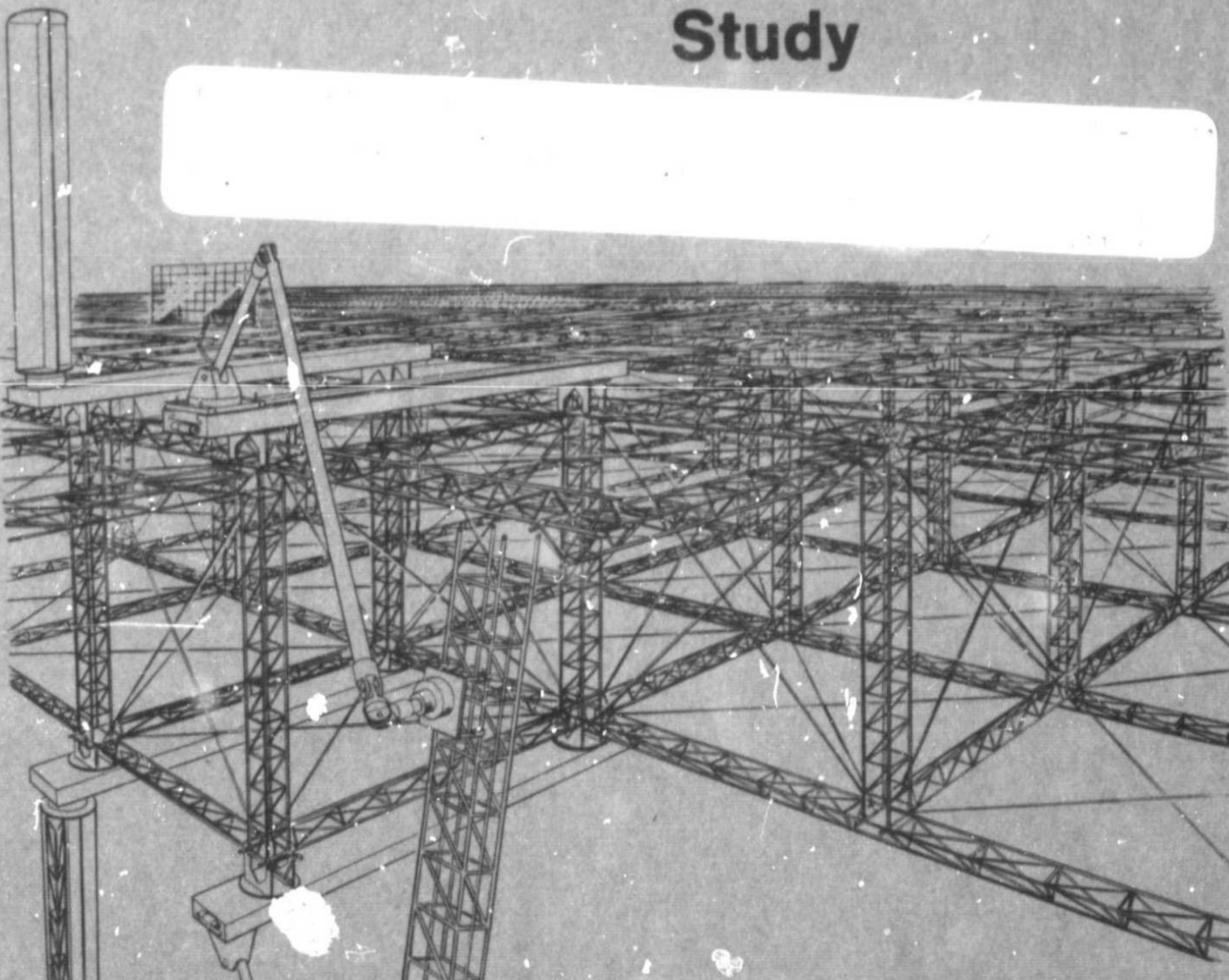
MCR-75-319
NAS9-14319

Final Report Executive Summary

NASA CR-144448

August 1975

Orbital Assembly and Maintenance Study



MARTIN MARIETTA

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ORBITAL ASSEMBLY
AND
MAINTENANCE STUDY

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FOREWORD

This document presents a brief summary of the results of work performed by the Martin Marietta Corporation while under contract to NASA L. B. Johnson Space Center. This report was prepared as partial fulfillment of Contract NAS9-14319, Orbital Assembly and Maintenance Study. The NASA Contracting Officer's Representative was Herbert G. Patterson of the Future Programs Office, Engineering and Development Directorate.

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ACRONYMS AND ABBREVIATIONS

ACS	attitude control system
AOT	average operational time
DEG	degrees
DIA, DIAM	diameter
DWS	disaster warning satellite
EOGP	earth observations geosynchronous platform
EOTS	earth orbital teleoperator system
EVA	extravehicular activity
FT	feet
FT^2	square feet
FT^3	cubic feet
GAC	Grumman Aerospace Corporation
GHz	Giga Hertz
GS	ground system
HDR	high data rate
HEO	high earth orbit
IN.	inch
I_{sp}	specific impulse
K	thousand
KG	kilogram
KM	kilometer
LBS	pounds
LEO	low earth orbit
M	meters, million
MA	mobile assembler
MDR	medium data rate
MHz	Mega Hertz
MIN	minimum, minutes
MMC	Martin Marietta Corporation

ACRONYMS AND ABBREVIATIONS (Continued)

MMU	manned maneuvering unit
MPTS	microwave power transmission system
MSM	manned servicing module
NASA	National Aeronautics and Space Administration
N. MI.	nautical miles
P/L	payload
PUT	payload utilization of Tug
RAT	radio astronomy telescope
RCS	reaction control system
RF	radio frequency
RI	Rockwell International
RMS	remote manipulator system
SEOS	synchronous earth observations satellite
SEPS	solar electric propulsion stage
SMA	slave manipulator arm
SSPD	Space Shuttle Payloads Description
SSPS	satellite solar power station
STDN	spaceflight tracking and data network
STS	space transportation system
TCCC	test conductor's control console
TDRS	tracking and data relay satellite
TR	transponder
TT&C	tracking, telemetry, and communications
TV	television
UOPD	unmanned orbital platform definition
VLF	very low frequency
°F	degrees Fahrenheit
°K	degrees Kelvin

I. INTRODUCTION

The most significant and exciting accomplishment of this study can be summarized as follows: We have developed a sound, practical approach for the assembly of very large structures in space. Programs like the Solar Power Satellite can now be pursued with a new level of technical confidence.

The objectives of this study include both assembly and maintenance of space systems. For the former, the study examines the methods and approaches for assembling two large structures where the operational orbit is higher than the Shuttle orbit. The maintenance objectives include the investigation of methods to maintain five geosynchronous satellites.

The two assembly examples are a 200-meter-diameter Radio Astronomy Telescope and a 1,000-meter-diameter microwave power transmission system. The Radio Astronomy Telescope (RAT) operates at an 8,000-mile altitude and receives RF signals from space. The Microwave Power Transmission System (MPTS) is part of a solar power satellite that will be used to transmit converted solar energy to microwave ground receivers. The MPTS operates at geosynchronous altitude.

For on-orbit maintenance study, five geosynchronous satellites are used as examples: Disaster Warning Satellite, DOMSAT C, Intelsat, Earth Observation Geosynchronous Platform, and Synchronous Earth Observation Satellite.

This final report is arranged with assembly of the MPTS covered in Chapter II, assembly of the RAT in Chapter III, and Maintenance in Chapter IV. Simulations for both the RAT and MPTS are included in Chapter II. Study conclusions and recommended future study areas are discussed in Chapter V.

II. ASSEMBLY OF THE MICROWAVE POWER TRANSMISSION SYSTEM (MPTS)

A. REQUIREMENTS

The Satellite Solar Power Station (SSPS) shown in Figure IIA-1, will operate in geosynchronous orbit and will convert solar energy into microwave energy, which is beamed to a receiving station on earth. This microwave energy is then converted back into electrical power for domestic use.

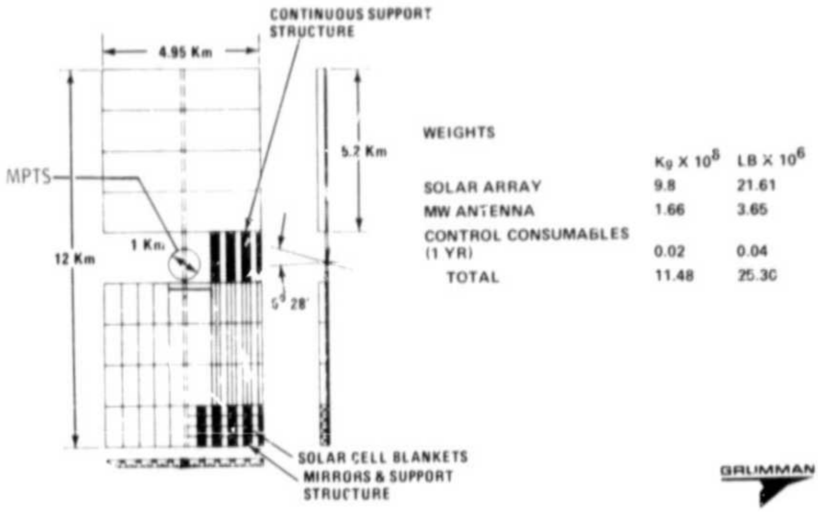


Figure IIA-1 Baseline SSPS

The microwave power transmission system (MPTS), shown in the center of the SSPS, was the subject of this portion of the study. The Raytheon/Grumman[1] design and requirements for the MPTS were used as the baseline.

The MPTS is composed of a structural grid to which amplitrons, waveguides, and associated microwave electronics are attached. The MPTS rotates on the main structure mast to maintain earth pointing as the solar cell structure maintains sun pointing. Power is transferred to the antenna through the rotating joint. The antenna is pointed in elevation by actuators at the elevation joint. Since the microwave generators, waveguide panels, and gimbal structure were not well defined at the time of need, our study was confined to design concepts and assembly techniques for only the antenna support structure.

B. MMC CONCEPTUAL DESIGN

1. Structure and Mechanisms

[1] Contract NAS3-17835.

a. Structural Configuration - The objective of this task was to conceive and design an assembly technique for the MPTS support structure. Initially, the Raytheon/Grumman (GAC) structural design was reviewed and their proposed assembly procedures analyzed. We found that the structure was not designed for easy assembly in orbit and not totally compatible with the presently defined Space Transportation System (STS).

Our redesigned structure concept included a unique central core cubical section which is assembled at the Shuttle orbiter. Additional structural sections are built up by attaching beam members to the central section. Assembly continually progresses by building onto previous sections.

Figure IIB-1 is a view of a typical structural section. The upper and lower trusses are triangular shaped, constructed from tubular members. Each member is attached to the previous truss member at each of the three legs. By doing this each member is truly continuous, which not only is structurally desirable but also simplifies the joint design as well as the design of the total member. The upper and lower trusses are tied together with similarly constructed but square-shaped columns. Each leg of the column intersects the centerline of the two crossing legs of the intersecting triangular truss members.

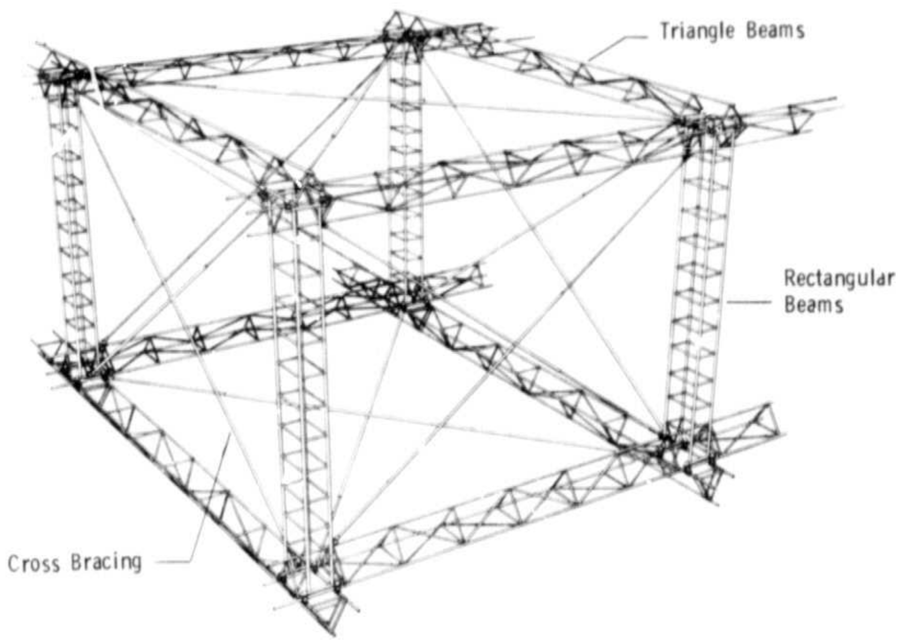


Figure IIB-1 Typical Structural Section

Figure IIB-2 shows a closeup view of how the members are fastened. Flat surfaces are utilized as the common member interfaces, with thermite-type fusion welding being used as the fastening technique. The purpose of the flat surface interface is to allow the members to be shifted for final alignment prior to final fastening. In a few cases, a pin at one end of a truss will

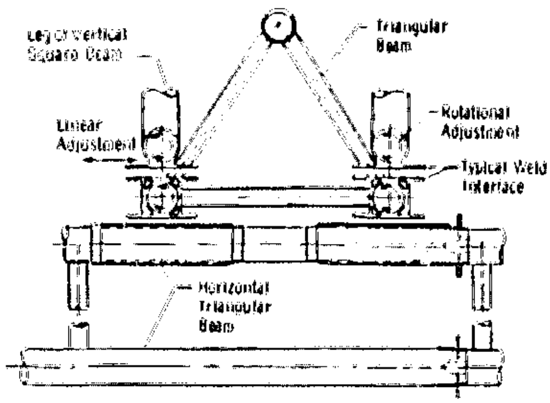


Figure IIB-2 Structural Joint Details

be used for initial positioning. In most cases, the three-leg attachment of the continuous member will adequately locate one end of the truss.

Telescoping tubular tension members (cross braces) are used to stabilize the structure in all planes. These members are locked at a fixed length by pyrotechnic-driven pins when the beam members are emplaced and aligned.

The total MPTS support structure is made up by 2709 of the structural cubes. The total structure weight (excludes microwave transmission equipment) is 1,947,436 lbs. The structure comprises:

11,056 triangular beams at 91 lbs each,
2,820 square beams at 101 lbs each,
21,884 "X" braces at 30 lbs each.

b. Thermal and Stress Analyses - Preliminary loads and sizing analyses were performed on the redesigned structure without considering heating from the microwave transmitters. An aluminum structure was assumed and the induced loads from gravity gradients, orbital transfer, Tug/pallet docking, and assembler operations were examined. Figure IIB-3 shows that with a 56.2-ft (center-to-center) beam spacing the structure's deflection due to gravity gradient torques will not exceed 0.032 arc min. This analysis was extremely conservative since all loads were reacted through only four beam pairs at the core, when in fact this load will probably be reacted through 6-8 pairs. Considering that the design limit for this antenna deflection is one arc min, this curve shows that the support structure could go to a minimum thickness of 20 feet and still be well below the 1 arc min deflection requirement.

Thermal analyses were performed considering incident solar radiation and the heat generated at the antenna. Temperature gradients across the structure are presented in Figure IIB-4. These gradients, as well as a differential across the 60-foot thickness, result in potential distortions, as depicted in Figure IIB-5. These distortions can be corrected by the active microwave panel pointing systems.

