Truss												
MT	Translate to truss face PA4F (Utilities Deploy) See Figure 15.	3.5	12.5	0	3.5	17.5	0	0	5	0	0	0	0
	Assemble Truss Bay #PA5												
	Prepare struts for installation												
Truss Strut	Retrieve and install PA5A-D	3.3	23	-3	-2.5	22.5	0	-5.8	-0.5	3	45	0	0
Node	Retrieve and install PA5A-N	3.3	23	-3	-2.5	25	-2.5	-5.8	2	0.5	0	0	0
Truss Strut	Retrieve and install PA5A-L	3.3	23	-3	-2.5	22.5	-2.5	-5.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA5A-B	3.3	23	-3	-2.5	25	0	-5.8	2	3	0	0	90
Truss Strut	Retrieve and install PA5L-L	3.3	23	-3	2.5	22.5	-2.5	-0.8	-0.5	0.5	0	0	0
Node	Retrieve and install PA5L-N	3.3	23	-3	2.5	22.5	-2.5	-0.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA5L-D	3.3	23	-3	0	22.5	-2.5	-3.3	-0.5	0.5	0	0	45
Truss Strut	Retrieve and install PA5L-B	3.3	23	-3	0	25	-2.5	-3.3	2	0.5	0	0	90
Truss Strut	Retrieve and install PA5F-L	3.3	23	3	2.5	22.5	2.5	-0.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA5F-N	3.3	23	3	2.5	22.5	2.5	-0.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA5F-D	3.3	23	3	2.5	22.5	0	-0.8	-0.5	-3	45	0	0
Truss Strut	Retrieve and install PA5F-B	3.3	23	3	2.5	25	0	-0.8	2	-3	90	0	0
Truss Strut	Retrieve and install PA5U-L	3.3	23	3	-2.5	22.5	2.5	-5.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA5U-N	3.3	23	3	-2.5	22.5	2.5	-5.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA5U-D	3.3	23	3	0	22.5	2.5	-3.3	-0.5	-0.5	0	0	45
Truss Strut	Retrieve and install PA5U-B	3.3	23	3	0	25	2.5	-3.3	2	-0.5	0	0	90

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Truss Strut	Retrieve and install PA5I-D	3.3	23	3	0	25	0	-3.3	2	-3	0	45	90
Cable Tray	Secure to Truss												
MT	Translate to truss face PA5F (Utilities Deploy) See Figure 16.	3.5	17.5	0	3.5	22.5	0	0	5	0	0	0	0
	Assemble Truss Bay #PA6												
Truss Strut	Prepare struts for installation												
Truss Strut	Delete strut PA6A-D												
Node	Retrieve and install PA6A-N	3.3	28	-3	-2.5	30	-2.5	-5.8	2	0.5	0	0	0
Truss Strut	Retrieve and install PA6A-L	3.3	28	-3	-2.5	27.5	-2.5	-5.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA6A-B	3.3	28	-3	-2.5	30	0	-5.8	2	3	0	0	90
Truss Strut	Retrieve and install PA6L-L	3.3	28	-3	2.5	27.5	-2.5	-0.8	-0.5	0.5	0	0	0
Node	Retrieve and install PA6L-N	3.3	28	-3	2.5	27.5	-2.5	-0.8	-0.5	0.5	0	0	0
Truss Strut	Retrieve and install PA6L-D	3.3	28	-3	0	27.5	-2.5	-3.3	-0.5	0.5	0	0	45
Truss Strut	Retrieve and install PA6L-B	3.3	28	-3	0	30	-2.5	-3.3	2	0.5	0	0	90
Truss Strut	Retrieve and install PA6F-L	3.3	28	3	2.5	27.5	2.5	-0.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA6F-N	3.3	28	3	2.5	27.5	2.5	-0.8	-0.5	-0.5	0	0	0
Truss Strut	Delete strut PA6F-D												
Truss Strut	Retrieve and install PA6F-B	3.3	28	3	2.5	30	0	-0.8	2	-3	90	0	0
Truss Strut	Retrieve and install PA6U-L	3.3	28	3	-2.5	27.5	2.5	-5.8	-0.5	-0.5	0	0	0
Node	Retrieve and install PA6U-N	3.3	28	3	-2.5	27.5	2.5	-5.8	-0.5	-0.5	0	0	0
Truss Strut	Retrieve and install PA6U-D	3.3	28	3	0	27.5	2.5	-3.3	-0.5	-0.5	0	0	45
Truss Strut	Retrieve and install PA6U-B	3.3	28	3	0	30	2.5	-3.3	2	-0.5	0	0	90
Truss Strut	Retrieve and install PA6I-D	3.3	28	-3	0	30	0	-3.3	2	3	0	45	90

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
Cable Tray	Secure to Truss												
	Install Upper Beta Gimbal/Solar Array												
	Grapple BG/SA												
	Release from Launch Craddle												
	Remove BG/SA from LC												
	Position BG/SA to center of	1.3	20.5	0.5	0	27.5	-1.5	-1.3	6.96	-2	0	90	0
EVA B	Egress APD												
	Translate to Upper Beta Gimbal												
	Position PFR for struts 1 to 4												
	retrieve and install #1	3.3	28	-3	1.25	26.2	2.5	-2.0	-1.7	5.5	0		45
	retrieve and install #2	3.3	28	-3	1.25	26.2	2	-2.0	-1.8	5	0	0	45
Upper	retrieve and install #3	3.3	28	-3	-1.2	26.2	2.5	-4.5	-1.7	5.5	0		-45
Beta	retrieve and install #4	3.3	28	-3	-1.2	26.2	2	-4.5	-1.8	5	0	0	-45
Gimbal	Position PFR for struts 5 to 8												
Transition	retrieve and install #5	3.3	28	-3	1.25	28.7	2.5	-2.0	0.75	5.5	0	0	-45
Structure	retrieve and install #6	3.3	28	-3	1.25	28.7	2	-2.0	0.7	5	0		-45
	retrieve and install #7	3.3	28	-3	-1.2	28.7	2.5	-4.5	0.7	5.5	0	0	45
	retrieve and install #8	3.3	28	-3	-1.2	28.7	2	-4.5	0.7	5	0		45
Upper	Retrieve from AWP												
Transition	Attach to Beta Gimbal												
Utility Tray	Attach to Utility Tray												
EVA B	Ingress APD												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS)									ROTATION		
		INITIAL POSITION			FINAL POSITION			LINEAR TRAVEL					
		X	Y	Z	X	Y	Z	X	Y	Z	ALPHA	BETA	GAMMA
	Install Lower Beta Gimbal/Solar Array See Figure 17.												
	Grapple BG/SA												
	Release from Launch Craddle												
	Remove BG/SA from LC												
	Position BG/SA to center of	1.3	20.5	0.5	0	27.5	-1.5	-1.3	6.96	-2	0	90	0
EVA A	Egress APD												
	Translate to Lower Beta Gimbal												
	Position PFR for struts 1 to 4												
	retrieve and install #1	3.3	28	3	1.25	26.2	-2.5	-2.0	-1.7	-5.5	0		45
	retrieve and install #2	3.3	28	3	1.25	26.2	-2	-2.0	-1.8	-5	0	0	45
Lower	retrieve and install #3	3.3	28	3	-1.2	26.2	-2.5	-4.5	-1.7	-5.5	0		-45
Beta	retrieve and install #4	3.3	28	3	-1.2	26.2	-2	-4.5	-1.8	-5	0	0	-45
Gimbal	Position PFR for struts 5 to 8												
Transition	retrieve and install #5	3.3	28	3	1.25	28.7	-2.5	-2.0	0.75	-5.5	0	0	-45
Structure	retrieve and install #6	3.3	28	3	1.25	28.7	-2	-2.0	0.7	-5	0		-45
	retrieve and install #7	3.3	28	3	-1.2	28.7	-2.5	-4.5	0.7	-5.5	0	0	45
	retrieve and install #8	3.3	28	3	-1.2	28.7	-2	-4.5	0.7	-5	0		45
Lower Transition Utility Tray	Retrieve from AWP												
	Attach to Beta Gimbal												
	Attach to Utility Tray												
EVA A	Ingress APD See Figure 18.												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
	Install Integrated Equipment Assembly See Figure 19.												
Truss Strut	Remove and stow strut PA5L-D												
IEA	Prepare IEA for removal from LC												
IEA	Grapple IEA with SSRMS												
IEA	Remove and relocate to cente truss bay PA5	4.9	13	0	0	22.5	0	-4.9	9.5	0	0	0	0
Truss Strut	Retrieve and install PA5L-D												
	Install IEA Transition Structure												
	Prepare struts for installation												
	Retrieve and install #1												
IEA	Retrieve and install #2												
Transition	Retrieve and install #3												
Structure	Retrieve and install #4												
	Retrieve and install #5												
	Retrieve and install #6												
	Retrieve and install #7												
	Retrieve and install #8												
Condenser	Deploy-Rotate 90 deg	0	0	0	0	0	0	0	0	0	0	90	0
	See Figure 20.												
	Mate Utility Connections												
IEA	Retrieve from AWP												
Transition	Attach to IEA												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS)									ROTATION		
		INITIAL POSITION			FINAL POSITION			LINEAR TRAVEL			ALPHA	BETA	GAMMA
		X	Y	Z	X	Y	Z	X	Y	Z			
Utility Tray	Attach to Utility Tray												
	End of EVA activities												
CETA	Translate EVA A and EVA B to airlock												
	Install Radiator Fins												
	Prepare Radiator Fins for Insertion												
Rad Fin	Retrieve and install # 1	6	15.3	-2	-1.2	23.8	1.5	-7.2	8.53	3.5	0	90	90
Rad Fin	Retrieve and install # 2	6	15.3	-2	-1.2	23.5	1.5	-7.2	8.2	3.5	0	90	90
Rad Fin	Retrieve and install # 3	6	15.3	-2	-1.2	23.1	1.5	-7.2	7.86	3.5	0	90	90
Rad Fin	Retrieve and install # 4	6	15.3	-2	-1.2	22.8	1.5	-7.2	7.53	3.5	0	90	90
Rad Fin	Retrieve and install # 5	6	15.3	-2	-1.2	22.5	1.5	-7.2	7.2	3.5	0	90	90
Rad Fin	Retrieve and install # 6	6	15.3	-2	-1.2	22.1	1.5	-7.2	6.86	3.5	0	90	90
Rad Fin	Retrieve and install # 7	6	15.3	-2	-1.2	21.8	1.5	-7.2	6.53	3.5	0	90	90
Rad Fin	Retrieve and install # 8	6	15.3	-2	-1.2	21.5	1.5	-7.2	6.2	3.5	0	90	90
Rad Fin	Retrieve and install # 9	6	15.3	-2	-1.2	21.1	1.5	-7.2	5.86	3.5	0	90	90
	See Figure 21.												
Upper Solar Array	Rotate Blanket Boxes												
	Deploy Solar Array												
Lower Solar Array	Rotate Blanket Boxes												
	Deploy Solar Array												
	See Figure 22.												

