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Executive Summary

# Integrated Orbital Servicing Study Follow-on

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TRW
SYSTEMS GROUP

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Executive Summary

# INTEGRATED ORBITAL SERVICING STUDY FOLLOW-ON

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## FOREWORD

This study was performed under Contract NAS8-30820 for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the direction of James R. Turner, the Contracting Officer's Representative. The final report consists of three volumes:

Volume I - Executive Summary;

Volume II - Technical Analyses and System Design;

Volume III - Engineering Test Unit and Controls.

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# I. INTRODUCTION

Orbiting satellites continue to grow in capability, increase in cost, and proliferate in numbers as the nation continues to struggle slowly but consistently across the frontiers of space. The great exploitation of space has by no means begun; in fact, the exploration is far from complete. More and more frequently, however, glimpses of its great potential are offered the informed and aware. Unlimited sources of power, highly efficient communications, and a continuously expanding application of specialized manufacturing processes are only a few opportunities. Man's imagination will undoubtedly multiply these manyfold. The challenge to the technological community today is not necessarily to find a use for space but to find the best ways to use it. The entrepreneurs will follow if space can be accessed quickly, safely, and cost effectively. The Space Transportation System, particularly the Shuttle Orbiter, is the first major step in that direction. It will eventually assure the necessary access. It is by no means the last step. A greater confidence in operating and working in space for long periods must be acquired. Space stations are obvious milestones toward this end. The sheer magnitude in both numbers and diversity of future orbiting satellites, facilities, and utilities necessary to encourage these opportunities will demand longer hardware life, more reliable operation, and a continuously greater accountability to cost. This will eventually demand routine maintenance of orbiting equipment, much as electrical power facilities, communications transmitters, manufacturing tools, and computing systems are maintained on earth today.

This theme has motivated the last several years of conceptual studies of on-orbit satellite maintenance under MSFC Contract NAS8-30820 and the many studies that have gone before.

Many alternatives for satellite maintenance have been identified, conceptualized, and evaluated--unmanned orbital servicing systems, manned extravehicular activities, highly reliable expendable designs, and retrieval for ground refurbishment and return to orbit. The first Integrated Orbital Servicing Study (IOSS) completed in September 1975 along with a parallel study, Integrated Orbital Servicing and Payloads Study, conducted by COMSAT Laboratories of the Communications Satellite Corporation, jointly concluded that:

- On-orbit servicing is the most cost-effective satellite maintenance approach;
- Development of a single on-orbit servicer maintenance system is compatible with many spacecraft programs;
- Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effects;
- The evolving Space Transportation System is designed to support on-orbit maintenance;
- Users need guarantees that servicing will be available and assurances that it will be cost effective.

As satellite designs continue to evolve, it becomes apparent that there is room for virtually all the alternatives of satellite maintenance at one point or other in the future. The question has become one of "How?", not "Which?" or "Why?". In a word, the "How?" sums up the thrust of this contract's activities. To that end, the following major outputs were produced:

- The conclusions of the first IOSS were verified.
- An optimum configuration for an on-orbit satellite servicer system was selected.
- A preliminary design of a flight-version satellite servicing mechanism was developed.
- A control system was configured for the servicer mechanism, and control modes were defined.
- Maintainable spacecraft designs were completed for representative high and low earth-orbit applications.
- A simulation and demonstration was conducted that showed the feasibility and utility of the servicer concept and designs.
- A 1-g servicing demonstration system representing the proposed servicing mechanism was designed, fabricated, assembled, and delivered for use as an evaluation tool at MSFC (Fig. I-1).

- The optimum approach to repair of geosynchronous satellites was identified, and life-cycle costs of on-orbit servicing were detailed.

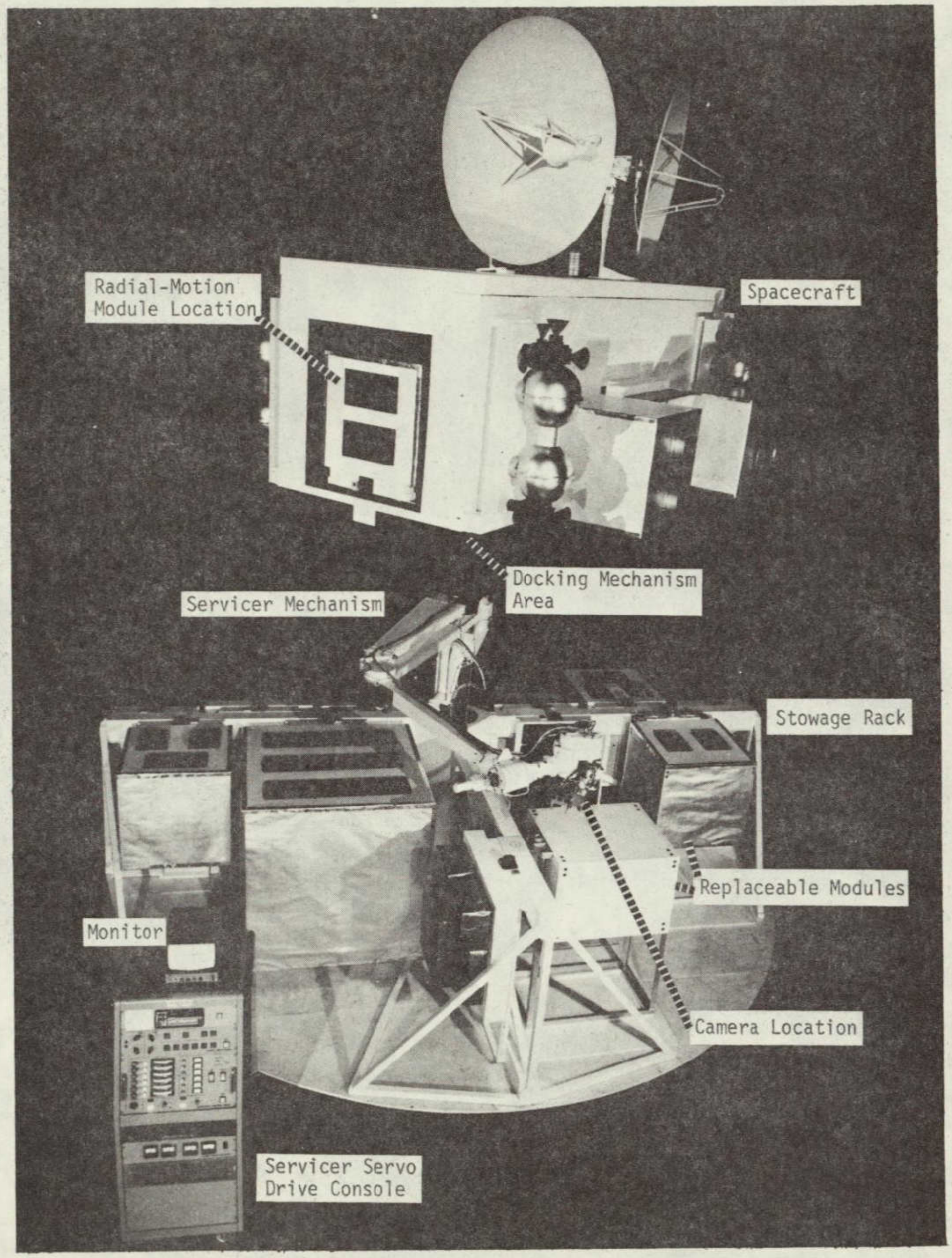


*Figure I-1 1-g Servicing Demonstration System*

As shown in Figure I-2, orbital servicing has broader applications than just repair, refurbishment, and resupply of expendables to spacecraft. Methods and techniques used for spacecraft

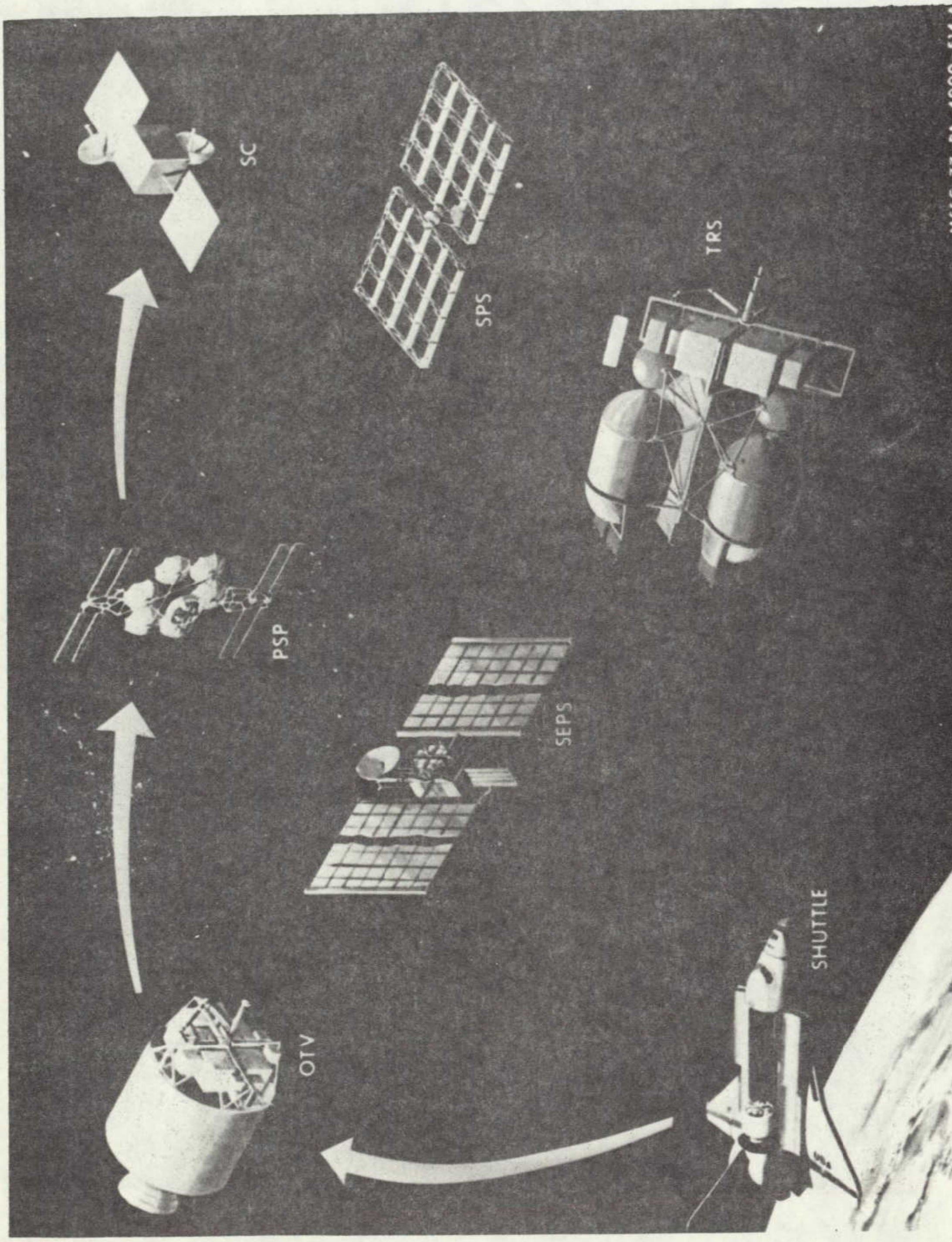


*Figure I-2 Orbital Servicer Applications* repair on orbit may also be applied to the maintenance, repair, assembly, or on-orbit modification of Public Service Platforms (PSP), Solar Power Stations (SPS), and construction of large space structures. The system is applicable to low earth orbits as well as geosynchronous orbits. It could be delivered to its operational destination by carrier vehicles such as the Orbit Transfer Vehicle (OTV), Solar Electric Propulsion System (SEPS), Teleoperator Retrieval System (TRS), and the Orbiter itself. In fact, the orbital servicer configuration, mechanism, and control work has broad application to the whole field of teleoperator technology and operations in space.

Martin Marietta was aided in this follow-on activity by TRW, Inc. under the direction of Mr. David H. Mitchell who was responsible for the serviceable spacecraft design work. Not only did the TRW work strengthen the practicality of the design of spacecraft for serviceability, it also vividly illustrated the usefulness of the related servicer mechanism configuration.

## II. STUDY OBJECTIVES

This study had two major objectives. The first was to continue development of orbital maintenance concepts that emerged from the first Integrated Orbital Servicing Study. Our study was to further the design definition of an automated spacecraft servicing system supported by the Space Transportation System. The objective was to be attained by an evolutionary effort characterized by analytical study, simulation, analysis, and three-dimensional modeling and mockup activities in preparation for design and fabrication of functional prototype subsystems and systems. These systems were to be evaluated for fit, function, interface, and adequacy with all other elements of the system to ensure that elements and objectives were in phase and represented the best interests of the NASA.

The second objective was to design, fabricate, test, and deliver certain equipment for 1-g demonstrations of axial and radial module exchange in three control modes. A six degree-of-freedom, servo powered, and counterbalanced servicer mechanism, capable of being operated in the three control modes, was to be provided. The manual direct control mode, where the operator controls the mechanism joints directly was to be fully incorporated in the delivered equipment. This backup mode, while not as easy to learn and use, is the simplest functionally. The preferred supervisory mode involves an alphanumeric display and keyboard for operator interfacing while a computer stores module trajectory data and actually controls the mechanism. For the manually augmented third mode, the operator uses a TV display and two hand controllers to operate the mechanism in a manner similar to the operation of a general purpose manipulator system.

