INTEGRATED ORBITAL SERVICING AND PAYLOADS STUDY

Final Report

Volume I

Executive Summary

Contract NAS 8-30849
Data Procurement Document No. 463
Data Document No. MA-04

Submitted to

Marshall Space Flight Center
Alabama 35812

September 1975

by

Communications Satellite Corporation
COMSAT Laboratories
Clarksburg, Maryland 20734

FOREWORD

This study was performed under Contract NAS8-30849 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 two volumes:

Volume I - Executive Summary,

Volume II - Technical and Cost Analysis.

Additional documentation in the form of working papers and drawings have been provided to Mr. Turner. Inquiries regarding this material may be addressed to the following individuals:

James R. Turner, COR/IOSS Study
NASA Marshall Space Flight Center
Attention: PD-24
Huntsville, Alabama 35812
Telephone: (205) 453-4165

Dr. Gary D. Gordon
Communications Satellite Corporation
COMSAT Laboratories
Clarksburg, Maryland 20734
Telephone: (301) 428-4517

Supporting information was prepared under a parallel study, Integrated Oribtal Servicing Study for Low-Cost Payload Programs, Contract NAS8-30820. Inquiries regarding this material may be addressed to Mr. Turner, or

Wilfred L. DeRocher, Jr., IOSS Study
Martin Marietta Corporation
Denver Division
P.O. Box 179, Mail No. 0402
Denver, Colorado 80201
Telephone: (303) 979-7000, Ext. 3085

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I. INTRODUCTION

A comparison has been made of the following modes of maintaining a satellite system:

a. expendable mode in which failed satellites are replaced,
b. on-orbit servicing where a satellite can be fixed by unmanned module exchange in space, and
c. ground refurbishment in which the satellite is brought back to ground for repairs.

It was concluded that on-orbit maintenance is the most cost-effective mode and that it is technically feasible. It can be used to repair failed satellites, to improve reliability of operating satellites, and to update equipment. On-orbit servicing can increase program flexibility and satellite reliability, lifetime, and availability. Analysis, design, fabrication of engineering test units should continue as well as the evaluation of on-orbit servicers. Servicing of spacecraft in low orbit can begin in some programs as soon as the shuttle is available. Widespread acceptance of orbital servicing in geostationary orbit will probably not occur until much later.

The significant conclusions and results reached by Martin Marietta and COMSAT in two companion studies are summarized at the beginning of Section V of this report. Each conclusion is discussed and supporting rationale presented either in Section V of this report or in Section V of the Martin Marietta report,[1] whichever is appropriate.

The opinions and conclusions in this report were generated in the course of this study. They should not be construed as official COMSAT policy. COMSAT has made no commitment about on-orbit servicing.

II. STUDY OBJECTIVES

This study was done in parallel with a study[1] performed by Martin Marietta (NAS8-30820). Close coordination was maintained between the studies, and the results of the two studies complement each other. The significant conclusions and results of both studies are presented in Section V.

NASA's fundamental objective for both studies was to provide the basis for the selection of a cost-effective, STS-supported orbital maintenance system. This maintenance concept/cost determination includes every operational, STS, and payload impact which is affected by each maintenance concept. Many studies have already been made of on-orbit servicing. The objective in these studies was not to be limited to a particular orbit, spacecraft program, or maintenance mode. Rather, the objective was to include the entire spectrum of spacecraft programs and maintenance modes.

COMSAT, as a commercial user of satellites, is in a unique position to provide an evaluation of on-orbit servicing. COMSAT's experience with communications satellites was used to make a special evaluation of the servicing of these satellites. In addition, COMSAT analyzed a servicing system from a user's viewpoint, identifying design criteria for the service unit and spacecraft that are required or desirable.

III. RELATIONSHIP TO OTHER NASA EFFORTS

A key input to the study was the spacecraft description defined by the Shuttle Systems Payload Data (SSPD) 1974 document.[2] This document provided the number of spacecraft, the weights, and the scheduled launch dates. A study of this document, from a maintenance viewpoint, indicated three separate classes. One group of spacecraft, such as those launched into planetary orbit, was not suitable for maintenance for obvious reasons. The other two groups are those that can be reached by the manned orbiter and those that require the use of an upper stage to attain their operating orbits. Several maintenance methods exist in the low-orbit group that is within reach since extravehicular activity and the shuttle remote manipulator system are available.

In the group beyond the reach of the manned shuttle, the largest potential users of an orbital maintenance system are communications satellites in geostationary orbit. They have an extra attraction in that the orbits are quite similar, and servicing of a number of satellites can be done without excessive fuel required to go from one to another. In addition to the communications satellites, there are some earth observation satellites in the same orbit that have similar requirements.

Table 1 lists the weight, desired time in orbit, and average number of satellites from the 1974 SSPD data for communications and navigation satellites. The weight reflects the user's orientation towards either Delta or Atlas-Centaur weight launching capabilities and may not represent optimum use of the STS capabilities. The average number of satellites was not usually listed directly, but was obtained from the launch schedule and the predicted lifetimes listed. For comparison, an independent estimate of the number of satellites was derived from other sources and is also listed in Table 1. Although the distribution is somewhat different, both estimates are of about 40 communications satellites operating in geostationary orbit throughout the next decade. This excludes U.S. military satellites, which adds significantly to the expected total in orbit.

Table 1. Communications/Navigation Satellites

Satellite	1974 SSPD Data			Independent Estimate
	Weight (kg)	Desired Time in Orbit (yr)	Average Number '85-'90	
International Communications Satellites	1,472	10	14	9
DOMSAT "A"	261	7	4	10
DOMSAT "B"	1,472	10+	7½	
Disaster Warning	583	5	1½	2
Traffic Management	298	5	3	7
Foreign Communications	308	7	3	12
DOMSAT "C"	868	7	4	3
Communications R&D	--	--	0	2
Weighted Average	1,050	7		
Totals			37	45

For reaching geostationary orbit, a full capability tug, 30 ft long and capable of deploying 7900 lb, was assumed. It could also retrieve 3400 lb, or make a round trip with 2070 lb of payload. The specified maximum on-orbit stay time of 6 days for the tug is a definite constraint if servicing of several satellites is desired. It was assumed that this tug would be available in 1982, which reduced the study period from 13 years (1978-1991) to 9 years (1982-1991).

IV. METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

Although there were two studies with the same objective proceeding at the same time, there was no attempt, nor desire, to duplicate effort. COMSAT's approach was to

a. provide information and assistance to Martin Marietta as desired,
b. review the work being done on both studies for completeness, and
c. perform tasks that complemented the other study.

Studies done by Martin Marietta covered the entire SSPD traffic model; COMSAT reviewed the whole picture, but used its expertise with communications satellites as a check point.

Several assumptions were made in the two studies. Only unmanned spacecraft were included, that is, spacecraft that operate without the presence of man. Also, for spacecraft beyond the reach of the orbiter, unmanned maintenance was assumed; this could be remotely controlled from the orbiter, but more likely would be controlled from the ground. Module exchange was the only type of maintenance seriously studied since this promises to be the most cost effective. Other types of servicing, such as inspection with a TV camera, moving spacecraft to a different orbit, use of a manipulator, aid in deployment of solar arrays or antennas, etc., are possible and may be done in some cases, but their use would not change the total picture.

In comparing an expendable system of satellites with on-orbit servicing or ground refurbishing, the number of launches was usually held constant; that is, a failure was assumed to occur after a period of years, and the satellite was either replaced with a new one (expendable mode), replaced with a ground spare and the old one taken to the ground (ground refurbishment), or fixed in space (on-orbit servicing). While the simplest approach was to keep the number of launches constant, one of the potential benefits of on-orbit servicing was missing. One alternative studied briefly was to perform on-orbit servicing more frequently to improve satellite reliability and decrease the cost of each servicing since more servicings are done and the servicing is less urgent. The results of this alternate study showed that while total program costs increased, the benefits justified this small increase.

It was also assumed that additional launches were for the purpose of replacement, and that the same function could be performed by on-orbit servicing. In some cases it is impossible to tell from the SSPD data whether a different spacecraft is being launched or whether a duplicate replacement is planned. As will be discussed later, the ratio of the program life (how long before the satellite is obsolete) to the satellite lifetime (how long before the satellite fails) has a critical effect on the usefulness of on-orbit maintenance.