ITEM TO BE MANIPULATED	OPERATION TO BE PERFORMED	POSITION IN SOLAR POWER MODULE COORDINATES (METERS) INITIAL POSITION X	Y	Z	FINAL POSITION X	Y	Z	LINEAR TRAVEL X	Y	Z	ROTATION ALPHA	BETA	GAMMA
MT	Translate to truss face PA1F	3.5	22.5	0	3.5	2.5	0	0	-20	0	0	0	0
Alpha Gimbal	Command to Stop and Align												
MT	Cross Alpha Gimabl, Translate to truss face PB7	3.5	2.5	0	3.5	-7.5	0	0	-10	0	0	0	0
Alpha Gimbal	Restart and Sun Align												
IB & OB Beta Gimbals	Command to sun align												
	See Figure 23.												
	Return Launch Craddle to Shuttle for Return Trip to Earth												
MT	Translate to truss face PB1F	Not Applicable to Solar Power Module Coordinate System											
SSRMS	Grapple GF #1 Release POA												
LC SRMS	Remove from MSC Grapple GF #2 Release GF #1 Position LC in Bay Command longeroen fittings to closed position												

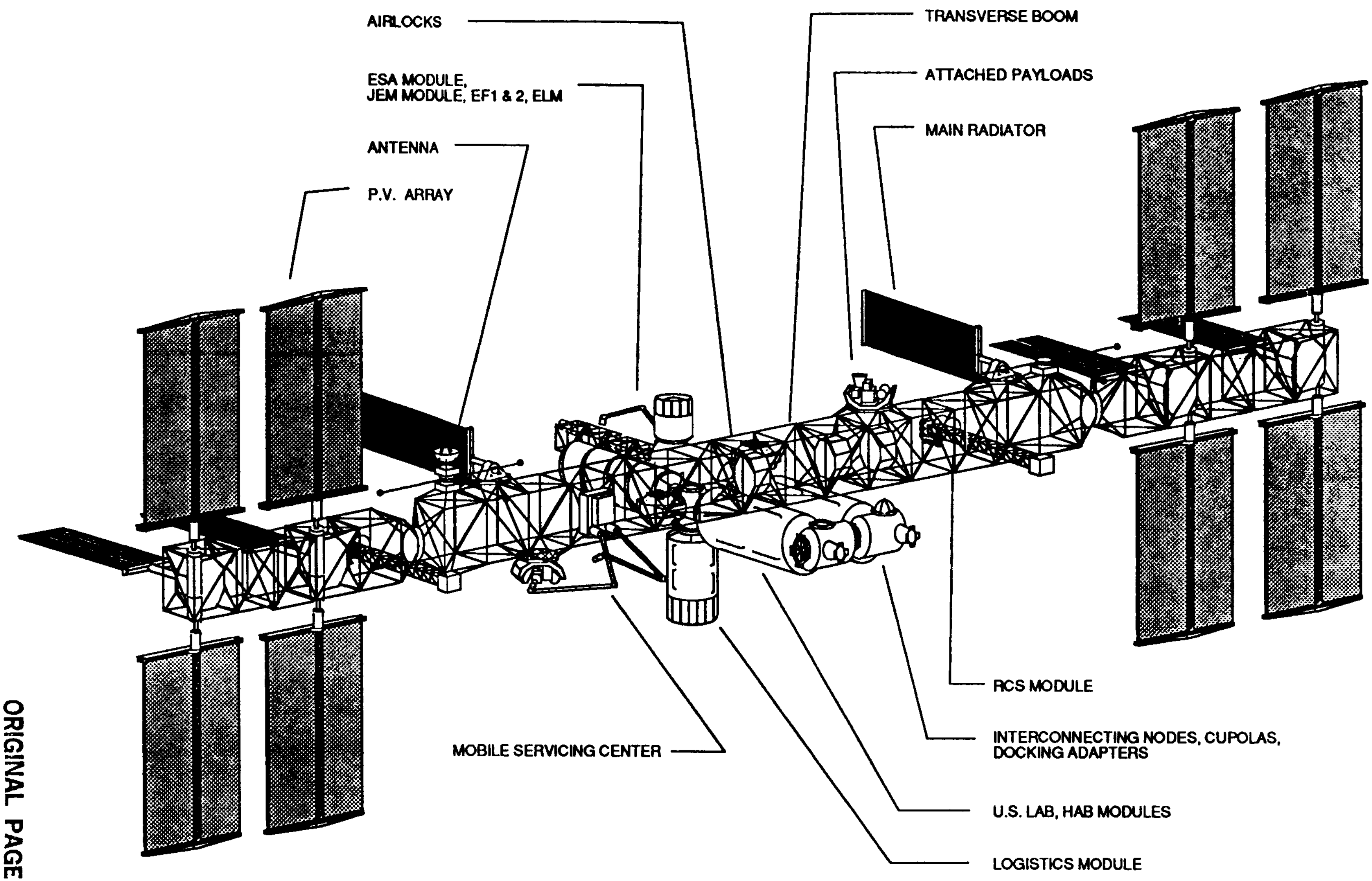

Figure 1. Space Station Freedom Configuration

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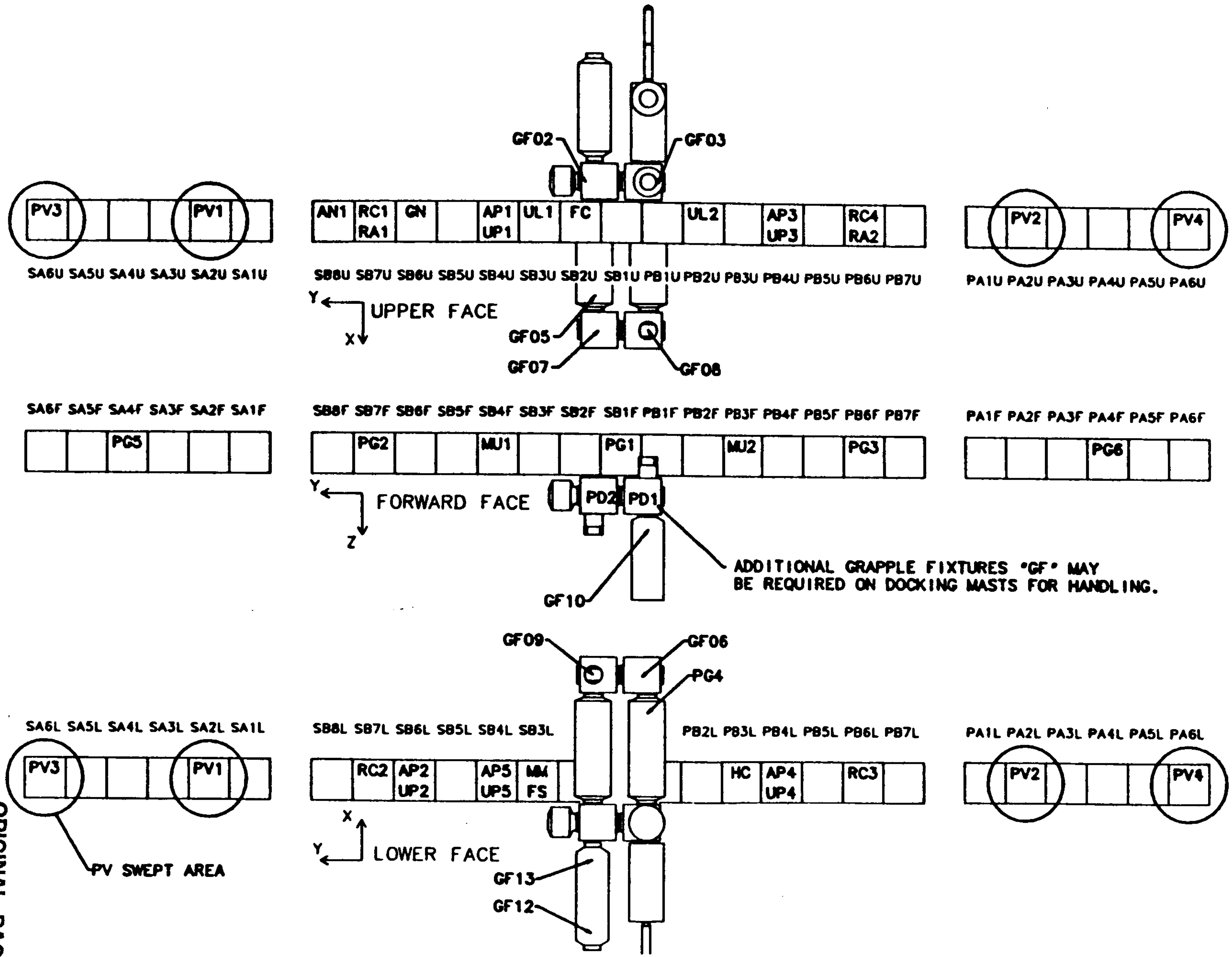