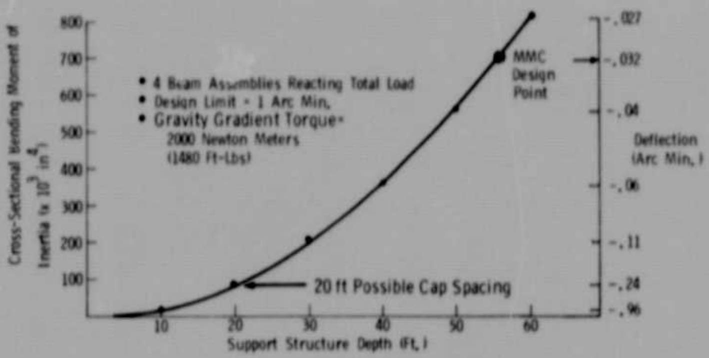


Figure IIB-3 Antenna Deflection Due to Gravity Gradient (Aluminum)

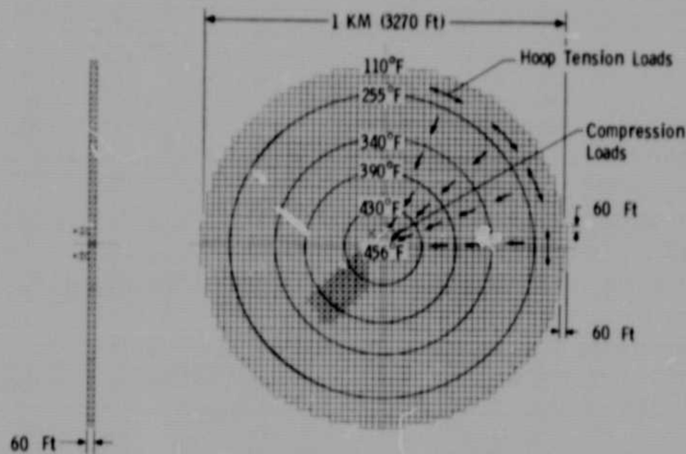


Figure IIB-4 Temperature Gradients

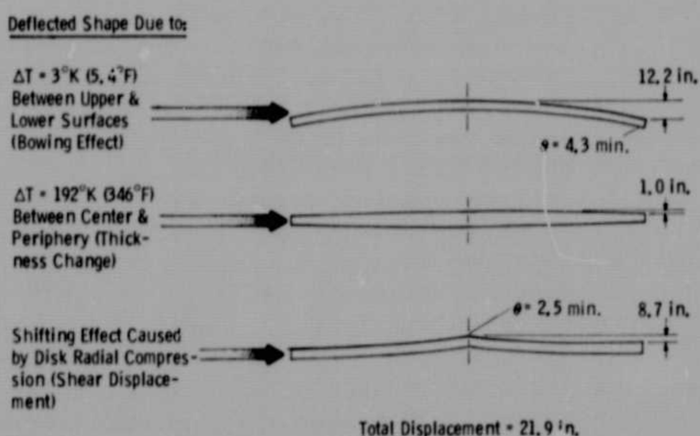


Figure IIB-5 Structural Distortions

Aluminum, steel, titanium, beryllium, and graphite polyimide were considered as candidate materials. Alloy steel was eventually selected as a suitable, low-cost, and practical material for use at the temperatures involved.

c. Mobile Assembler - A unique mobile assembler (MA) was conceived to perform the highly repetitious assembly operations. The MA is composed of a 72-foot, 7 degree-of-freedom manipulator on a mobile carriage and a beam pallet on a separate mobile carriage. Dual systems are provided to enable assembly operations on both sides of the structure.

Communications and electrical power systems are provided at each system. Alignment cameras are provided at each end of the manipulator carriage. Video cameras are located in the manipulator end-effector jaws to aid in beam placement and alignment.

Docking provisions are provided on the beam pallet carriage to enable docking a resupply beam pallet and returning the empty beam pallet.

Both mobile carriages have the capability to retract legs at one end and self-rotate that end to another structure joint location. This enables "walking" the mobile assemblers along the structure as assembly progresses. Views of the overall support structure and the mobile assembler in operation are presented in Figure IIB-6.

2. Packaging for Delivery to Orbit

a. Structural Members - In an attempt to achieve higher payload bay loading densities, collapsible beam members were designed. These collapsible beams are depicted in Figures IIB-7 and IIB-8. As the beams are deployed, telescoping cross braces are extended and locked in place using pyrotechnic-driven pins.

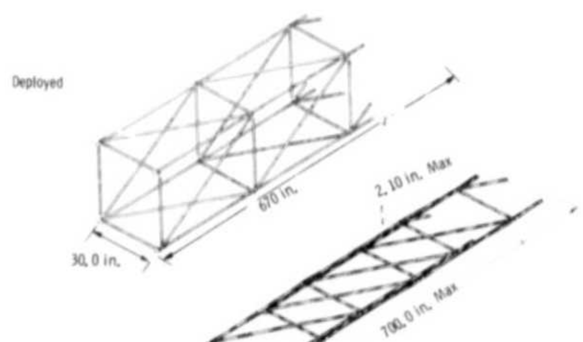


Figure IIB-7 Collapsible Square Beam

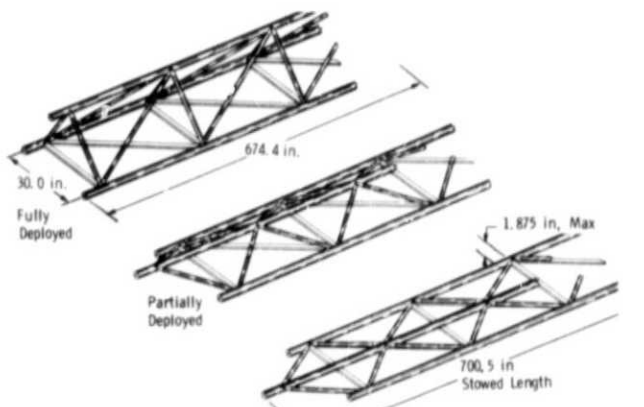
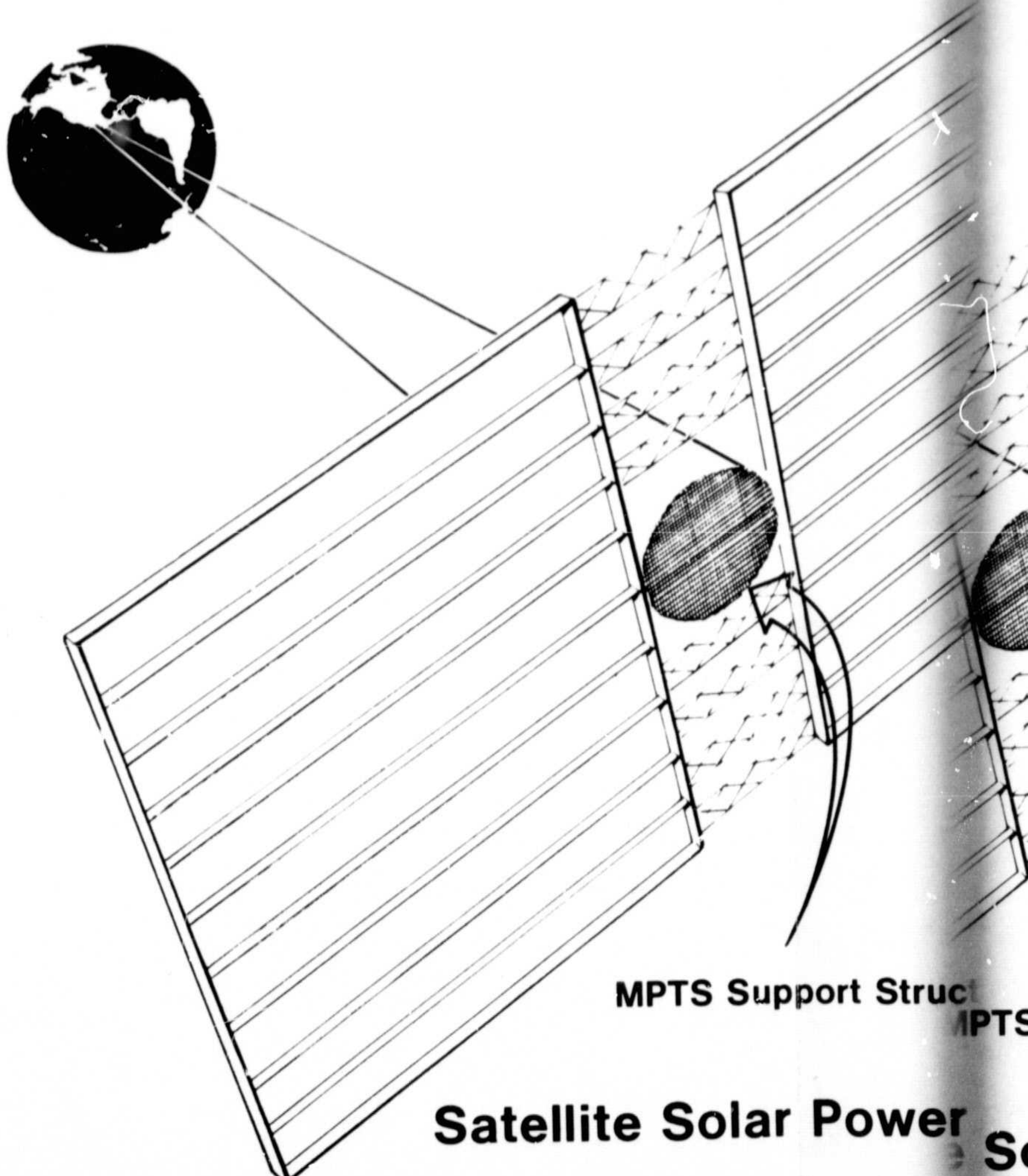
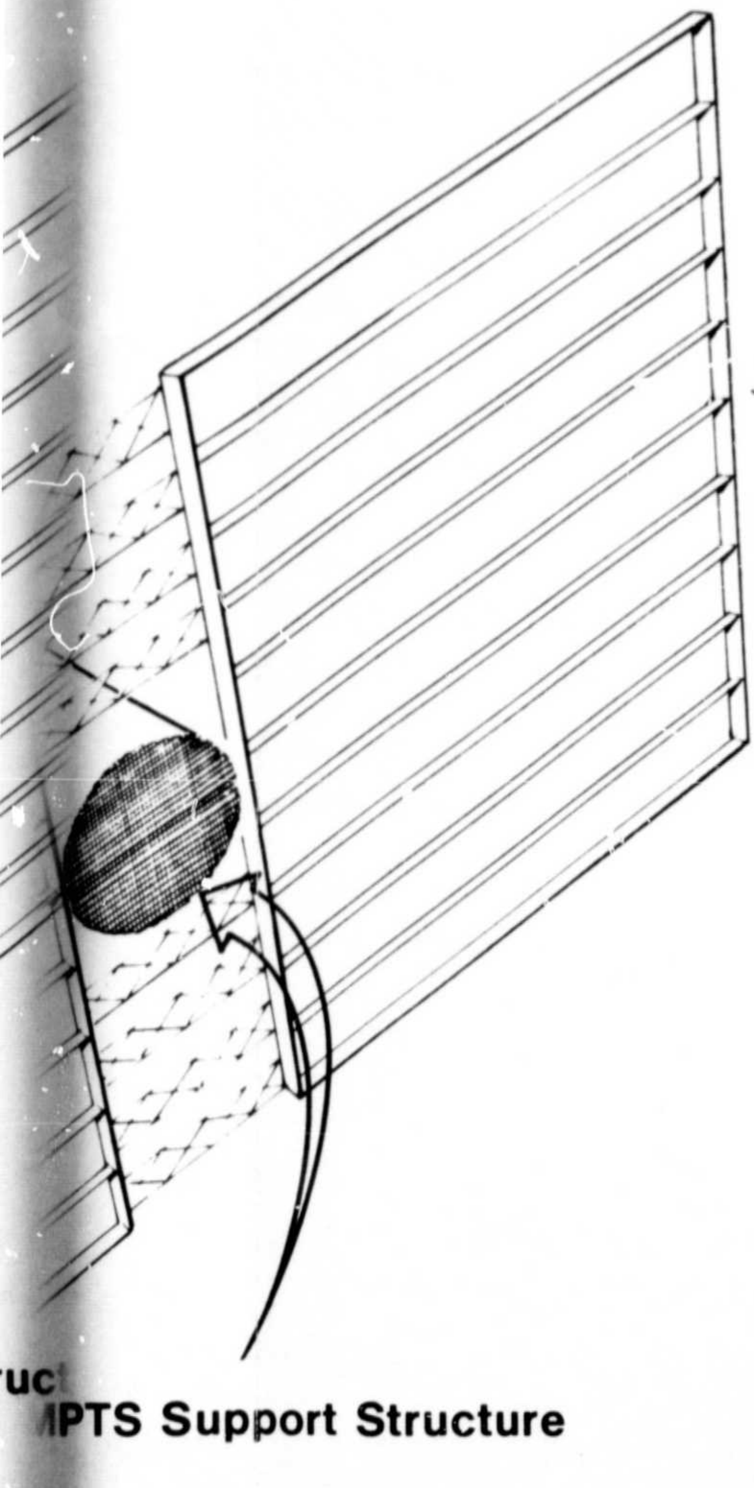


Figure IIB-8 Collapsible Triangular Beam



Satellite Solar Power



ruc
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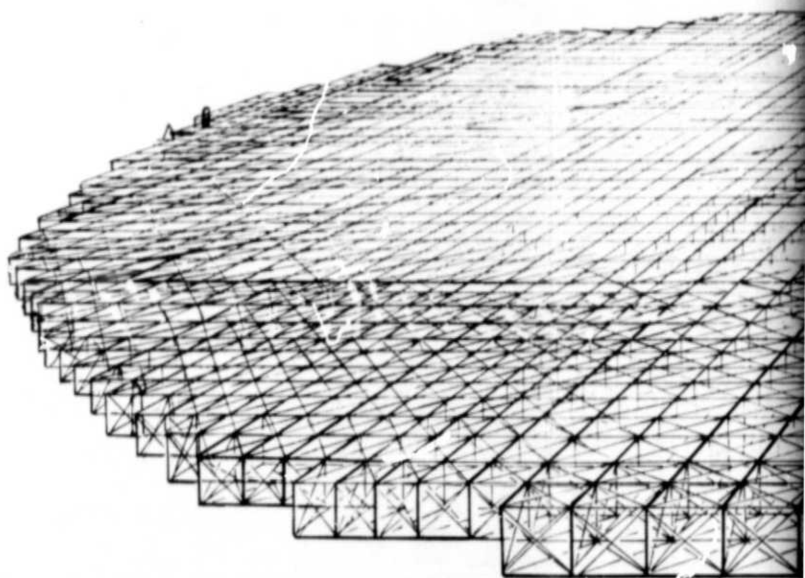
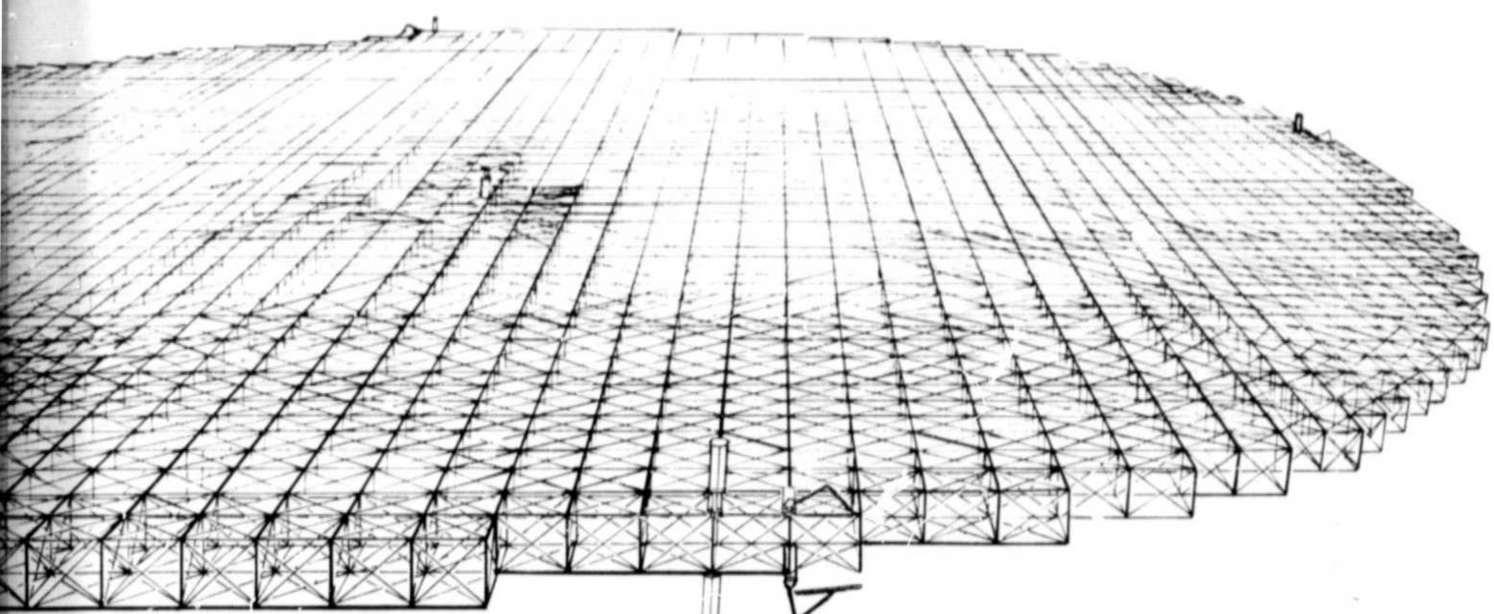


FOLDOUT FRAME 2

ort Structure Overview



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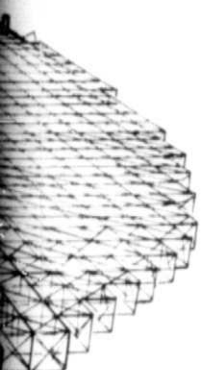