The requirements for building a serviceable satellite were studied, but it was assumed that equal amounts of redundancy would be used compared to an expendable satellite. While this assumption is made on most servicing studies, it is not clear that an optimum has been chosen. While some redundancy will be desired on a serviceable satellite, there are some subsystems where redundancy could be eliminated. As an example, north-south stationkeeping thrusters are often redundant, yet they are used only a few times a year and could be replaced by a servicer within that time. Hence, redundancy of a north-south thruster is probably not justified for a serviceable communications satellite.

All spacecraft have been assumed to be body stabilized; many satellites are now body stabilized and more are expected. While servicing of spinning satellites is technically feasible,[3] the additional complexity and cost does not make it attractive.

An additional assumption is that the attitude control is operational when servicing occurs. This is a reasonable assumption for most satellite failures will not affect the attitude control system. Furthermore, if the attitude control system has failed, it may be possible to control the attitude through an alternate mode for a limited time. Many attitude control systems have different sensors that can be used, and a thruster system can also be used if momentum wheels have failed. The assumption that the satellite attitude is fixed and known (even though it may be in a backup stabilization mode) simplified the docking operation and should be made.

For purposes of communications satellite design, a configuration was assumed based on satellites to be launched in the next few years. Even though these satellites are not candidates for on-orbit servicing, technical details are better known. A request for proposals has recently been issued by INTELSAT for an INTELSAT V launch in late 1979. It is obvious that this is definitely not a candidate for on-orbit servicing and, in fact, will probably not be modularized, the first step toward an on-orbit serviceable design.

Early definition studies on INTELSAT VI, the next generation of commercial international communications satellites, have been started. Current planning, based on requirements predicted by international communications traffic forecasts, calls for a first launch in 1986. Based on previous time scales, the request for proposals for INTELSAT VI will be issued around 1982. Hence, this may be a candidate for on-orbit servicing, but only if a representative on-orbit demonstration is carried out before the RFP is issued, probably in 1981 or 1982. Delaying this demonstration until the mid-1980's will probably preclude even INTELSAT VI from being a candidate for on-orbit servicing.

BASELINE APPROACH TO ON-ORBIT SERVICING

As an introduction to the study, a brief review will be given of how an on-orbit servicing might be done on a spacecraft.

A satellite provides information by means of its functioning and its telemetry. A decision to do a maintenance function (either replacement or repair) is based on the satellite's expected performance in the near future and the cost of the maintenance function. Decisions may also be affected by availability of modules, spare satellites, and/or transportation.

Once the decision is made, the servicer and module are put in the shuttle/tug and taken to geostationary orbit. Orbit tracking places the tug with the servicer within less than a kilometer of the spacecraft. Acquisition of the spacecraft is then accomplished by means of radio waves or light, and a closer approach is made. Most studies assume that rendezvous and docking will be done by techniques already developed and proven.

After docking, a pivoting arm servicer removes a module from the spacecraft and replaces it with a new module from the stowage rack. The old module is stored in the stowage rack which may or may not be returned to ground. Several modules may be replaced; while the servicing may have been initiated by one module, the exchange of other modules may be desirable. During this procedure, the attitude control of the spacecraft has probably been turned off, and the tug maintains attitude control.

After module exchange, some checking may be done through the spacecraft telemetry. Additional checking would be done after the tug/servicer have undocked, but while they are still in the vicinity of the spacecraft. The tug may then go on to service another spacecraft or return to low orbit.

V. BASIC DATA GENERATED AND SIGNIFICANT RESULTS

The significant conclusions and results reached in the two integrated orbital servicing studies are presented below with the major conclusions shown in italics. Many secondary results and supporting conclusions are given in the rest of this section and in the Technical Volume. The following significant conclusions and results were generated by the principal parties in the Martin Marietta and COMSAT studies. These conclusions, where COMSAT has performed a significant part of the work, are discussed and their supporting rationale are presented in the remainder of this section.

1. Top-Level Conclusions

a. *On-orbit maintenance is the most cost-effective mode.*
b. *Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effects.*
c. The module exchange form of servicing is applicable to repairing failed satellites, improving reliability of operating satellites, and updating equipment.
d. Analysis, design, engineering test unit fabrication, and evaluation of on-orbit servicers should continue.
e. On-orbit servicing can increase program flexibility and satellite reliability, lifetime, and availability.
f. Ground refurbishment is not cost effective for most geosynchronous satellites.

2. Maintenance Concepts

a. *The on-orbit servicer maintenance concept is recommended.*

b. The on-orbit servicer, extravehicular activity, and shuttle remote manipulator system are all technically feasible.

c. Only the on-orbit servicer is applicable to both tug- and orbiter-based missions

d. Remote control of module exchange with an on-orbit servicer is technically feasible.

3. On-Orbit Servicers

a. *The pivoting arm on-orbit servicer was selected and a preliminary design was prepared.*

b. On-orbit servicer concepts exist that will permit a broad range of spacecraft design alternatives.

c. On-orbit servicing is compatible with standardized modules or spacecraft, but does not require them to be effective.

d. Side- and bottom-mounting forms of space replaceable unit interface mechanisms are useful and have been designed.

4. Economics Evaluations

a. *Use of on-orbit servicing over the twelve years covered by the 1974 SSPD and the October 1973 Payload Model results in savings greater than*
   - *nine billion dollars over the expendable mode, and*
   - *four billion dollars over the ground-refurbishable mode.*

b. The life cycle costs of the on-orbit servicer represent approximately one percent of the overall savings, and these costs can be fully recovered by 1982.

c. Cost sensitivity analyses showed that wide variations in cost data, especially mission model size and fraction of spacecraft replaced, affect specific savings but do not change the major study conclusions.
d. A long-life free-flying servicer at geostationary orbit is potentially cost effective.
e. Specific launch cost reimbursement policies can be an important factor in which form of servicing is adopted for individual spacecraft programs.
f. Expendable satellites are cost effective where satellite lifetime meets program lifetime requirements.

5. Development implications

a. *A single development of an on-orbit servicer maintenance system is compatible with many spacecraft programs and is recommended.*
b. *Orbital maintenance does not have any significant impact on the space transportation system.*
c. On-orbit maintenance with the pivoting arm servicer is compatible with a variety of delivery vehicles such as the orbiter, full capability tug, free-flying servicer, solar electric propulsion system, earth orbital teleoperator system, and some forms of the interim upper stage.

6. User Acceptance

a. *Users need guarantees that servicing will be available and assurances that it will be cost effective.*
b. A deeper understanding of the orbital servicing cost structure is required before initiating drastic changes

in conventional satellite construction and operations methods.

c. Scheduling delays of several months are tolerable for many servicing requirements.

d. Development of the on-orbit servicer should include early in-space demonstrations of module exchange along with rendezvous and docking.

e. Building, flying, and servicing a serviceable satellite is needed to obtain widespread acceptance of orbital servicing.

PRIMARY CONCLUSIONS

1a. *On-orbit maintenance is the most cost-effective mode.*

This is the most important conclusion of the two studies. Various assumptions and qualifications are given throughout the two reports. On-orbit maintenance is more cost effective for large spacecraft than for small ones and for low orbits than for high orbits.

1b. *Spacecraft can be designed to be serviceable with acceptable design, weight, volume, and cost effective.*

Studies that have focused on individual projects have designed serviceable spacecraft.[4,5] Part of this study consisted of the design of a serviceable satellite suitable for international communications. Some of the details are presented here.

The serviceable communications satellite is a modularized design based on 48 travelling wave tubes (TWTs), divided up into eight modules with six TWTs per module. Travelling wave tubes which have 6-W RF outputs with a heat dissipation of 14.8 W and a maximum allowable collector temperature of 45°C have been considered.

The radiator requirement of this module then sized the face of the module, which looks either north or south (perpendicular to the orbit plane) for a geosynchronous orbit.

A new type of travelling wave tube is a dual collector unit. This type of tube with a 5-W RF output, for example, would have 9 W of heat dissipation with a maximum allowable collector temperature of 75°C. This combination of higher efficiency and higher allowable radiator temperature would allow for a smaller module.

Other modules which have size problems are the attitude control module and the stationkeeping or hydrazine module. An attitude control module with an externally gimbaled momentum wheel is a large unit. For a mid-1980's satellite, however, the technology can easily be extrapolated to skewed reaction wheels, an internally gimbaled momentum wheel, or a much higher speed momentum wheel using magnetic suspension and a fiber-reinforced rotor. Any of these developments will result in a much smaller wheel or wheels which will allow for a smaller attitude control module.