Figure 2. Transverse Boom Space Allocation 1 of 2

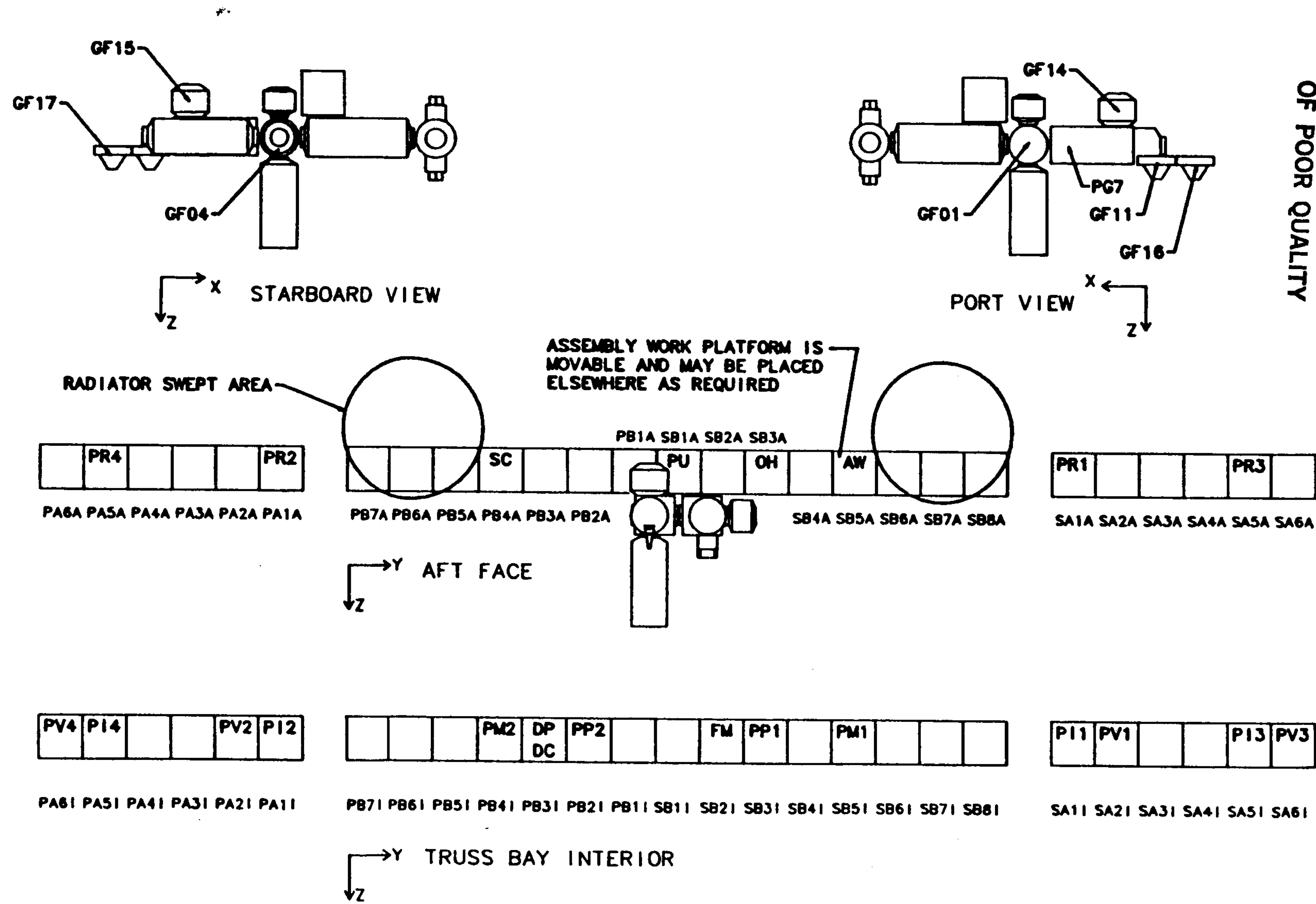

Figure 3. Transverse Boom Space Allocation 2 of 2

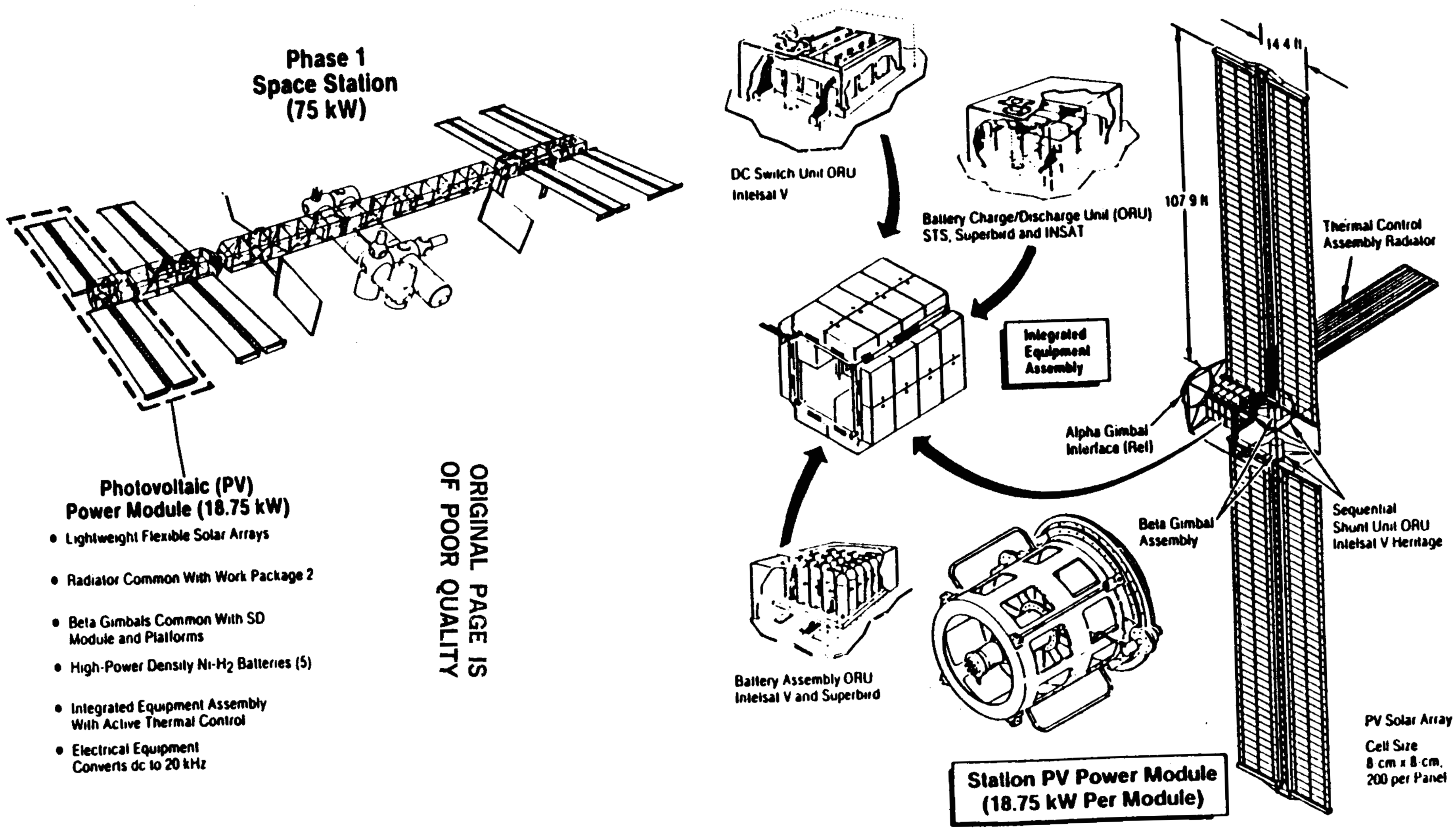

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Figure 4. PV Module Components

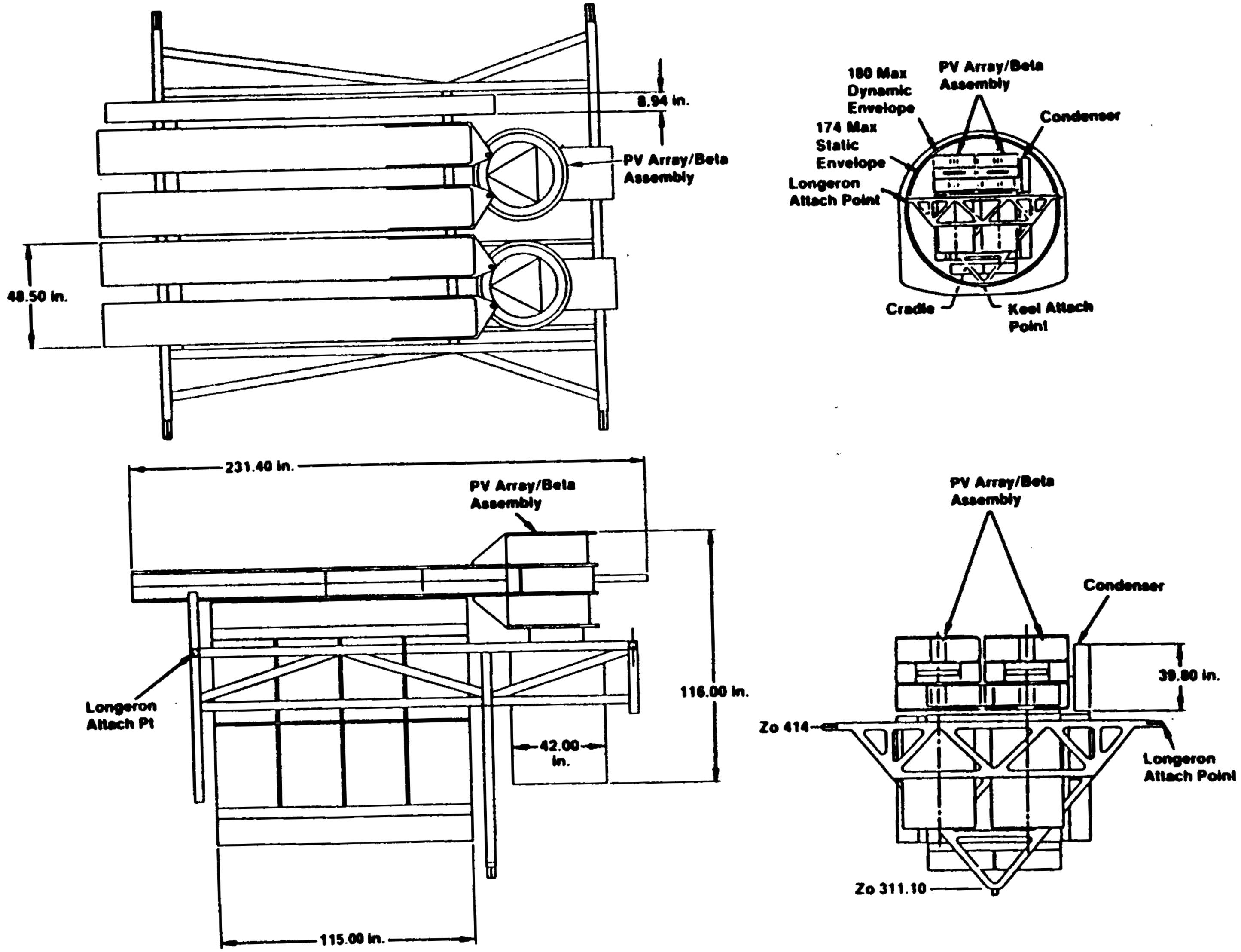

Figure 5. PV Module Launch Package

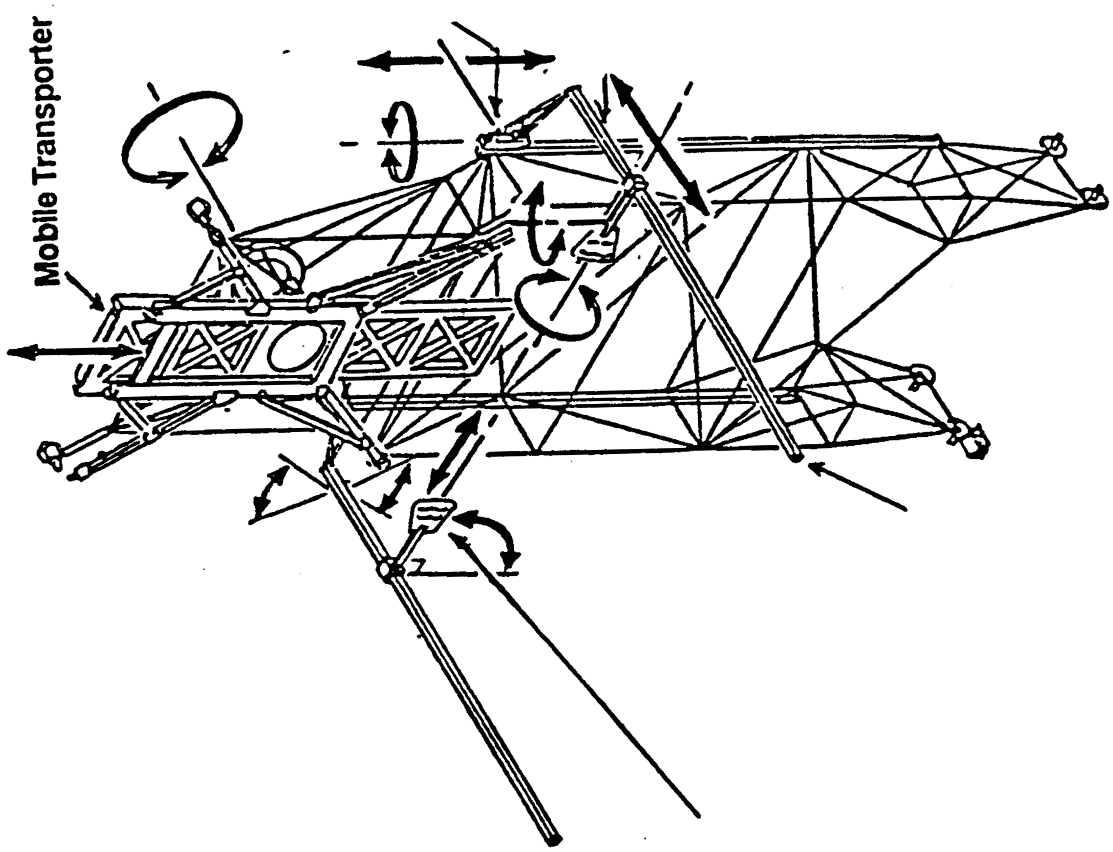

Figure 6. Assembly Work Platform

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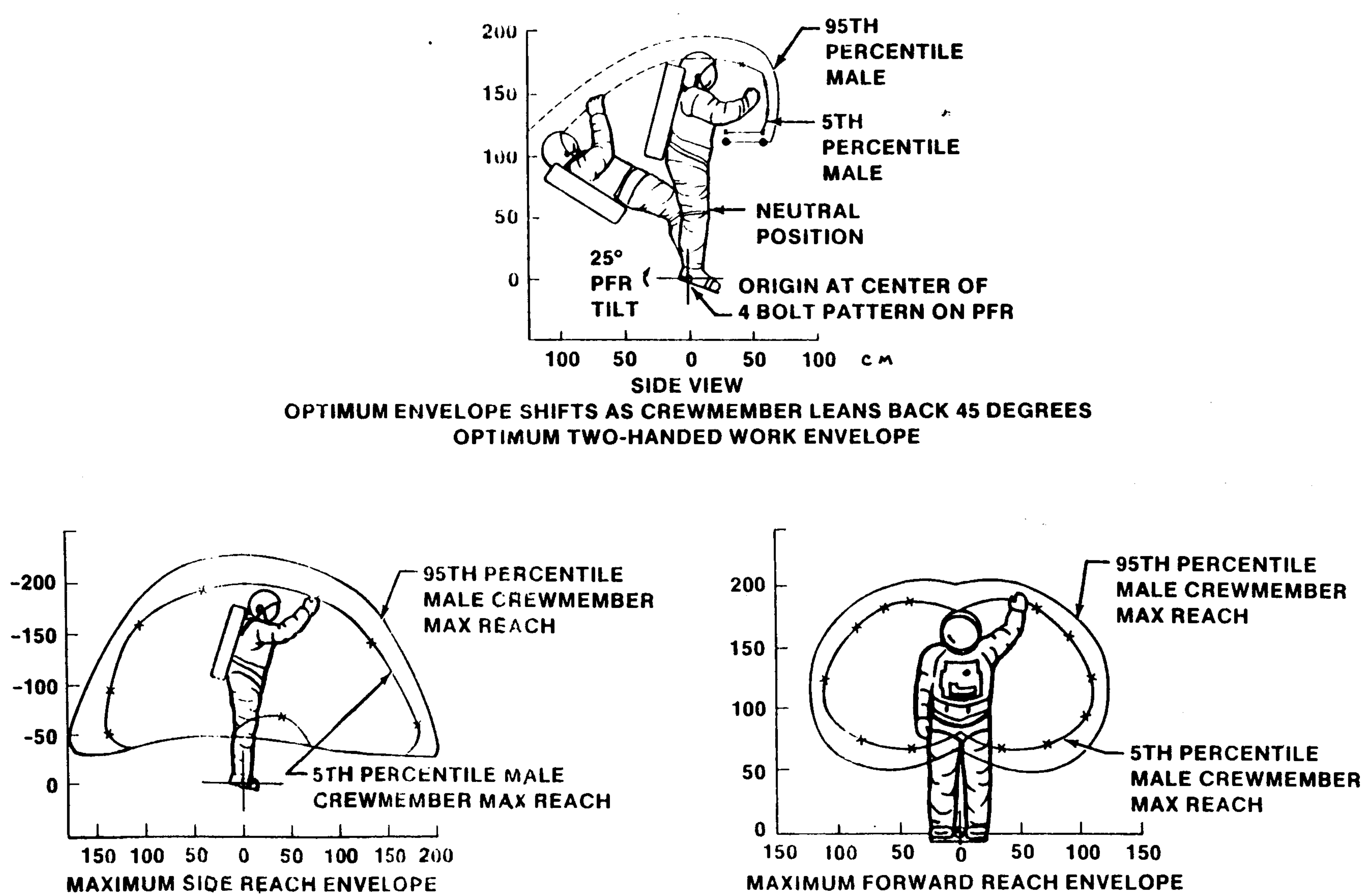