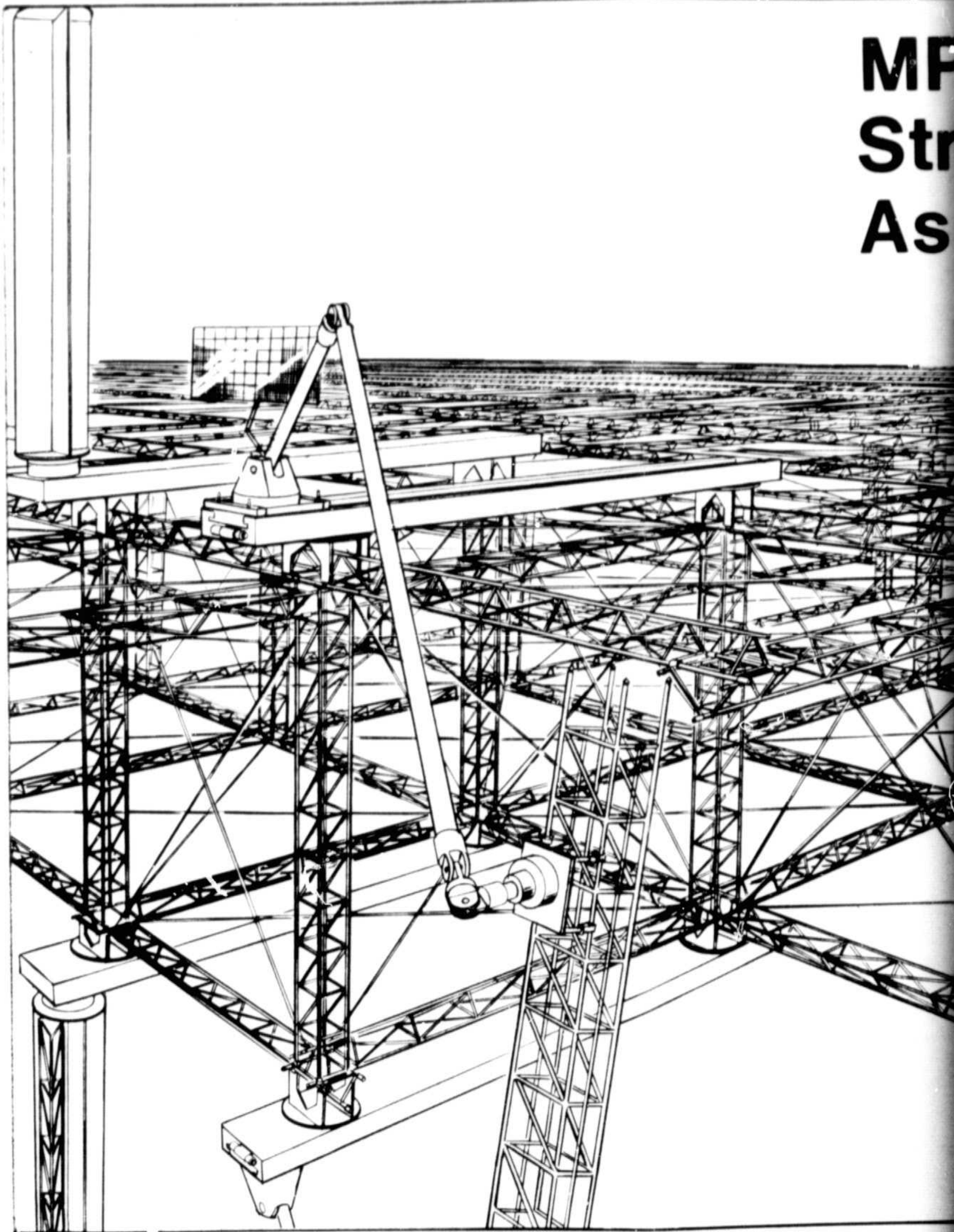

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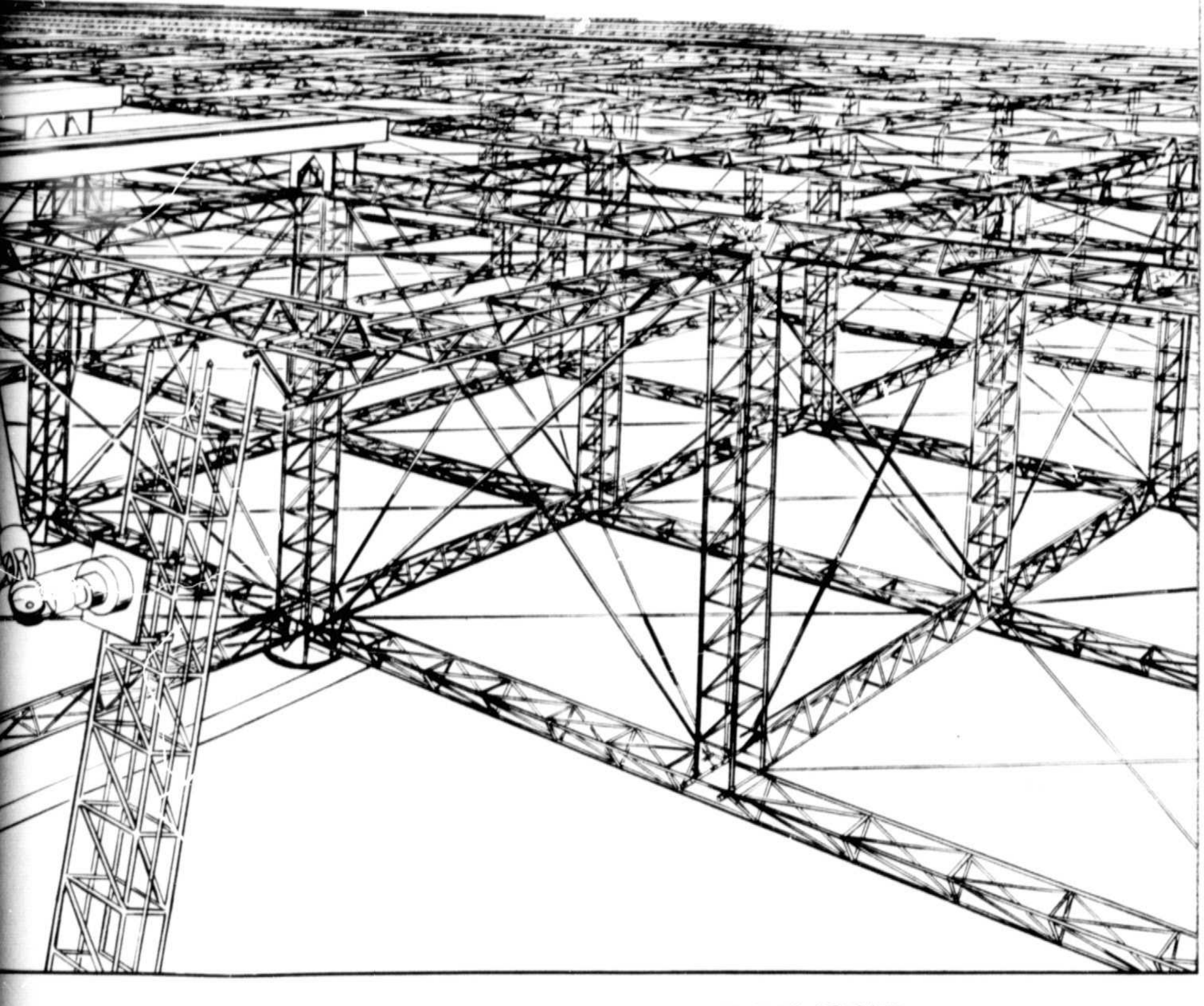
Figure IIB-6 Artist's Concept of MPTS Support Structure Nearing Completion

FOLDOUT FRAME 4

MPTS Support Structure in Assembly Phase



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PTS Support Structure Nearing Completion

II-7 and II-8

OUT FRAME 4

FOLDOUT FRAME 5

b. Beam Packaging and Dispensing Pallet - Due to the packaging and dispensing requirements of the structural members with this approach, a specialized pallet was developed to serve as a storage package on the ground, in transit (Shuttle), and in orbit as a beam dispensing unit for the mobile assembler.

The pallet (Figure IIB-9) basically consists of a central tube with docking rings at each end. Four structural dividers extend radially outward from the central support tube to a diameter of 180 inches.

Collapsed beams and cross members are stowed in each of the four quadrants as shown in Figure IIB-9. Proper mixing of the structural members is predetermined and the quadrants are packed so that the member needed by the mobile assembler is available in the proper sequence.

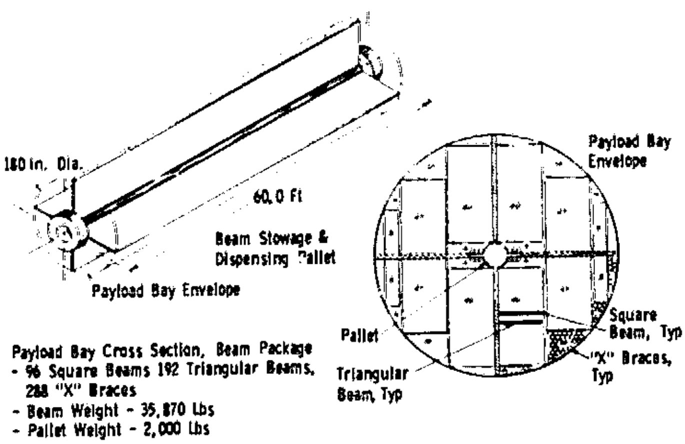

Figure IIB-9 Beam Pallet and Shuttle Payload Section

3. Alignment Concept

Accuracy of alignment of the central core is assured by two methods: (1) ground test erection and alignment with precision tools, and (2) verification of alignment (and necessary adjustments) when assembled at the orbiter, through optical sightings by EVA crewmen.

Alignment of the outlying cubes will be achieved by adjustments, based on optical sightings, as the beams are fastened. The assembly will proceed in a spiraling manner such that two types of cube-assemblies will occur. Referring to Figure IIB-10, cube 1 (full cube) will require assembling 3 sides. Cubes such as 2 and 3 (partial cubes) require assembling two sides.

The cubes directly in line with the core section will be assembled very accurately. This is achieved by use of video cameras on each end of the assembler bases which are adjusted to accurate bench marks on the central core. The partial-cubes will be aligned less accurately, with greater reliance on the accurate alignment of the full-cubes and on manufacturing accuracies. These cubes will be leveled accurately by reference of the alignment cameras to the core bench marks.

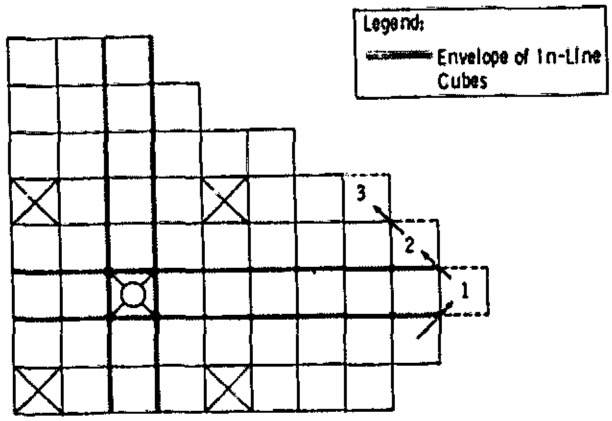

Figure IIB-10 Structure Assembly Progression

4. Assembly Support Subsystems

Requirements for subsystems to support the assembly operations were investigated to the extent necessary to determine system feasibility and define potential problem areas.

a. Communications - Commands and data are relayed (through antennas at the central core) between the NASA Satellite Tracking Data Network (STDN) and the assemblers. The core antennas are deployed to extend beyond the faces of the structure. Dual systems are provided to prevent structure RF interference. The antenna boom mechanisms incorporate capacitive coupled rotary joints. Commands for the assembler are transmitted through a secondary core transmitter and helix array subsystem to the antenna arrays, diametrically stationed such that commands are available to either assembler. Reception of commands is provided by the command control subsystem provided for each assembler.

b. Electrical Power Systems - Solar array panels provide electrical power to the core instrumentation (425 watts), each mobile assembler (3780 watts), and each beam pallet carriage (970 watts). The assembler solar array is installed on the manipulator shoulder to prevent inadvertent contact between the array and the manipulator. This requires two axes of motion to track the sun. The beam pallet carriage and core (both sides of structure) solar arrays are fixed in place and would have one axis of rotation.

c. Attitude Control Systems - Attitude control thrusters located at the edges of the central core structural cube would be used to stabilize the structure during low-earth-orbit (LEO) assembly. As the structure increases in size, attitude control requirements increase greatly. It was proposed that the structure be allowed to seek gravity gradient stabilization during the remainder of the assembly operations. This would result in an attitude where the disc would be edge-on to the earth. This attitude would also minimize solar pressure torques.

It was determined that an active attitude control system would be needed to stabilize the structure during other disturbances. The worst disturbance would result from docking a beam pallet (using a Tug) at the rim of the full structure. It was proposed that 5-lb thruster systems be installed on the structure (at 140-foot moment arms) during the LEO assembly, for active stabilization during momentary disturbances.

5. Structural Model

As part of Task 2 (Conceptual Design), a 1/40th scale model of the structure core section and one adjoining cube was designed and fabricated. Figure IIB-11 presents a photograph of the model structure. The complete model also contained a mobile assembler, a beam pallet, and the respective mobile carriages. This model aided in establishing assembly procedures and the manipulator reach and freedom requirements.

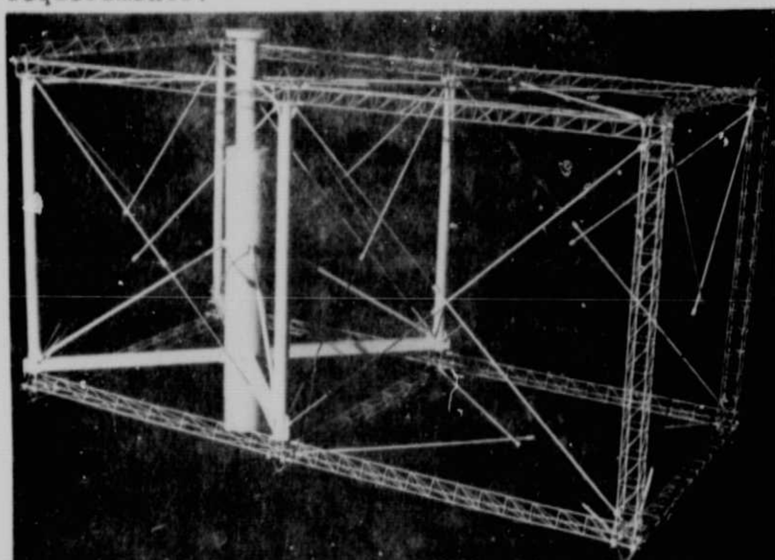

Figure IIB-11 MPTS Scale Model

C. TRADEOFFS

1. Manned vs Automated

Tradeoffs were conducted to determine the most feasible approach to the assembly of the MPTS structure. Our assembly approach is based only on the MPTS support structure. As the total power station assembly procedure evolves in the future, the need for an on-site, manned station may become necessary. We based our decision to minimize manned direct activities because of the size of the beams and the repetitiveness of the tasks. The support structure contains 2709 identical 60-ft cubes, which in turn contain 32,700 beams and "X" braces. The assembly contains only three different types of components. This concept creates an assembly procedure that is extremely repetitious. Our timeline analysis showed that using a pair of mobile assemblers, it will take nine months at 24 hours a day to complete the MPTS support structure.* In addition, the beams are 60 ft long and can weigh up to 100 lbs each. Translation and alignment of thousands of beams by EVA astronauts in a MMU-type vehicle has enormous logistics problems for both the astronauts and the MMU resupply. An MMU-type vehicle would also have difficulty handling the inertias of the 60-ft beams.

We have concluded that the assembly tasks as defined by our structural concept are best accomplished with an on-site machine. This machine, the mobile assembler, has both manual and automated control functions. Since the beam alignment task requires making tolerance buildup adjustments, this phase is best accomplished by remote (via TV) manned control. The major translations of the beams, from the beam pallet to the installation site, are best controlled by preprogrammed computer control mode.

The core section of the assembly (in LEO) is unique and will depend strongly on EVA/MMU astronaut activities for initial alignment, inspection of assembled components. These tasks will take place near the Shuttle orbiter.

2. Transportation, Logistics, and Cost

Tradeoffs were performed that addressed the transportation logistics for the assembly of the MPTS and the associated costs.

The parameters which impact assembly transportation are SEPS lifetime (700 days) and its performance capabilities in terms of the mass that can be transported in some period of time. Problem areas such as sun occultation (both by the earth and by the payload to be moved) and the overall control limitations of SEPS are items that should be studied at a later time.

Calculations of the total transportation cost to boost 5.8×10^6 lbs of payload (support structure and the microwave transmission equipment) into geosynchronous altitude resulted in the information depicted in Figure IIC-1. The two-Tug-ladder reusable mode is shown to be the best approach from a cost standpoint, assuming $5.9M per expendable Tug and $1M for a reusable Tug cost. Shuttle costs are assumed to be $10M each. The right hand portion of the curve represents the total costs when the intermediate altitude is geosynchronous (i.e., no SEPS are used). One can see that 290 Tugs are needed and no SEPS. As the SEPS begins being considered, a substantial savings occurs at an optimum altitude in the 15,000 to 17,000 n mile range.