### A. BACKGROUND

The first IOSS was an 18-month, $264,000 effort completed in 1975. It primarily investigated the comparison of servicing and maintaining spacecraft on orbit as opposed to flying the mission with expendable spacecraft or with spacecraft returned to earth for refurbishment. In this regard, it was not necessary to define the various systems in considerable detail. The study's objective was to provide the basis for selection of a preferred spacecraft repair method (expendable, ground refurbishable, or on-orbit maintainable) supported by the Space Transportation System. For those scenarios where on-orbit maintenance appeared practical, the study was to recommend a cost effective orbital system approach. The many previous studies for NASA and DOD were used as a basis.

Of the many approaches to providing the servicing function, module exchange was selected for evaluation of the maintenance concept because it satisfies the majority of servicing operations with a single technique. This selection is consistent with the primary findings of previous studies. Module exchange can provide the servicing functions of (1) repair failed equipment, (2) repair degraded equipment, (3) overcome design failures, (4) replace or replenish worn-out equipment, and (5) update mission equipment as well as subsystem equipment.

At the outset of the first IOSS, the 1973 NASA payload model was reviewed and 47 spacecraft programs were selected as the maintenance-applicable spacecraft set. Based on these spacecraft designs and from the alternative on-orbit maintenance concepts in the literature, the pivoting arm mechanism, which exchanges modules in an axial direction, was selected. Figures II-1 and II-2 illustrate serviceable configurations of the large x-ray telescope and the INTELSAT being serviced by an on-orbit servicer where the Orbiter and Tug are the respective carrier vehicles. The figures show two applications of the on-orbit servicer system recommended by this first IOSS that can also be applied to a teleoperator retrieval system, a geosynchronous free flyer, the solar electric propulsion system, and to some forms of the interim upper stage. The selected on-orbit servicing mechanism was also found better than either EVA or the remote manipulator system for maintenance at the Orbiter.

An extensive cost analysis showed that the savings across the 47 spacecraft programs when using on-orbit servicing were significantly greater than for ground refurbishment or the expendable spacecraft mode where at least one repair action per on-orbit spacecraft was required. In addition to the on-orbit servicer preliminary design, 1/10-

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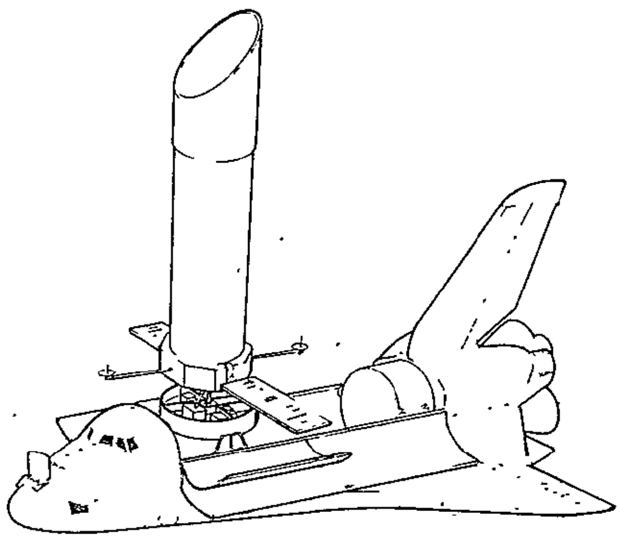

*Figure II-1*
*Servicing the Large X-ray Telescope at the Orbiter*

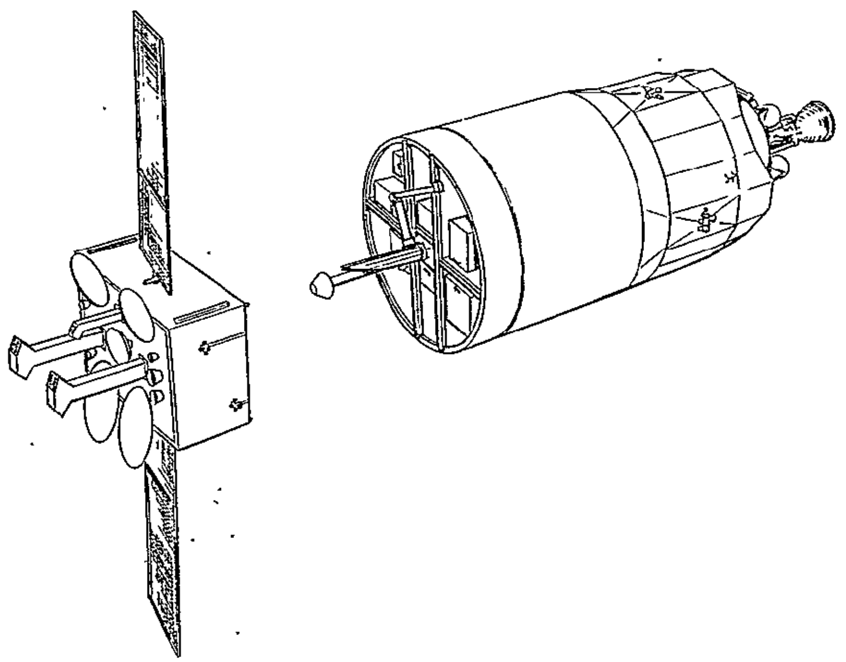

*Figure II-2*
*Servicing the INTELSAT via the Full-Capability Tug*

scale models of the servicer, stowage rack, and three spacecraft were delivered. Two versions of the significant structural interface between modules and spacecraft were designed, fabricated, and delivered. The first IOSS and several spacecraft studies clearly show that space hardware and operational economies can be obtained through maintenance or servicing of certain spacecraft on orbit. These study conclusions were obtained even though the servicer system and spacecraft trade studies were not conducted at a level that could determine the degree of dependence or autonomy that should be given to the servicer system, spacecraft, delivery vehicle, or other elements of the operational system. The wide range of spacecraft configurations and/or options that can efficiently use maintenance were not developed nor displayed. The current study showed that quite simple systems were obtained when the interdependence of spacecraft and servicer complexity is considered and each of the two systems is designed with the other's capabilities in mind.

## B. TECHNICAL ANALYSES AND SYSTEM DESIGN OBJECTIVES

This part of the follow-on effort was intended to define the functional and physical requirements of the system. Both low and high earth-orbit servicing and maintenance operations were to be addressed. The effort was to continue the first IOSS preliminary design of the system in enough detail to support fabrication of functional mockups combined with engineering trade studies leading to definition of compatible, maintainable spacecraft and servicer system configurations.

The full range of variables was to be exercised to define the system elements through engineering trades of the servicer system interacting with a typical carrier spacecraft matched to the emerging upper-stage designs and STS system capabilities. The activity was to examine a range of serviceable spacecraft to determine on-orbit servicer design requirements. It was to result in a preliminary design of the servicer system and the interface with a serviceable spacecraft, plus rationale for the design approach selected. In addition, the effort was to provide for the design, fabrication, and demonstration of hard functional mockups of the servicer system and the corresponding spacecraft interface.

Specific objectives for this part of the study were thus directed toward optimizing initial designs from the first IOSS and developing more detail in all hardware areas related to servicing. These objectives were to:

- Define on-orbit servicer functional and physical requirements to support both low and high earth-orbit servicing and maintenance operations;
- Select an on-orbit servicer and interface mechanism concept that would maximize the utility of a single design approach;
- Provide a higher level of servicer-system design detail than that of the first IOSS and describe a preferred and highly integrated design that would fulfill all established servicing requirements;
- Identify a refined and usable control system preliminary design that would increase the operational utility of the servicer mechanism;
- Develop a detailed characterization of all potentially maintainable spacecraft;
- Prepare a preliminary design of serviceable versions of three selected spacecraft;
- Conduct an analysis to develop an understanding of, and approaches to, the design of mission equipment for serviceability;
- Conduct a demonstration and simulation of a functional hard mock-up of the on-orbit servicer system and associated portions of the selected spacecraft to validate the concepts and demonstrate feasibility;
- Prepare an evaluation of the relative utility and profitability of selected high earth-orbit maintenance and servicing approaches;
- Prepare a comprehensive review of servicer system life-cycle costs as derived from analysis of system requirements;
- Provide an on-orbit servicer implementation plan involving an early ground demonstration and subsequent flight deominstration.

Significant issues addressed in this part of the study included:

- Identification of criteria for selecting the on-orbit servicer concept;

- Identification of a "best" balance between servicer system complexity and versatility;
- Selection of a representative set of mission equipment, and identification of approaches to their design for serviceability;
- Identification of significant serviceable spacecraft design issues;
- Selecting the best approach for conducting the demonstration and simulation.

C. ENGINEERING TEST UNIT AND CONTROLS OBJECTIVES

The second part of the follow-on effort was to provide a fully operational 1-g servicer demonstration system for MSFC. It was to be the best possible functional representation (configuration, mechanical design, and controllability) of the space servicer system within available resources and schedule. Specific objectives were:

- Design, fabricate, assemble, test, and deliver a full-scale 6-degree-of-freedom (DOF), counterbalanced, fully powered servicer mechanism that is a valid representation of the space design;
- Design, fabricate, assemble, check out, and deliver a self-contained electronics console that will permit operation of the servicer mechanism in the manual direct mode;
- Update the spacecraft and stowage-rack functional hard mockups to provide for axial and radial module exchange using both the side and base interface mechanisms with a minimum of setup time between axial and radial exchanges;
- Design the electronics system to be compatible with the 6-DOF servicer mechanism; the three control modes of (1) supervisory, (2) manual direct, (3) manual augmented; and with demonstration of the total system at MSFC using the SEL 840 computer and teleoperator facility base;
- Conduct a demonstration of the 1-g servicing system at Martin Marietta, Denver, using all three control modes, axial and radial module motion, and both side and base interface mechanisms;
- Provide integration support for compatibility of the delivered

equipment with the MSFC facility and provide assistance during mating of the equipment with the MSFC-developed computer programs;

- Set up, check out, and demonstrate the delivered equipment at MSFC.

Significant issues addressed in this part of the study included:

- Identification of the servicer mechanism design approach that would maximize the return to NASA;
- Identification of a control system design approach that would provide a self-contained manual direct control capability;
- Identification of an effective approach to servicer mechanism operation in 1 g;
- Identification of a spacecraft and stowage-rack design approach that would permit investigation of the full range of module location and replacement direction variables;
- Identification of an operational approach that would maximize the effectiveness of the two demonstrations.

## III. RELATIONSHIP TO OTHER NASA EFFORTS

After years of spacecraft evaluations, maintenance trade studies, and conceptual designs, the work on this contract can be be characterized as a focusing of all the earlier work toward selection of an optimum on-orbit servicing system configuration, and the preliminary design of that selection. To validate the concepts selected, mock-ups and early prototype hardware were actually fabricated and demonstrated.

The more hardware-oriented nature of this contract decreased the need for the extensive interactions with other NASA efforts that characterized the first IOSS. However, the contacts established then provided leads to those situations where interactions were beneficial during this contract.

Most related NASA studies of satellite maintenance were completed before this contract started. Some of the more significant of these studies are listed in Table III-1. Their conclusions and results are all available and were used where applicable. They proved most useful in the analyses to characterize potentially maintainable satellites and the operations analyses. In this regard, the DSCS-II study by TRW was based on existing TRW spacecraft and provided much detailed data for the serviceable spacecraft preliminary design.

*Table III-1 Significant Previous Studies*

| Title | By | Date |
|---|---|---|
| Payload Supporting Studies for Tug Assessment | MSFC | 1973 |
| In-Space Servicing of a DSP Satellite | SAMSO/TRW | March 1974 |
| Unmanned Orbital Platform | MSFC/RI | Sept 1973 |
| Payload Utilization of Tug | MSFC/MDAC | May 1974 |
| Operations Analysis | NASA/Aerospace | July 1974 |
| Servicing the DSCS-II with the STS | SAMSO/TRW | March 1975 |
| Earth Observatory Satellite System | GSFC/contractors | 1976 |
| Integrated Orbital Servicing and Payloads Study | MSFC/COMSAT | Sept 1975 |
| Multi-Mission Support Equipment | MSFC/Martin Marietta | April 1975 |
| Orbital Assembly and Maintenance | JSC/Martin Marietta | August 1975 |
| Study to Evaluate the Effect of EVA on Payload Systems | Ames/RI | Jan 1976 |
| Multi-Mission Support Equipment (Launch Site) | MSFC/Martin Marietta | June 1975 |
| Earth Orbital Teleoperator Systems Concepts and Analysis | MSFC/Martin Marietta | April 1976 |

Table III-2 lists five concurrent studies that provided helpful information to the IOSS follow-on. Servicer mechanism electromechanical drives for both the space version and the engineering test unit were adapted from the protoflight manipulator arm designs. The HEAO Block II study data were used as basic information for development of the serviceable Characteristic Large Observatory spacecraft preliminary design by TRW. The PLUS data, along with other Solar Electric Propulsion System (SEPS) data, were used in the geosynchronous spacecraft servicing operations analysis. The Fairchild Stratos fluid disconnect was integrated into the side interface mechanism and became part of the 1-g servicer system demonstrations at Martin Marietta, Denver.

*Table III-2 Concurrent Studies*

| Title | By | Date |
|---|---|---|
| Proto-Flight Manipulator Arm Assembly | MSFC/Martin Marietta | April 1977 |
| Analytical Study of Electrical Disconnect System for Use on Manned and Unmanned Missions | MSFC/Martin Marietta | Jan 1977 |
| Design, Development, Fabrication and Testing of a Fluid Disconnect for Space Operations Systems | MSFC/Fairchild Stratos | Sept 1976 |
| High-Energy Astronomy Observatory (HEAO) Block II Study, Preliminary Design | MSFC | Dec 1975 |
| PLUS, Payload Utilization of SEPS | MSFC/Boeing | July 1976 |

## IV. STUDY APPROACH

Figure IV-1 illustrates the many alternative forms of satellite maintenance. Each alternative form is directed toward increasing spacecraft availability, which is a measure of the time that a spacecraft is ready to perform its intended mission. On-orbit maintenance or servicing is one way to reduce the cost of spacecraft availability.