The four stataionkeeping modules each contain about 105 lb of hydrazine to support a full 7-year mission (ΔV 1300 ft/s) of attitude control and stationkeeping. Due to very high hydrazine weight penalties (300 lb for INTELSAT IV and 400 lb for INTELSAT IV-A), associated primarily with north-south stationkeeping of communications satellites, both bipropellants and electrically augmented hydrazine systems are being seriously considered. Either of these would raise the specific impulse from 220 to 300 s which would reduce the amount of propellant required, thus resulting in smaller tank requirements.

The trend in all these areas seems to be toward smaller, lighter components. In addition, INTELSAT V will have approximately one-quarter of its transponders operating in the 11- and 14-GHz band, which should also result in small components. The mid-1980 time frame should also allow time for the nickel-hydrogen batteries to replace the nickel-cadmium batteries, resulting in energy storage capacities of 18 Whr/lb rather than the current 6 Whr/lb.

On the basis of these trends, the module size has been chosen as 16 × 24 × 36 in. to allow for latch and attach mechanisms and to permit the overall structure to fit comfortably into the shuttle cargo bay. This configuration is reflected in the model of an advanced modularized communications satellite shown in Figure 1. The module weights are given in Table 2, and the weight of the entire spacecraft is shown in Table 3. A model of this satellite was built and photographed by Martin Marietta.

The weight penalty for a modularized satellite as opposed to an expendable, non-modularized satellite such as INTELSAT IV-A or INTELSAT V is estimated to be between 20 and 30 percent. Even if the weight of many components is reduced as a result of advanced technology, the penalty expressed in percentage form should still be about the same. An exact comparison is difficult because INTELSAT V, the expendable baseline case, will have only 27 operating transponders (plus spares) a factor which has an effect on the power supply weight. The important conclusion is that the weight penalty associated with an exchangeable module-type design is estimated at 20 to 30 percent rather than a factor of 2 or 3, as concluded by some early studies.

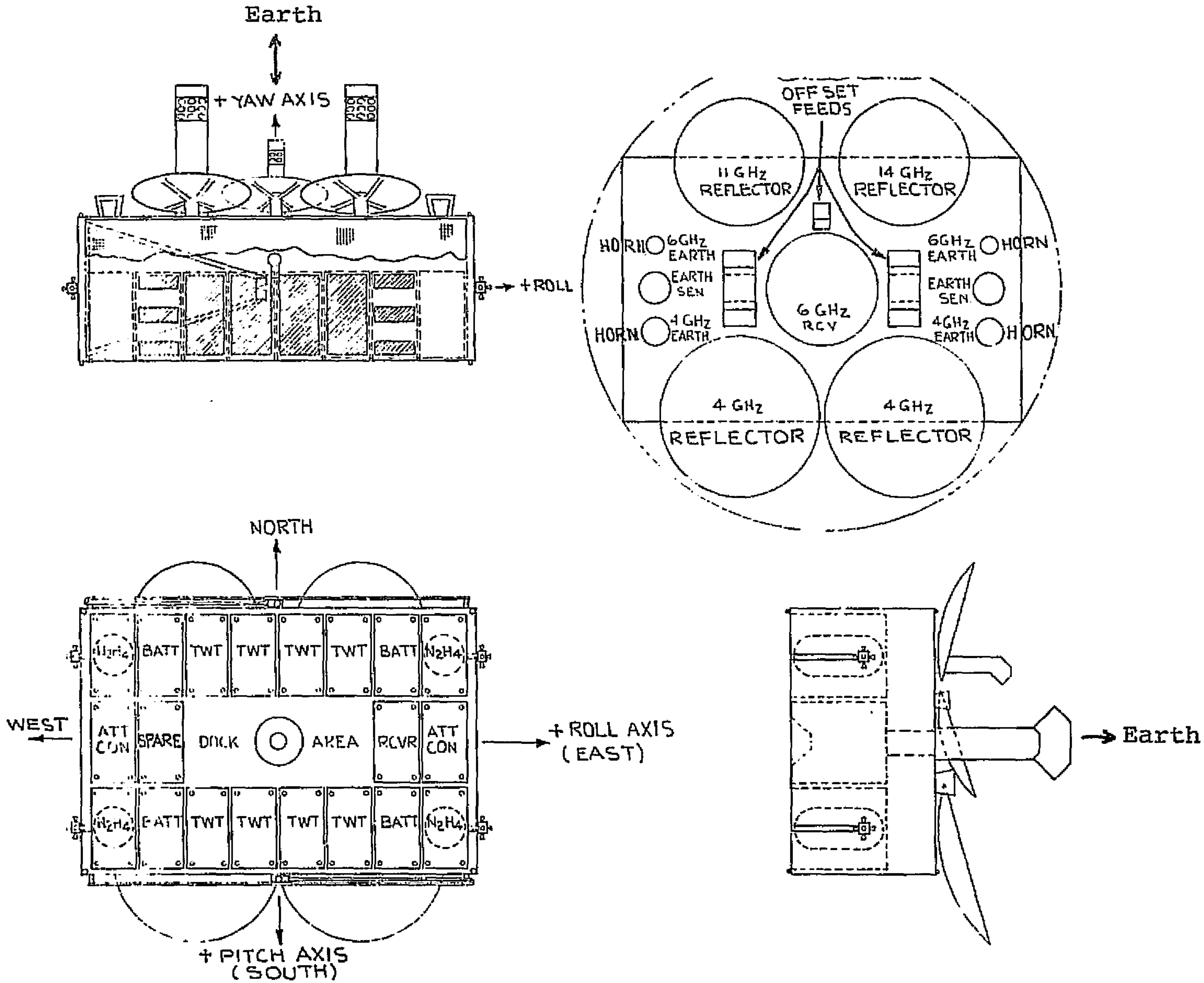

Figure 1. Modularized Communications Satellite Configuration

Table 2. Modularized Spacecraft Module Weights
Present Technology

Module	Component Weight (lb)	Structure, Harness, Connectors (lb)	Latch/ Attach Mechanisms (lb)	Total Weight (lb)	No. of Modules (lb)	System Total (lb)
TWT	60	12	14	86	8	688
Receiver	66	13	14	93	1	93
Attitude Control	60	12	14	86	2	172
Battery and T&C	75	14	14	103	2	206
Battery and Converter	60	12	14	86	2	172
Propulsion	120	21	14	155	4	620
						1951

Table 3. Modularized Spacecraft Weight

Modules	1951
Structure and Harness	325
Temperature Control	60
Solar Array	125
Antenna, Feeds	250
Total	2711 lb

Modularized Penalty:

$$\frac{2711 - 2100}{2100} = 29 \text{ percent}$$

The details of the relationship between the latch/attach machanism and heat transfer have not been worked out. To minimize temperature gradients within the module, the electronic components should be mounted on the inside surface of the module radiator plate. This should be a fairly thick plate to diffuse the heat from the components uniformly over the radiator surface. The latch/attach side of the module should also be reasonably thick to take the loads required to mate the connectors. It may be possible to integrate these two requirements into the same side of the module if the latch/attach mechanism does not overly constrain the component mounting problems or cause excessive blockage of the radiator view to clear space. A reasonable compromise could be to mount the latch/attach mechanism to one of the east/west sides of the module. In that case, the components could be mounted on both the inside of the radiator and the latch/attach side, and the thick plate of the latch/attach side could efficiently transfer the heat from the components to the radiator.

Figure 1 shows the layout for the modules. The higher power dissipation modules (the transponder or TWT modules) are located with a direct view to space through the north or south faces of the satellite. The concept envisioned is that the spacecraft structure allows the modules to "look through" the structure in a north or south direction so that the module can essentially contain its own radiator. Thus, the other five faces can probably be designed adiabatically so that the thermal design of the modules balances the internal power dissipation versus the net external heat exchange from the radiator.

The propulsion modules are located in the four corners for advantageous location of the thruster modules. Each module is envisioned to contain one center-fed hydrazine tank with a bladder retention device and a thruster module of five thrusters. The total of 20 thrusters on the spacecraft allows for full functional redundancy for all attitude control and stationkeeping modes with one of the four propulsion modules inoperative. With one module failed, east-west stationkeeping will result in some small propellant penalty by requiring the firing of a yaw axis thruster to compensate for the resulting disturbance torques about the yaw axis. Also the loss of one propulsion module will result in a satellite center of mass shift as propellant is drawn from the other three modules. The maximum value of this shift has been calculated as 4 in. along the roll axis. During north-south stationkeeping, the disturbance torque resulting from this shift can be offset by off-modulation techniques of the stationkeeping thrusters.