These curves all assume that SEPS total lifetime of 700 days will be used, which effectively adds 700 days to the total transportation time. Tugs can deliver the payloads in a matter of hours. As an example, if 400 Shuttle flights are needed and one Shuttle is launched every day, it will take 400 days to get all the payload to LEO. The last payload can then be delivered to HEO on the 400th day using Tug. Using SEPS, the last payload would not get to HEO until the 1100th day.

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* Assembly time can be reduced linearly with the number of mobile assemblers used. However, launch frequency limitations could restrict the rate of supplying new beam pallets to the assembly site.

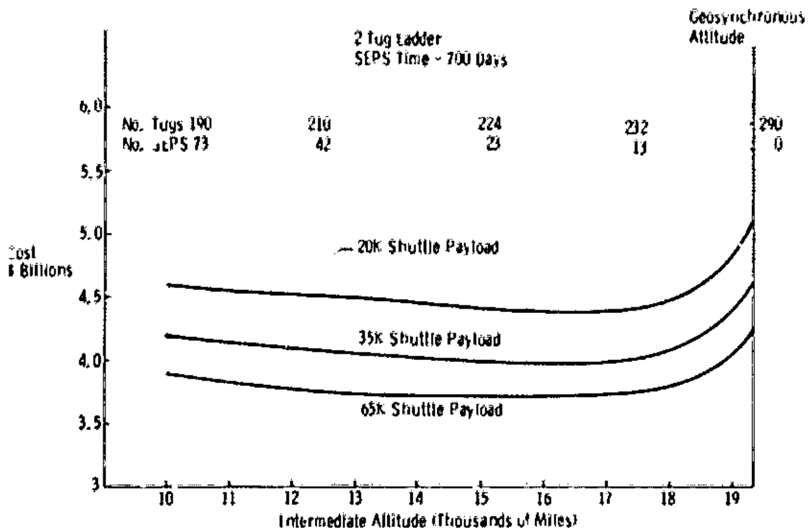


Figure IIC-1 Transportation Costs to Boost 5.8 x 10^6 lbs to Geosynchronous Orbit for Varying Intermediate Altitudes and Shuttle Payloads

Table IIC-1 shows total transportation time and cost to deliver 5.8 x 10^6 lbs to geosynchronous orbit, for Shuttle launches once a day and once every three days, versus Tugs only and Tugs and SEPS combinations with different SEPS lifetimes. The reference intermediate orbit is assumed to be 15,000 n miles. Shuttle costs were assumed to be $10 million; Tugs $1 million, and SEPS $10 million.

Table IIC-1 Total Transportation Time vs Cost to Boost 5.8 x 10^6 lbs to Geosynchronous Orbit

	SEPs TRAVEL TIME	NO. OF TUG FLIGHTS	NO. OF SHUTTLE FLIGHTS	NO. OF SEPs FLIGHTS	ELAPSED TIME FROM 1st TO LAST SHUTTLE FLIGHT	TOTAL TRANS-PORTATION TIME	TOTAL TRANS-PORTATION COST, $BILLIONS
SHUTTLE LAUNCH EVERY DAY	(No SEPs) 700 350	290 228 234	423 357 363	0 23 46	423 357 363	423 1057 713	4.5 4.0 4.34
SHUTTLE LAUNCH EVERY THREE DAYS	(No SEPs) 700 350	290 228 230	423 357 359	0 23 28	1269 1071 1077	1269 1771 1427	4.5 4.0 4.05

NOTE: All SEPs usage assumes 15,000 nautical miles intermediate earth orbit.

By considering SEPS in conjunction with other mission constraints, such as how often a Shuttle can be used, may offer substantial savings at not too great a percentage loss in transport time. This should justify a more detailed study of the SEPS performance capability problem areas as well as the added justification that the SEPS cost has a good chance of being reduced more drastically than Shuttle or Tugs over the next few decades.

D. PROCEDURES AND TECHNIQUES

1. Phase 1 - LEO Assembly

The MPTS support structure is assembled in two phases. In the first phase, a core structure is constructed while attached to the Shuttle Orbiter. The Shuttle Remote Manipulator System (RMS) and manned extravehicular activity (EVA) is used in the process. Accuracy of alignment of the central core is assured by two methods: (1) ground erection and alignment with precision tools, and (2) verification of alignment (and necessary adjustments) when assembled at the orbiter, through optical sightings by EVA crewmen. Mobile assemblers and communications and attitude stabilization equipment are installed and the assembly is deployed. Figure IID-1 shows the steps in constructing the core section.

After the core section is deployed, the assemblers continue building cubes until the structure is a rectangle 5 cubes by 7 cubes in size (including the gimbal support structure). This center segment of the antenna structure is then boosted to geosynchronous orbit.

2. Phase 2 - HEO Assembly

In the second phase, the remaining 2670 cubes are assembled in geosynchronous orbit. The additional structure elements contained in beam pallets are transported to orbit by Shuttle and Tug vehicles, and docked to the structure. Figure IID-2 presents views of the sequence for assembling an in-line cube (full cube).

3. Use of Man

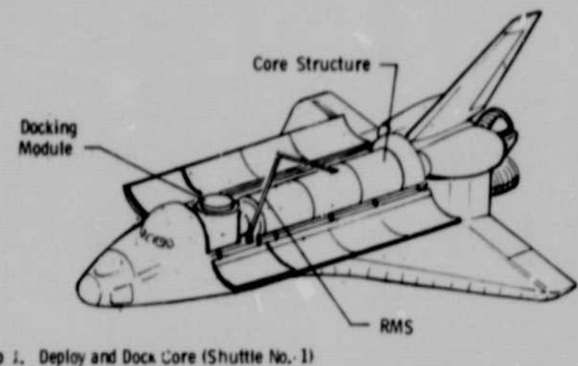
During the LEO operations at the orbiter, Shuttle crewmen will command the RMS operations to assemble the core section and will perform the activation, checkout, and monitoring of the core subsystems and the mobile assemblers. Shuttle EVA crewmen will assist in the initial assembly operations by monitoring and verifying the accurate alignment of the beams. They will also perform any resupply and maintenance operations that may be required on the core systems and the mobile assemblers.

During the assembly operations using the mobile assemblers, Shuttle crewmen and/or ground controllers will control the assembly operations at LEO. Ground controllers will control the operations at HEO. Contingency maintenance on the structure supporting subsystems and mobile assemblers at HEO would require boosting a manned module to the geosynchronous work site and subsequent EVA operations.

E. SIMULATIONS

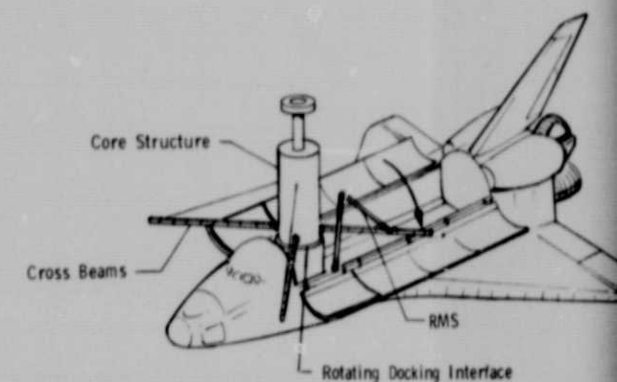
1. Objectives

Our primary concern was related to remote handling of large, 60-ft long, beams in space. This handling includes extraction from a stowage area,



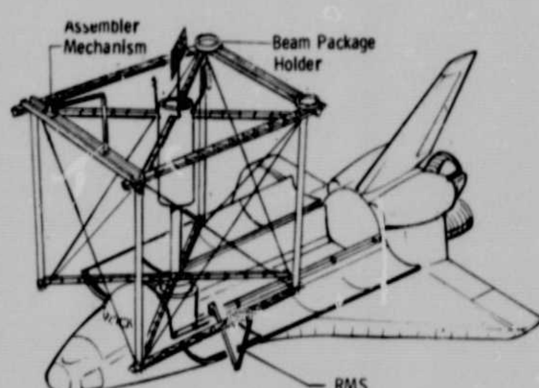
Step 1. Deploy and Dock Core (Shuttle No. 1)

The first phase in the total construction process is to assemble the middle 60-ft cube of the microwave antenna. The first Shuttle flight contains the basic core structure with folding alignment and support members, 12 beam members with X braces, and two sets of mobile assemblies and beam holders. During Step 1, the center core is extracted from the Cargo Bay, positioned and docked on the Shuttle docking module with the RMS.



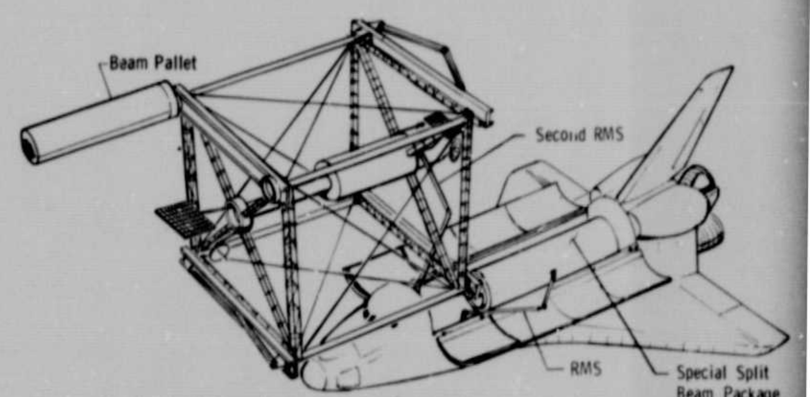
Step 2. Extend Cross Braces (Shuttle No. 1)

During Step 2 of the antenna core assembly, the alignment beams are unfolded fr the core structure and the tension rods are positioned. Each beam is checked and vern justments are made for precise alignment. A rotary docking interface is required at th port since the RMS cannot reach completely around the core structure. This rotary do ring can be an unpowered slip ring since the RMS can position the core beams by pulli structure around.



Step 5. Rotate Assembly, Emplace Upper Beams, and Install Assembler Equipment (Shuttle No. 1)

The second set of assembler equipment is installed on the bottom side.

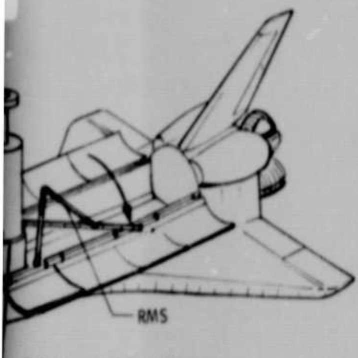


Step 6. Install Beam Packages (Shuttle No. 2)

The second Shuttle flight contains two beam packages. These are nonstandard in that they are split longitudinally so that a package can be placed on each side of the 60-ft core cube. The beam packages are 60-ft long and fill the cargo bay. This eliminates the use of the docking module kit. A second RMS is used to capture and stabilize the antenna core while the primary RMS places the beam package in the assembler beam package holders. This task is repeated on the opposite side. The antenna core is now ready to self-erect additional 60-ft cubes.

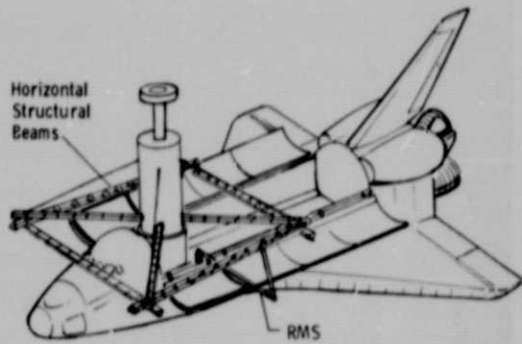
Figure IID-1 Core Structure Assembly Steps

FOLDOUT FRAME



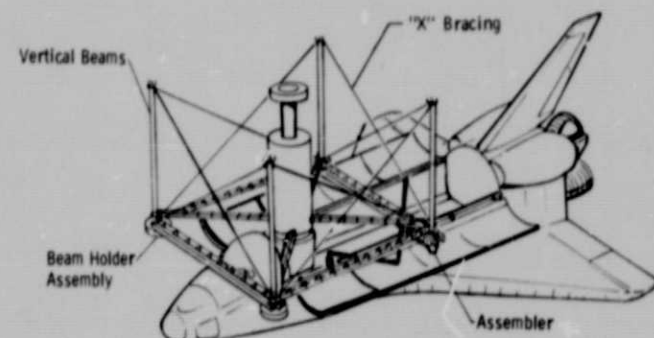
1)

mbly, the alignment beams are unfolded from beside positioned. Each beam is checked and vernier ad- A rotary docking interface is required at the docking around the core structure. This rotary docking he RMS can position the core beams by pulling the



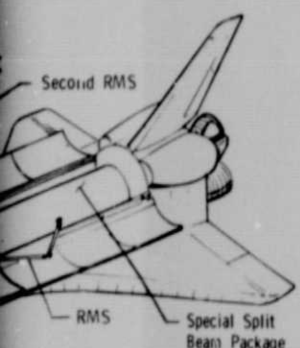
Step 3. Emplace Horizontal Beams (Shuttle No. 1)

Step 3 consists of extracting the beams from the cargo bay and placing these lower triangular beams onto the alignment beams and welding them in place, one at a time.

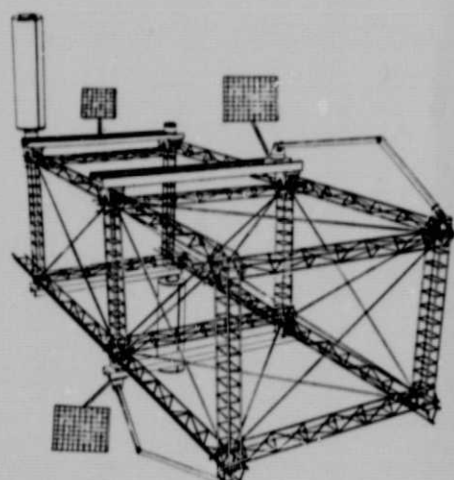


Step 4. Emplace Vertical Beams, Cross Bracing, and Assembler Equipment (Shuttle No. 1)

Step 4 consists of placing and welding the vertical beams plus placement of a set of assembler equipment. The vertical beams used for this core segment are special tubular members which also contain two adjustable tension tubes, hinged from the top. Each vertical beam is placed on its adjoining corner receptacle and welded. The tension tube is extended in its plane and welded on the unattached end. The beam is then aligned in that plane with the RMS and the pyro-pin is activated within the telescoping segment of the tension tube to lock the tension tube in that position, which in turn holds the beam in alignment. This sequence is repeated for each vertical beam. One mobile assembler and one mobile beam package holder are placed on their receptacles on the lower core structure.

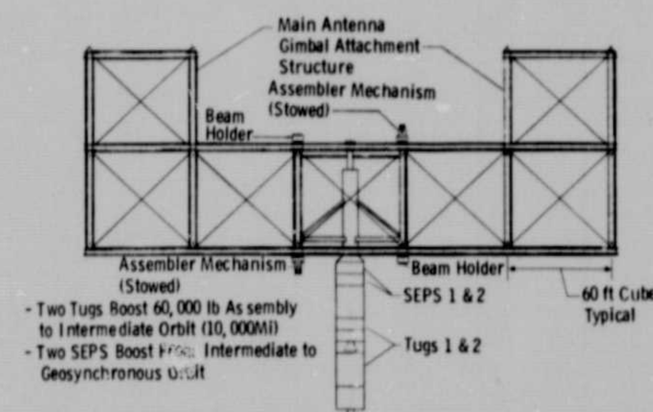


kages. These are nonstandard in that they d on each side of the 60-ft core cube. The This eliminates the use of the docking bilize the antenna core while the primary package holders. This task is repeated on self-erect additional 60-ft cubes.



Step 7. Construct LEO Structure

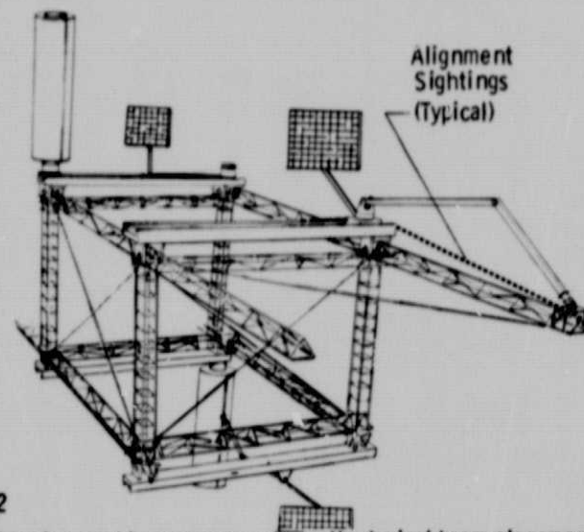
Thirty eight more cubes are constructed using the assemblers. When this structure is completed, the assembly equipment is stowed and the structure is readied for boost.