Figure 7. EVA Astronaut Reach Envelope

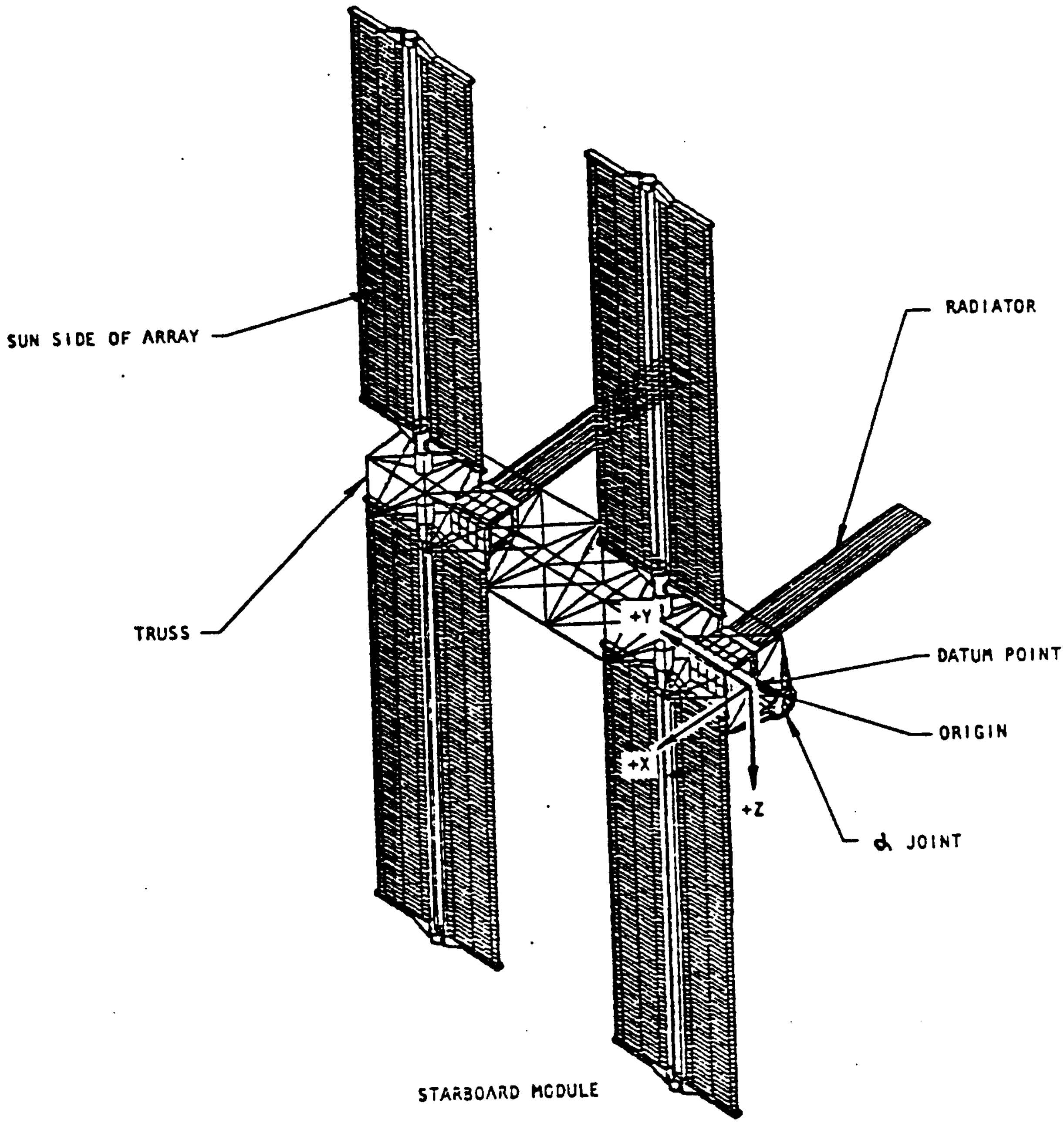

Figure 8. Solar Power Module Coordinate System

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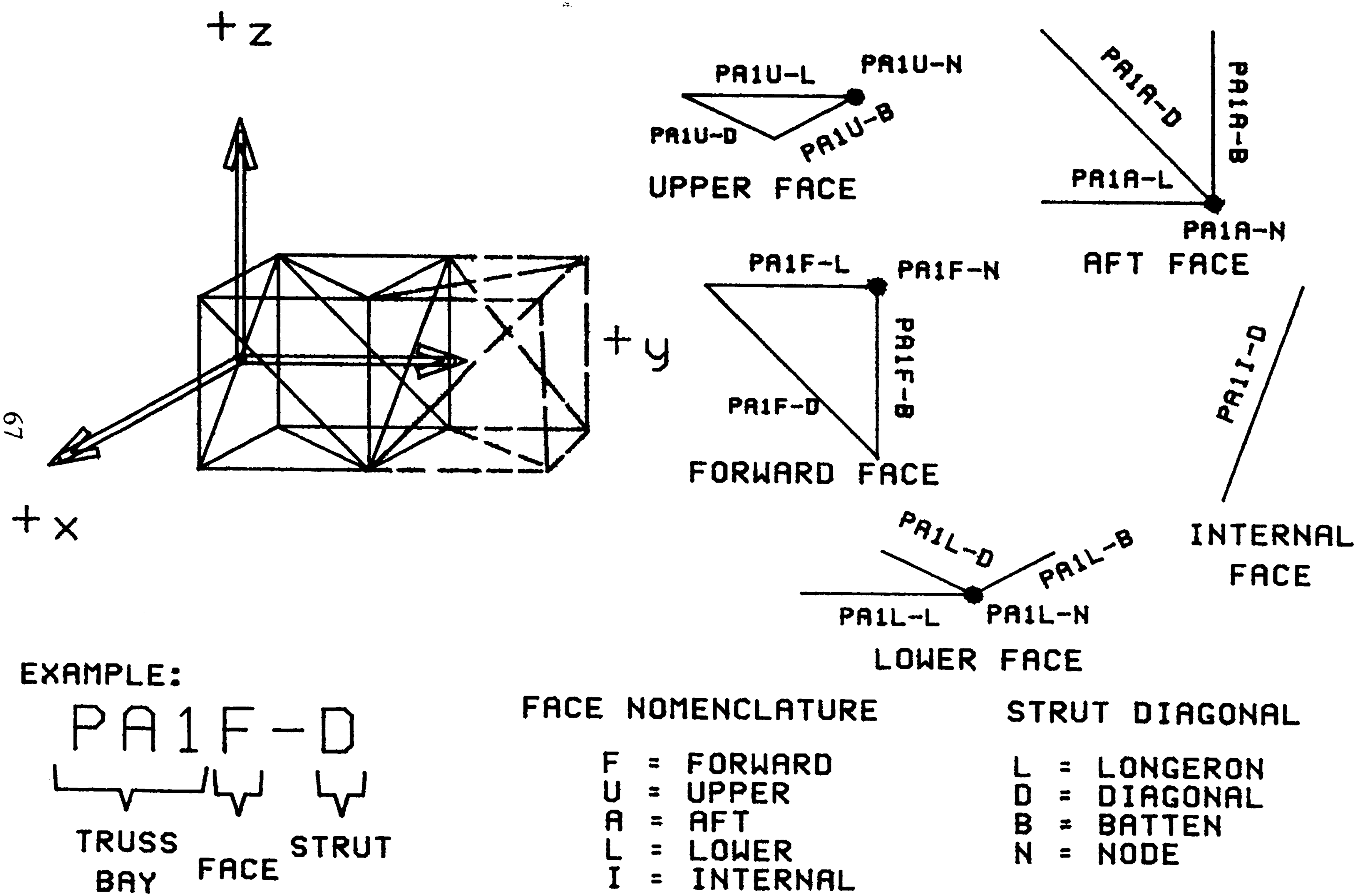