The battery modules are also located so that their radiator can have direct views to cold space because battery cells should be kept at low temperatures (~10°C) for long cycle life.

For efficient satellite configuration, some of the modules are located so that they have no direct views to space. In this layout these modules are the attitude control modules and a receiver module. It should be possible to design these low-power modules to transfer their heat load to the spacecraft structure for eventual radiation to space. The attitude control modules contain an attitude sensor and a processor as well as momentum storage devices. Figure 1 shows an earth sensor located in each attitude control module which must be able to look through the spacecraft bus to have a view of the earth for attitude reference and error determination. There may also be small antennas for operation with RF beacons on the earth. The important requirement is that either module must be capable of supplying the complete attitude control function for the satellite.

For this satellite, the docking face for module exchange is the anti-earth face. It should be recalled that this is a communications satellite in geosynchronous orbit. One side of the satellite always faces the earth so that the communications antennas can be attached to this face. In addition, the satellite is 3-axis stabilized so that one face always faces north and one side south. These are the faces used as the heat rejection radiators. Since the plane of the ecliptic is inclined at 23.5° to the equator, the sun can shine on the radiator surfaces only at 66.5° off the radiator normal. The solar array drive axes, which are perpendicular to these faces, are located to pass through them. Also, there is always one face facing east, one face facing west, and one face looking away from the earth. The latter face, known as the anti-earth face, has been chosen as the docking face for several reasons:

a. there is no interference with the antenna;
b. there is no interference with the solar arrays; and
c. all modules can be reached from a single docking.

Meteorological satellites, which may also be body-stabilized with an earth view face to mount the sensing instruments, may be candidates for the same type of on-orbit servicing configuration.

Problems addressed in the study which need further attention are those associated with connectors. Since the satellite is a communications satellite with eight transponder modules and one receiver module, the RF interconnections are quire complicated. There may be as many as eight RF connectors on the receiver module and four on each of the transponder modules. Since a number of different frequencies may be utilized, a number of different waveguide sizes will be required and the alignment tolerances may be quite severe, e.g., ±0.003 in. for a 14-GHz waveguide. The connectors will be required to have low dissipative losses, low leakage losses, and low voltage standing wave ratio (VSWR) losses. Problems of leakage may also be quite severe. Hence, an experimental hardware program to build such connectors and actually measure losses and leakage when using an automated latch/attach mechanism would be valuable. These types of connectors would probably use alignment pins, a short length of flexible waveguide, and RF choke couplings with crushable gaskets as shown in Figure 2. Reproducibility of results over a number of operations would be required.

The case of multiple-pin electrical connectors also requires hardware demonstration to show the compatibility of the latch/attach mechanism with the alignment accuracy and forces required.

1c. *The module exchange form of servicing is applicable to repairing failed satellites, improving reliability of operating satellites, and updating equipment.*

To evaluate servicing, it is useful to look at past subsystem failures and defects that have occurred on communications satellites (see Table 4). While this list is not complete, and the same failures will not occur in the future, the overall picture is probably applicable to future failures. The large list of INTELSAT satellites is due to the author's more extensive knowledge of these satellites and the large number of satellite years represented by these satellites. In spite of the problems listed, some of these satellites have not only fulfilled their mission, but have continued to provide service well beyond their design life. Early Bird is an example of a satellite that might be used today if it could be refueled. (It might be rented to a foreign country as a domestic satellite.)

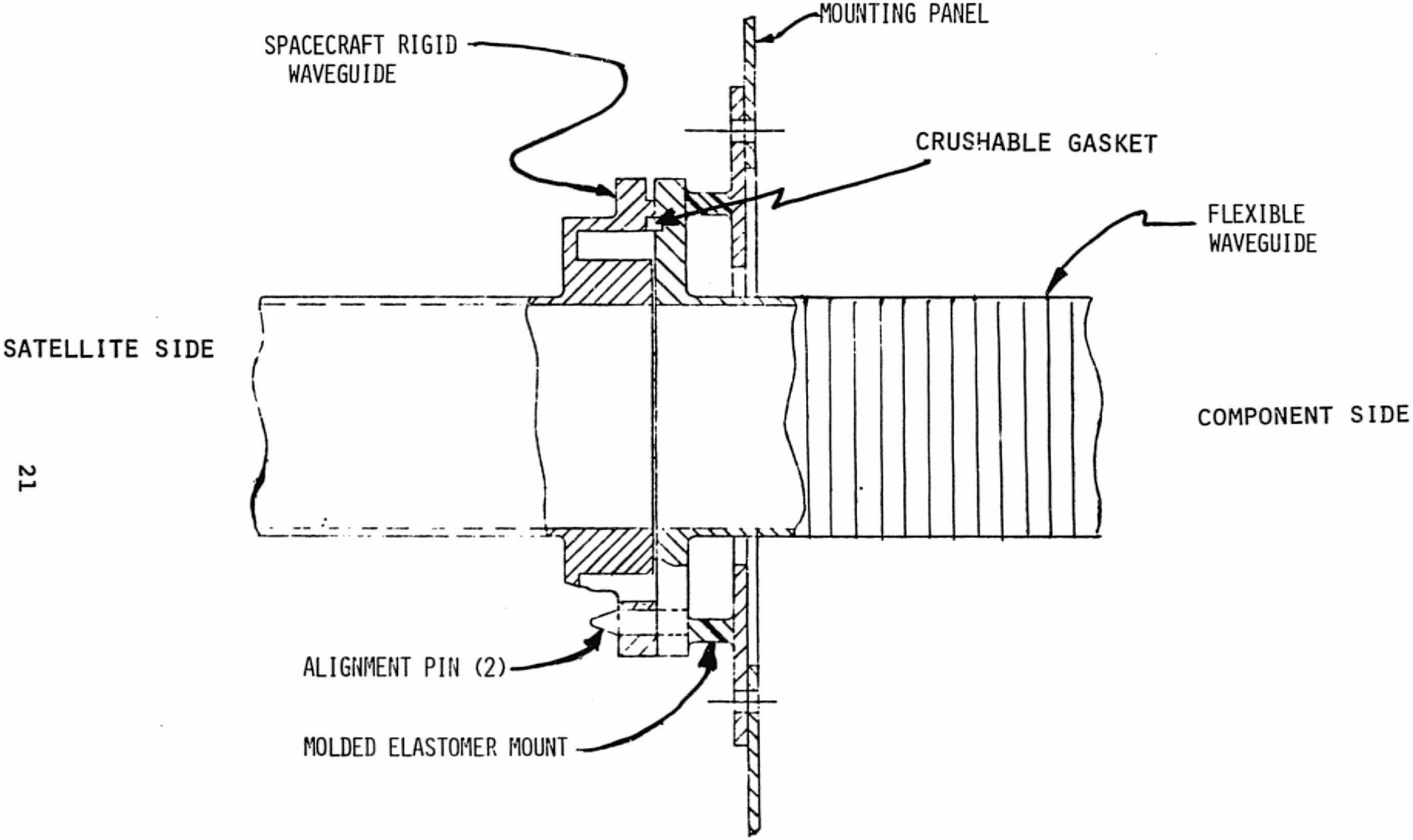

Figure 2. Waveguide Alignment Compensation Device

Table 4. Typical Subsystem Failures of Communications Satellites

Satellite	Component Failure	Type	Reparable
COURIER	Decoder	Design	Yes
TELSTAR	Decoder	Design	Yes
	Battery	Random	Yes
RELAY	Power Conditioning	Random	Yes
SYNCOM	Telemetry	Random	Yes
EARLY BIRD	Fuel Depletion	Wear-out	Yes
NIMBUS[a]	Solar Array Bearings	Design	Difficult
ATS-5	Attitude Control	Design	No
TACSAT	Structural Bearings	Design	Difficult
DSCS-2	Deployable Structures	Design	No
TELESAT	Power Conditioning	Random	Yes
INTELSAT II	Battery	Random	Yes
	Propellant Feed	Design	Probably
	Propellant Relief Valves	Design	Yes
	Solar Array Degradation	Design	Probably
INTELSAT III	Structural Bearings	Design	Difficult
	Low Orbit[b]	Random	Yes
	Battery	Random	Yes
	Receiver	Design	Yes
	Transponder	Random	Yes
	Earth Sensor	Design	Yes
INTELSAT IV	Receiver	Design	Yes
	Thruster	Design	Yes
	Earth Sensor	Random	Yes
	Telemetry Beacon	Random	Yes

[a]NIMBUS is not a communications satellite, but had a problem that may occur on future communications satellites.
[b]One INTELSAT III was injected into a low transfer orbit; hydrazine propulsion was used to achieve proper orbit.