Step 8. Structure Ready for Boost to HEO

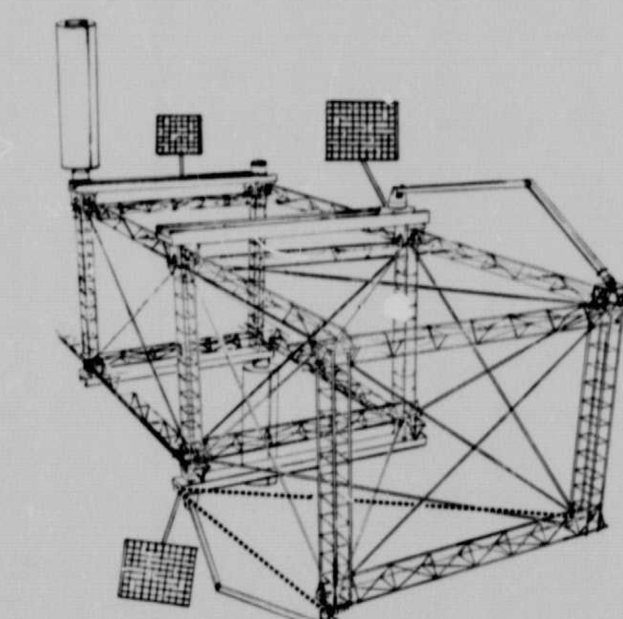
The 39 cube structure is readied for boost by docking two Tugs and two SEPS. This assembly will then be boosted to intermediate orbit with two Tugs. The Tugs will return and the two SEPS will boost the assembly to high earth orbit.

FOLDOUT FRAME 2



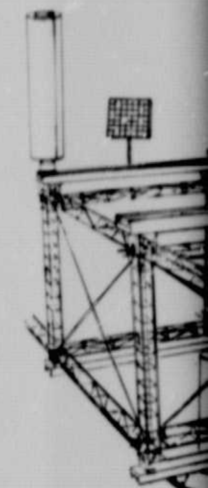
Steps 1 and 2

This series of assembly sequences shows the typical beam placement tasks required to complete each 60-ft structural cube. The first triangular beam is placed on the end of the previously constructed beam end and welded in place. The horizontal telescoping tension tube is extended to the opposite corner and welded. The manipulator positions the beam to align in the plane of the tension tube. The pyro-pins are activated to lock the telescoping tension tube segment and in turn holds the beam in place. This procedure is repeated for the vertical tension tube. By locking the tubes in this manner, proper alignment of the beam is assured. This is repeated for the second horizontal cap beam.



Step 6

Step 6 places the lower triangular cross beam at the lower ends of the vertical beams. It is aligned and welded on each end.



Step 3

Step 3 places the crossing, triangu
and welded in place. The manipulator
with alignment pins. It will then mov
along the other horizontal beam. Onc

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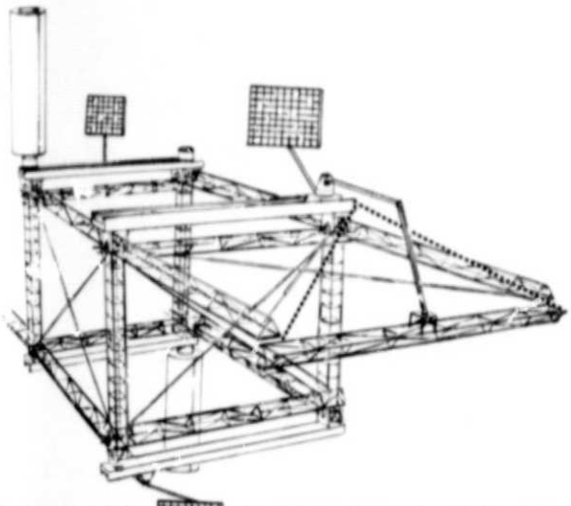
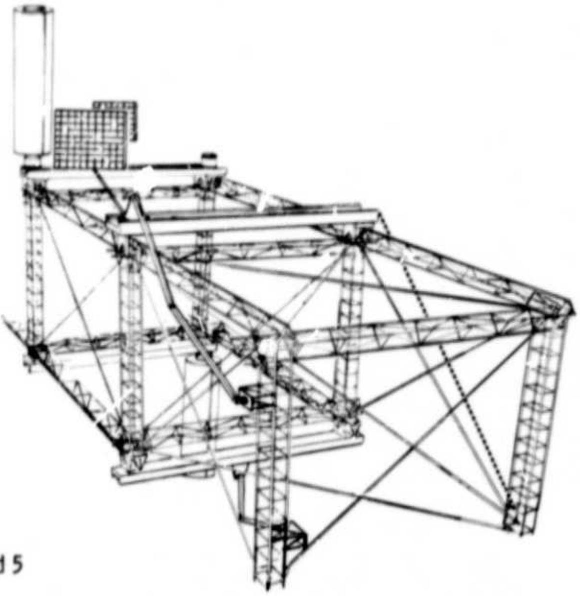
Figure IID-2 Structural Section Assembly Steps

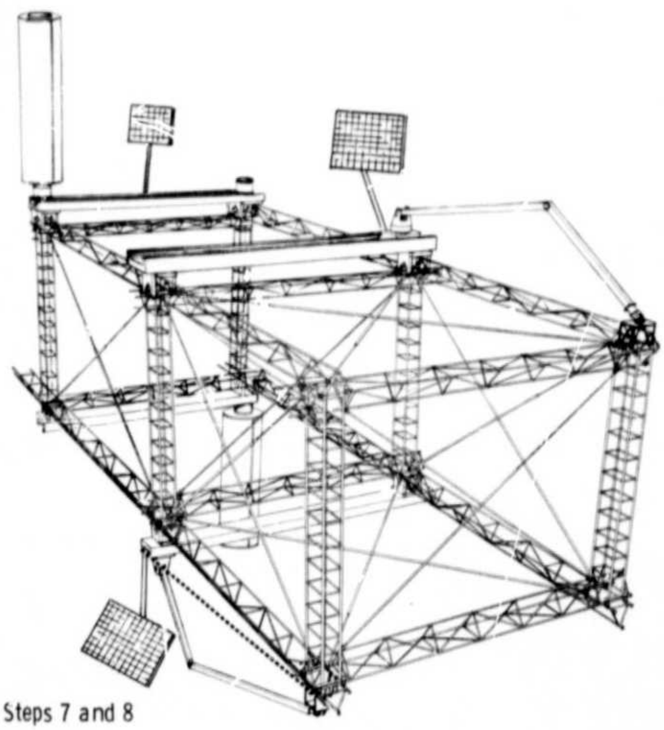


p 3 places the crossing, triangular beam at the outer beam ends. This beam is aligned
ded in place. The manipulator arm will hold the beam in the center and locate one end
gnment pins. It will then move to the other end of the beam and locate the cross beam
e other horizontal beam. Once in position both ends will be welded in place.



Step 4 and 5

These steps places the two vertical (square) beams on the cube end. Their ends are welded in place and again aligned with the cross braces. Both the top and bottom manipulators will be used for this task.



Steps 7 and 8

The two lower horizontal beams are now put into place. They are individually abutted to the adjoining beam end and welded. They are aligned on the outer end and also welded in place. The lower tension tubes are locked as the manipulator locates the end of each horizontal beam.

translation and alignment, and attachment on one or both ends. The main objective of the assembly simulation is to determine whether or not the beam handling tasks can be accomplished while utilizing the proposed equipments and techniques, to develop recommendations for manipulator design, alignment aid design, and to determine further simulations.

The resulting data showed all tasks to be not only feasible but fairly easy for the trained operator to perform within the constraints of the simulation. The secondary objectives were met as well.

2. Description and Operation of the Simulation Facility

Martin Marietta's simulation facility consists of a Slave Manipulator Arm (SMA), a Test Conductor's Control Console, an Operator's Console, Video and Audio Communications System and Analog Computers, as shown in Figure IIE-1.

Slave Manipulator Arm - This manipulator has a 12-ft operational reach and is fully counter-balanced.

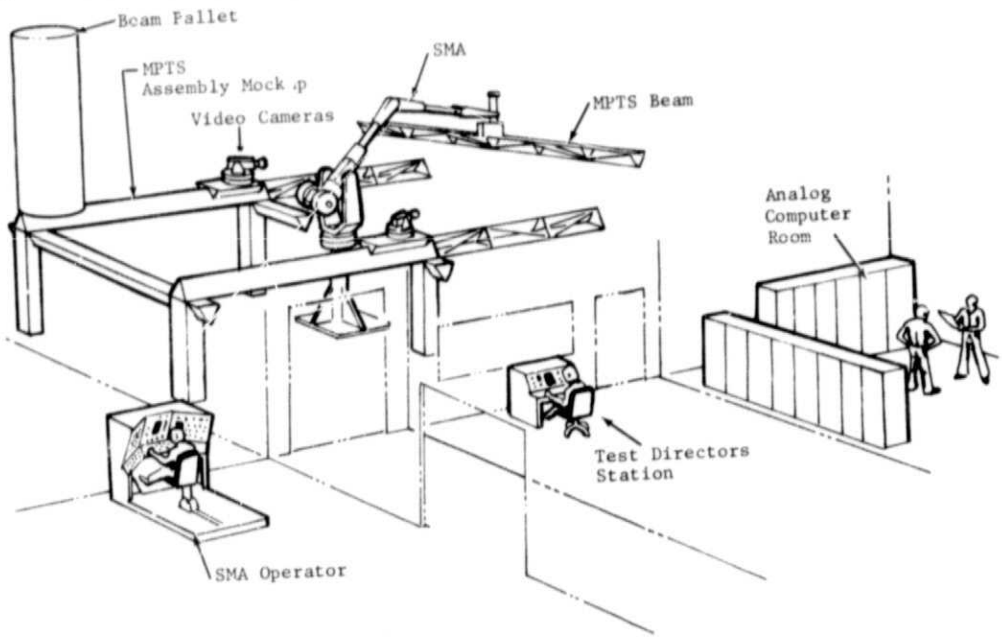


Figure IIE-1 Simulation Facility

Test Conductor's Control Console - The Test Conductor's Control Console (TCCC) provides the equipment necessary to power the SMA, select operating modes, monitor system operation and provide limit warnings.

Operator's Console - This control station was designed and laid out for optimum manned interface characteristics, such as controller reach and visual angle limits for our mono and stereo TV monitors. The present configuration is laid out around the two video monitors which are the operator's only visual feedback, since there can be no direct vision in this task. Two Apollo-type rate controllers are provided for SMA control.

Video and Audio Communications - The SMA itself has provision for two cameras in the vicinity of the wrist and one at the elbow. TV cameras can be placed at other locations on the mockups as needed. Two monitors each are located in the TCCC and the operator's console. Cameras are selected by the test subject and controlled either manually by the test subject or by the computers. Two-way voice communications is provided between the operator, the test conductor, and the computer room.

Analog Computers - Two EAI 231-R analog computers were used to program the control law equations, to close control loops around the manipulator joints, and to interface with inputs from the operator's console.

3. Simulation Description

a. Assembly of Radio Astronomy Telescope - The actual in-orbit task consists of attaching eight 55-ft long beams to a center telescoping core. This core is 8 ft in diameter and 45 ft long. The core is located on the Shuttle docking port. Each beam is extracted from the cargo bay and attached, in sequence, to the exterior of the core. This beam attachment task was simulated. Figure IIE-2 shows this simulation in progress.

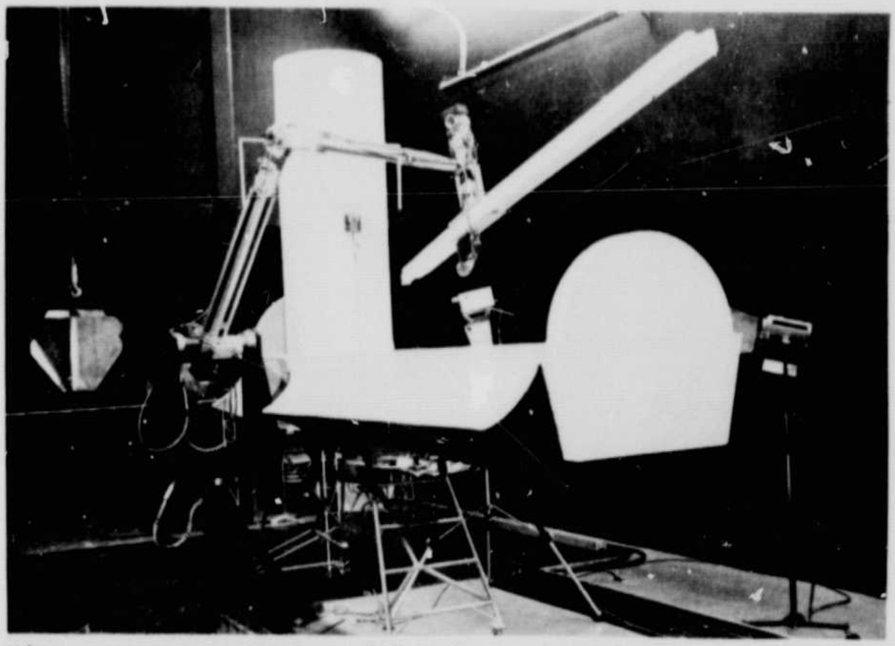


Figure IIE-2 RAT Assembly Simulation - Beam Translation

The Shuttle manipulator is presently 50 ft long. Our SMA has a 13-ft reach. The mockups are 1/4 scale to be compatible with the 13/50 ratio between the SMA and the Shuttle payload handling systems. The mockups consist of a portion of the Shuttle cargo bay, a center telescope core with a female beam attachment mechanism, and a beam with a male attachment mechanism.

Translation and coarse alignment were not a control problem. Final alignment requires attitude and position alignments to within $\pm$ 1/16". This fine alignment is probably more critical than would be designed into a space system. However, our total system provided operator control which allowed this task to be successfully completed. The antenna beam assembly task was broken into the following subtasks for the simulation: 1) Extract beam from cargo bay, 2) translate beam to core attachment interface, 3) position and align beam (male) attach mechanism at core (female) attach mechanism, 4) maneuver lower (2) beam attach pins into core receptacles and verify placement, and 5) pitch beam to engage upper two pins and verify.

b. Assembly of Microwave Power Transmission System (MPTS) - The assembly of a total MPTS represents a massive in-space assembly task. The one-kilometer transmission antenna structure is composed of thousands of 60-ft long beams which are all attached at their ends.

Our mockups, shown in Figure IIE-3 are approximately 1/5 scale, sized by the 13/70 ratio between the SMA and the assembler manipulator. The mockups are composed of 12 beam segments and four cross-braces. This represents the upper segments of two 60-ft cubes.

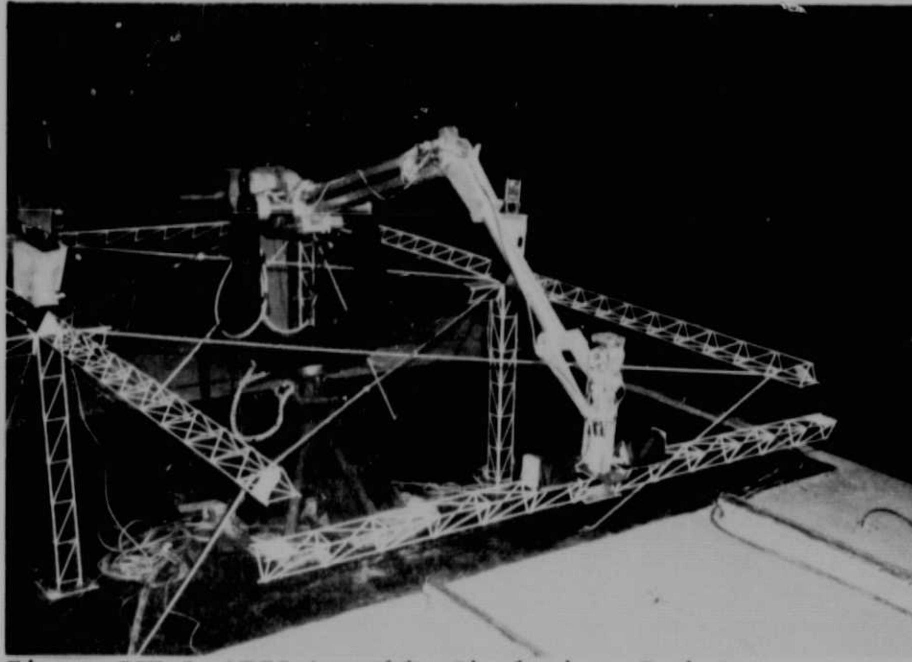


Figure IIE-3 MPTS Assembly Simulation, Task 1 - Beam Initial Alignment

This simulation series consisted of emplacement of the two horizontal (triangular) beam segments which make up the upper and lower end caps of the antenna support structure. Task 1 (Figure IIE-3) was to extract the beam segment from the beam pallet, translate and rotate the beam to the installation site, position and align both ends and contact the alignment plates while maintaining alignment. The second task (Figure IIE-4) was to install the triangular beam which is located 90 deg to the task 1 beam. This task differs significantly from task 1 in that the beam must be butted end-to-end rather than an overlay type task.