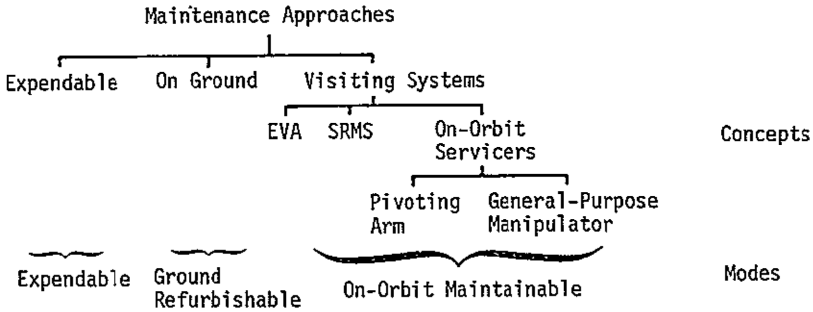


*Figure IV-1 Spacecraft Maintenance Approaches*

Previous studies evaluated these varied concepts and modes, and, in the first IOSS, concluded that on-orbit spacecraft maintenance with a special-purpose manipulator was the preferred approach. As stated in Chapter II, the objective of our study was to review the initial configuration and expand the hardware design and interface definition of that concept to the point of fabricating preprototype and mockup hardware for concept validation in an MSFC servicing demonstration facility. The study divided the effort into 11 tasks whose interrelationships are shown in Figure IV-2.

Task 1 was a trade study to determine whether there is a better alternative to the pivoting-arm on-orbit servicer mechanism or to the side- and base-mounting space-replaceable unit (SRU) interface mechanisms resulting from the first IOSS. The task also included development of rationale for selection of a spacecraft and set of mission equipment for use as the reference in other study tasks.

Task 2 was a further level of design of the on-orbit servicer concept selected in Task 1. Task 2 provided greater detail than the first IOSS and was directed to space application. Coordination between the servicer and spacecraft interface design activity of Task 3 was maintained to ensure a highly integrated design.

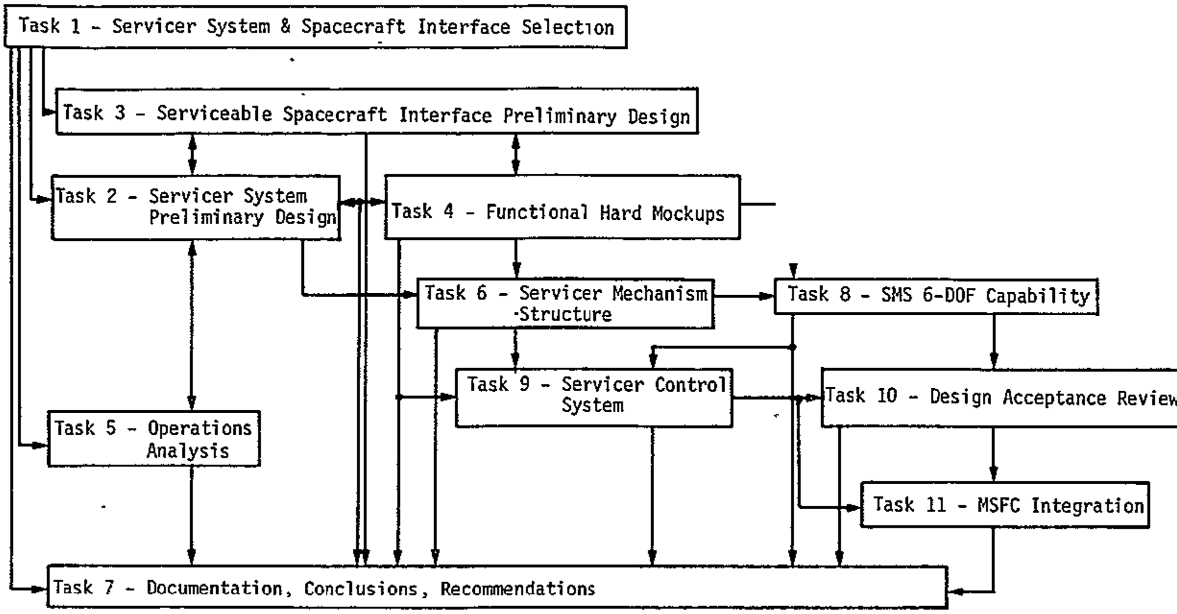


*Figure IV-2 Study Task Flow*

The purpose of Task 3 was to develop a serviceable spacecraft design for space application of a selected spacecraft, with emphasis on the interface aspects. Both spacecraft subsystems and mission equipment were addressed. Module mechanical interfaces and servicing operations aspects were considered. The Systems Group of TRW, Inc. performed Task 3 on a subcontract.

To obtain the hard functional aspects, Task 4 mockups employed existing Martin Marietta motion generators, control stations, and control logic systems combined with interface mechanisms fabricated under the first IOSS.

The first part of Task 5 further explored the benefits of on-orbit servicing in high earth orbits, while the second part addressed the major part of on-orbit servicer life-cycle costs, which occur in the operations phase.

Task 6 addressed the design, fabrication, assembly, and delivery of a full-scale, counterbalanced, powered engineering test unit of the on-orbit servicer mechanism.

Task 7 developed an on-orbit servicing implementation plan with emphasis on identification of ground and on-orbit demonstrations that would lead to early user acceptance. For simplicity, documentation and coordination activities were included in Task 7.

Task 8 upgraded the servicer-mechanism engineering test unit to 6 DOF, provided the necessary feedback elements, and increased the wrist-roll-joint torque capability. The number of interface mechanism receptacles and support structures was increased to three of each type to provide for effective demonstration of both radial and axial module removal.

Task 9 involved the design, fabrication, assembly, and checkout of the servicer control system. The control system was compatible with the 6-DOF ETU and with the three system control modes [(1) supervisory, (2) manual direct, (3) manual augmented] and with demonstration of the total system at MSFC using the SEL 840 computer and teleoperator facility base of the MSFC Electronics and Control Laboratory.

Task 10 involved a design acceptance review at Martin Marietta, Denver Division. The review was to demonstrate the ability to exchange SRU mockup modules between the functional mockups of the spacecraft and stowage rack and involved the upgraded ETU, control system, and a Martin Marietta computer and peripheral equipment. The ability to control the system in each of the Task 9 control modes was included.

Task 11 involved delivery of equipment produced in the previous tasks to the MSFC Electronics and Control Laboratory, and their setup and checkout in that facility. Integration support was provided for compatibility of the delivered equipment with the SEL 840 computer, the related MSFC-developed computer program, and the teleoperator control center.

The trade studies in Task 1 addressed the important question of system complexity as opposed to system capability. This question was difficult when applied to on-orbit servicing because the level of capability required in terms of module removal directions and mechanism reach were not known, nor could they be known. Our first iteration through this question was based on a detailed analysis of 28 serviceable spacecraft designs from the literature. Alternative servicer configurations were evaluated in three-dimensional 1/10-

scale mockups. Preliminary considerations led to a trade study of five different servicer configurations that represented five combinations of complexity and capability. Each configuration's capability was optimized for its level of complexity. NASA was thus able to select the combination of complexity and capability most suitable at that stage of on-orbit servicer development. These trade studies involved all six considerations used in the first IOSS: spacecraft design aspects, effects on the Space Transportation System, technical feasibility, operational areas, programmatics, and cost.

Task 1 analyses also led to a firm recognition of four factors that became the very basis of our approach to servicer system design. One is a realization of the very simple nature of the tasks or actions involved in module exchange: remove, flip, relocate, and insert. These four actions are all that are involved in replacing a whole set of modules in a failed spacecraft. There are no other tasks.

The second factor is that module locations, both in the spacecraft and the stowage rack, are known well before launch of a servicing mission. There is no need to search for the failed-module location. Thus, module locations can be stored in the on-board computer, and all module exchange trajectories (Fig. IV-3) can be preprogrammed as well.

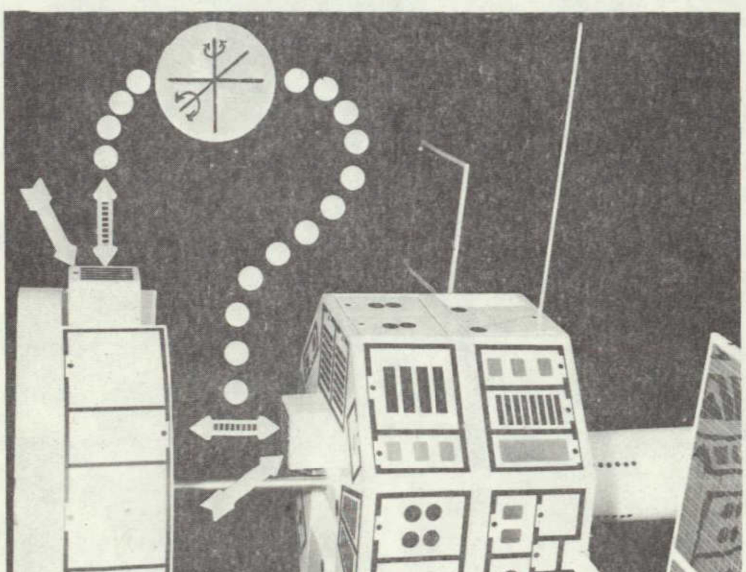

*Figure IV-3 Preprogrammable Module Trajectory*

The third factor is that the working volume for the on-orbit servicer mechanism is a solid of revolution with its axis coincident with the docking axis.

The fourth major factor is that control-system and mechanism designs should be developed together so they complement each other and system operability is enhanced. These factors became the basis of our approach to servicer system design.

The early simulation and demonstration were very valuable because they provided a graphic demonstration of how important it is to have good control systems and illustrated what must be done to develop these systems. The approach to the simulation and demonstration used an existing Martin Marietta motion generator configured to represent the on-orbit servicer mechanism, as shown in Figure IV-4. The stowage rack and spacecraft mockups that provided a sense of realism and size are also shown. An existing Martin Marietta control station was used to house the specific controls and displays. The major step of the selected approach was to use a digital computer rather than the analog computer previously used with this motion generator

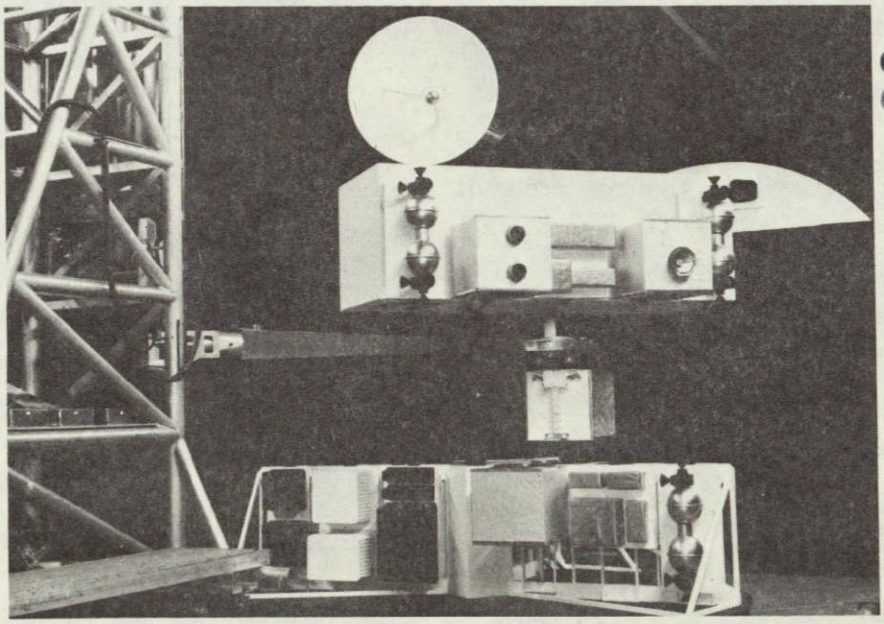



*Figure IV-4*
*Motion-Generator Mockup for Simulation and Demonstration*

The digital computer provided a direct and easy interface with the input keyboard and output displays of the supervisory mode as well as a simple way of storing the necessary display words. The digital computer also provided greater precision for the coordinate transformations needed.

The need to minimize expenditure of time and money for the 1-g servicer system was a significant constraint. Major items used in the design approach are listed in Table IV-1. We took advantage of the fact that the protoflight manipulator arm had recently been completed and detailed information was available to judge the applicability of its joint designs to the servicer mechanism requirement. In this way, design resources were converted to higher-quality gears, bearings, and other electromechanical components. While the axial/near-radial geometric configuration of the flight design was used for the 1-g servicer, it was decided to use arm lengths that would reduce the design problems yet provide an excellent demonstration tool. Selected arm lengths were accommodated by acceptance of radial module motion from the short end of the spacecraft mockup. By using these approaches in the design process, it was possible to produce a useful system and conduct very successful and impressive demonstrations.

*Table IV-1 1-g Servicer System Design Approach*

| |
|---|
| Base on flight-unit preliminary design |
| Provide self-contained electronics for manual direct control mode |
| Use digital computer to provide control-system design flexibility |
| Adapt Task 4 stowage-rack and spacecraft mockups for 1-g servicer use |
| Minimize differences between two demonstration setups |
| Accept reasonable torque or speed capability differences from flight-unit design |
| Use as many of the protoflight manipulator-arm joint designs as feasible |
| Provide capability for checkout and problem diagnosis |

# V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

Significant results obtained in the study and the conclusions drawn are given below. The conclusions of the first IOSS have been verified and extended in many areas related to the "how" of on-orbit servicing.