In the column labeled "type" in Table 4, failures have been classified in terms of reliability. A "design" failure occurs early in life; its identification indicates that the reliability was not as high as planned. In some cases this may actually be a problem associated with the original design of the part; in other cases the original design may be satisfactory, but a problem may have occurred in the production (quality control).

A "random" failure may occur at any time; a single occurrence does not change the estimate of the component reliability. Usually the failure rate is assumed to be constant, and such a failure can occur at any time in the life of the satellite. A "wear-out" is a failure that occurs late in the design life of the satellite; it may be an actual wearing out or some other expected failure such as fuel depletion. In a few cases the classification of failures is arbitrary. For example, the failure rate of some components may increase with time; a failure may occur early in the life of the satellite (random), but becomes more likely as the satellite becomes older (wear-out).

The column entitled "reparable" in Table 4 is an estimate of whether a failure is serviceable; this depends on the design of the serviceable satellite and the design of the servicer. Theoretically any failure of a serviceable satellite can be repaired in space by a remote manipulator, but some repairs may not be cost effective. The economical approach to this question assumes that most of the subsystems are built as replaceable modules; that the satellite retains some capability for attitude control, orbit determination, and rendezvous; and that the servicer can exchange modules and do little else. Even with these limitations, most of the failures can be repaired in a serviceable satellite.

A striking feature of Table 4 is the large number of design dailures. This makes servicing more attractive for two reasons:

a. repairing a satellite early in its design life provides years of additional service, and
b. often such a failure suggests servicing of similar satellites in which failures have not yet occurred.

It should also be noted that only one wear-out failure is listed. At present most communications satellites have not reached the point at which wear-out failures predominate.

In the design of a servicing system, it is useful to know the effects of various failures and the urgency of the repair. For each of the subsystem failures in Table 4, the effect of the failure, the allowable repair time, and the remedial action taken (if any) are listed in Table 5.

The allowable repair time is subjective. Usually the urgency is less when the satellite is first injected into orbit because the user is not dependent on the satellite, and traffic requirements (if any) are smaller. On the other hand, when a communications satellite is in operation and a critical subsystem fails, a repair is desirable immediately, preferably within minutes or seconds. However, there are often alternative modes of operation which permit repairs to be delayed. Batteries, for example, are needed only during the eclipse season. Furthermore, battery failures are usually preceded by about a year's warning so that replacement can be scheduled in advance.

Note that half of the repairs in Table 2 can be delayed for months or years. This may be surprising to those who believe that a communications satellite should be serviced in a week or two. However, it is a direct result of the redundancy built into communications satellites, the fact that not all subsystems are used continuously, and the warning of failure (or graceful degradation) that often precedes actual failure.

Table 5. Consequences of Subsystem Failure

Satellite	Component	Effect	Repair Time Allowed	Remedial Action	
				Failed Satellite	Others
COURIER	Decoder	Lost Command	Days	---	---
TELSTAR	Decoder	Lost Command	Days	---	---
	Battery	Low Eclipse Power	Months	---	---
RELAY	Power Cond.	Lost 3 Weeks	Days	Self-repair	---
SYNCOM	Telemetry	Lost Information	Months	---	---
EARLY BIRD	Fuel Depletion	Lost Position	Years	---	---
NIMBUS	Solar Array Bearings	Lost Power	Hours	---	---
ATS-5	Attitude Control	Lost Attitude	Weeks	---	---
TACSAT	Structural Bearings	Lost Attitude	Seconds	---	---
DSCS-2	Deployable Structures	Lost Attitude	Days	---	---
TELESAT	Power Cond.	Lost Power	Days	---	---
INTELSAT II	Battery	Low Eclipse Power	Months	---	---
	Propellant Feed	Lost Position	Months	---	---
	Propellant Relief Valves	Lost Tank Pressure	Months	---	---
	Solar Array Degradation	Power Degradation	Years	---	+Cover
INTELSAT III	Structural Bearings	Lost Attitude	Seconds	Invert	+Heaters
	Low Orbit	Wrong Position	Weeks	Reposition	---
	Battery	Low Eclipse Power	Months	---	---
	Receiver	Lost Amplitude	Weeks	---	Fixed
	Transponder	Lost Channel	Days	---	---
	Earth Sensor	False PIP	Months	Another	+Test
INTELSAT IV	Receiver	Lost Amplitude	Months	---	QC
	Thruster	Lost Some Life	Years	Another	+Connect.
	Earth Sensor	Extra Noise	Months	---	---
	Telemetry Beacon	Lost Redundancy	Months	---	---

As might be expected, the remedial action taken on present "expendable" satellites is limited. Nevertheless, there are cases in which redundant components (or an alternate mode) can be commanded on, cases in which special commands have been given to minimize a problem, and at least one case in which the satellite has fixed itself. (In RELAY a crack in a transistor case allowed moisture to leak in; once in space, the moisture leaked out and the satellite repaired itself.)

More significantly, a number of subsystem failures have led to specific changes on other satellites in the same program. This is excellent proof that, if servicing were available, changes would be desirable on satellites already launched.

Because design failures are common, and because they are especially significant in terms of servicing missions, Table 6 highlights the subsystem failures or anomalies in INTELSAT satellites. This table includes several anomalies not considered serious enough for inclusion in preceding tables. The first column notes the number of satellites in which design failures have been observed. The next column notes the number of satellites in which a replacement module is needed. To estimate this figure, the severity of the problem is compared with the estimated cost of a servicing mission. In a number of cases the severity is not sufficient to justify a mission; yet if the satellite were to be serviced for another reason, that module would be replaced.

On the basis of these statistics, it can be predicted that, on the average, each new program can expect two design failures, of which one is sufficiently serious to warrant a module replacement. The time at which a failure has appeared in programs to date has varied from a few hours to 4 years. On the average a design failure appears about one year after injection

Table 6. Design Failures or Anomalies in Communications Satellite Subsystems

Satellite	Component	Number of Failures Observed	Number Needing Replacement	Total Satellites Injected	Total Satellites Launched
II	Propellant Feed	3	3	3	4
	Relief Valves	3	3		
	Solar Array	1	0		
III	Structural Bearings	5	5	5	8
	Receiver	1	1		
	Earth Sensor	5	0		
IV	Receiver	4	4	7	8
	Thruster	1	1		
	Structural Bearings	2	0		
	Earth Sensor	1	0		
TOTAL		26	17	15	20

of the first satellite in the program. An additional year or two is required to identify the cause and to procure replacement modules without the defect.

In summary, if servicing is available, most communications satellites will use it. In the first three years of a system of satellites, it can be expected that every satellite will require module replacement due to design failures. During the life of a satellite, the probability that servicing will be required to correct a random failure is somewhere between 0.5 and 1.0. If the satellite lifetime is extended beyond present design lifetimes, additional satellite servicing will be required to fix wear-out failures and additional random failures.

1d. *On-orbit servicing can increase program flexibility and satellite reliability, lifetime, and availability.*

In many studies of servicing it has been assumed that the satellite is untouched until it fails; at that point it is either repaired (servicing system) or replaced (expendable mode). If the delay in replacing the satellite is equal to the delay in repairing it, the availability is unaffected. However, availability is important to commerical communications satellite systems. Hence, a simulation study has been conducted to investigate the effect of different modes of servicing on availability.

One method of decreasing the cost of servicing is to service more than one satellite in a trip. This requires one satellite to be serviced at a time that may be determined by failures on other satellites, since failures will not generally occur simultaneously. The satellite with a failed module must wait several months for module replacement.

For this simulation study, the weights taken to geostationary orbit, including weights of original satellites, replacement satellites, replacement modules, and servicer, have been calculated. It is assumed that, if costs had been calculated, they would increase with weight.

The communications model used is similar to the one described in the previous section. For the reliability model, ten subsystems were selected, with the redundancy and failure rates shown in Table 7. The degree of redundancy and failure rates shown are typical of those in present expendable satellites. When a failure occurs, the module is replaced; in a few cases, the module weight is much larger than the weight of the actual component. The module weights are lighter than those shown in the previous section, but the differences do not affect the conclusions.