Figure 9. Truss Strut Nomenclature

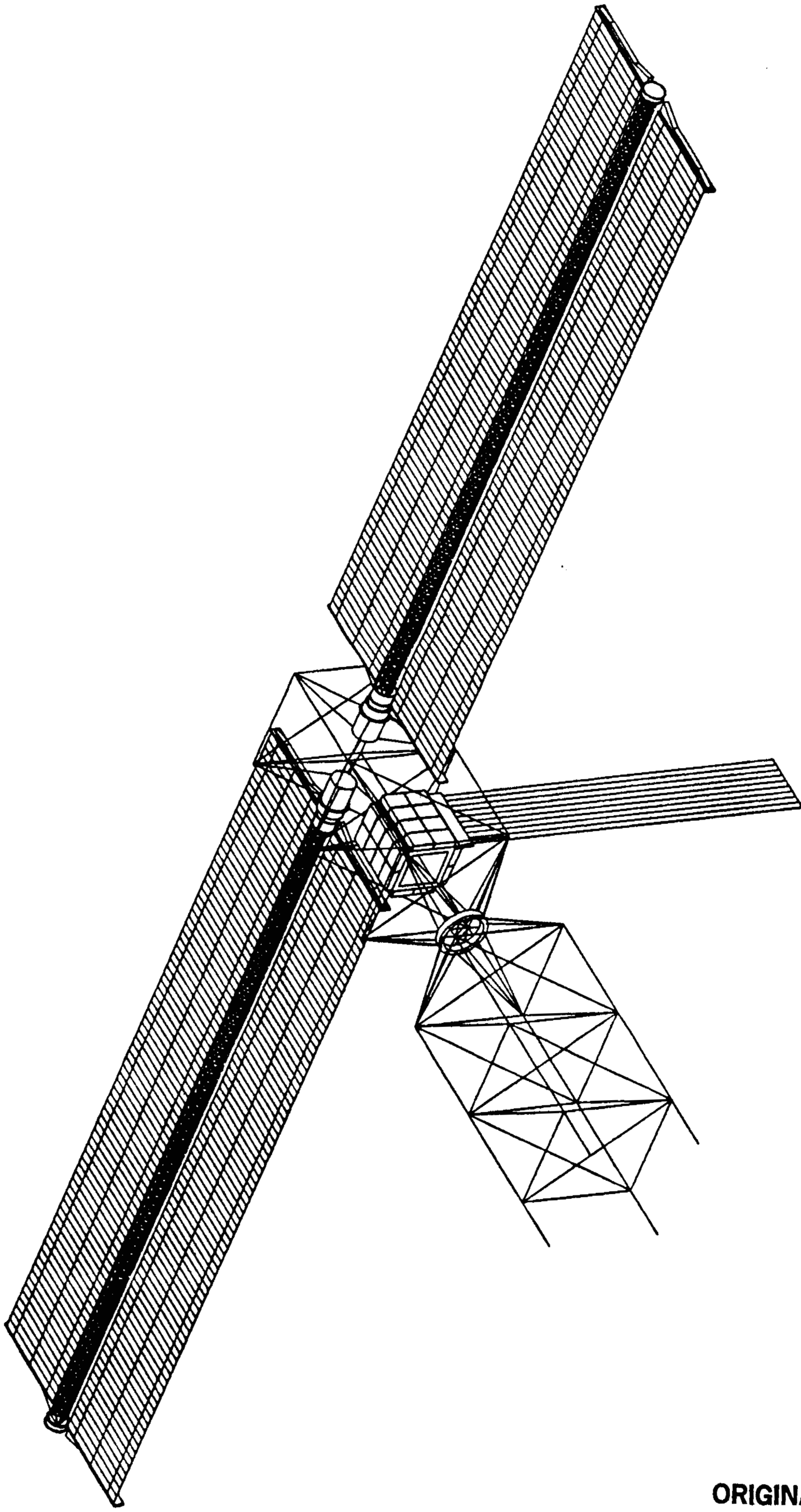

Figure 10. Inboard PV Module

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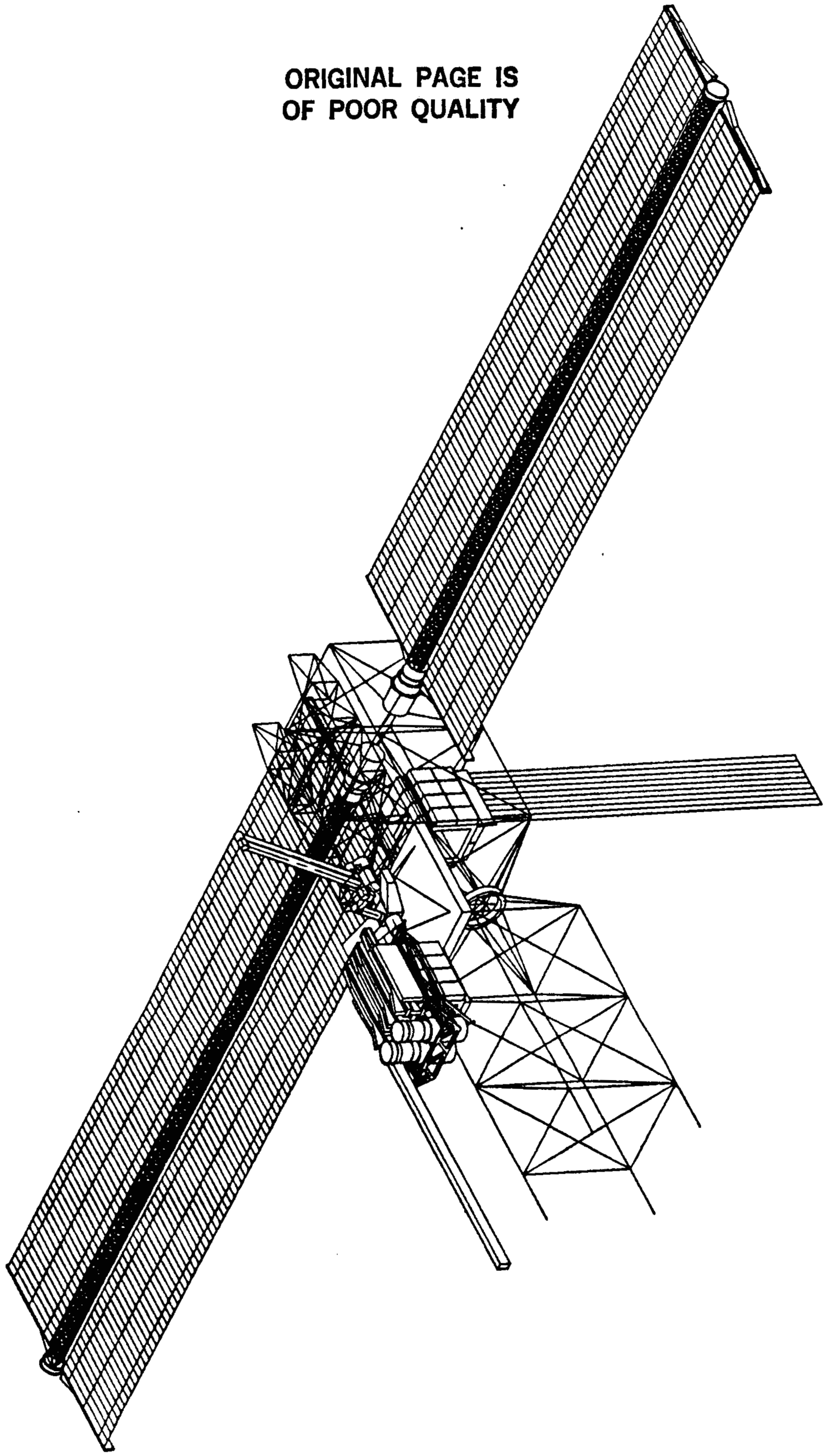

Figure 11. Mobile Transporter Crossing the Alpha Gimbal

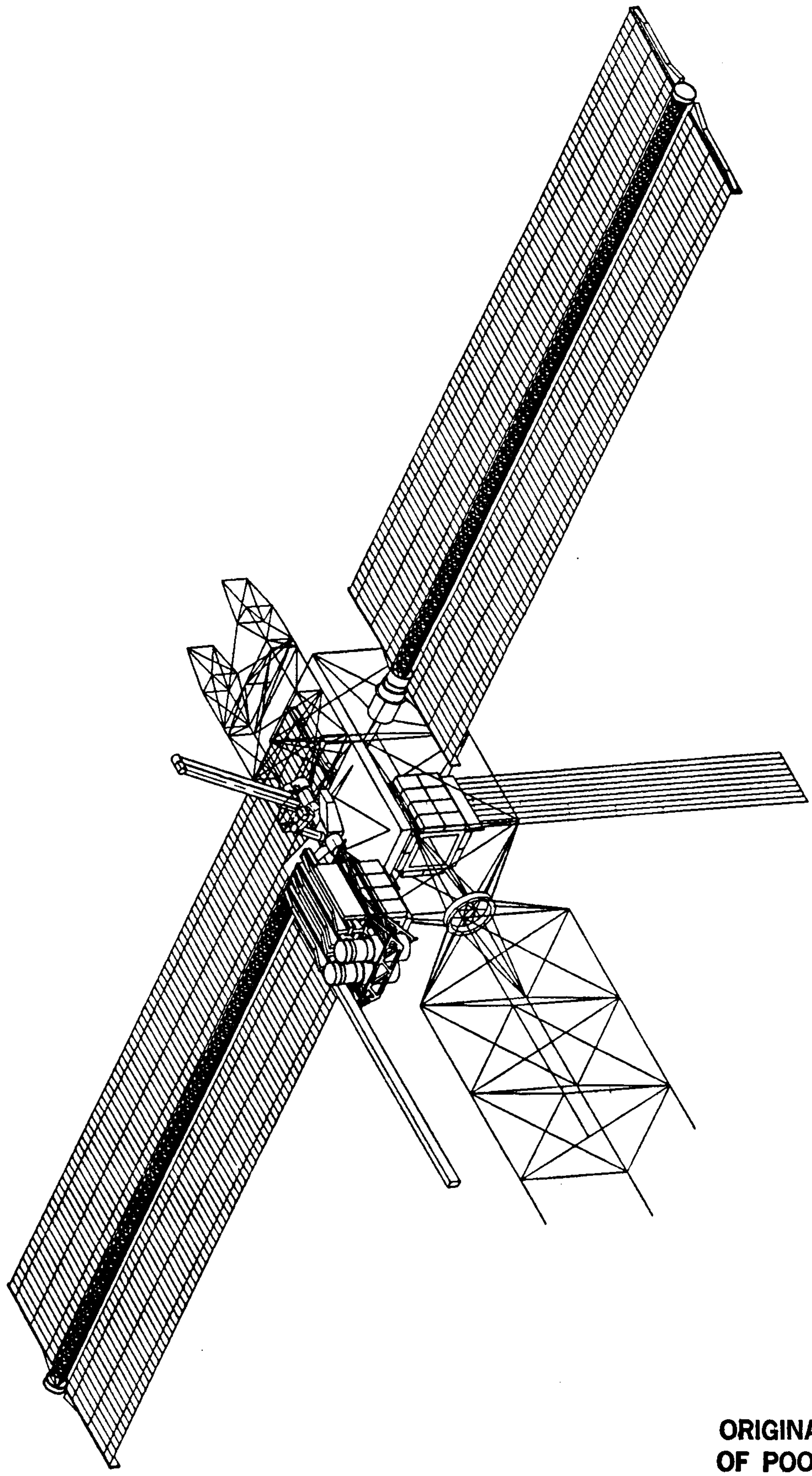

Figure 12. Start of EVA Assembly of the Outboard PV Module

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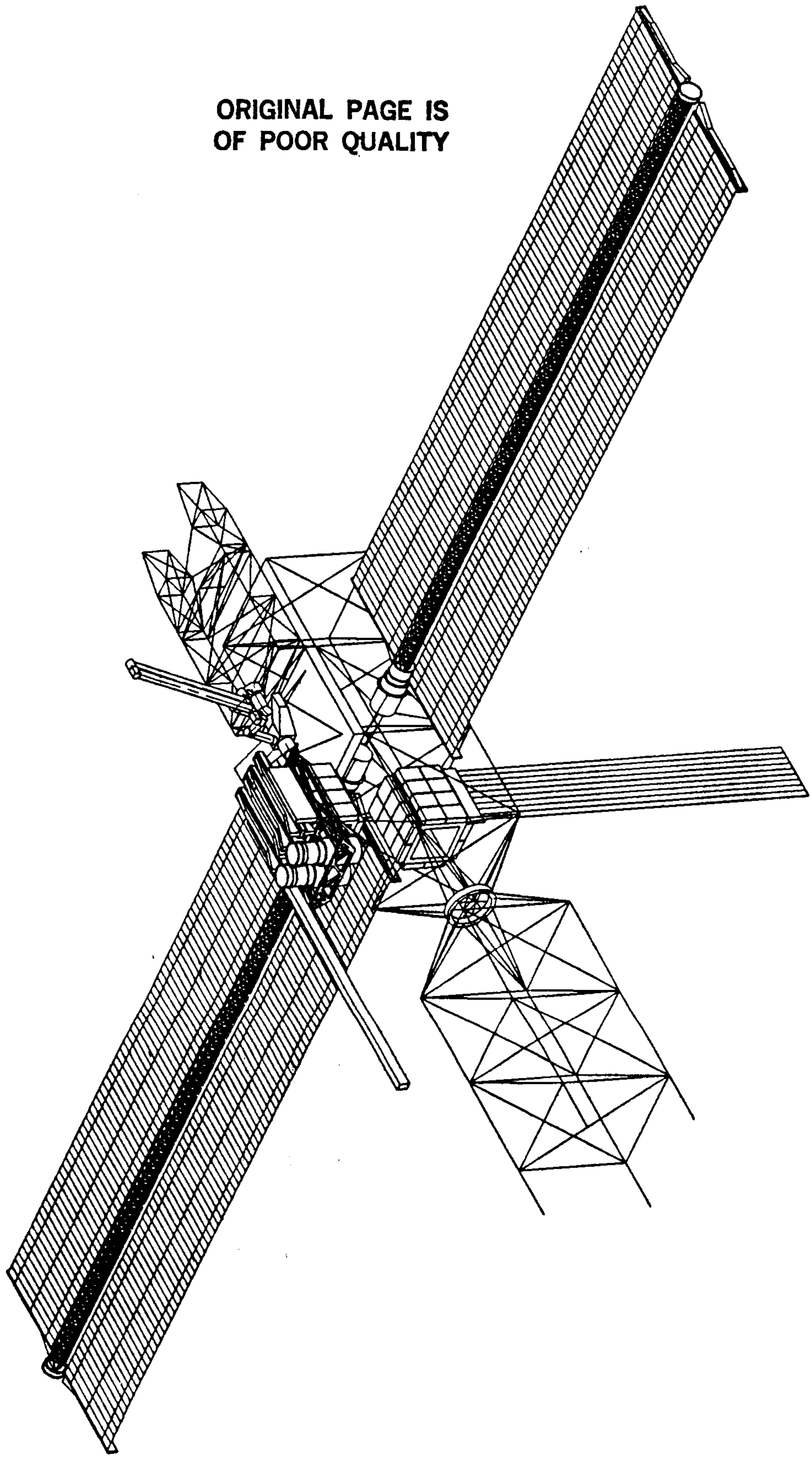