1) On-orbit servicing is a feasible and useful method of significantly reducing spacecraft program costs.
2) A single on-orbit servicer development can satisfy serviceable spacecraft requirements.
3) Design of a spacecraft for serviceability is straightforward, with acceptable weight and cost effects.
4) A servicer-system preliminary design has been prepared that exploits the simple nature of the module exchange task.
5) On-orbit maintenance is the most cost-effective mode for maintenance of geosynchronous spacecraft.
6) A 1-g servicer demonstration system, representing the space design at full scale, was designed, fabricated, and delivered to MSFC.
7) An on-orbit servicer implementation plan involving an early ground demonstration and subsequent flight demonstrations has been prepared.

The overall conclusion continues to be that there is no technical or long-term economic reason why on-orbit servicing should not be established as an ongoing Space Transportation System capability.

## A. SATELLITE SERVICING REQUIREMENTS

*A valid set of servicer system requirements has been developed from an analysis of 28 serviceable spacecraft designs.*

Establishment of on-orbit servicer system requirements was approached by examining the literature for spacecraft designed for on-orbit maintainability. Twenty-eight useful designs by ten organizations were identified, organized, analyzed, and evaluated. Pertinent servicing-related characteristics considered included docking conditions; solar arrays; antennas; number of tiers; basic structure; spacecraft weight and size; module weight, size, shape, and quantities; servicer arm reach; and connectors. Table V-1 summarizes major requirements resulting from the study.

*Table V-1 Spacecraft-Derived Servicer System Requirements*

| |
|---|
| - All replaceable components can be modularized. |
| - Maximum of two tiers per docking. |
| - Module size: |
|   - Minimum: 15-in. cube |
|   - Maximum: 40-in. cube |
| - Module weight: |
|   - 10 to 700 lb |
| - Servicer mechanism reach from docking port: |
|   - Minimum: 0 in. axial, 20 in. radial |
|   - Maximum: 100 in. axial, 90 in. radial |
| - Both axial and radial outward module removal are required on the same spacecraft. |
| - Off-axis radial module removal is a strong possibility. |

These requirements were complemented by additional factors identified by reviewing and updating the requirements established in the first IOSS in the areas of (1) Space Transportation System, (2) low earth and geosynchronous orbits, (3) development process implications, (5) economics, (6) technical. One of the significant implications is that the servicer mechanism working volume should be a solid of revolution. The result was a valid set of requirements that could be used for servicer system design.

Concern regarding the two-tier requirement prompted an analysis to determine the effect of putting the most reliable equipment in the second tier and not replacing it. The least reliable modules were placed in the first tier, where they could be replaced on failure. This was found to be a most effective strategy in that 95% of the potential savings for two-tier spacecraft could still be obtained. The implication is that a one-tier module exchange capability is preferred over a two-tier capability.

A useful benefit from the analysis of the 28 serviceable spacecraft designs was the set of design implications in Table V-2. These are the implications most often identified or best justified in the literature. They were reviewed with TRW during their serviceable design work, and TRW concurred in their applicability. The first implication says that the docking system developed for space operations should be a central rather than peripheral system. This is particularly important because it has been shown that on-orbit servicing is economically better than satellite retrieval.

*Table V-2 Serviceable Spacecraft Design Implications*

| |
|---|
| - Use central docking system. |
| - Minimize number of dockings per spacecraft service. |
| - Docking direction should be normal to solar-array drive axis direction. |
| - Solar arrays and other appendages need not be retractable. |
| - Consider use of replaceable solar-array and antenna drives. |
| - Use most of the Orbiter cargo bay diameter. |
| - The dominant structure type is web. |
| - Select spacecraft shape to suit other design requirements. |
| - Use between 10 and 30 modules. |
| - Electrical, waveguide, and fluid connectors are acceptable. |
| - Avoid conductive thermal connectors. |

## B. SERVICER MECHANISM CONFIGURATION SELECTION

*An integrated set of five modular servicer mechanisms was found to span all servicer requirements.*

*The axial/rear-radial servicer mechanism configuration, which has the best balance between capability and complexity, was selected for preliminary design.*

Selection of a configuration for the servicer mechanism explicitly entails selection of the best arrangement of servicer arm segments (quantity and length, joint orientation, and joint order. The configuration directly affects all aspects of the subsequent design--particularly the mechanism and control system. The challenge in this task arose from the many variables in the problem, which result in, theoretically, a seemingly infinite number of potential configurations. The problem was compounded by the fact that, while one could be confident that the probable upper bound on requirements was known, the most useful requirements could not be known at this stage of development.

The initial effort was to identify configurations that would satisfy the upper bound. A canonical forms analysis was conducted that reduced a multitude of candidates to 12. These were evaluated, some were rejected, and other more general forms were added to result in ten candidates for detailed consideration. After three levels of evaluation, including use of 1/10-scale mockups, a three-segment, 7-DOF configuration was selected as the best of the ten. Because of the complexity of this system, the requirements were reevaluated to see if a more phased development approach was feasible. The result was adoption of a modular arm configuration approach that could eventually grow toward the full capability while permitting initial development of a simpler version that meets most of the requirements of the early years of servicing.

When servicer system requirements were examined in greater detail, it was recognized that only two parameters really affect mechanism configuration. Moreover, the elements of these two parameters can only be combined in the five logical ways shown in Table V-3. Each combination can be associated with a servicer configuration that best meets the specific requirement. This led to thinking of a family of five servicers (Table V-3), which embody common design approaches and equipment and which can be developed as a set. The question then became--which of the five would be the best combination of versatility and complexity in the early years of servicer system development?

*Table V-3 Logical Spacecraft Servicing Requirements Groupings*



| Removal Direction | No. of Tiers | Designation |
|---|---|---|
| Axial | 1 | Axial |
| Axial & Radial | 1 | Axial/Near-Radial |
| Radial | 1 | Near Radial |
| Radial | 2 | Two-Tier Radial |
| Axial & Radial | 2 | Axial/Two-Tier Radial |

Each of the five modular forms was defined, evaluated, and optimized. Their growth capability was estimated, and advantages and disadvantages were listed. The selection was based on (1) public image of servicing, (2) balance of versatility versus simplicity, (3) utility aspects, (4) complexity aspects, (5) 1-g servicer aspects. The decision was to use the axial/near-radial configuration shown in Figure V-1 for preliminary design. The term "near-radial" means that the end effector attachment locations for radial motion must lie in a common plane that is normal to the docking axis. The figure also illustrates the 1/10-scale models that were found to be so cost-effective during configuration selection.

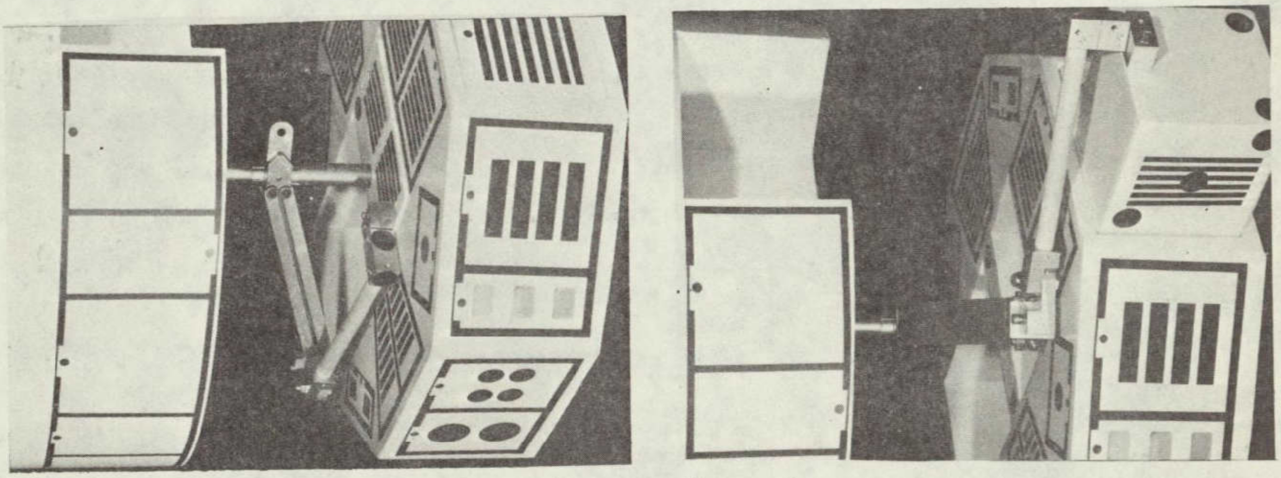

*Figure V-1 Axial/Near-Radial Servicer Configuration*

C. SERVICEABLE SPACECRAFT PRELIMINARY DESIGN

*Design of spacecraft for serviceability is straighforward, with acceptable weight and cost effects.*

*Significant attributes and design characteristics of a serviceable spacecraft that can enhance user acceptance have been identified.*

Study results show that it is possible to design serviceable spacecraft to perform a wide range of upcoming NASA, DOD, and commercial missions. The spacecraft meet mission performance requirements and are designed to enhance orbital servicing. Automated payloads examined in detail by TRW are shown in Figures V-2, V-3, and V-4. These can all be readily serviced by the selected servicer system.

One of the major characteristics of automated serviceable spacecraft will be packaging of equipment in replaceable modules. A number of other characteristics are given in Table V-2. Additional factors are:

1) Use of a data bus;
2) Basis of allocation of functions to modules;
3) Form of the interface mechanism or structural attachment between modules and spacecraft.

Each of these areas has been addressed and solutions identified that will simplify the next step by potential users. It should be noted that the total dollar investment in serviceable spacecraft in the Shuttle era will be many times the investment in servicer systems. Therefore, spacecraft economies by users have a much larger potential payoff than economies in servicer systems design.

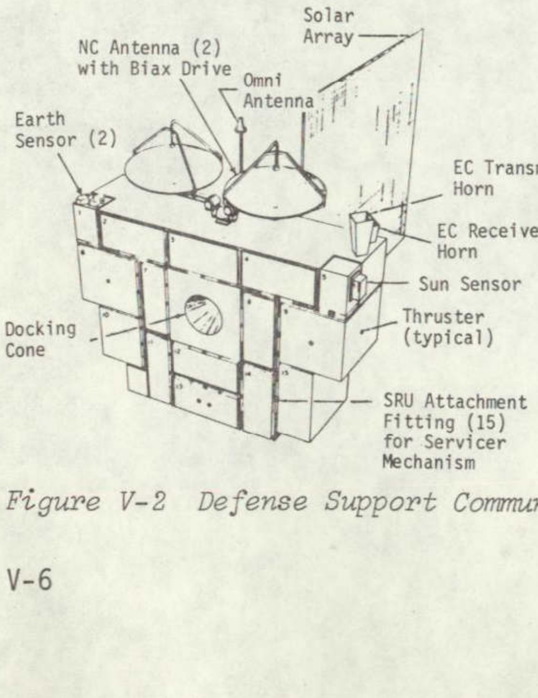


*Figure V-2 Defense Support Communications Spacecraft II*

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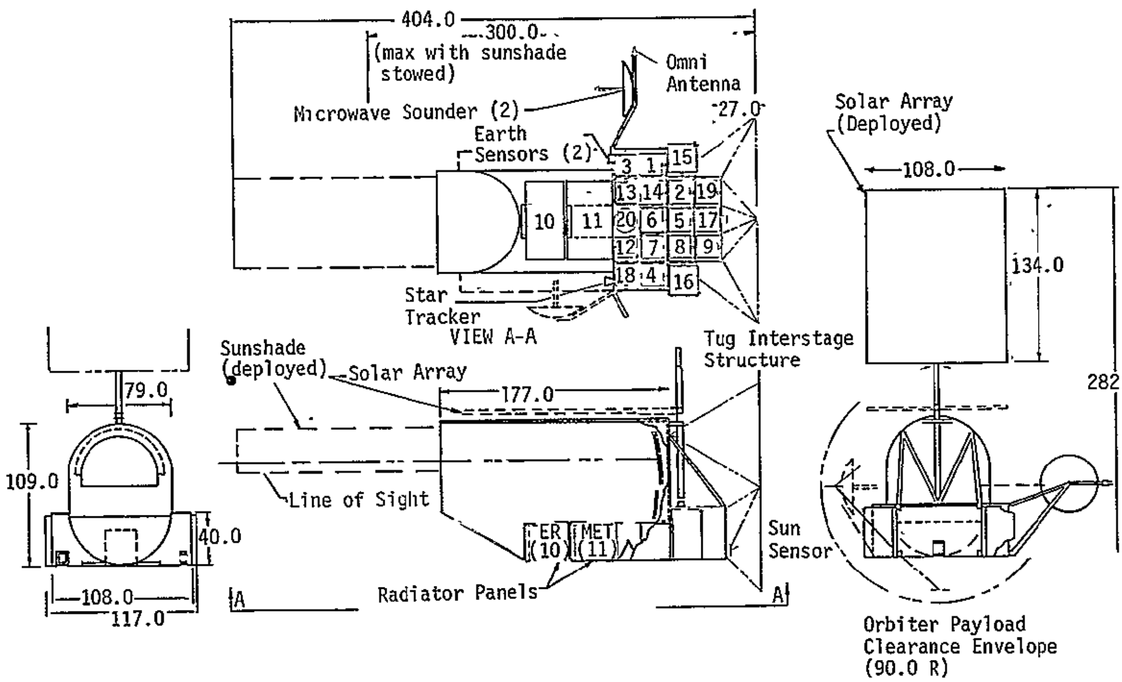