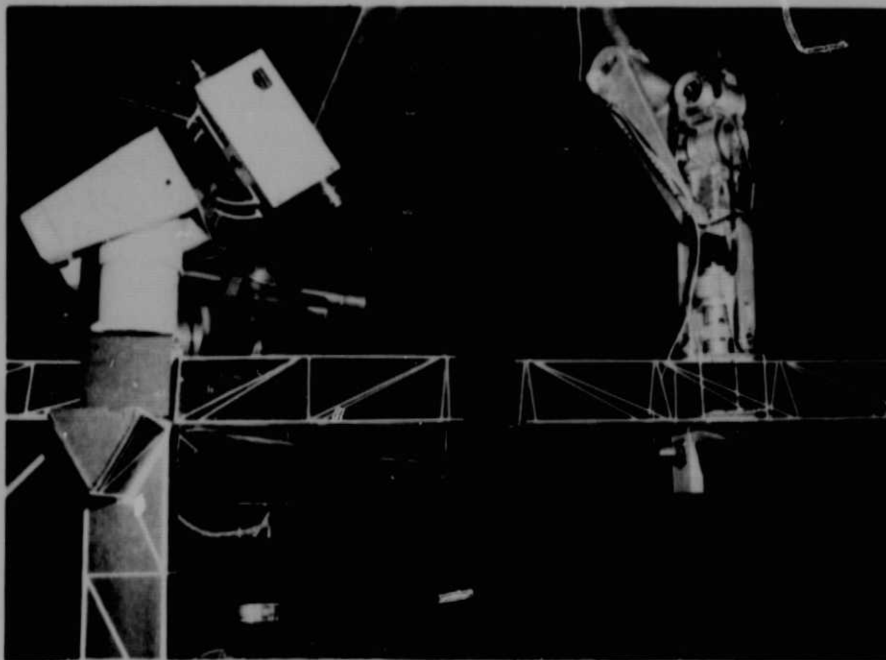


Figure IIE-4 MPTS Assembly Simulation, Task 2 - Beam Initial Alignment

4. Results and Recommendations

a. Test Subject - Three MMC operators (engineers) were used for the simulation. The run times averaged 2 to 4 min for each of the three assembly tasks. Initial run times were from 8 to 10 min. The translation phases were readily learned. The final beam alignment and/or attachment was more demanding on the operator. A total of 90 data runs were conducted.

b. Conclusions - We have demonstrated that the proposed in-space assembly technique, using a remotely controlled manipulator, is feasible. We have shown that the beam assembly times are less than anticipated and that these times can be reduced through the use of preprogrammed translation control modes. A simplified proportional rate control system was successfully used. Not only was this control system found acceptable, but highly desirable. This documentation de-emphasizes the need for a complicated manipulator control system such as used with a force feedback (bilateral) position controller. Secondary manipulator system conclusions include:

- Coordinated manipulator control motions are required for these in-space assembly tasks.
- Manipulator control axis alignment with the video system camera used for the prime visual feedback is mandatory.
- Manipulator shoulder and wrist torque output control is required at the operator's console.
- A partial (range) and fully automatic manipulator wrist attitude hold modes are required.
- Supplemental alignment aids, such as cross-hairs and standoff crosses are required for final beam positioning and alignment. The alignment aid technique used on the operational system should be standardized throughout the total assembly.

III. ASSEMBLY OF RADIO ASTRONOMY TELESCOPE

This chapter addresses briefly the orbital assembly of a 200-meter-diameter radio astronomy telescope (RAT). This parabolic antenna will be used to detect RF sources in the celestial sphere in the 5 to 10 MHz band. It will be placed in an 8,000 n mi altitude circular orbit of 0 deg inclination.

Figures III-1 and III-2 show the proposed design for the RAT. It consists of a circular parabolic reflector surface 650 ft in diameter and approximately 100 feet deep. The reflector surface focuses on a 85 x 97-ft feed located on top of a 275-ft mast. The reflector surface is covered with 332,000 sq ft of thin copper wire, placed in a 4-in. grid spacing. The telescope assembly is broken into nine major components. These are the mast and eight beams. The mast contains six telescoping segments. The lower segment, which is 10 ft in diameter and 55 ft long, contains the other five segments, the feed, the beam attach points, and the major electrical subsystems.

Each of the eight beams is 330-ft long and collapse into 55-ft long packages. Each has nine 55-ft segments. The inner three segments telescope, while

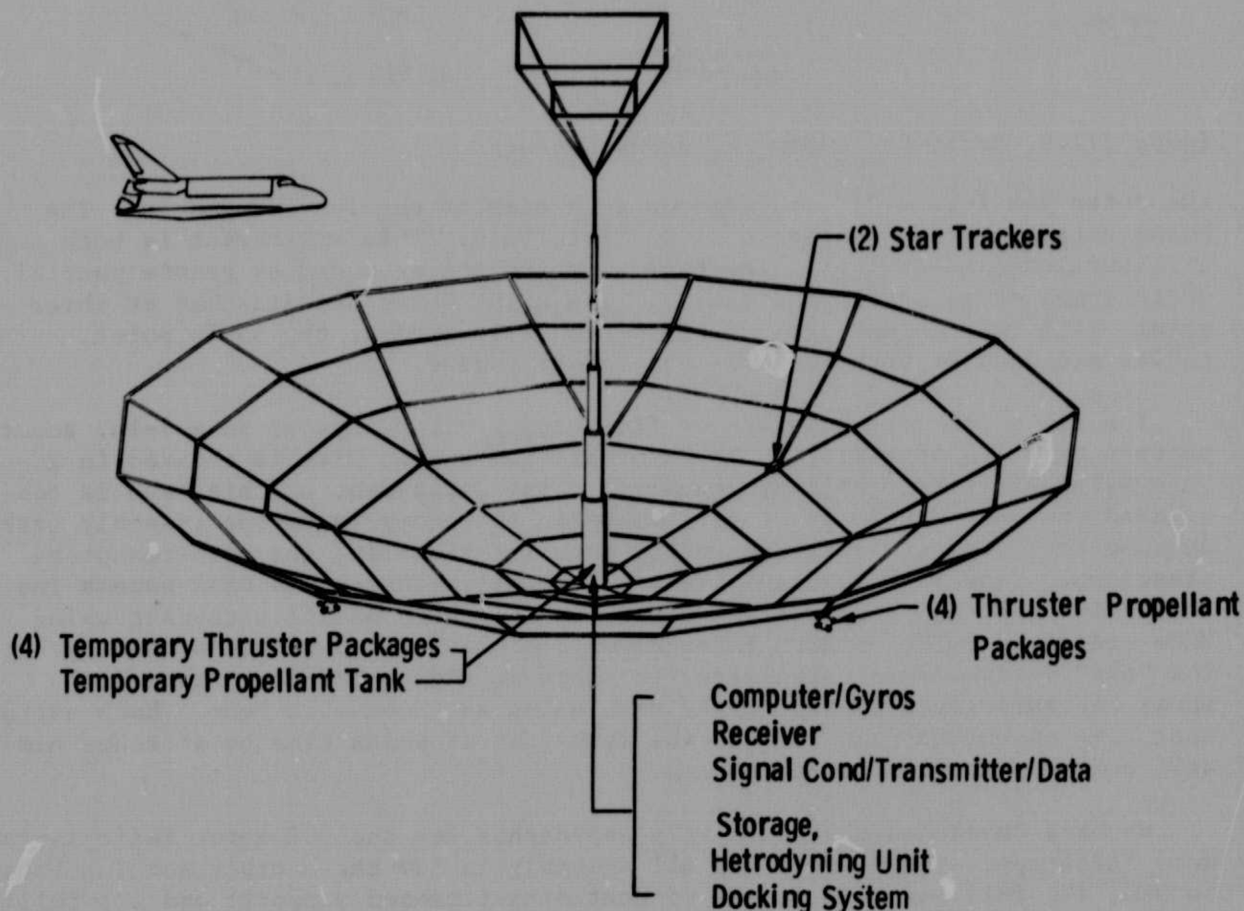


Figure III-1 Radio Astronomy Telescope Assembly

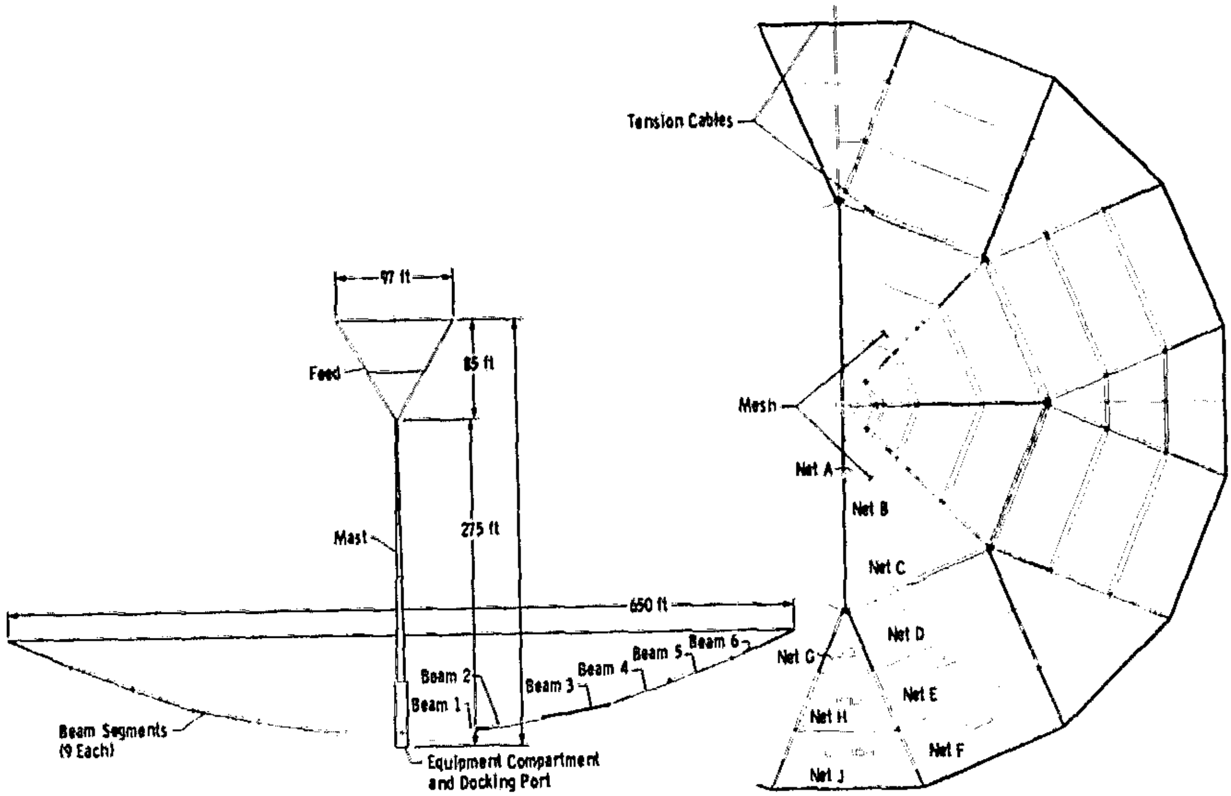


Figure III-2 Radio Astronomy Telescope Layout

the outer six form a "Y" and fold on each side of the inner segments. The beams attach to the inner core at 45° intervals. This attachment is both structural and electrical. The beam segments are extended by remote control of internal drive motors and cables. The eight beams are attached at three points with tension members. A rigid member is used at the 55-ft point, cables are used at both the 165- and 330-ft radius.

The reflector mesh consists of fine copper wires, spaced in a 4-in. square pattern over 1/3 of a million sq ft area. The copper wire is encased in a thin mylar sheet to facilitate handling. The deployment of this mesh is considered the most difficult of all the Radio Astronomy Telescope assembly tasks. Because the beams are attached to the core individually, the mesh cannot be preattached from beam to beam. We are presently stowing 184 mesh panels inside the individual beam segments and deploying them with an EVA astronaut using MMUs and/or an EOTS. Figure III-3 shows the mesh stowed within a beam package. The "net" designations correlate with those in Figure III-2. Figure III-4 shows the astronauts deploying the mesh using an extendable boom. Each astronaut uses an MMU to translate to the worksite, at which time he attaches himself to the beam with waist tethers.

We have developed three assembly approaches for the 200-meter Radio Astronomy Telescope. These are: (1) all assembly in low earth orbit and Tug boost to HEO; (2) full assembly in HEO without direct manned support; and (3) full assembly in HEO with direct manned support. Figures III-5 through III-7 depict these three approaches.

The non-cost comparison of the three assembly approaches is presented in Table III-1. These seven items were chosen as the most representative factors to be anlayzed due to their contribution to overall mission success. They are quite general but form a good basis to compare assembly approaches. A subjective weighting scheme is shown which compares each of the seven items

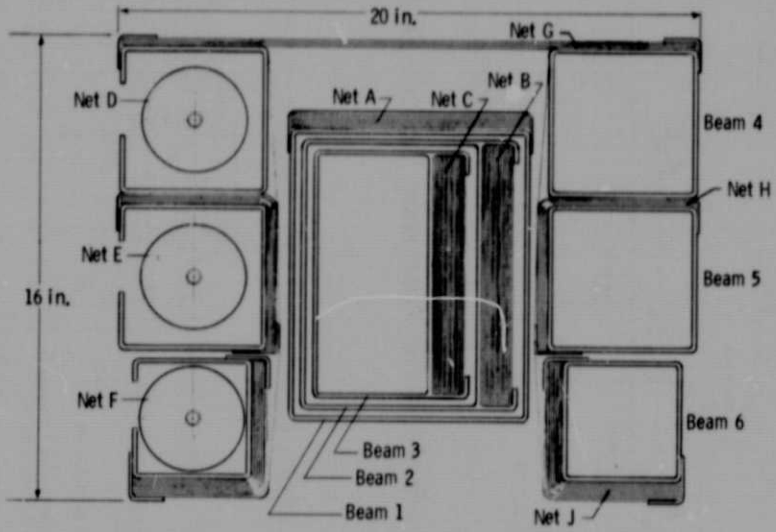


Figure III-3 Beam Package Cross Section

with respect to each other with the higher values corresponding to the more significant items. A unit rating is then assigned which numerically compares the three approaches for each item. A one is considered the best rating while a ten is considered worst.

Both this subjective scheme and a cost analysis (not shown here) indicate that approach 1 (assembly in LEO) is the preferred approach.