Figure 13. Assembly of First Outboard PV Module Truss Bay

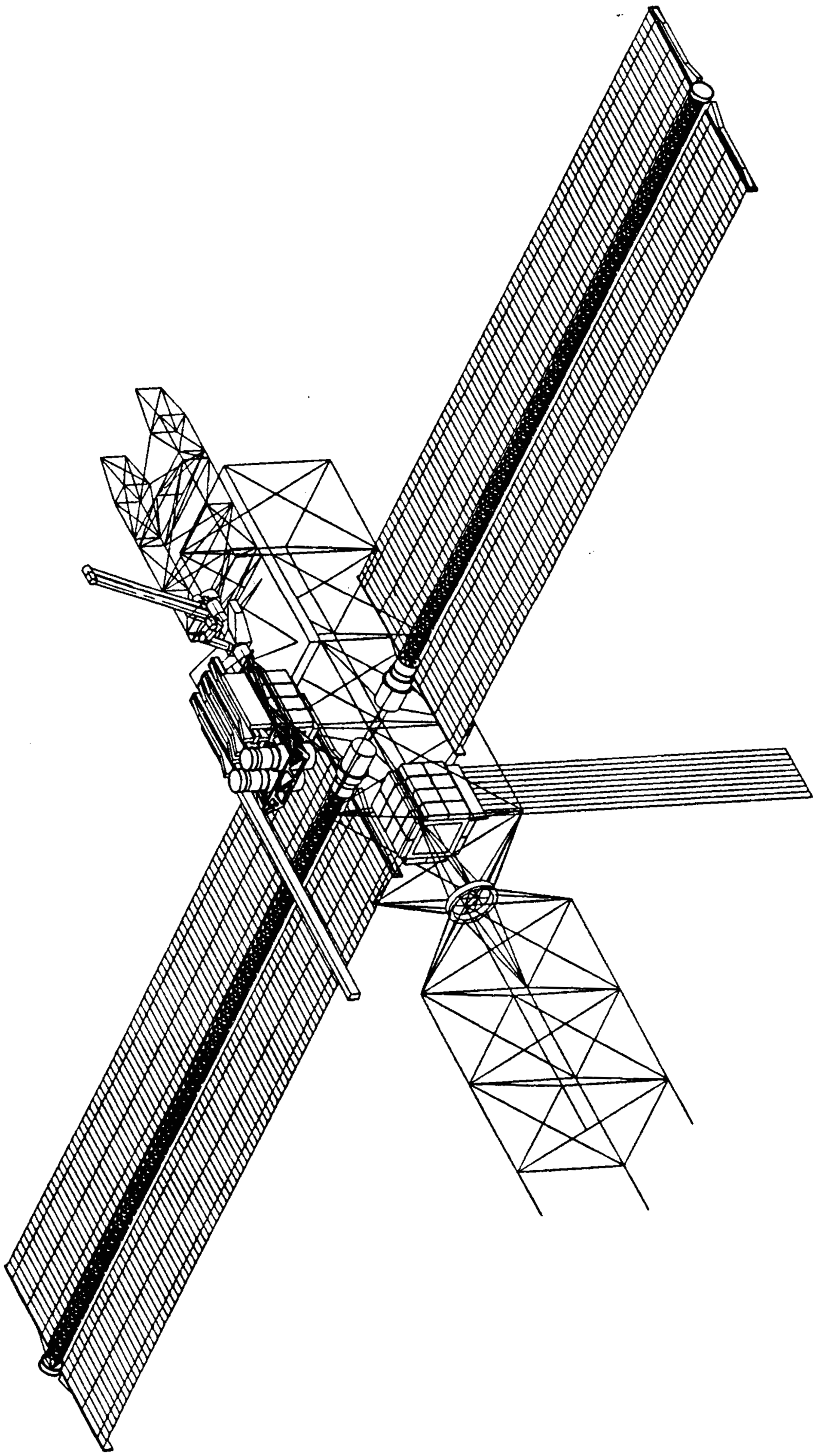

Figure 14. Assembly of the Second Outboard PV Module Truss Bay

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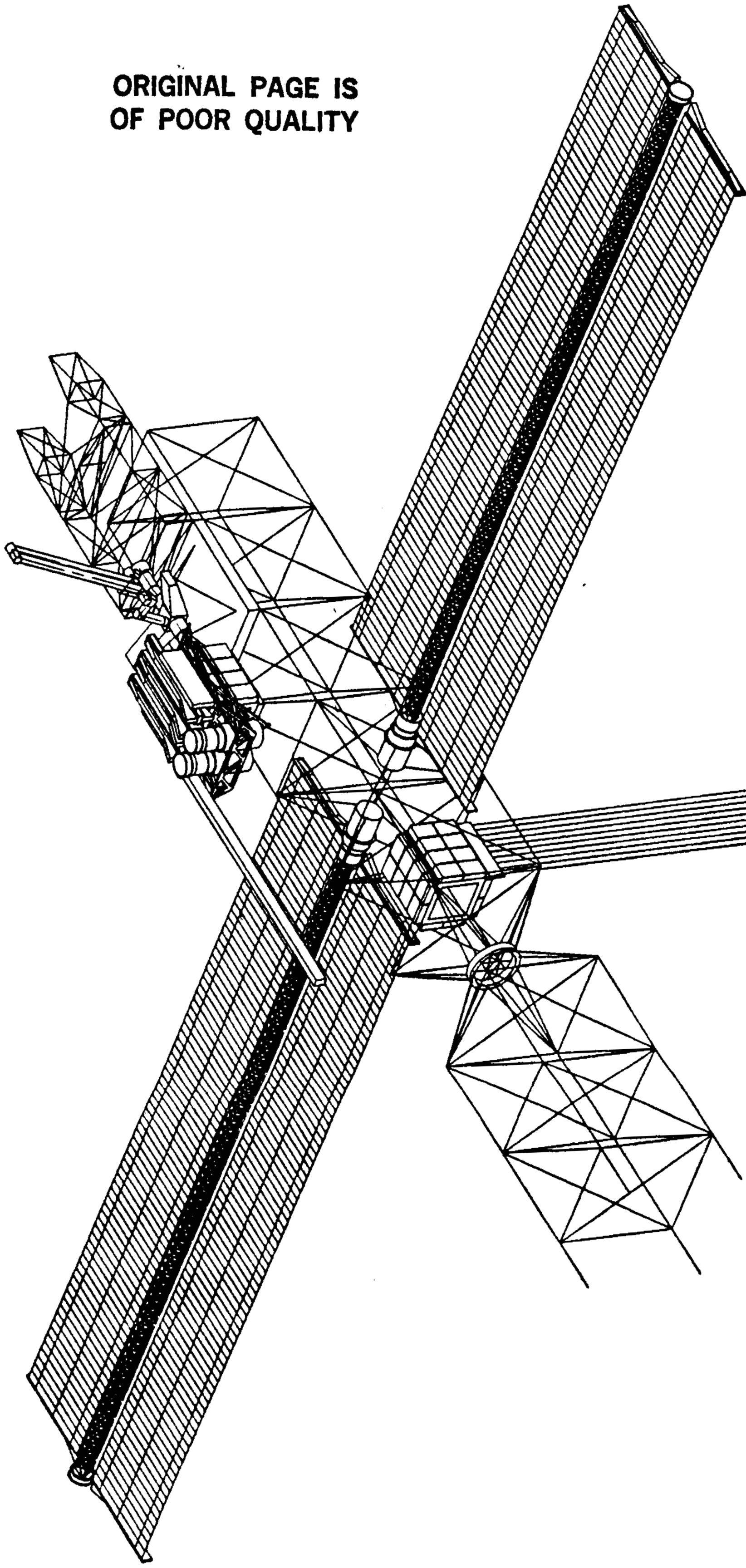

Figure 15. Assembly of the Third Outboard PV Module Truss Bay

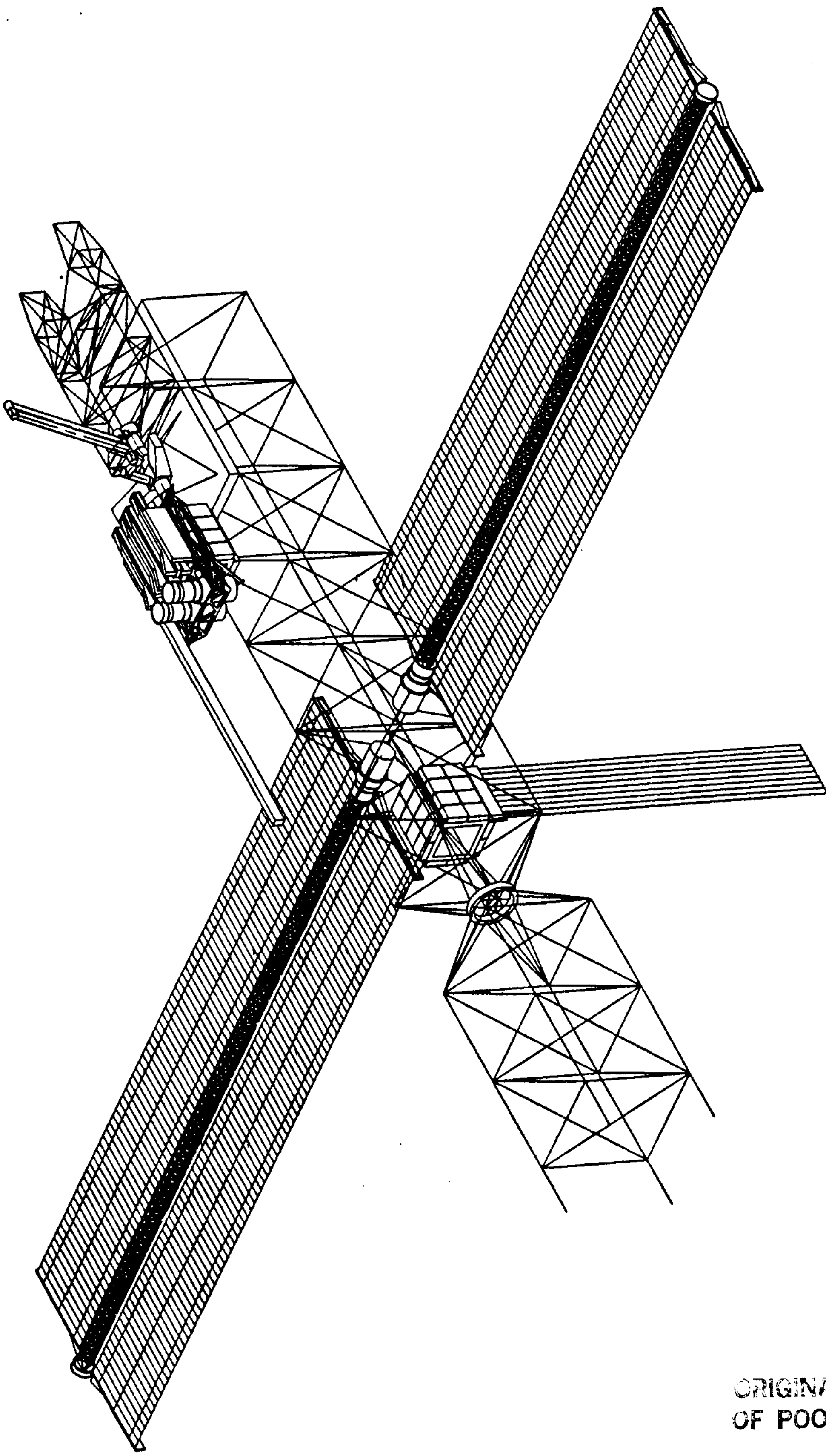

Figure 16. Assembly of the Fourth Outboard PV Module Truss Bay

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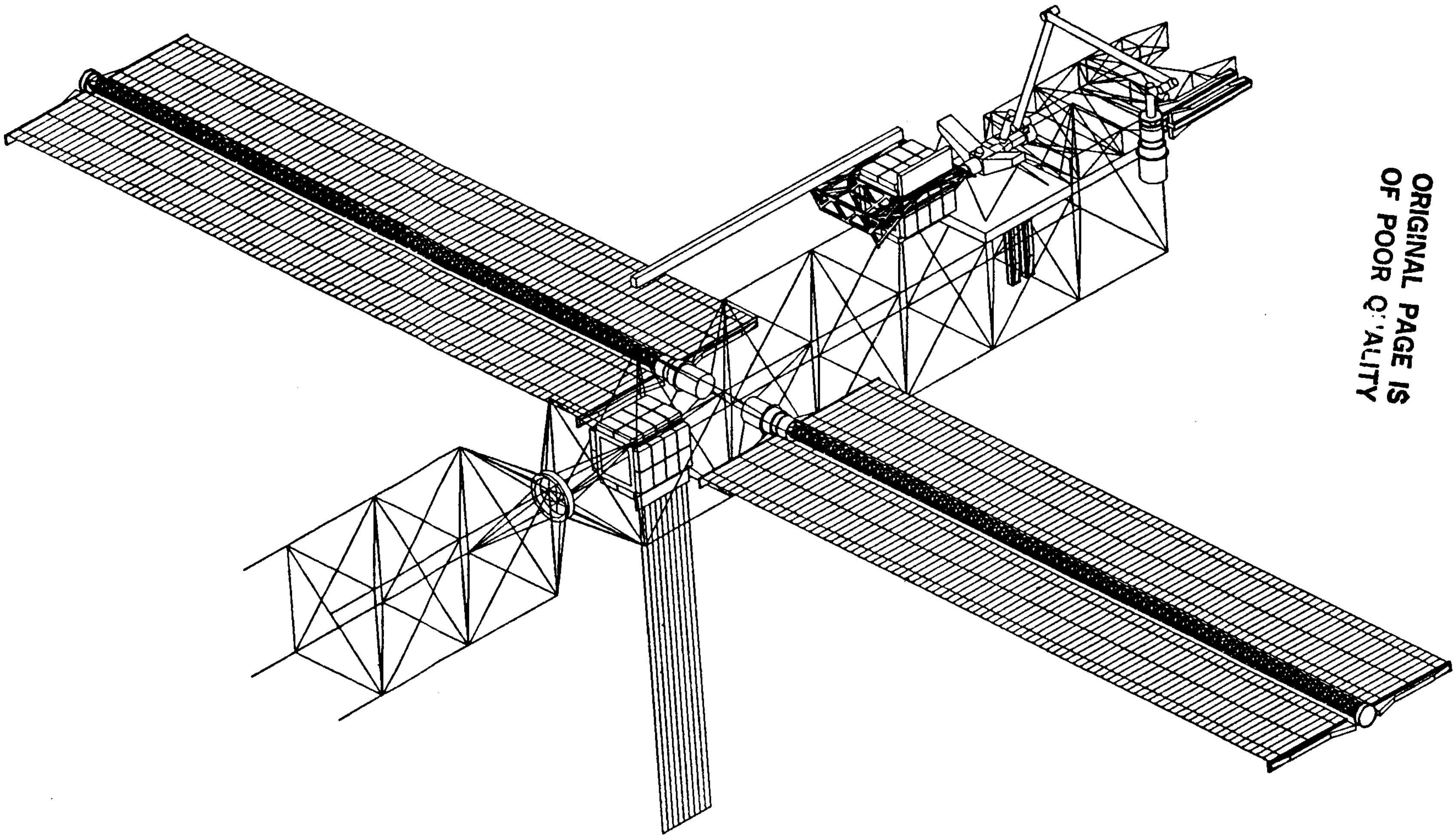