*Figure V-3 Synchronous Earth Observations Satellite*

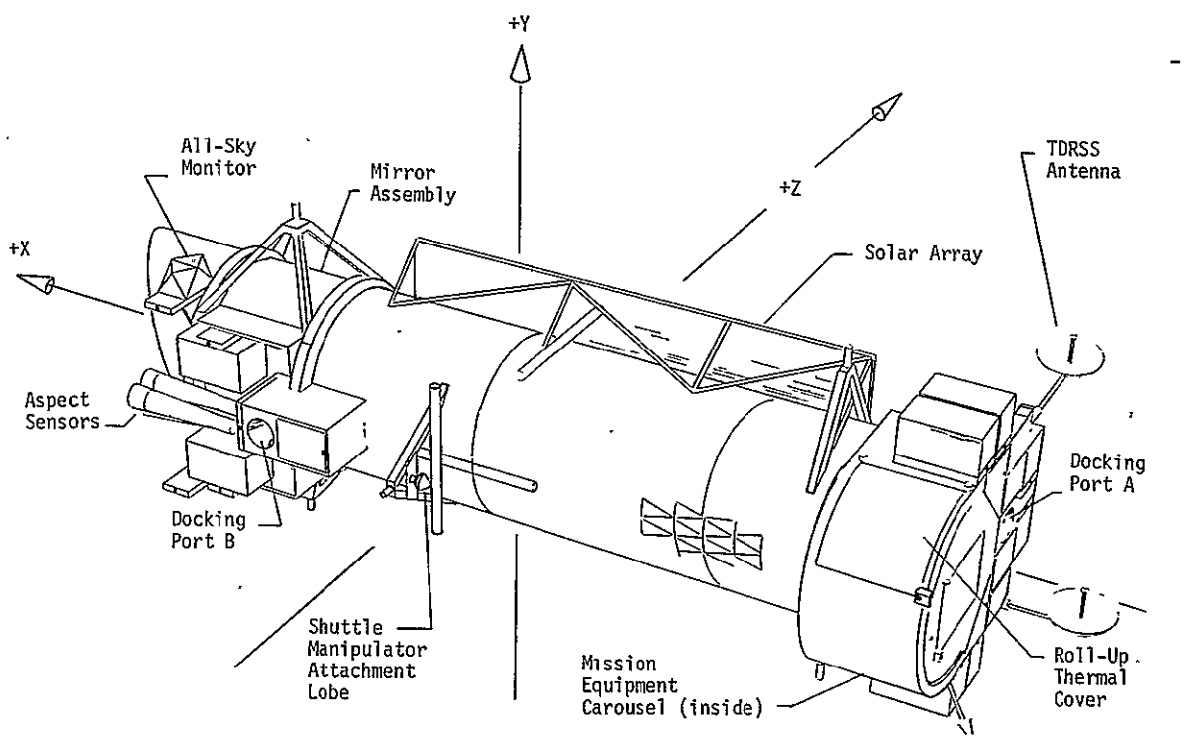


*Figure V-4 Serviceable Characteristic Large Observatory*

## D. ON-ORBIT SERVICER SYSTEM

*A servicer system preliminary design has been prepared that exploits the simple nature of the module exchange task.*

The basic conflict encountered in developing the servicer concept is with the user's desire for a highly capable, versatile servicer with minumum effect on spacecraft or support system versus the designer's desire for a simple configuration and design with low development risk. That conflict was successfully resolved with a design approach that focused on three distinct areas.

First, it was noted that module attachment locations form a surface of revolution about the spacecraft centerline as shown in Figure V-5. The base of the servicer arm is conveniently mounted on the axis of the cylinder, which also becomes the docking axis. The radially mounted modules extract ideally along the radius direction of the cylinder, while the axially mounted modules extract along the other coordinate--the axial direction--of the cylindrical elements.

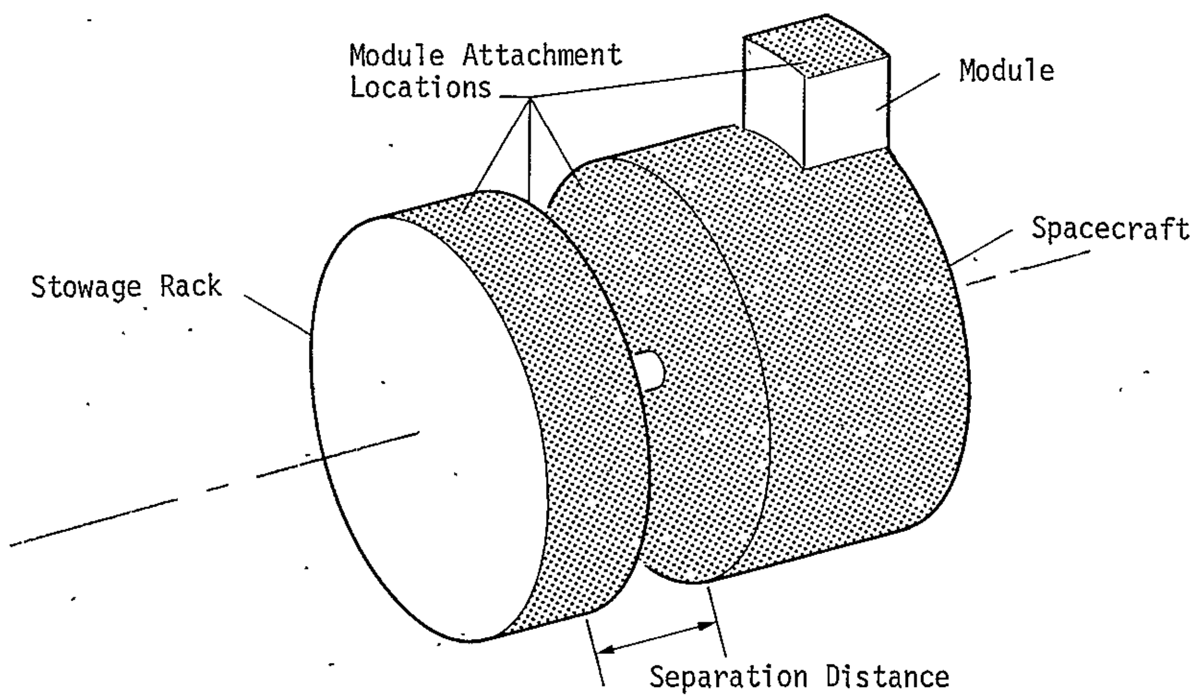


*Figure V-5 Servicing Task Geometry*

Second, the very nature of the servicing function permits complete definition of all hardware elements and locations before flight. All dimensions are known and the relationship between vehicles can be accurately established ahead of time. Consequently, complete trajectory sequences can be defined before flight and stored on board--a distinct simplification for the control system. All these factors lead to simple, accurate automated sequences--remove, flip, relocate, and insert.

The third area of benefit relates to properly allocating the servicing operational activities between the man, the control system, and the mechanism. The mechanism can be built to provide the basic motions in a good coordinate system as well as to accommodate strain-relief functions and misalignments. The control system and its software can provide the desired level of automation and procedures on a CRT from stored software, and can enhance versatility through coordination of arm motion to visual displays, where desired. The man is most effective as a judge of success or failure and in implementing backup control when necessary. These factors have been carefully considered in the design of the arm and its control system. The result is an integrated design that is simple and straightforward in implementation yet capable and versatile in the eyes of the majority of potential users.

Of the servicer system-level requirements given in Table V-4, the first is the most important and the one that was primary during design of the servicer mechanism and control system.

*Table V-4 Servicer System-Level Requirements*

| |
|---|
| - Impose minimum restrictions on spacecraft and module designers by allowing flexible and efficient packaging of modules in spacecraft. |
| - Be compatible with most automated serviceable spacecraft. |
| - Compensate for tolerances and misalignments in 6 DOF. |
| - Allow for uncertainties in module position at attachment. |
| - Operate interface mechanism latches. |
| - Interface mechanism to provide connector make and break forces. |
| - Interface mechanism components shall be mechanically passive. |

## E. SERVICER MECHANISM PRELIMINARY DESIGN

*A servicer mechanism preliminary design has been prepared that satisfies all established requirements.*

Design of the space or flight version of the on-orbit servicer mechanism evolved through a series of iterations during which a wide variety of alternatives was considered. The result (Fig. V-6) is believed to be sound; it meets all requirements, is well within today's state of the art, and it can be carried to a flight design. The concept shown can be extended to all five modular forms with a minimum of new drive development. The dual-path rotary-drive configuration incorporates all the necessary feedback and safety elements; is lightweight, stiff, has high torque, minimum backlash, and is back-driveable.

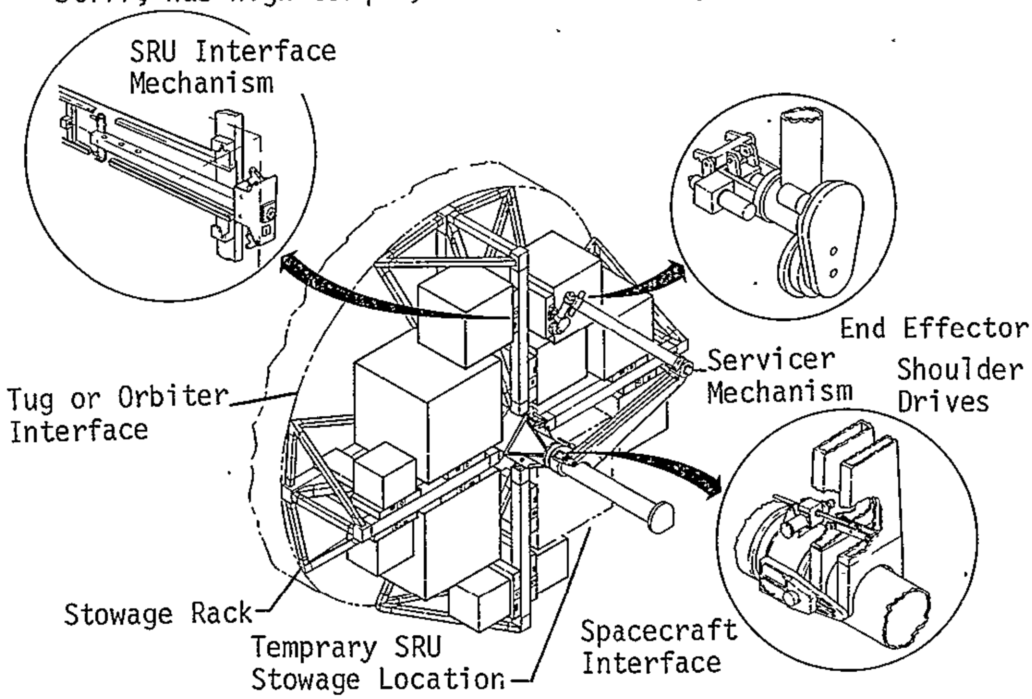


*Figure V-6 On-Orbit Servicer--Space Design*

Table V-5 shows the major characteristics of the selected axial/near-radial servicer configuration. Serviceable spacecraft designers have been provided with a great deal of freedom. There are very few restrictions on module replacement direction, spacecraft diameter, interface mechanism type or module size, weight, or shape.

A major difference between this design and the first IOSS design is use of a parallelogram-linkage form of upper arm. The approach keeps the lower or

*Table V-5 Major Characteristics of On-Orbit Servicer*

| |
|---|
| - Axial module replacement |
| - Radial module replacement |
| - Attachment locations in a common plane |
| - Tip force = 20 lb |
| - Maximum operating radius = 7.5 ft |
| - Module Mass = 10 to 700 lb |
| - Module size = 17- to 40-in. cube |
| - Time to replace one module = 10 minutes |
| - Stowed length = 71 in. |
| - Mechanism weight = 140 lb |
| - Stowage rack weight = 309 lb |
| - Degrees of freedom = 6 |
| - Operable in 1 g with bolt-on counterbalance |

forearm parallel to the stowage rack and spacecraft faces, which simplifies the hazard-avoidance problem. However, it is a stiffer and lighter mechanism.

With regard to the interface mechanism, it was determined that the spacecraft designer should be allowed to design his own interface mechanisms as long as they are compatible with the servicer mechanism and module stowage rack. However, two general-purpose interface mechanisms have been designed--side and base mounting. It was found through an analysis of the 28 serviceable spacecraft designs that three standard interface mechanism sizes can handle 90% of the anticipated modules. These are applicable to either the side- or base-mounting interface mechanisms and are:

- 17-in. cube, less than 75-lb modules;
- 26-in. cube, less than 200-lb modules;
- 40-in. cube, less than 400-lb modules.

The selected weight-efficient truss-type module storage rack can stow enough modules for servicing, two DSCS II spacecraft, two SEOS spacecraft, or one CLO spacecraft.

## F. SERVICER CONTROL SYSTEM

*A control system approach and implementation have been developed that involve three modes:*

- *Supervisory as the primary mode;*
- *Manual direct as the backup mode;*
- *Manual augmented to represent conventional teleoperator control.*

The control system is a vital element in satellite servicing. Its design is influenced directly by the servicer arm configuration, and, with good design, it can be made to exploit and enhance the mechanical design features to achieve operational simplicity, yet maintain all desired capabilities. As summarized in Table V-6, all three control modes were found to be useful, and their continued development is recommended.

*Table V-6 Summary of Control Modes*

| Mode | Implementation | Rationale |
|---|---|---|
| Supervisory (Primary) | - Automated segments<br>- TV monitor<br>- Manual "Go's"--step by step<br>- One axis driven at a time | - Man performs evaluation & status monitoring<br>- Well-defined, safe trajectory<br>- Module location known before flight |
| Manual Direct (Backup) | - Joint driven directly from panel | - Minimum hardware & software required<br>- Provided for failure case |
| Manual Augmented (Alternate) | - Manual control from hand controllers<br>- Arm motion coordinated with visual displays | - Can acquire any target of opportunity within reach<br>- Representative of "conventional" teleoperator control approaches |

The supervisory mode of control is the normal mode of operation. All servicer arm motions and trajectories are determined before flight and stored on board in cylindrical coordinates. The computer or microprocessor implementing this mode will sequence from one segment of the trajectory to the next, but only when the man has evaluated the state and provided a "go."