Table 7. Subsystems in Reliability Model

Subsystem	Required	Provided	Failure Rate (10^{-9}/hr)	Module Weight (lb)
Transponders	35	48	3000	60
Receivers	1	4	6000	66
Attitude Control	1	2	1500	60
Onboard Processor	1	2	700	60
Momentum Wheel	1	2	700	60
Batteries	4	4	500	75
Telemetry, Tracking and Command (TT&C)	1	2	4000	75
Power Conditioning	2	2	100	60
Tanks	4	4	400	120
Thrusters	1	2	1000	120

The reliability of the satellite has been calculated for the random failure rates listed in the preceding table and for various times up to 10 years. For the distribution truncated at 10 years, the calculated average lifetime is 7.9 years. This reliability is compatible with some specifications that require a reliability of 0.7 at the end of 7 years. It remains a moot point as to whether satellites can consistently achieve this reliability.

Three cases have been considered: expendable, servicing done upon satellite failure ("demand"), and servicing done when a redundant component failed. The latter has been labeled "scheduled" servicing in this study, and it is assumed that the opportunity for service comes at regular intervals. For the expendable mode, down times of 4 months, 2 months, or 1 month have been assumed. This is the total time from a satellite failure until a new satellite starts operation.

In the demand servicing mode, no action is taken until the satellite has stopped operating. Upon servicing, it is assumed that all redundant components that have failed will be replaced, and that the satellite is equivalent to a new satellite.

In the scheduled servicing mode, servicing occurs only at regular intervals. At that time, if any redundant component has failed, the satellite is serviced and the failed components replaced. In actual operation, scheduling intervals would vary, and the numbers used in this study, 24, 12, or 6 months, would represent the averages of the actual scheduling intervals.

Computer generated random numbers were used to make 200 simulated runs. For more accurate comparisons, correlations between the various runs were made. For example, the baseline case was a 10-year program; the calculation for a 20-year program was made by using the results for the 10-year program and extending them another 10 years.

The baseline system chosen consisted of two operating satellites and one in-orbit spare, corresponding to the present configuration for international communications over the Atlantic Ocean. The weight penalty associated with building a serviceable satellite (estimated as 20-30 percent) was not included. The weight of the satellite was assumed to be 2100 pounds and that of the servicer for demand servicing was assumed to be 500 pounds. For scheduled servicing, the weight of the servicer, which would be shared among the satellites being serviced, was neglected.

The calculated availabilities and weights have been plotted in Figure 3 for each of the nine basic cases. As might be expected, the expendable mode shows the highest weight. The differences would be smaller if the servicer weight for scheduled servicing and penalty for modularization were included, but the order of increasing weights would still be the same.

The availability for the expendable mode or demand servicing is about 0.999 for a 4-month delay. It is important to note that this availability can be achieved with scheduled servicing at 12-month intervals. In actual practice, including an occasional "demand" servicing and using the failure warnings provided by some components would make it possible to achieve even higher availabilities with scheduled servicing.

If the program is extended from 10 years to 20 years, the weights launched in the expendable mode are almost doubled. But the additional weights of modules and servicer are small, so the total weights launched in the servicing mode do not increase substantially. Thus increasing program life makes servicing more attractive. The availability of the scheduled servicing mode hardly changes, since satellites are being maintained by replacing failed redundant components. Availabilities for the other two modes decrease slightly, since more failures occur in the second decade.

One conclusion from this analysis is that servicing may be delayed for periods of a year or so without excessive availability penalties. This will depend on the degree of redundancy that is built into the satellite; without redundancy, it is not possible to service a satellite before failure. With servicing, some redundancy will still be required in the satellite.

Servicing becomes more attractive if the ratio of program life to satellite life is increased. If satellites can be built

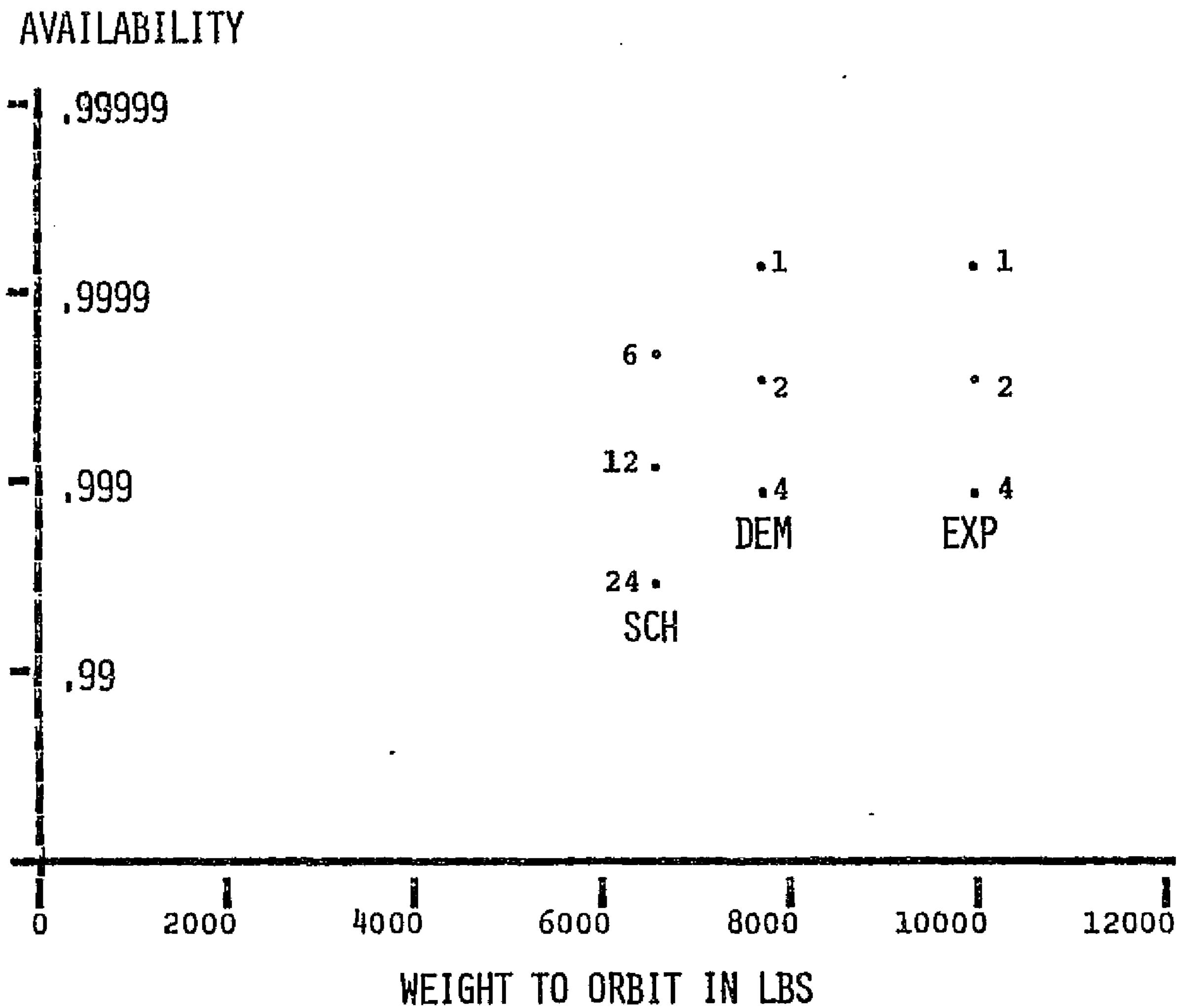

Figure 3. Scheduled Servicing (SCH), Demand Servicing (DEM), and Expendable (EXP), 10-Year Program--Two Operating and One Spare (Number by each point is month's delay before service restored.)

with an average life of 7 years, and if they become obsolete after 10 years, servicing is not particularly useful. On the other hand, if a satellite has only a 5-year life, and does not become obsolete for 15 years, then servicing becomes more attractive.

1f. *Ground refurbishment is not cost effective for most geosynchronous satellites.*

It is sometimes difficult to fully realize the distance from the earth to the geosynchronous orbit. A greater velocity change (ΔV) is required to place something in geosynchronous orbit than to completely escape from the earth's gravitational field. For ground refurbishment the fuel needed to bring a spacecraft back must first be taken to geostationary orbit. In terms of weight, the shuttle can place 62,000 lb in low earth orbit, but the maximum weight for a ground refurbishment mission (to take up a replacement and bring back the old satellite) is only 2000 lb.

A spacecraft may be returned to earth to clean up the orbits, to diagnose past difficulties, or to refurbish the spacecraft. Cleaning up the orbits is commendable, but not part of this study. While bringing back spacecraft for diagnosis appears attractive, in most communications satellite failures it has been possible to determine the failure mechanism from the telemetry signals. In this study the primary reason for bringing back a spacecraft is to fix it and return it to space, and the transportation costs for bringing back a communications satellite are more than twice the cost of taking it up!