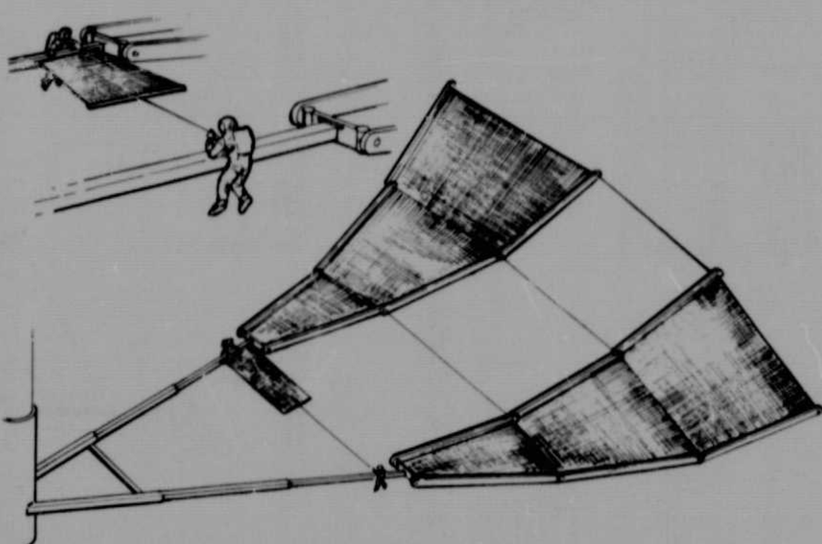


Figure III-4 Astronauts With MMU's Installing Mesh

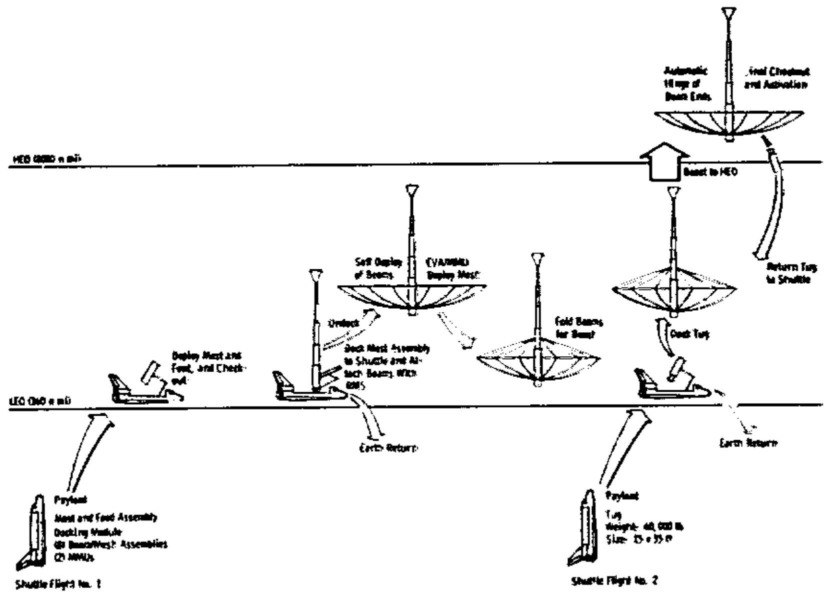


Figure III-5 Radio Astronomy Telescope Approach 1

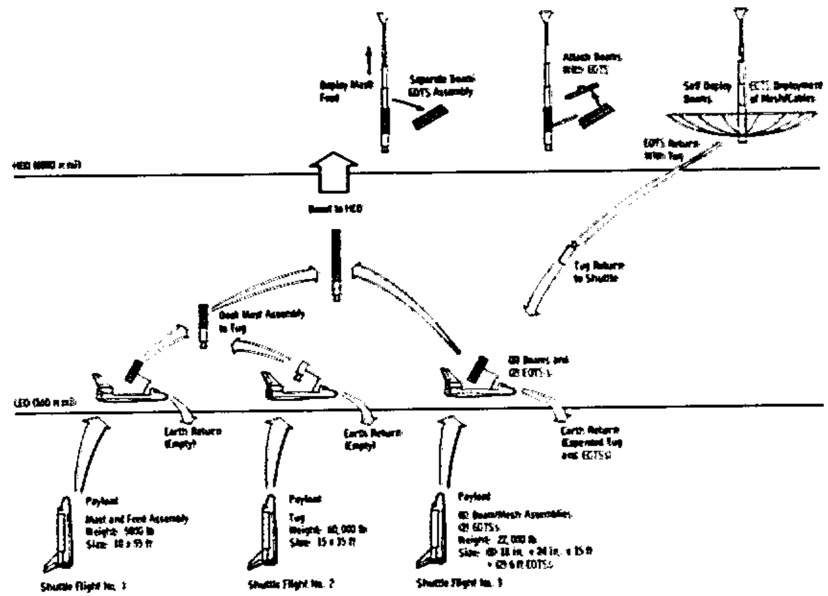


Figure III-6 Radio Astronomy Telescope Approach 2

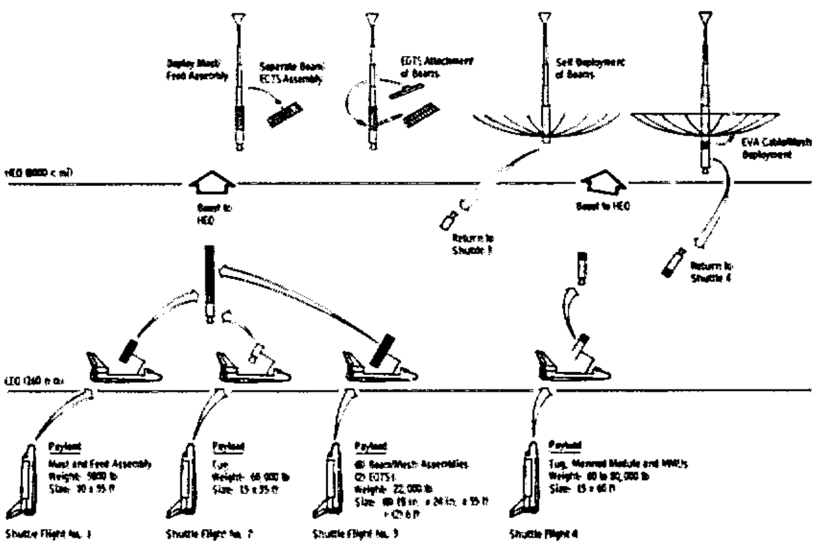


Figure III-7 Radio Astronomy Telescope Approach 3

Table III-1 Non-Cost Comparisons

		Approach 1 Assembly in LEO		Approach 2 Assembly in HEO Unmanned		Approach 3 Assembly in HEO Manned	
	Weight	Unit Rating	Total Rating	Unit Rating	Total Rating	Unit Rating	Total Rating
A. Man Safety	25	1	25	4	100	8	200
B. Assembly Reliability	20	2	40	5	100	4	80
C. Support Equipment Complexity and Development Program	15	2	30	9	135	5	75
D. Equipment Safety	15	2	30	5	75	5	75
E. Potential Problems in Transit	13	7	91	2	26	2	26
F. Mission Complexity	7	3	21	9	63	6	42
G. Mechanical Complexity	5	3	15	8	40	5	25
TOTALS	100		252		539		523

IV. MAINTENANCE

A. INTRODUCTION AND SUMMARY

The objective of the Maintenance position of this study was to investigate maintenance methods and requirements for the Earth Observations Geosynchronous Platform (EOGP), the two space systems selected for the assembly portion of the study, and four geosynchronous satellites to be selected from the October 1973 Space Shuttle Traffic Model. Since insufficient data existed on the MPTS operational systems, this structure was not investigated for maintenance requirements and the time was applied to other maintenance investigations.

After selection of the four geosynchronous satellites:

Disaster Warning Satellite (DWS),
U.S. Domsat C (Tracking and Data Relay Satellite - TDRS),
Intelsat,
Synchronous Earth Observations Satellite (SEOS),

data on the baseline configurations of the six selected satellites were compiled. The satellites were reconfigured to serviceable versions which incorporated replaceable subsystem modules but retained the baseline operational characteristics and hardware. The module arrangements and replacement task requirements were purposely made different with each reconfiguration to permit investigating maintenance requirements for several of the configurations that satellites might take. Three maintenance approaches, based on using baseline or considered STS vehicles, were analyzed.

A fourth maintenance mode was investigated in a separate task, wherein an on-orbit geosynchronous maintenance vehicle is left in orbit for a period of time and performs module replacement maintenance. The RI version of the SEPS was assumed for the propulsive vehicle.

All maintenance missions were analyzed to the depth necessary to determine mission STS requirements, timelines, servicer general requirements, Shuttle and Tug general support requirements, and additional satellite characteristics required for compatibility with the maintenance options.

A concept was proposed to use the Earth Orbital Teleoperator System (EOTS) attached to the front of a baseline Tug as the servicer in one maintenance approach. This concept was a result of the need for a low-mass maneuverable servicer for maintenance of the radio astronomy telescope.

Cost estimates were developed and subjective evaluations were conducted for the four satellite programs (DWS, TDRS, Intelsat, and SEOS) presently schedule in the Traffic Model. In general, the manned maintenance mission options rated best subjectively but were more costly due to more STS flights required. Vehicles with greater transport capability might make these options less costly.

B. REQUIREMENTS AND SATELLITE SELECTION

From the 17 geosynchronous satellites listed in the Space Shuttle Payloads Descriptions (SSPD) documents, July 1974 and The October 1973 Space Shuttle Traffic Model, NASA TM X-64751, Revision 2, January 1974, the DWS, TDRS, Intelsat, and SEOS were selected because they offered a good cross-section of characteristics of interest to the maintenance study, e.g., weight, size, variety of equipment and subsystems, etc.

C. CONCEPTUAL DESIGNS

Related studies and other supporting documents were to be considered and used in this study to avoid duplication of effort. In reviewing other studies, it became apparent that there are a multitude of potential satellite configurations, in regards to the methods for locating replaceable units. It was, therefore, decided that a unique and desirable output of this maintenance study should be the investigation of maintenance requirements from the standpoint of different satellite serviceable configurations.

Data were compiled on the baseline versions of the subject satellites. The satellites were then redesigned, where applicable, into serviceable versions (see Figure IVC-1). These conceptual designs were carried only to the depth necessary to investigate maintenance requirements and were purposely limited to conserve time.

1. Disaster Warning Satellite (DWS)

Baseline data on the DWS was taken from Disaster Warning Satellite Study, TM X-68122, NASA-Lewis Research Center, March 1971. The open face axial-module-extraction configuration was based on a concept from the Unmanned Orbital Platform Definition Study (UOPD), SD73-SA-0122, Rockwell International, September 1973.

2. U. S. DOMSAT C (Tracking and Data Relay Satellite - TDRS)

The baseline configuration used for the TDRS was the second alternate configuration developed in the TDRS Configuration and Tradeoff Study (Part II); Vol. III, Spacecraft Design, NASA CR-130218, Rockwell International, April 1973. This configuration was used since it most closely matched the Level A data presented in the 1974 SSPD.

The rectangular-matrix module serviceable arrangement was based on a concept used in A Study of Payload Utilization of Tug (PUT), Vol. II, MDC G5356, McDonnell-Douglas Astronautics Company, June 1974.

3. Intelsat

Baseline Intelsat data from the Integrated Orbital Servicing and Payloads Study (Contract NAS8-30849), COMSAT Laboratories and the DSP Space Servicing Study, TOR-0073(3421-07)-1, The Aerospace Corporation, August 1973, were used

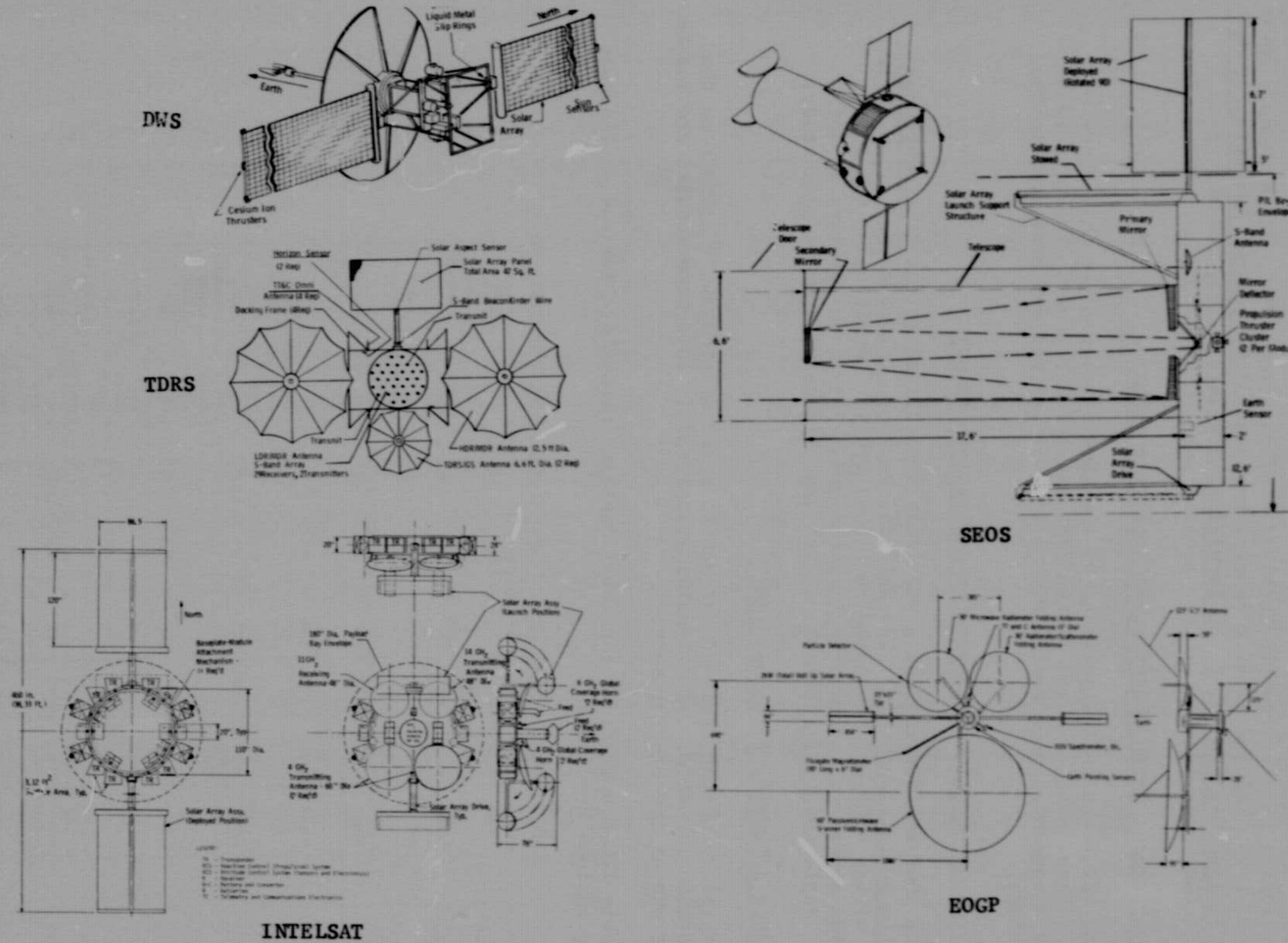


Figure IVC-1 Geosynchronous Satellites Investigated in developing the serviceable Intelsat configuration. This radial-module configuration was modeled after a concept proposed in Operations Analysis (Study 2.1), Payload Designs for Space Servicing, ATR-74(7341)-3, The Aerospace Corporation, June 1974.

4. Synchronous Earth Observations Satellite (SEOS)

The serviceable configuration of the SEOS developed for this study was based on concepts presented in the SSPD and the PUT study. The torroidal module arrangement with radial extraction was derived and presented in the UOPD study.

5. Earth Observations Geosynchronous Platform (EOGP)

The EOGP was designed as a serviceable satellite in the Geosynchronous Platform Definition Study, SD73-SA-0036, Rockwell International, June 1973. Views of the EOGP are presented in Figure IVC-1. Servicing of the EOGP requires access to internal replaceable modules through openings at both ends. Replacement of external modules was also considered in this study.

6. Radio Astronomy Telescope (RAT)

Replaceable star trackers and ACS pods are located at "Y" joints on the RAT antenna rib structure. Remaining replaceable subsystem modules are located in the end of the central core.

Table IVC-1 summarizes the serviceability parameters for the serviceable configurations developed.

Table IVC-1 Summary of Serviceability Parameters

Satellite	Baseline Satellite Weight (lb)	Satellite Weight (lb)	Weight of Total Spares Complement (lb)	Volume of Total Spares (Assuming 0.05 ft^3/lb) (ft^3)	Maximum Number of Modules	Largest Module Weight (lb)	Largest Module Envelope Dimensions (ft)
DWS	1,284	1,904	1,329	66.5	14	222 Solar Array Assembly	2x2x8.5
TDRS	659	1,139	758	37.9	17	77 Solar Array Assembly	2x6x9
Intelsat	3,245	2,710	1,986	99.3	22	135 Solar Array & Propulsion Module	2x4x[illegible] 2x2x2
SEOS	3375 - per SSPD 3760 - per PUT Study	3,697	1,782	89.1	12	206 Attitude Control System	3.5x3x1.7 Truncated Pyramid x2 Thick
EOGP	NA	8,491	4,287	214.4	43	392 Battery Pack 415 External Scanner 310 Antenna	2x2x2 3x4x6 2.5 Dia x 10
Radio Astronomy Telescope	NA	27,000	830	41.5	13	120 Momentum Wheels & Electronics	1x2x2

D. PROCEDURES AND TECHNIQUES

The following three maintenance mission approaches were analyzed for the subject satellites:

Approach 1 - Maintenance in Geosynchronous Orbit using Reusable Tug/ Servicer
Approach 2 - Maintenance in Geosynchronous Orbit via EVA from Manned Servicing Module (MSM)
Approach 3 - Maintenance in Shuttle Orbit using Shuttle Remote Manipulator System (RMS) and EVA

Approach 1 requires only one Shuttle/Tug flight to place a servicer in geosynchronous orbit and return it. The following operational steps are depicted in Figure IVD-1:

1. Tug transfers servicer to satellite orbit and docks.
2. Servicer connects umbilical and deactivates satellite.
3. Servicer performs maintenance activities by preprogrammed direction or man-remote ground control.
4. Tug orients assembly to ground pointing.
5. Servicer activates satellite.
6. Preliminary checks performed by ground controllers.
7. Tug/Servicer separates from satellite.
8. Final satellite functional checks.
9. Tug/servicer returns to Shuttle Orbiter.

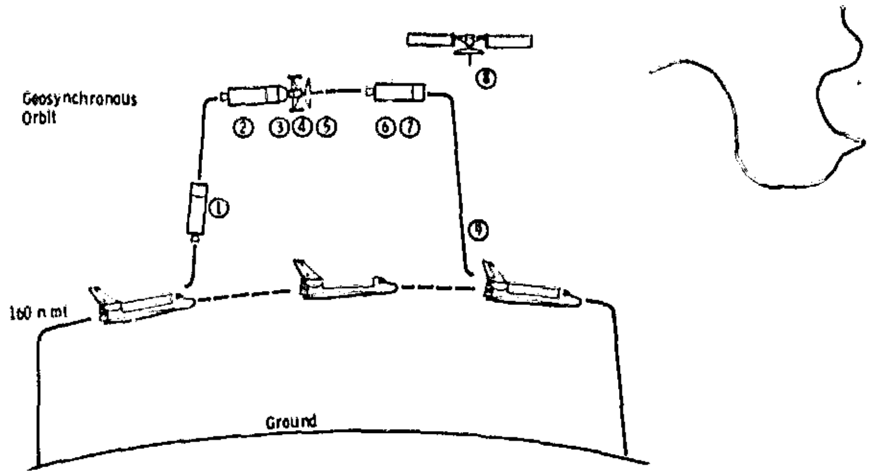


Figure IVD-1 Maintenance Mission - Approach 1

Approach 2 requires two Tugs in tandem to deliver the MSM to geosynchronous orbit. The first Tug will place the total assembly in an elliptical phasing orbit of about 160 x 7000 n mi. During the first orbit, the Tugs will separate. At perigee, the first Tug will burn to return to the Orbiter. The second Tug will burn into a transfer orbit to geosynchronous altitude. The operational steps are depicted in Figure IVD-2.