The manual direct mode is provided as a totally unsophisticated means of backup control. It sends commands directly to the joints themselves. Commands are given one joint at a time. Motion is with respect to each joint's mounting base rather than with respect to the display coordinate system.

The manually augmented mode (Fig. V-7) has man doing most of the arm control as in the direct mode, but using hand controllers instead of panel switches. The computer is also still in the loop to facilitate the direction of motion of the arm and provide optimization of its motion with respect to the image from a single end-effector-mounted TV camera. Its most useful role is to perform unscheduled motions to previously unidentified targets of opportunity.

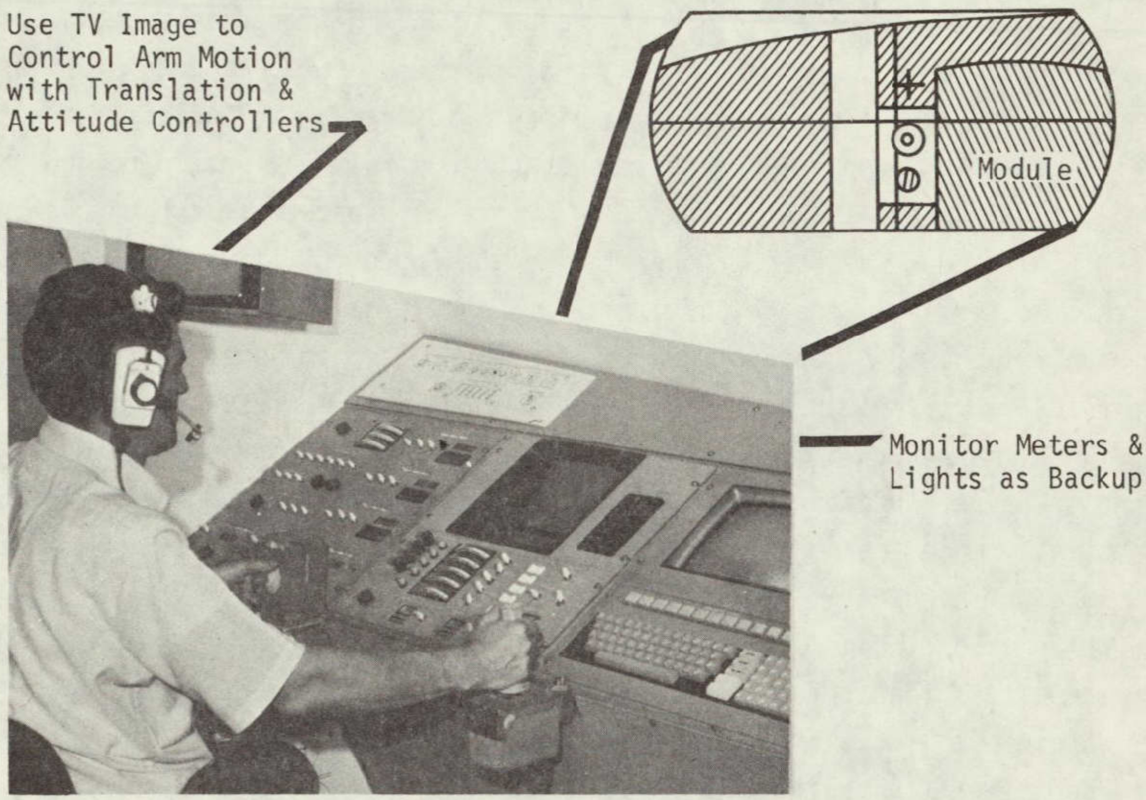


*Figure V-7 Manual Augmented Mode Operations*

The control and diplay system selected can be readily accommodated in the Orbiter's payload specialists station and has been integrated across the three control modes so that secondary backup displays are available for the major functions. Also note that the same basic trajectory sequence can be used for all three control modes and for every module exchange--only the trajectory-segment end conditions, data storage format, and display will vary.

G. SIMULATION AND DEMONSTRATION

*A simulation and demonstration using an existing Martin Marietta motion generator, computer and control station were conducted.*

Simulation and demonstration of the servicing module-exchange operation represented a preliminary to the design and fabrication of the 1-g servicer system and its subsequent use at MSFC. It was the first "hands on" controls activity and resulted in acceptance of greater emphasis on the controls aspects, bringing them into better balance with the mechanical and economic aspects. The approach to physical simulations involved use of an existing Martin Marietta physical motion generator, control logic systems, and control stations in conjunction with a partial full-scale mockup of a serviceable spacecraft and module stowage rack (Fig. V-8). The motion generator is the Space Operations Simulator (SOS), which operates in Cartesian coordinates, has a large weight capacity, and permits operations to be conducted at full scale. The simulated control station shown in Figure V-9 emphasizes the supervisory control mode.

The primary result is that the control system discussed in Section F was found to be very useful and should be continued. Each person who tried the supervisory mode learned it easily and quickly. The manual direct mode is feasible but harder to use. Additional results included:

1) Definition of control and display scaling factors;
2) Identification of TV system parameters (lens focal lengths, need for focus adjustment, location, gimbaling, etc);
3) Identification of visual aids;
4) Suitability of the payload specialists station as a control station;
5) Adequacy of joint rates and torques;
6) Adequacy of attachment capture volumes;
7) A set of recommended module transfer trajectories;
8) Verification that selected timelines are suitable.

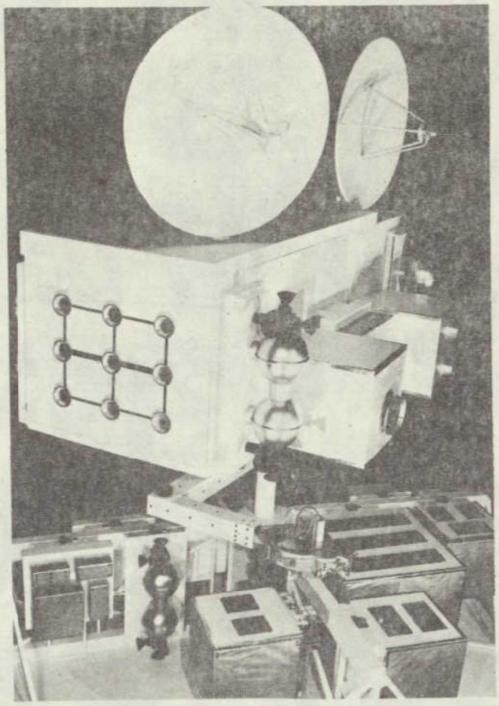

*Figure V-8 Stowage Rack and Spacecraft Mockup*

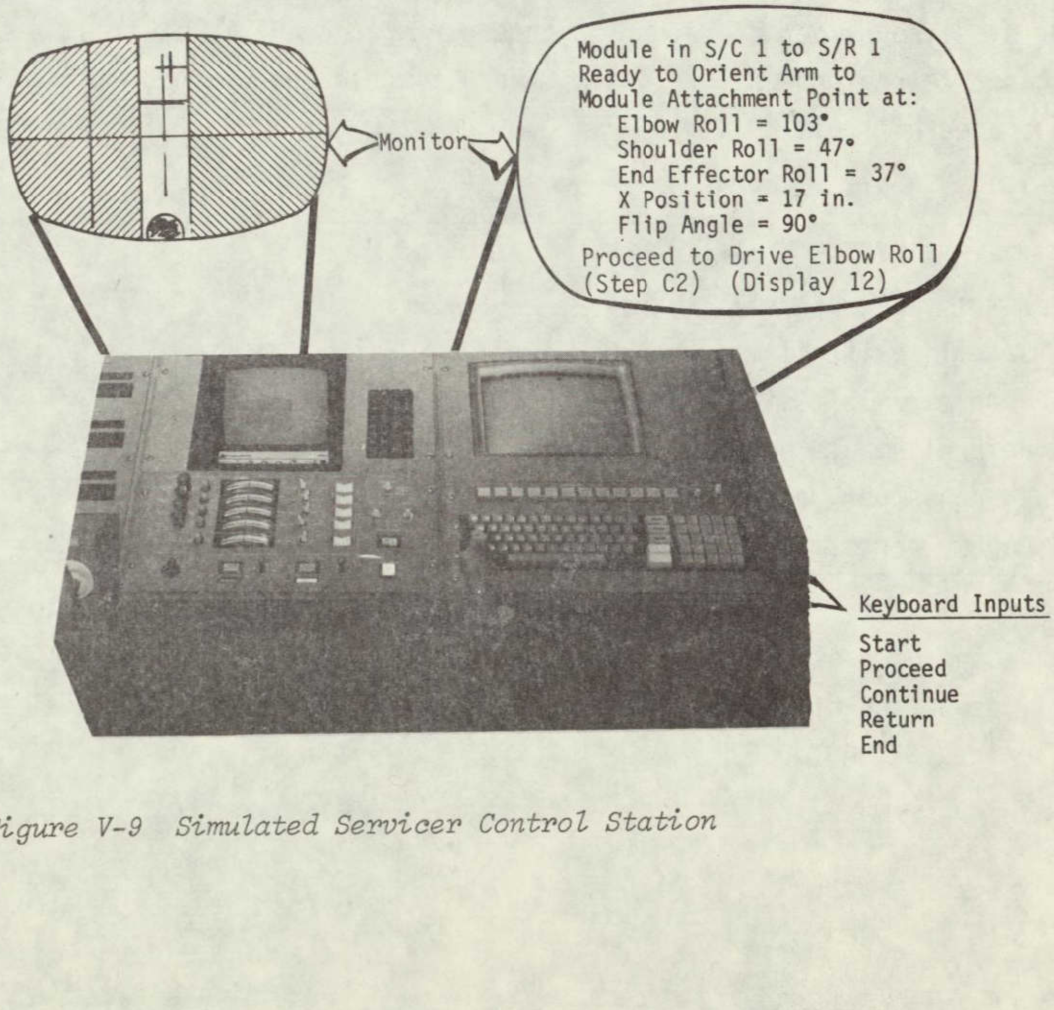


*Figure V-9 Simulated Servicer Control Station*

## H. GEOSYNCHRONOUS SERVICING ANALYSIS

*On-orbit maintenance is the most cost-effective mode for maintenance of geosynchronous spacecraft.*

The profitability of repairing geosynchronous satellites on orbit was shown in the first IOSS for one form of on-orbit servicing. Our study evaluated 12 alternative methods using parameters in Table V-7 as well as expendable satellites launched by a reusable tug or an interim upper stage.

*Table V-7 Mission Scenario Parameters*

- Reusable tug vs interim upper stage
- Demand vs rover warehouse vs fixed warehouse
- Full sparing vs partial sparing
- Chemical vs solar electric propulsion stage
- Two circuits per year vs two spacecraft per trip

The mission model used (Table V-8) is large by current NASA standards for the schedule dates used, but is reasonably appropriate for a later 15-year period. The number of refurbishments per spacecraft is at the low end of the acceptable region. A more optimum result could be obtained with some adjustment in spacecraft reliability.

*Table V-8 Geosynchronous Mission Model*

- 13 satellite programs
- Total time span = 15 years
- Satellite lifetime = 2 to 6 years
- On-orbit fleet size = 1 to 12 per program = 52 total
- Refurbishments = 1 to 4 per satellite = 75 total
- Launches per year = 2 to 13
- Repair parts factor = 0.14 to 0.38

As shown in Table V-9, the major conclusion of the analysis is that on-orbit servicing of geosynchronous satellites is less costly than use of expendable satellites. Each of the two servicing scenarios results in potential savings of more than $1,000,000,000.

The tug demand scenario leaves all spares on the ground until failures occur. A mission is flown when two satellites can be serviced. The fixed warehouse stores all spares on orbit and uses a solar electric propulsion system to service two satellites on each trip from the warehouse. The advantage of the warehouse system is that a failed spacecraft can be repaired in a week; the tug demand concept will take several months due to Orbiter scheduling rules.

*Table V-9 Economic Effects*

| Scenario | 1977 Dollars, Billions | | | | |
|---|---|---|---|---|---|
| | Launch | Spacecraft | Maintenance | Total | Savings |
| Expendable | 1.6 | 5.4 | 0 | 7.0 | N/A |
| Tug Demand | 1.3 | 3.3 | 1.1 | 5.7 | 1.3 |
| Fixed Warehouse | 1.4 | 3.3 | 1.3 | 6.0 | 1.0 |

These potential economic benefits indicate that development of geosynchronous upper stages with a rendezvous and docking capability should be accelerated. The spread in costs between the 12 servicing scenarios was ±3%, which indicates that the choice might well be made on another basis. Costs of returning items from geosynchronous orbit are such that it is more economical to expend servicers, modules, and stowage racks in orbit. The cost projections used for the upper stages favored reusable systems.

## I. SERVICER-SYSTEM OPERATIONS SUPPORT

*For a range of mission model sizes, operations costs are the largest part of servicer system life-cycle costs.*

The objective of the analysis was to reevaluate all elements of servicer system operations costs and support activities to determine whether the costs were properly stated and all support activities were identified. Two aspects were addressed in significant detail. The first is the communication links between the various elements of the on-orbit servicing operation for both low and high orbits. The second is a bottoms-up identification of servicer system operations costs compared to the similarity approach of the first IOSS. The heart of the analysis is the allocation of each specific functional and cost-generating requirement to a cost allocation element. This allocation was done in a manner (coding) that clearly identified functions that were in the basic system (e.g., Obiter launch costs) and those that are extra cost items.