Figure 17. Upper Beta Gimbal/Solar Array Installation

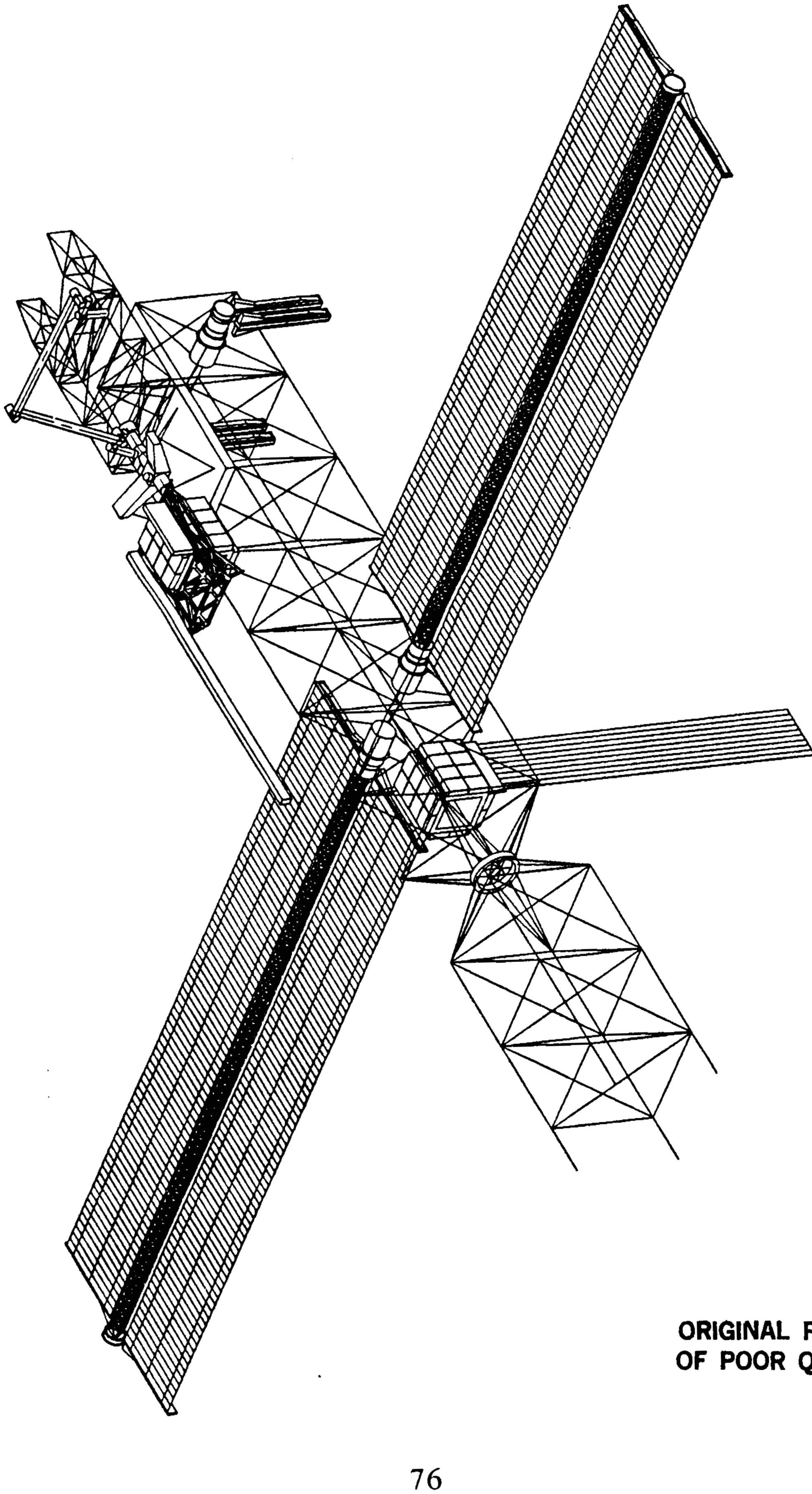

Figure 18. Beta Gimbal/Solar Array Installation Complete

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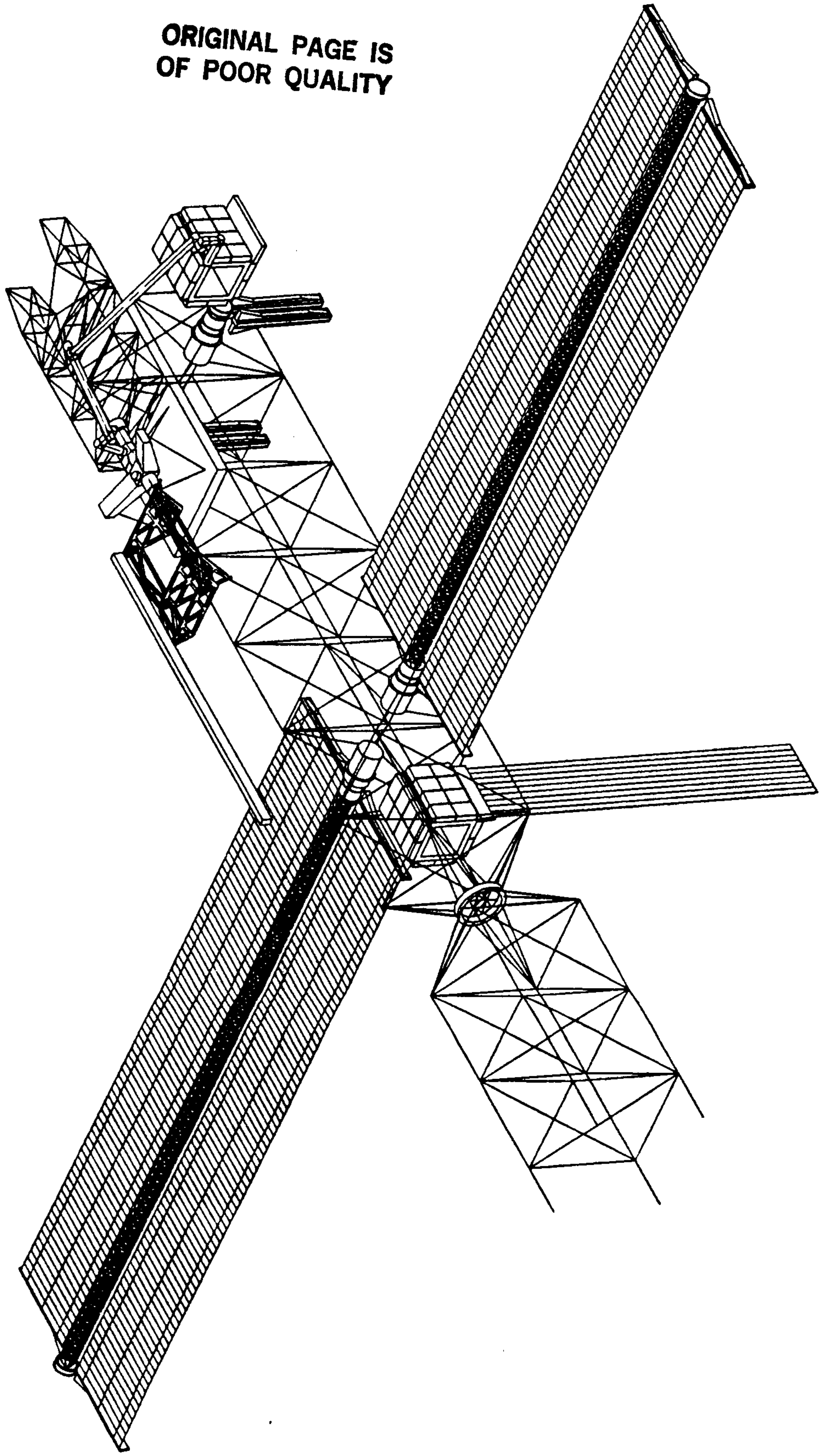