There are two suggested methods of refurbishing a spacecraft on the ground. The usual approach is to assume that the spacecraft will be completely overhauled, each box opened and inspected, the spacecraft reassembled, and a complete environmental test run. The transportation costs of bringing the spacecraft back and the costs of refurbishing it amount to a substantial fraction of the initial cost of the spacecraft.

An alternative suggestion for refurbishing is to use a "bare bones" approach. When the spacecraft is returned, a module is pulled off and a replacement is put on. The spacecraft is ready to go after a few checks to ensure that the spacecraft is indeed working. This appears to be contrary to the present philosophy of launching spacecraft. On the other hand, there may be some question as to whether the reliability of a box is increased or decreased by opening it up and inspecting it.

Ground refurbishment is the one maintenance mode that requires a full capability tug (or at least a tug that returns to low orbit). This study has used the cost and schedule presently quoted for the full capability tug.

ECONOMICS EVALUATIONS

4d. *A long-life free-flying servicer at geostationary orbit is potentially cost effective.*

While initial on-orbit servicings at geostationary orbit will probably be done with the tug (full capability or interim), the maximum benefit can be achieved with a free flying servicer. The argument for a free flying servicer is as follows: A drastic change in satellite design and construction is required to build a serviceable satellite. Once such a change has been made, this capability, which implies many servicings (perhaps two per satellite during its lifetime) should be fully exploited. The full capability tug can stay in geostationary orbit for only six days. A day or more may be required to move from one satellite to another so that the full capability tug can service an average of only three satellites.

The servicing configuration discussed here is shown in Figure 4. It consists of a free flying servicer that will be taken to geostationary orbit by the shuttle/tug. It will then move from

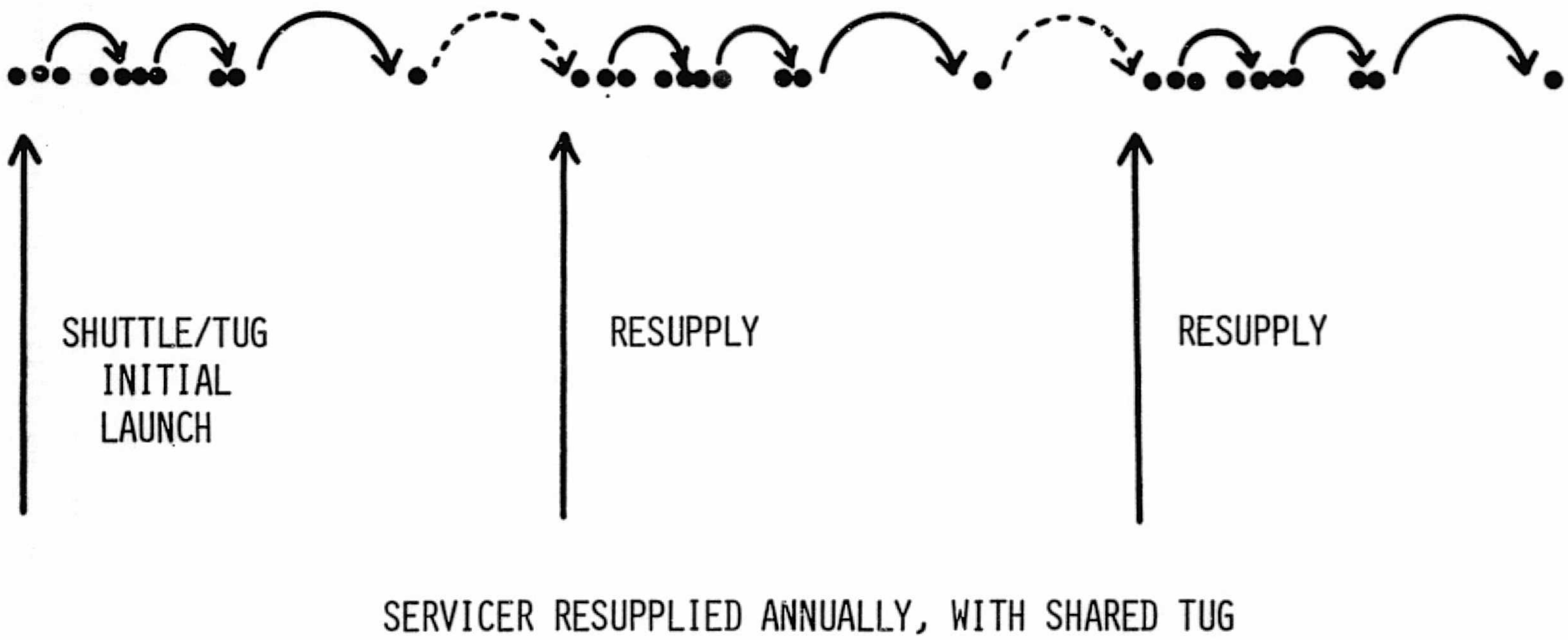

Figure 4. Free Flying Servicer
(30 satellites serviced in 3 years)

satellite to satellite, replacing modules as it goes. After it has serviced all the satellites that need servicing around the geostationary orbit, it may coast for a while or it may be called on to service a satellite with a module that it has on board or a module taken from another satellite. At regular intervals, perhaps annually, it will be resupplied by the tug and sent out on another round of servicing.

An efficient servicing method is to move from one ocean region to another, servicing each satellite that needs service as the servicer goes around the orbit. The actual schedule would represent a tradeoff among the various priorities and the fuel required to reach particular locations. In some cases the satellite might change location to meet the servicer at some desired point.

To determine the probable distribution of satellites, the location of all the INTELSAT III and IV satellites, the desired locations of a number of domestic satellites as filed with the FCC, and the locations of a few other satellites were determined. Four clusters were identified over the Atlantic Ocean, U.S.A., Pacific Ocean, and Indian Ocean. While the exact locations of satellites in the next decade will be different, the general pattern will be the same.

As an example, 10 satellites taken at specific longitudes, are shown in Table 8, and a total mission time of four months was selected to visit the 10 satellites. Velocities were selected to minimize the fuel used in this tour. That is, higher velocities were used for long jumps, and smaller velocities for short jumps; velocities actually varied from 0.8° per day (for 5° jumps) to 3.7° per day (for 110° jumps). This strategy may not be optimum; for example, it may be desirable to increase the total mission time, that is, the time until the last servicing, and to service some of the earlier satellites more quickly.

The actual modules that would have to be exchanged have been estimated from data on satellite failures as well as experience in operating a satellite system. During a period of three years,

Table 8. Visiting 10 Satellites - 4 Months Fuel
5 Percent or 200 lb of Hydrazine

	Assumed Longitude (°E)	Longitude Change (deg)	Transit Time (days)	Velocity (deg/day)	ΔV (ft/s)
Atlantic Ocean					
	340				
		10	9	1.1	22
	330				
		5	6	0.8	17
	325	40	18	2.2	44
U.S.	285	15	11	1.4	27
	270	10	9	1.1	22
	260	5	6	0.8	17
	255	75	25	3.0	60
Pacific Ocean					
	180	10	9	1.1	22
	170	110	30	3.7	73
Indian Ocean					
	60				
Total			123 days		305 ft/s

30 satellites would be serviced. About half of these would receive modules with new batteries and transponders. Other modules replaced would probably include receivers, earth sensors, momentum wheels, and various electronic components. This list is still preliminary, and will change as some components become more reliable. For satellites that require north-south stationkeeping, it is expected that refueling will be quite attractive. These satellites may be launched with four or five years of fuel and refueled every three years.

If the free flying servicer exchanges modules on 30 satellites, its cost per servicing becomes quite small. The estimated 5 percent for fuel per year is quite conservative. The main cost factors then become the price of building a satellite to be serviceable and the cost of building and transporting the new modules to geostationary orbit. One added benefit is that many shuttle/tug flights can be loaded with additional modules or fuel, so that the loading factor for the tug should improve with a system that includes a free flying servicer.

Once a free flying servicer is available and the cost per servicing is low, new possibilities emerge. It then becomes feasible to perform many servicing operations that do not justify a separate shuttle/tug flight. In particular, satellites that are still operating should be serviced. Servicing can then be used to increase the reliability of an operating satellite: design failures can be corrected, failed redundant components and wear-out items replaced, and fuel added.