To better match current NASA intentions, the first IOSS mission model was reduced to the 75% and 50% levels. The number of operating cycles was reduced where possible, but no programs were eliminated. A significant change occurred in the launch cost reimbursement policy, and the 1977 version was used. In addition to increasing the level of launch costs, premiums were added for late commitment to a launch. The effect of this launch cost reimbursement policy is to enhance NASA near-term objectives, but it puts many on-orbit maintenance requirements into the extra-cost category. However, these extra costs are not expected to overcome the advantages of on-orbit maintenance.

Because the Space Transportation System was designed to accept on-orbit servicing, no serious potential impacts were identified. Table V-10 shows the total life-cycle costs identified for the on-orbit servicer system. There has been little change in these costs due to the reassessment. There is an effect associated with mission model size that shows up in the significant operations category. These costs are for a fully qualified, integrated, operational system. Protoflight or demonstration flight systems would have significantly lower costs.

Spacecraft program costs for the Large X-ray Telescope and the Synchronous Earth Observation Satellite were developed for 75% and 50% mission model sizes (Table V-11).

*Table V-10 Servicer System Costs*

| Mission Model | 1977 Dollars, Millions | | | |
|---|---|---|---|---|
| | DDT&E | Production | Operations | Total |
| First IOSS | 33.8 | 20.0 | 66.1 | 119.9 |
| 75% | 37.3 | 21.5 | 48.7 | 107.5 |
| 50% | 37.3 | 16.0 | 33.5 | 86.8 |

*Table V-11 Spacecraft Program Costs*

| Spacecraft Program | Mission Model | Expendable Mode* | On-Orbit Maintainable Costs* | | | Savings | |
|---|---|---|---|---|---|---|---|
| | | | Basic | Servicer | Total | $* | % |
| LXRT | 75% | 582.0 | 500.1 | 0.3 | 500.4 | 81.6 | 14 |
| SEOS | 75% | 532.4 | 387.4 | 1.2 | 388.6 | 143.8 | 27 |
| | 50% | 407.5 | 355.7 | 0.7 | 356.4 | 51.1 | 13 |

* 1977 dollars, millions

As expected, the savings were smaller than for the 100% mission model of the first IOSS. The smaller mission models correspond to only one servicing per unit of on-orbit fleet size. This situation usually resulted in a 10 to 15% savings. On-orbit servicer operations cost on a per-mission basis continues to be a small part of the savings. Thus, while servicer system life-cycle costs in Table V-10 appear large, they are actually a small part (<3%) of the potential cost savings. These savings are greater when the spacecraft and servicer systems are designed with consideration of each other's requirements and capabilities.

## J. ONE-g SERVICER SYSTEM

*A 1-g servicer demonstration system representing the space design at full scale was designed, fabricated, and delivered to MSFC.*

Figure V-10 shows major elements of the spacecraft servicing demonstration facility at MSFC and as established at Martin Marietta, Denver, for the preliminary demonstration. All equipment is common for the two demonstrations except the control station and digital computer, which were individually provided by the two facilities. The servicer mechanism has six degrees of freedom, is full scale, fully powered, counterbalanced, and has a 7-ft operating radius. It is servo controlled, fully integrated into the control system, operates very smoothly, and is capable of going from axial to or from radial module removal with no special setup time. It is a high-quality, precision mechanism. Two versions of interface mechanisms are provided--side and base mounting. They can be used interchangeably in the three module locations of the spacecraft mockup (two axial and one radial) or the many module locations of the stowage rack. The single end effector works with both styles of interface mechanism.

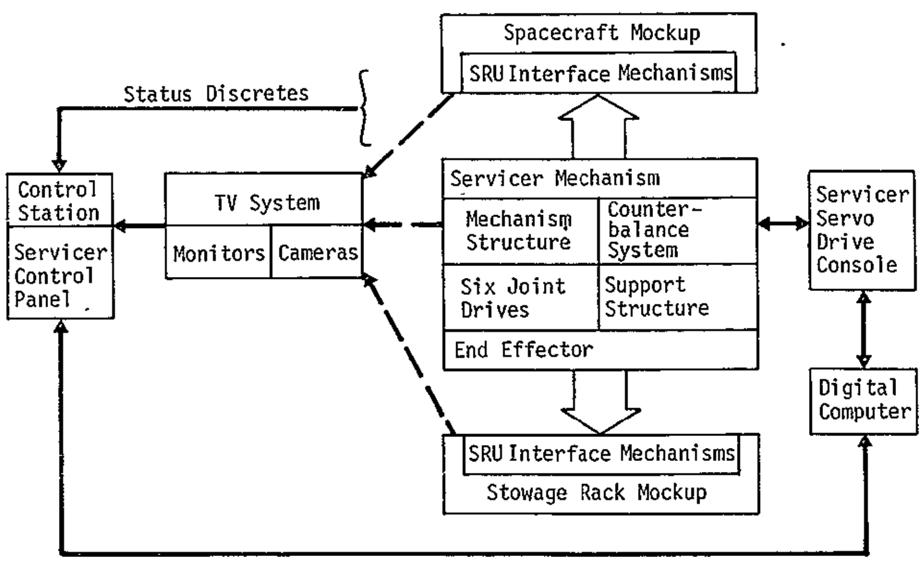


*Figure V-10 Spacecraft Servicing Demonstration Block Diagram*

The spacecraft and stowage-rack mockups (Fig. V-11) were made soft in the appearance areas to minimize cost and maintain adaptability to change. However, they were hard and fully functional with regard to interface mechanism receptacles and supports. A solid-state TV system with auto-iris lens was included to provide small size, light weight, short focal length, and good depth of field.

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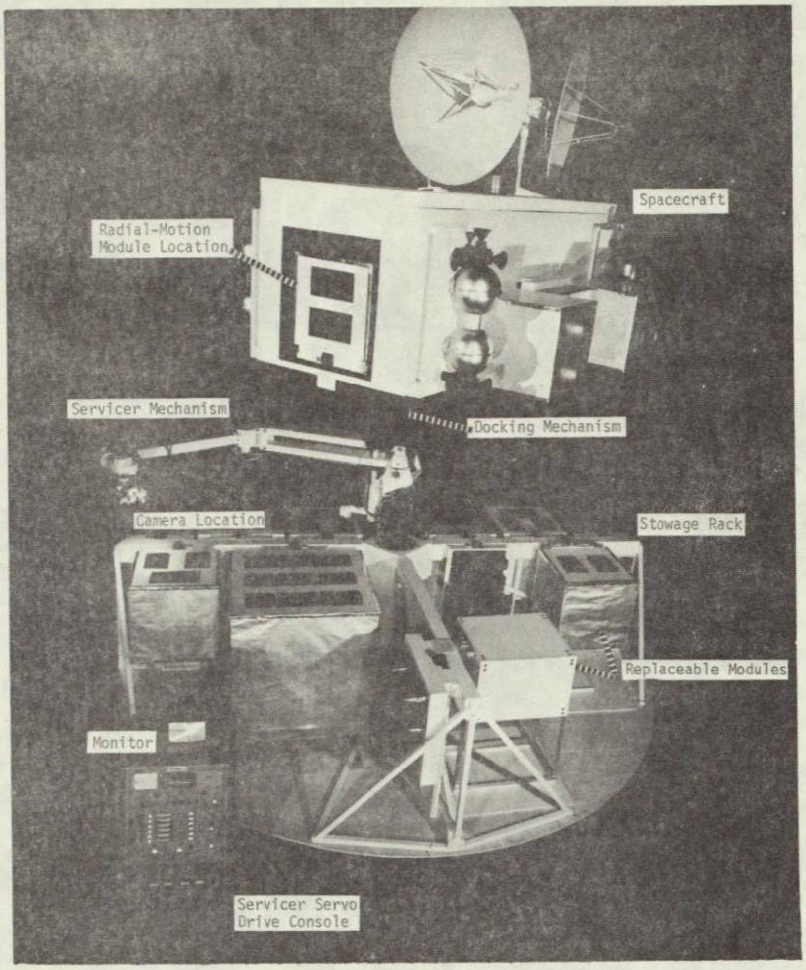


*Figure V-11 1-g Servicing Demonstration System*

This system was designed to provide MSFC with an advanced facility for the development--in a full-scale hands-on situation--of on-orbit servicing systems. The counterbalanced servicer mechanism operates with both the side-mounting and base-mounting interface mechanisms, can exchange modules axially from the stowage rack and both radially and axially from the spacecraft mockup, has a full six degrees of freedom, and is adaptable to the investigation of a wide range of electromechanical problems. A usable control system can be obtained with only the Servicer Servo Drive Console (SSDC). The SSDC permits investigating manual direct methods of module exchange and provides an effective method of servicer system checkout and problem diagnosis. When interfaced with a suitable digital computer and program, the 1-g servicing demonstration system provides a most effective tool for investigating all types of control systems, including the supervisory and manual augmented modes. The digital computer permits rapid change of control-law constants, trajectory sequences, operator displays, and coordinate-system transformations. The computer is also ideally adapted to data collection and processing, so experiment results can be understood easier and faster, and more readily communicated to others.

Table V-12 shows a number of representative specific areas of utility for the 1-g servicer. These investigative areas have been addressed on the basis of design layouts and analysis in earlier studies, yet many of them are problems in dynamics that are difficult to solve analytically. The conventional and useful approach to studying these dynamics and man-machine problems is an iteration of analysis, simulation, and demonstration. By working back and forth between analysis and experiment, the development process becomes more efficient and more real.

*Table V-12 Utility of 1-g Servicing Demonstration System*

| | |
|---|---|
| Primary element of a complete on-orbit servicing devlopment facility | |
| Provides a functional representation of the space design | |
| Discovery, refinement, and expansion | |
| Permits: | |
| <u>Mechanical Design Evaluations</u> | <u>Control System Evaluations</u> |
| Force & torque levels | Control variables |
| Structural stiffness | Capture volumes |
| Back-driveability | Structural stiffness interactions |
| Interface mechanisms | Trajectory interactions |
| Guide configurations | Hazard avoidance |
| Degrees of freedom | Visual systems |
| Motion restrictions | Remotely manned backup |
| 1-g test & checkout effect investigations | |
| Increases confidence in the space design | |
| Timely & cost-effective approach to on-orbit servicing development | |
| Provides focus for encouraging user acceptance | |

In the larger view, the servicing demonstration facility will become the focus for much of the servicing technology work. Its activities will parallel and complement servicer flight-article development. Both technology and development are essentials of the long-range implementation plan. As specific technological problems are identified in the development activity, they will be addressed in the demonstration facility. The facility will also provide a focus for encouraging user acceptance.

The Servicer Servo Drive Console is a self-contained electronics console that contains all the functions for operation of the system in a direct joint-by-joint manual control mode as shown in Figure V-12. When complemented with a suitably programmed digital computer and control station, the system can also be operated in the supervisory and manual augmented control modes.

The SSDC incorporates the dc power supplies, servo power amplifiers, signal processing electronics, 6-DOF servicer control panel, servo drive panel, and a digital voltmeter. The servicer control panel can be used locally as part of the SSDC or remotely as part of a control station.

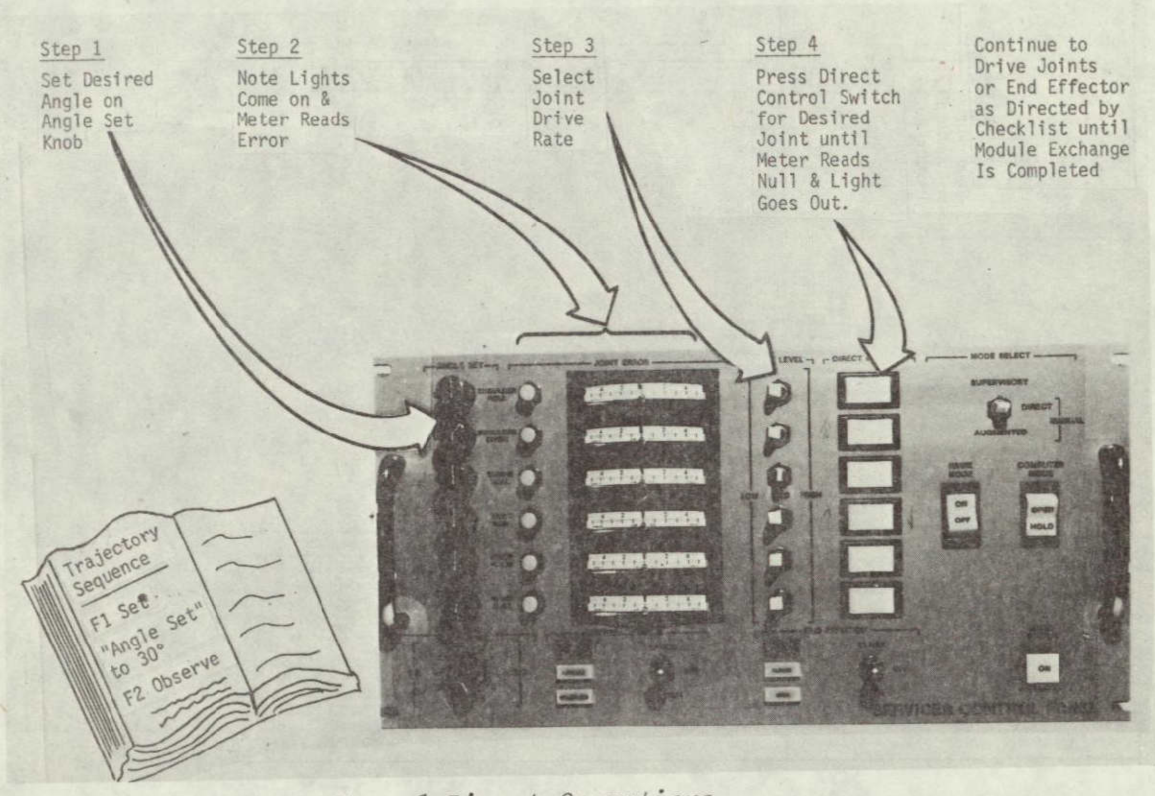


*Figure V-12 Manual Direct Operations*

Demonstrations of system operation in all three control modes for both side- and base-mounting interface mechanisms and exchanging modules in both the axial and radial directions were conducted at the Denver Division of Martin Marietta Corporation in February 1978. The equipment was later delivered to MSFC, assembled, checked out, and demonstrated. The system is scheduled for familiarization operations and will then be used to evaluate spacecraft orbital servicing system alternatives leading to a set of requirements for flight-system development by way of a protoflight servicing system.