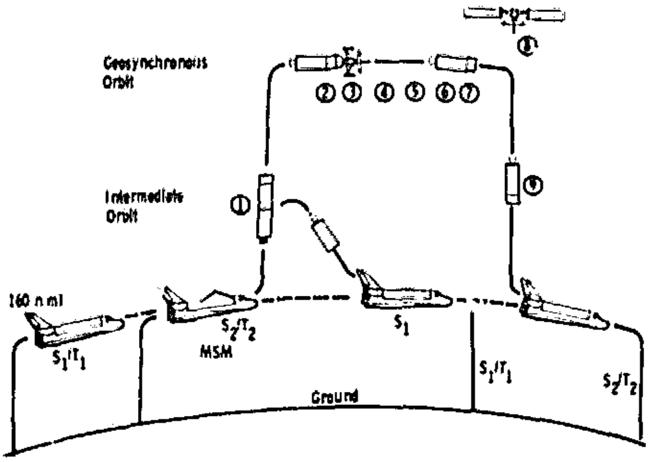


Figure IVD-2 Maintenance Mission - Approach 2

Approach 3 requires two Tugs; one to retrieve the satellite from geosynchronous orbit and another to deploy the serviced satellite. Larger satellites require 3 or 4 Tugs to retrieve and return the satellite to orbit. For maintenance at the orbiter, the RMS would be used as a work platform or to transfer the EVA crewmen and/or spares to the worksite.

Scenarios, mission budgets, and timelines for the three maintenance approaches were analyzed for the subject satellites. The results are summarized in Table IVD-1.

Table IVD-1 Significant Results of Maintenance Approach Analyses

SATELLITE	APPROACH 1 SERVICER IN HEO	APPROACH 2 MSM IN HEO	APPROACH 3 RMS/EVA IN LEO
DMS	Solar Arrays must be retracted. Tug capability for full spares complement.	Two Tugs required. Sufficient capability for full spares complement. Solar arrays must be retracted	Solar array must be retracted. Antenna probably must be refolded. Two Tugs required. LEO pointing and checkout of antenna more difficult and time consuming.
TDRS	No need to retract solar array except for replacement. Sufficient capability for full spares complement.	Two Tugs required. Sufficient capability for full spares complement	Antennas easier to refold. Two Tugs required.
INTELSAT	Solar arrays must be retracted. Tug capability for 60% spares replacement.	Two Tugs required. Sufficient capability for full spares complement. Solar arrays must be retracted	Solar arrays must be retracted. Two Tugs required
SEOS	Solar arrays must be retracted. Tug capability for 67% spares replacement.	Two Tugs required. Sufficient capability for full spares complement. Solar arrays must be retracted. Optical contamination protection required	Three Tugs required. Solar arrays must be retracted. Optical contamination protection required.
EOGP	Tug capability for 28% spares replacement. Solar arrays must be retracted. Antennas and scanner platform must be retracted. VLF antenna creates caution during rendezvous. Docking at both ends of satellite. Longer timeline because of more modules	Two Tugs required. Tug capability for 61% spares replacement. Optical contamination protection required. Solar arrays must be retracted. Antennas and scanner platform must be retracted. VLF antenna creates caution during rendezvous. Docking at both ends of satellite. Longer timeline because of more modules.	Four Tugs required. All appendages must be retracted and again deployed. Optical contamination protection required
RADIO ASTRONOMY TELESCOPE	Sufficient Tug capability for full spares complement. Free-flyer type servicer required for star trackers and propulsion modules.	Single Tug required. Sufficient capability for full spares complement. Free-flyer or MMU required for replacing star trackers and propulsion modules	Three Tugs required. Possibly could not return satellite - depending on configuration.

These analyses also led to the following general requirements for maintenance of satellites.

General Requirements for Servicer

1) Docking provisions compatible with the satellite and integrated with The Tug rendezvous and docking systems (if docking is between the satellite and the servicer);
2) Servicing system controlled by instructions from preprogrammed Tug computer circuitry or by commands from ground sources;
3) Lighting and TV aids for remote control module changeout;
4) Umbilical system for docking engagement to satellite to convey control commands and electrical power;
5) Backup means of separation in the event of docking latch failure to open;
6) Provide stowage provisions for replaceable spares;
7) Servicing system capable of reaching and exchanging all replaceable units on the subject satellite;
8) Servicer end-effector compatible with the satellite module latch mechanisms.

General Requirements for Satellites

1) Capability to retract appendages (solar arrays, antennas, external experiments, etc.) that are not able to withstand docking impact loads or that may impact the docking system (reasonable maneuvering space required);
2) Capability to command retraction of appendages (item 1) by signals from remote sources (ground, orbiter, TDRS);
3) Capability to deploy appendages by remote command and hardline link through the servicing system;
4) Capability for multiple deployment and retraction of appendages for Approach 3 maintenance;
5) Laser radar reflectors (docking aids) and other docking provisions compatible with servicing system;
6) Receptacle for umbilical attachment from servicing system;
7) Circuitry for disengaging selected satellite equipment functions by remote control or through the umbilical from the servicing system;
8) All functional systems (excluding such equipment as passive antennas) replaceable as modules or self-contained units;
9) Module latch mechanisms should be compatible with capabilities of servicer end-effectors or hand-held EVA tools;
10) For EVA maintenance, redundant fluid and mechanical shutoffs, structural safety factors, and elimination of sharp edges and protrusions are required to minimize hazards to EVA crewmen;
11) Capability of remotely commanding opening and closing of covers on contamination sensitive optical equipment.

General Requirements for Shuttle/Tug

1) Provisions for Tug docking directly with the satellite in Approach 3 and also in Approach 1 if the servicer is separate ~~equipment~~ installed inside the Tug docking frame;
2) Tug computer and circuitry to provide preprogrammed instructions to the servicer (if applicable);

General Requirements for Shuttle/Tug (Cont'd)

3) Tug circuitry to relay remote commands and power to the servicer and/or satellite:
4) Tug relay of data from the servicing system and/or satellite to the ground or to the orbiter during checkouts;
5) Backup means of separation in the event of docking latch failure;
6) Provide external stowage provisions for large replaceable units such as solar array and antenna packages;
7) Provisions for P/L bay stowage (including environmental protection) of replaceable units for Approach 3;
8) Provide portable foot restraints and lighting in Approach 3;
9) Adapter for tandem Tug operations.

The analysis of maintenance requirements for the radio astronomy telescope disclosed the need for a servicer that could maneuver and dock at several places on the structure for maintenance. This could be a very common maintenance requirement for future large-structure space systems. The consideration of an EOTS attached to a Tug and controlled remotely through the Tug systems appeared to fit this requirement. Such a concept for a servicer for use with other satellites offers other advantages. If the EOTS manipulator is compatible with the reach and task functions, the EOTS could perform the Approach 1 maintenance tasks analyzed in this study. If a single point servicing were called for, an unfueled EOTS would be used and would remain attached to the Tug throughout the mission. Use of EOTS would save much of the development costs of a new servicer design.

E. ON-ORBIT GEOSYNCHRONOUS MAINTENANCE VEHICLE

The purpose of this study was to investigate the feasibility of an on-orbit automated maintenance vehicle that can remain in geosynchronous orbit for an extended period of time and carry equipment and spares to conduct maintenance, servicing, and refurbishment operations.

It was assumed that the vehicle is the RI version of the Solar Electric Propulsion Stage (SEPS), with an attached servicer.

The SEPS, with full mercury propellant load, is capable of 625 days thrusting time. The on-orbit operational capability is 3 years, based on solar array degradation. Nominal thrust levels are 0.206 lb_f with an I_{sp} of 3000 seconds.

A modified traffic model was developed in the Integrated Orbital Servicing Study, (Contract NAS8-30820), Martin Marietta Corporation, 1975 to make the satellite programs compatible with servicing. This model was used for the four satellites analyzed in this portion of the study.

Module replacement times were determined from failure rates estimated from data presented in the Operations Analysis (Study 2.1) by The Aerospace Corp. In addition to failure replacements, it was assumed that wearout items (solar arrays, power modules, ACS propulsion) are replaced at the AOT period.

If a SEPS servicing assembly were kept in geosynchronous orbit for a three-year period, it would need to contain module spares to enable exchange of the modules expected to fail or be depleted/degraded in that period. In addition, at least one spare was assumed available for any unique model. Since there would be many modules involved in a three-year period, it would not be practical or even workable to carry all spares along with the SEPS/servicer. An assembly such as that shown in Figure IVE-1 appears feasible and is proposed. This assembly contains one or more spares tiers. Each tier would hold in the order of 24 spares modules. The SEPS/servicer would carry along only the single tier needed for maintenance of a satellite at some other longitude in orbit. The remaining spares tiers would be maintained at a "home base" longitude (100 deg W assumed) by a stabilization unit.

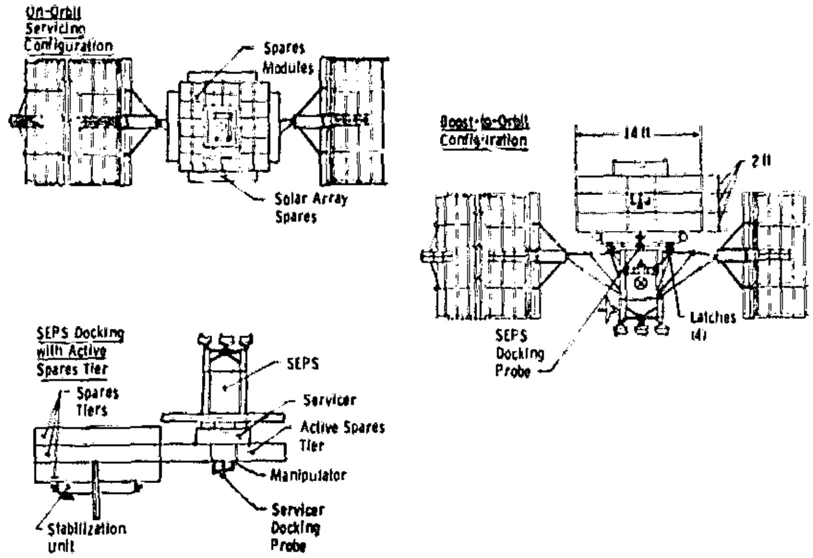


Figure IVE-1 SEPS/Servicer/Spares Assembly Configuration

Three 3-year maintenance periods between 1983 and 1991 were analyzed. The second and third missions required refueling the SEPS during the on-orbit period, using the RI proposed SEPS refueling unit.

The SEPS maintenance scheme would require eight Shuttle/Tug flights if the SEPS are not recovered--three tandem Tug flights to put SEPS/servicer/spares in orbit; two Tug flights for refueling SEPS. Recovery of the SEPS/servicers would require three additional Shuttle/Tug flights. However, this would permit refurbishing the SEPS/servicer for later missions.

F. TRADEOFFS

1. Cost Comparisons

The three maintenance approaches were analyzed for the four satellites listed in the Traffic Model by assuming servicing of failed modules at the end of each average operational time (AOT). This permitted comparing program costs on a basis similar to that for the SEPS on-orbit maintenance scheme.

Table IVF-1 summaries the total program cost estimates for all maintenance modes (with options). Although there are several gross estimates in these cost analyses that prevent specific conclusions, some general conclusions can be made.

Table IVF-1 Total Program Costs with Maintenance

MAINTENANCE MODE	OPTIONS	COSTS, $B
1. SEPS - Three 3-Year Missions	A. Retrieve SEPS B. Not Retrieve SEPS	1.348 1.346
2. Tug/Servicer - at AOT	A. Return Modules B. Expended Modules	1.400 1.316
3. MSM - at AOT	A. Return Modules B. Expended Modules	1.440 1.462
4. Satellite Retrieval - at AOT	A. Orbiter Maintenance B. Ground Refurbishment	1.587 1.707

There would be little cost difference in the SEPS maintenance mode whether the SEPS vehicle is recovered or left in space.

Considerable savings in STS flights and net costs could accrue from leaving replaced modules in orbit, with the Tug/servicer maintenance mode. However, this procedure would create much more space litter. This maintenance mode does appear to be the most economical method of maintenance.

The manned servicing module (MSM) method of maintenance is competitive with the other methods when more than one satellite can be serviced on one mission. Previous analyses which assumed single-satellite maintenance did not fully use the excess capacity of the tandem Tugs and resulted in high program costs.

Retrieval of satellites from geosynchronous orbit for maintenance at the orbiter appears to be more costly relative to the other methods. Return of the satellites to the ground for refurbishment would be even more costly. However, this would permit more thorough updating of the satellite technology and capabilities.

2. Subjective Comparisons

A subjective evaluation of the three maintenance approaches (excluding the on-orbit vehicle) was performed. Weighted evaluation factors, such as man safety, mission and servicing systems complexities, and program development requirements, were rated individually. Ratings were totalled to get the overall subjective comparisons.

3. Conclusions and Recommendations

In general, costs of the various maintenance options are inversely proportional to the results of the subjective evaluations. Manned maintenance operations appear to be more desirable in spite of some safety hazards. However, costs of manned operations tend to be greater. The benefits of man in any maintenance operation cannot be forecast in any analytical evaluation.

For instance, the need for manned repair capabilities on Skylab could not be predicted but the value of direct manned repair activities in those missions are now known to all. In the maintenance of satellites, many component failures can be predicted and mechanical means devised to effect most repairs. However, manned participation in maintenance activities becomes invaluable in those type of repairs where unpredicted failures occur which call for on-the-spot trouble-shooting, inspections, and repairs of non-modular type hardware. In the case of the satellites investigated in these studies, the following potential maintenance activities would be more feasible or appropriate for manned activities.

<u>Repairs</u>

- Broken wires
- Defective module attachment mechanisms
- Bent/defective pin connections
- Ripped/punctured antennas
- Fluid system leaks
- Frozen (contact weld) joints
- Replace fixed sensors
- Replace appendages not designed for changeout
- Attach thermal control coverings

<u>Inspections</u>

- Electrical shorts
- Bent or loose members
- On-the-spot electrical circuit checks
- Corrosion/wear points

The primary difference in the costs between the various maintenance options is the costs of the Shuttle/Tug flights. Boost vehicles and orbit-to-orbit vehicles of greater capacity could make the manned maintenance modes more atractive. This potential should be investigated in other studies.

V. STUDY CONCLUSIONS

In the study of maintenance of geosynchronous satellites, we have reached the following conclusions:

1. On-orbit servicing is technically feasible;
2. Designing satellites for servicing result in an increase in weight and size;
3. The most economical approach to servicing is the remotely controlled Tug and attached servicer;
4. Retrieval to Shuttle with manned servicing has the highest probability of success;
5. Geosynchronous orbit servicing with a Tug manned module could become the overall preferred approach if multiple satellite servicing is considered;
6. SEPS is useful as a geosynchronous maintenance vehicle, but has no major advantage over other approaches.

In the study of the orbital assembly of large structures, we have reached the following conclusions:

1. The erection of a large structure--such as a Solar Power Station--is technically feasible;
2. Many of the routine, repetitive operations can be controlled from the ground;
3. The role of man at the erection site is that of a supervisor and/or trouble shooter;
4. The simulation has confirmed that the basic assembly tasks can be carried out remotely, and suggests that the times required may be less than anticipated.

Further studies in the following areas are recommended to provide technical depth in key elements and to assess potentially important areas not analyzed in this study because of time and scope limitations.

Total Power Satellite Design - Expand MMC and Raytheon/Grumman assembly studies to an indepth analysis of assembly requirements for the total Satellite Solar Power Station.

Packaging Density Analysis - Investigate ways to increase the launch packaging density of structural components.

Space Logistics Analysis - Analyze and perform tradeoffs on logistics techniques for more effective space transportation systems for large space structures.

Structural Commonality - Develop common base structures and assembly approaches for all proposed large space structures.

Manned Orbital Assembly - Perform tradeoff analyses to investigate use of man in high earth orbit assembly operations.

In-Depth MPTS Analysis - Conduct further MPTS analysis and design in the following areas:

- Mobile assembler
- Structural dynamics
- Thermal control
- Remote welding and bonding
- Pyrotechnics for assembly
- Video systems and lighting
- Alignment devices and methods
- Maintenance of MPTS hardware

On-Orbit Fabrication Plant - Analyze potential benefits of an on-orbit fabrication facility in support of large structure assembly, including the use of expended orbiter external tanks as raw material.

Low Earth Orbit Demonstration of Assembly Techniques - Conduct missions to evaluate and demonstrate assembly techniques in orbit.

SEPS Maintenance Program Reliability - Analyze the reliability of the propulsive vehicle, associated support equipment, and spares modules over a long-duration maintenance mission.

Low-Thrust Boost Vehicles - Investigate the use of low-thrust boost vehicles not hindered by low-orbit radiation degradation and earth shadowing, for use in large structure assembly and transportation.