4f. *Expendable satellites are cost effective when satellite lifetime meets program lifetime requirements.*

A key factor in the evaluation of servicing is the ratio of satellite lifetime to program lifetime. Satellite lifetime is the average time that a satellite operates until some failure destroys its usefulness (using some predetermined definition of successful operation). Program lifetime is the length of time before a satellite becomes obsolete and must be replaced by a new generation of satellites.

The lifetime of communications satellites has been of the order of a few years. INTELSAT I (Early Bird) was designed for one year and lasted considerably longer. INTELSAT III had an average lifetime of only two years. INTELSAT IV was designed for a 7-year lifetime, but it is too early to determine the actual value. In the future, a 5-year lifetime can probably be achieved, but the feasibility of a 10-year life is still questionable.

The program life of communications satellites has been fairly short. There have been four generations of international communications satellites during the course of 10 years. In the future, program lifetime will be considerably longer. The launch of the first INTELSAT V is presently planned for around 1979, which is eight years after the first launch of INTELSAT IV. However, since there is also an INTELSAT IV-A, it is debatable whether that period of eight years should be equivalent to one generation or two. Plans for INTELSAT VI are still sketchy, but a launch in 1986 is a possibility; this implies a program lifetime of seven years for INTELSAT V. Thus, at present and for the foreseeable future, the program lifetime is not much greater than the anticipated satellite lifetime.

For most of the mission models in the SSPD document,[2] it is difficult to determine the program lifetime in the sense used above. The assumption was that, within the 13 years under study, substantially identical spacecraft were launched. For international communications satellites it was assumed that launches in 1980 were the same as those in 1990. A 7-year lifetime was used and it was assumed that servicing would extend the useful lifetime of this satellite for another seven years.

For most of the geostationary orbit programs in the 1980's a program lifetime of over 10 years is rather optimistic. However, for the 1990's it becomes a more realistic assumption. There is a definite trend toward increasing program lifetimes, and it is only a matter of time before program lifetimes of 10 years or more will be realized.

VI. STUDY LIMITATIONS

The conclusion that on-orbit servicing is attractive in geostationary orbit is subject to several limitations. The ratio of satellite lifetime to program lifetime has just been discussed in the last section. The other limitations can be discussed in terms of the cost of servicing versus the benefits to be derived.

The cost of a servicing operation includes the cost of the modules, the transportation costs, the added cost of making the satellite serviceable, the costs of operations, and the cost of the servicer. The transportation costs can be decreased if the number of servicings per mission is more than one. If the probability of servicing a satellite is low, then the added cost of modularizing unserviced satellites must be added to the costs of servicing a satellite. For example, if only every third satellite is serviced, then the costs of each service operation must include the costs of modularizing three satellites.

It is usually assumed that a satellite to be serviced is not carrying communications traffic; instead, the traffic may be on an in-orbit spare or an outage may have occurred. The possibility of servicing a satellite while it is operating needs further study. Although there are problems involved in shutting off power to a module and maintaining attitude control, these may not be insurmountable. Several minutes are required to switch traffic to an in-orbit spare at a different longitude; while such an outage is tolerable, it is undesirable. Even if an outage occurs during the shock of docking, such an outage may be preferable to switching the traffic to a spare satellite.

Another limitation of these studies is that there has been a tendency to compare present expendable maintenance modes with future on-orbit servicing. It may be possible to improve the expendable mode (e.g., by increasing satellite lifetime), and the potential advantages of such improvements must be compared[6] with the potential savings of on-orbit servicing.

VII. IMPLICATIONS FOR RESEARCH

The development of an on-orbit servicer maintenance system can be useful to many spacecraft programs. It can be used with both standardized modules and with modules built for a single program or satellite. Standardized modules will yield some cost savings due to standardization and will also be more readily available on the earth or in space. On the other hand, a pivoting arm servicer can handle nonstandard modules, even of different sizes, as long as there is some standardization of latch-attach mechanism and end effector.

The orbital maintenance system considered here is compatible with the space transportation system as presently configured. In some respects the shuttle/tug to geostationary orbit can be used more efficiently if the loading factor is increased by adding modules and fuels for satellites already in orbit.

On-orbit maintenance with the pivoting arm servicer is compatible with a variety of delivery vehicles. The baseline configuration is the orbiter and the full capability tug. In low orbit the servicing can be done with a pivoting arm servicer, or alternatively with the shuttle remote manipulator system or extravehicular activity. In geostationary orbit, servicing can be done directly with the full capability tug or a free flying servicer. The free flying servicer implies a vehicle that remains in geostationary orbit; this may be a vehicle built especially for the purpose, a solar electric propulsion system, or a modified interim upper stage.

VIII. SUGGESTED ADDITIONAL EFFORT

6a. *Users need guarantees that servicing will be available and assurances that it will be cost effective.*

Any potential user of a service system must be assured that the service will be available at a reasonable cost when he needs it; otherwise, he will be reluctant to incorporate serviceability in his design. To provide this assurance, there are a few possible mechanisms. If the service system is government-owned, a government promise to maintain and provide a service system for a period of at least 10 years (perhaps 20 years for some users) beyond the point at which the user decides to employ a serviceable design is necessary. Is the government's promise sufficient? How will future costs be determined? If service is provided by a commercial entity--either the spacecraft contractor or a separate servicing company--can the user be protected by contract in terms of costs and future performance?

INTELSAT's performance-type contracting would work here; for example, an INTELSAT contract could include scheduled service by the contractor with future service charges calculated by some mutually approved equation. The third possibility is a user-owned and operated system. Only here does the user have complete control and hence confidence. Of course, only the larger users are likely to have sufficient service functions to justify the ownership. Commercial sale of surplus service capacity to smaller users becomes a possibility.

Unlike launch services, the commitment to service a spacecraft program extends many years into the future, particularly in the case of commercial communications satellites.

6b. *A deeper understanding of the orbital servicing cost structure is required before initiating drastic changes in conventional satellite construction and operations methods.*

The present studies have examined the traffic model and estimated the potential cost savings. However, it must be realized that project managers have greater confidence in methods that have proven reliability. Furthermore, the actual benefits for a program require a deeper analysis than was possible in the present studies. Unless compelling reasons are found for servicing in a particular program, the project manager is likely to prefer the well-proven expendable maintenance mode. A savings of 10 or even 20 percent in a program may not be sufficient to justify on-orbit servicing.

6c. *Scheduling delays of several months are tolerable for many servicing requirements.*

To achieve the maximum benefits of servicing, it must be used to improve the reliability of operating satellites as well as the repair of failed satellites. Analysis of communications satellite operations indicates that the majority of servicings will be done on operating satellites. The urgency of servicing is then drastically reduced, since it depends on the reliability of remaining equipment. The results of one study, shown in Figure 3 on page 32, indicate that, if redundant elements are replaced with an average delay time of 6 months, the performance of the system (availability) is better than if servicing is delayed until the satellite fails and the satellite is serviced with an average delay of two months. The former will require more servicing operations, but if the cost of these operations can be made sufficiently small, then the system performance will justify the servicings.

6d. *Development of the on-orbit servicer should include early in-space demonstrations of module exchange along with rendezvous and docking.*

A number of studies have already investigated the technical feasibility of unmanned module exchange and module exchange has been demonstrated on the ground. The next step is to prove by demonstration in space that this is feasible. This demonstration will not only be useful in proving the feasibility, but will also indicate the ease of certain operations and perhaps some problem areas that still need additional research.

Rendezvous and docking have been demonstrated by NASA on numerous occasions during the past years. For servicing operations far from the orbiter, it will be necessary to show that unmanned rendezvous and docking are also feasible. For servicing of operating satellites it may be desirable to increase the accuracy of rendezvous and decrease the closing velocity at impact.

6e. *Building, flying, and servicing a serviceable satellite are needed to obtain widespread acceptance of orbital servicing.*

In spite of many studies and demonstrations, widespread acceptance of orbital servicing will require many years. The development will take place slowly. It will progress from low orbit, where the manned shuttle is available, to geostationary orbit, where it is not. It will be first be applied to large, expensive satellites where the benefits are dramatic and then progress to smaller, cheaper satellites.

Project managers are hesitant to accept new methods, particularly those involved with commercial communications satellites. While some acceptance may come in the 1980's, widespread use of servicing the geostationary orbit will probably not be fully accepted until the 1990's. The tug is not available until the early 1980's.

A few project managers may make a decision based on a flight demonstration of servicing. Many project managers will wait until a number of operational programs have proven the advantages of servicings in the late 1980s. After a project decision is made, two or three years are needed to build and launch a satellite, and additional years will be needed before servicing occurs.

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