Figure 19. Integrated Equipment Assembly Installation

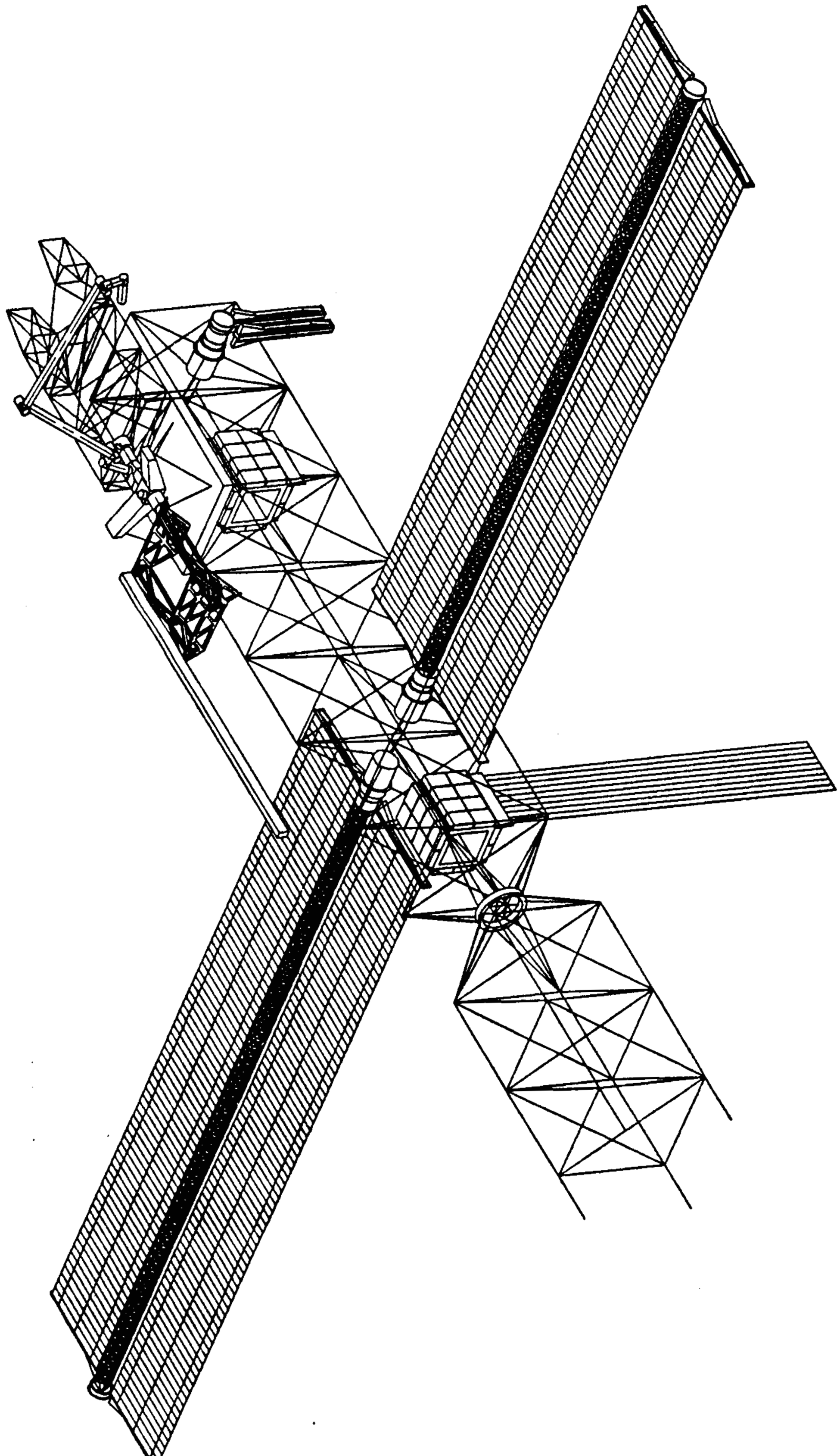

Figure 20. Integrated Equipment Assembly Installation Complete

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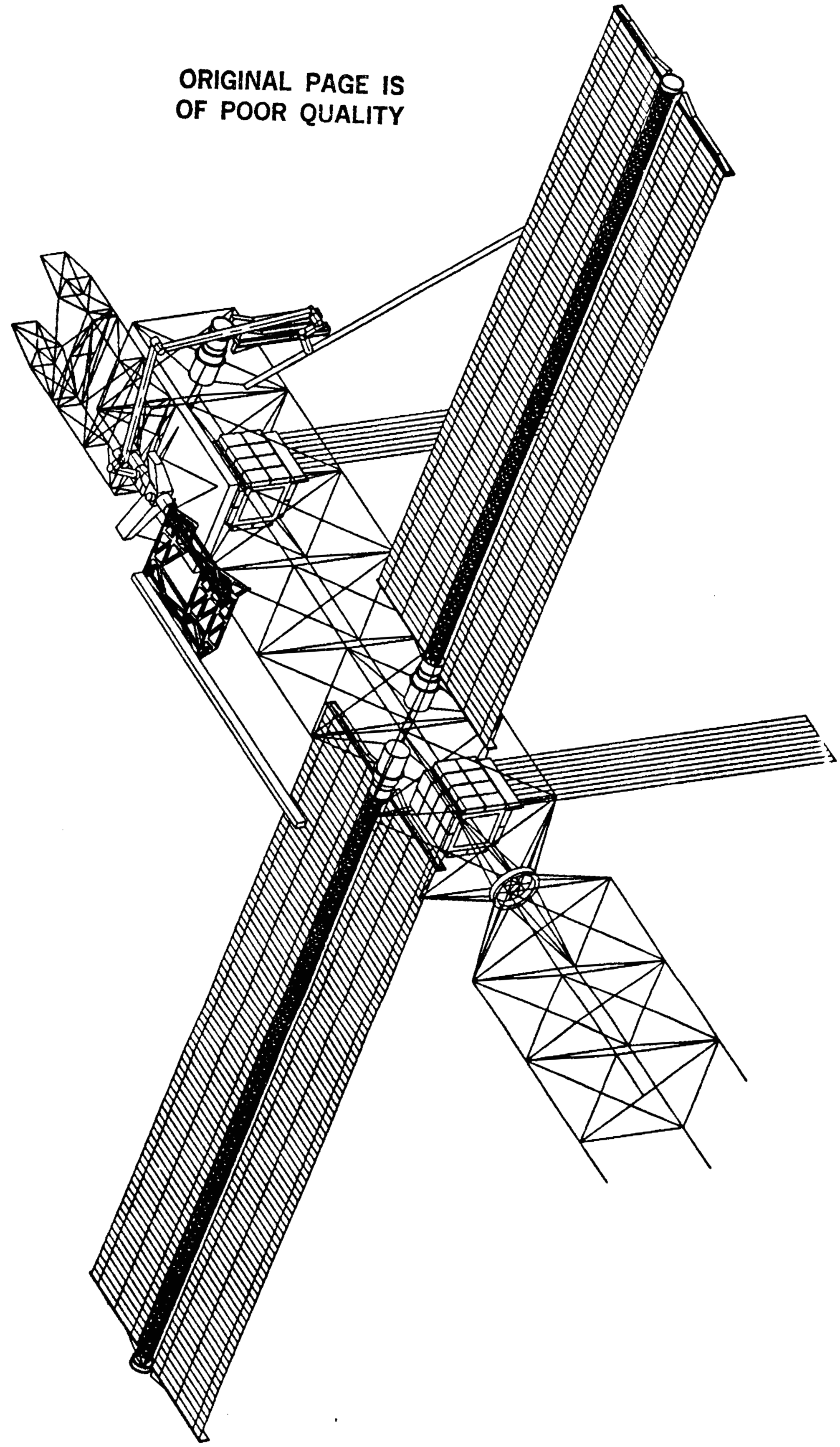

Figure 21. Heat Pipe Radiator Fins Installation

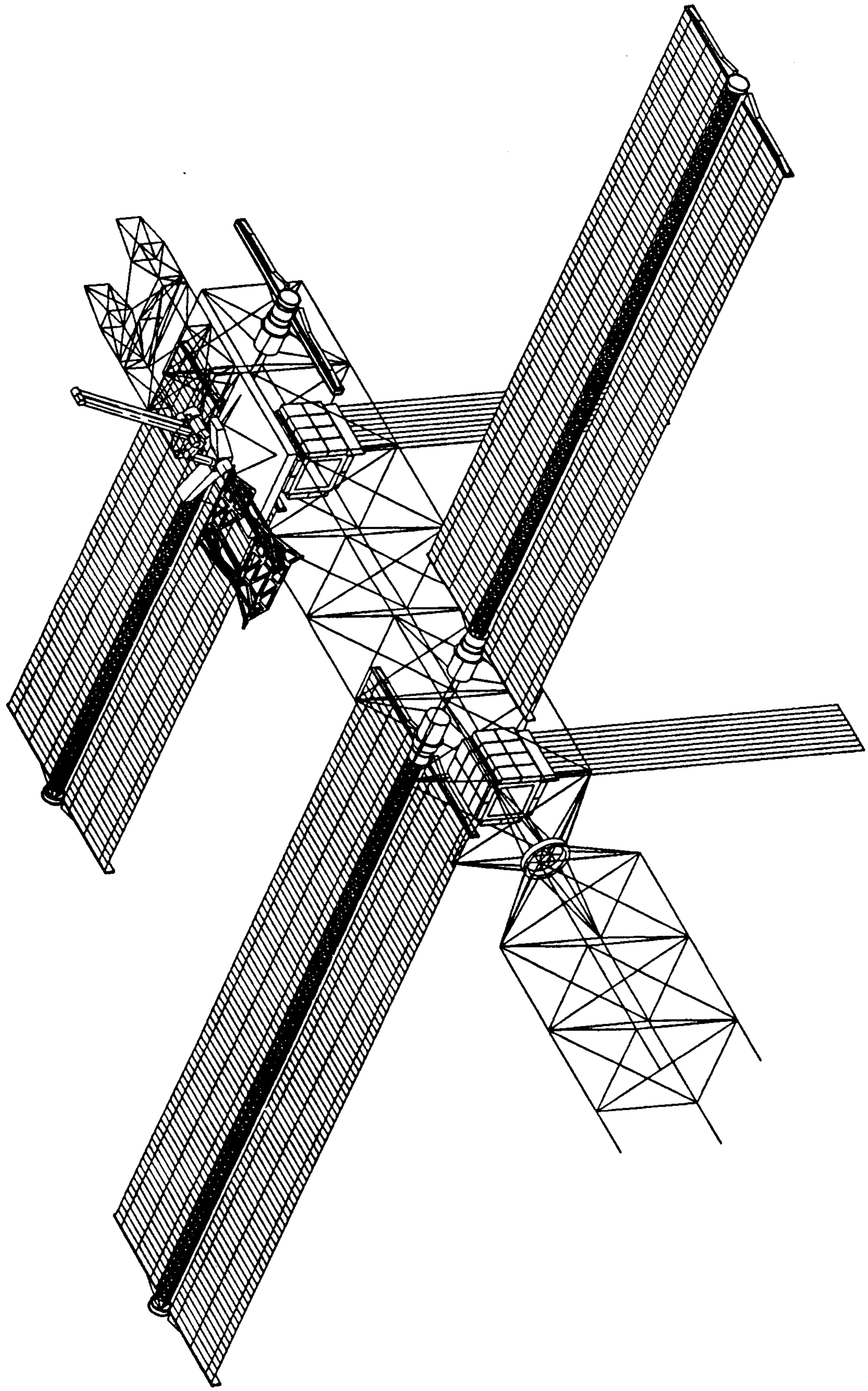

Figure 22. Solar Array Deployment

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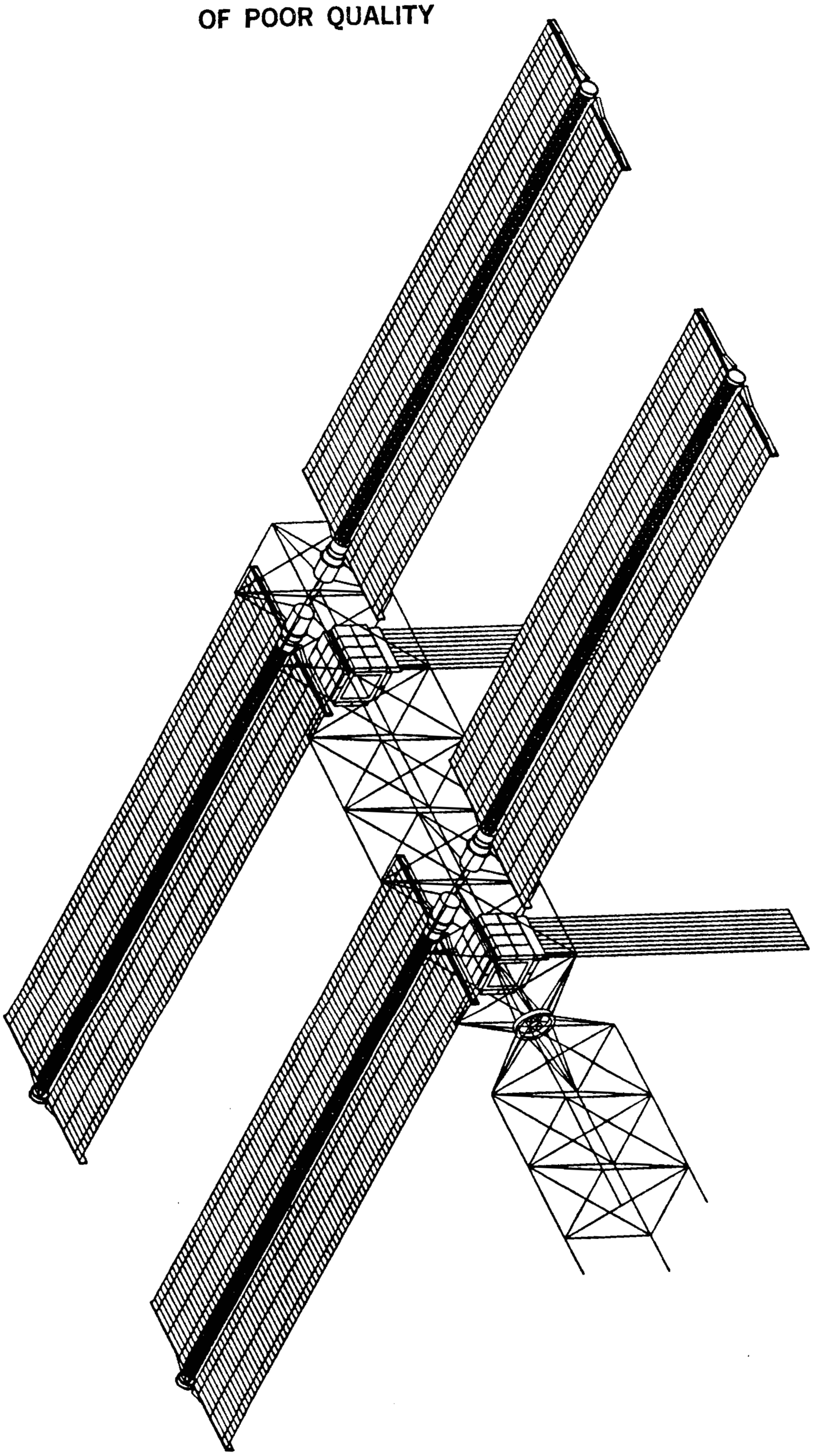

Figure 23. Solar Power Module Assembly Complete

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Report Documentation Page

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7. Author(s) Thomas J. Sours		8. Performing Organization Report No. E-4712
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16. Abstract

This report describes a concept for the assembly of the outboard PV modules for Space Station Freedom. Analysis of the on-orbit assembly operations was performed using CADAM design graphics software. A scenario for assembly using the various assembly equipment, as currently defined, is described in words, tables and illustrations. This work is part of ongoing studies in the area of space station assembly. The outboard PV module and the assembly equipment programs are all in definition and preliminary design phases. This study will provide input to the design process of assembly equipment programs. This study establishes that the outboard PV module assembly operations can be performed using the assembly equipment currently planned in the Space Station Freedom Program.

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