## K. IMPLEMENTATION PLAN

*A continuing servicer system development program is necessary for user acceptance.*

Formation of the *Implementation and Test Program Plan*, MCR-76-258, April 1978, started with an appreciation of what had been done and where we are in the development process, as shown in Figure V-13. The process started with a number of studies before 1974 and has led to the MSFC servicing development facility (described in Section J) through the steps shown.

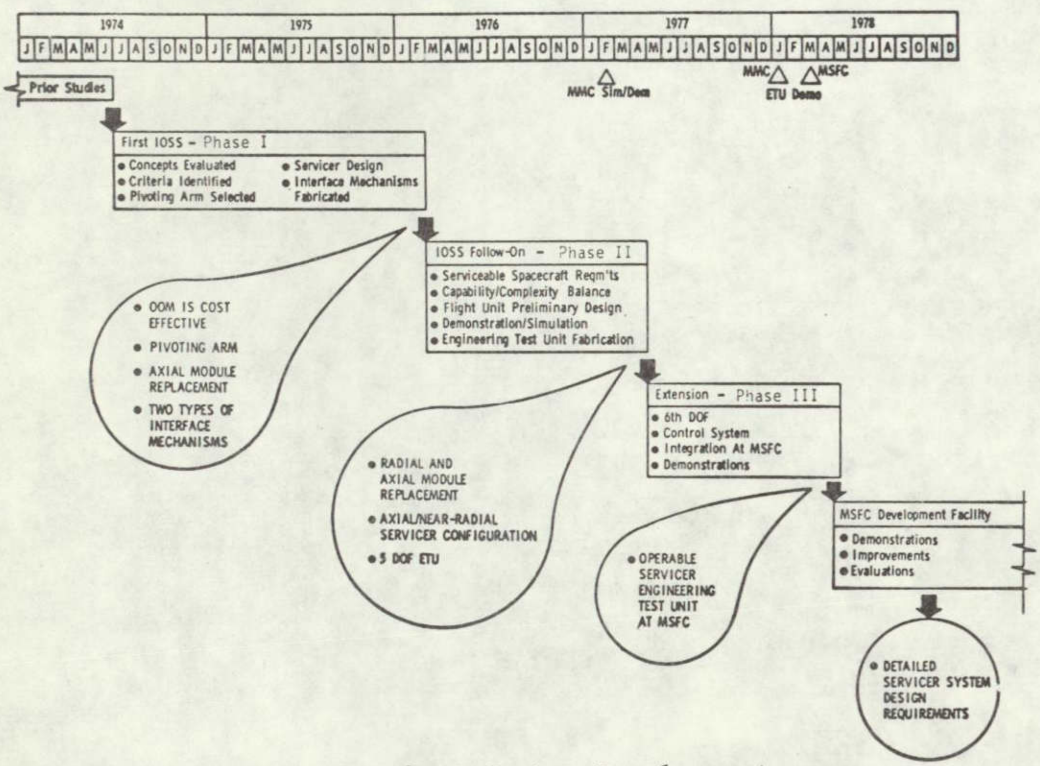


*Figure V-13 Servicer System Development*

Proposed next steps are outlined in the schedule in Figure V-14, which assumes parallel development of the spacecraft and servicer system. Only one servicer system needs to be developed for a wide variety of spacecraft programs in both high and low earth orbits. The servicer 1-g test and demonstration activity can demonstrate to the user community a simple, effective, and reliable method of performing servicing module exchange. Investigations to be performed include control variables, capture volume, structural stiffness interactions, trajectory generation, hazard avoidance, and visual systems.

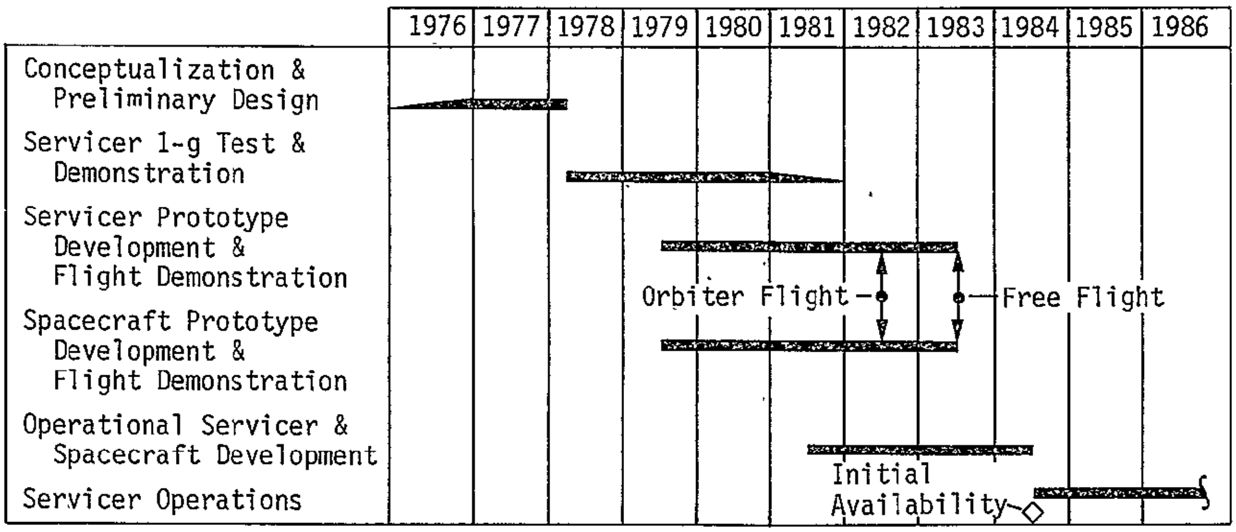


*Figure V-14 Servicer and Serviceable Spacecraft Development Schedule*

The prototype development and flight demonstration programs led to an Orbiter flight test first, then to free-flight test demonstrations. Verification of on-orbit servicing involves two separate activities: 1) the ability to handle modules, and 2) interactions with elements of the Space Transportation System. The basic module handling questions can be answered at the Orbiter. The next four levels of verification leading to geosynchronous operations primarily involve Space Transportation System effects such as interactions with remote manipulator system, upper-stage compatibility, and communication link effects.

Near-term spacecraft options for the servicing demonstration appear to fall into five groups: (1) MSFC-designated serviceable spacecraft, (2) serviceable spacecraft from the general user community, (3) partially serviceable spacecraft, (4) test-bed-type spacecraft, (5) dummy spacecraft or test panel. Each has a place in the implementation plan. A representative demonstration program consistent with the Orbiter flight-test opportunity is:

Phase A - Definition: July 1979 through January 1980;

Phase B - Preliminary Design: February 1980 through August 1980;

Phase C/D - Design and Procure: September 1980 through June 1982.

This schedule indicates that activity should be initiated soon if the STS/OFT opportunity is to be used.

# VI. STUDY LIMITATIONS

As noted in the Introduction and as can be seen from the study data and results, emphasis has been on the "how" of on-orbit servicing. Thus, the "which" and "why" were not addressed to the same level as during the first IOSS.

As with most useful systems, on-orbit servicing involves a number of aspects that must all work together. We have addressed each of these areas (servicer mechanisms, interface mechanisms, stowage rack, spacecraft, control systems, module, and simulations), but there has not been an opportunity to make everything operate together as a total system.

Control-system details were developed to a level necessary to demonstrate and simulate axial exchange of modules using the supervisory and manual direct control modes. However, the manual augmented control mode and radial module removal were not addressed until the 1-g servicer demonstration system was available.

The functional hard mockup simulation and 1-g servicer system were made to operate and were demonstrated for a number of people. However, we were unable to systematically vary parameters and collect data so that demonstration conclusions could be rigorously backed up. More extensive data are required to be able to establish allowable tolerances on system parameters.

In the latter phase of the first IOSS, questions were raised about whether the mission model considered was too ambitious for the anticipated funding levels. Those questions were answered in a sensitivity analysis by considering drastic cuts in the size of the mission model. The other side of the coin was not addressed. However, it is still valid to question to what extent on-orbit servicing techniques might be applied to:

1) DOD spacecraft;
2) Planetary spacecraft (before leaving low earth orbit);
3) Large structures in space:
4) Space manufacturing.

# VII. IMPLICATIONS FOR RESEARCH

All on-orbit servicer mechanisms considered, especially the modular set recommended, used approaches, components, techniques, and arrangements that are well within present state of the art. However, several associated aspects have been identified as candidate supporting research and technology items in the advanced development category. These are discussed in the following sections.

## A. CONTROL TECHNIQUES FOR ON-ORBIT SERVICERS

This study continues the recommendation of a combination of supervisory and remotely manned control. These techniques should be further considered to ensure that the most effective system for control of the module exchange process is employed.

## B. SPACE-REPLACEABLE UNIT INTERFACE MECHANISMS

The mechanical interface between space-replaceable units and the spacecraft and stowage rack needs a level of standardization if a single servicing concept is to be used across many spacecraft programs. Although two versions of the SRU interface mechanism have been designed and engineering test units fabricated, significant technology and development work must be performed before any interface mechanism can be established as a standard.

## C. CONNECTORS

When modules or SRUs are exchanged, connectors will be demated and mated with a single push or pull action. No such connectors suitable for this use were found--they must be developed. In addition to the usual electrical power and electronic signal connectors, waveguide connectors are needed. The Fairchild Stratos fluid connector work (NAS8-32806) should be continued.

## D. LONG-TERM SPACE ENVIRONMENTAL EFFECTS

Long-term effects of the space environment on the ability to replace modules and continued operation of the various parts of nonreplaceable units are not known. It is desirable to verify predictions that modules can be replaced and that nonreplaceable units will have an adequately long life.

## E. CENTRAL DOCKING SYSTEM

The on-orbit servicer system was designed on the assumption that a central type of docking mechanism would be developed. Maintenance and retrieval capabilities of the Space Transportation System will not be realized until a docking system is available.

## F. SENSORS AND CONTROL LAWS FOR RENDEZVOUS AND DOCKING

Rendezvous and docking are required functions if the STS is to be capable of maintenance or retrieval. The start of the Teleoperator Retrieval System in addressing these areas should be expanded to longer ranges and geosynchronous orbits.

## G. APPLICATIONS OF SUPERVISORY CONTROL MODE

The supervisory control mode being developed for on-orbit servicing might be usefully applied to repetitive tasks in space such as structural assembly as well as module exchange tasks.

## H. EXPLOITATION OF SOLID-STATE TV CAMERA CAPABILITY

The design of solid-state TV cameras is such that the location of each pixel or sensing element is precisely known with respect to every other element. This fact can be used to develop geometrical relationships in the scene being viewed, e.g., range to a target. This unique capability should be investigated to see how it might simplify operation of manipulator systems in space.

# VIII. SUGGESTED ADDITIONAL EFFORT

Justification of the probable utility of on-orbit servicing continues to be distinct. Many technical analyses have been made, and a 1-g servicing demonstration system is available. The next need is to repeat the analyses at even greater depth.

1) Management Aspects
   a) Initiate servicer system development
      - As a Space Transportation System operational capability
      - As part of a specific spacecraft program
      - As part of manufacturing in space
   b) Application to Teleoperator Retrieval System
   c) Application to Multi-Mission Spacecraft
   d) Investigation of programmatic and scheduling aspects of the STS
   e) Consideration of operational mode alternatives
   f) Identification of safety implications
2) Economic Aspects
   a) Development of better cost data, including spacecraft standardization, mission model and scheduling effects
   b) Generation of confidence limits on cost data
   c) Application to DOD programs
   d) Investigation of potential servicer benefits with other spacecraft not in the mission model considered in this study, i.e. DOD, large structures in space, and space manufacturing.
   e) Determination of the effects of continuing development of NASA launch cost reimbursement policy plans on economics and operations of servicing
   f) Investigation of availability, lifetime, and servicing strategies with a reliability simulation
   g) Development of cost data for a variety of servicer system definitions and applications

3) Engineering Aspects

   a) Analysis, design, and evaluation of on-orbit servicers
   b) Improvement of design and operability of 1-g servicer demonstration system
   c) Development of SRU interface mechanisms
   d) Development of electrical, waveguide, and fluid connectors compatible with SRU interface mechanisms
   e) Simulations of module exchange including full-scale SRU interface mechanisms
   f) Investigation of on-orbit servicer control following the approach that has been suggested
   g) Design of representative serviceable spacecraft
   h) Development of spacecraft structural configurations that are compatible with space-replaceable units
   i) Investigation of multiple-payload rendezvous techniques and energy requirements
   j) Preparation of specifications for an operational servicer system

4) User Aspects

   a) Conduct an on-orbit servicer demonstration program
      - Ground demonstration
      - On-orbit verification of module exchange
      - On-orbit verification of STS interface capabilities
   b) Prepare manual for design of serviceable spacecraft
   c) Identify and fabricate equipment for concept verification and test facility.