EXECUTIVE SUMMARY

SATELLITE SERVICING

ECONOMIC STUDY

December, 1990

Undertaken By
SPACE SYSTEMS/LORAL*
Palo Alto, California

For The
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Huntsville, Alabama

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* Formerly Ford Aerospace Corporation

ACRONYM LIST

AXAF	Advanced X-Ray Astrophysics Facility	ODC	Other direct charges
C&DH	Command & data handling	OMV	Orbital Maneuvering Vehicle
CSSO	Communication satellite systems operations	ORU	Orbital replacement unit
DMS	Data management system	OTV	Orbital Transfer Vehicle
DMSP	Defence Meteorological Satellite Program	P(s)	Probability of success
DRM	Design Reference Mission	PED	Platform equipment deck
ELV	Expendable launch vehicle	POP	Polar Orbiting Platform
EOS	Earth Observation System	R	Recurring
EP	Explorer Platform	RMS	Remote Manipulator System
ESS	Expendable servicing system	SADA	Solar array drive assembly
EUVE	Extreme Ultraviolet Explorer	SATCAV	Stochastic space mission life cycle cost & availability model
EVA	External vehicular activity		
FSS	Flight Support System	SSES	Satellite Servicing Economic Study
FTS	Flight Telerobotic Servicer	SSF	Space Station Freedom
GPBS	Geostationary Platform Bus Study	SSS	Satellite servicing system
GSE	Ground support equipment	STS	Space transportation system
IOSS	Integrated Orbital Servicing System	TDRSS	Tracking and Data Relay Satellite System
IVA	internal vehicular activity	WTR	Western Test Range
LCC	life cycle cost	XTE	X-Ray Timing Experiment
MACS	Modular attitude control system		
MMS	Multi-mision Modular Spacecraft		
MPS	Modular power system		
NR	Non recurring		

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INTRODUCTION AND BACKGROUND

This study was initiated by MSFC, in an attempt to consolidate previous servicing studies into a common database. In general, these studies have concluded that satellite servicing is a cost effective solution over an expendable satellite. The potential benefit of a consistent database of previous studies will provide a basis so that performance trends can be used when analyzing new servicing missions.

Space Systems/Loral (formerly Ford Aerospace Corporation) was tasked with collecting and reviewing the various program studies, and to apply the same methodology in an analysis of currently planned and funded programs. This would provide an independent cost analysis of new programs, and assess the overall life cycle cost benefits of servicing versus satellite replacement.

INTRODUCTION AND BACKGROUND

- **Previous studies have shown that satellite servicing is cost effective**

- **However, all of these studies were of different formats, dollar year, learning rates, availability, etc.**

- **It was difficult to correlate any useful trends from these studies**

- **This study was initiated to:**

  - Correlate the economic data from past studies into a common data base, using a common set of assumptions

  - Analyze a select set of existing funded programs to provide an independent analysis of the servicing options and potential economic benefits

STUDY TASKS

The goals of the study were to;

1. Review some of the previous servicing studies primarily as background data, and for life cycle cost (LCC) comparisons. The following programs were evaluated during the study. The Integrated Orbital Servicing System (IOSS), Spacecraft Assembly, Maintenance and Servicing, Satellite Servicing Working Group Studies, FAC/NASA studies on the Geostationary Platform Bus, Communication Satellite Systems Operations (CSSO) with the Space Station study, the Geostationary Platform Bus Study (GPBS), and the Defense Meteorological Satellite Program (DMSP) Block 6 study undertaken for the USAF. The data presented in these studies was transposed to a common data base and the costs normalized in 1989 dollars.

2. Develop new design reference missions (DRMs) that would be in place in the 1995 to 2010 time frame. The DRMs developed were for the Advanced X-Ray Astrophysics Facility (AXAF), the Polar Orbiting Platform (POPs), and the Explorer Platform. In general, four basic missions were established: Expendable, Expendable Servicing, Shuttle Servicing and Space Station Servicing. Shuttle and Space Station Servicing were not considered for the POP.

3. To conduct (a) a normalizing of the economic data of the selected scenarios from existing studies to produce life cycle costs (LCCs) and (b) economically analyzing the scenarios for the new DRMs. From this data, parametric curves were produced showing the sensitivity effects on the LCC by varying the satellite costs, reliability, servicer system cost and launch costs.

STUDY TASKS

- Review previous servicing studies and generate a common database normalized in 1989 dollars. Perform a life cycle cost (LCC) analysis for comparison with previously generated results.

- Develop new design reference missions (DRMs) in the 1995 to 2010 time frame. Examine the expendable satellite versus serviceable satellite option scenarios.

- Normalize the economic data for the selected expendable and serviceable scenarios to generate life cycle cost data. Generate parametric curves showing the sensitivity effects on the LCC by varying satellite costs, reliability, servicer cost, and launch costs.

STUDY GROUND RULES

The common financial base was established in 1989 dollars. Any input or derived costs were escalated to FY89 dollars. The learning curve input was set at 100%, this was based on experience with the INTELSAT V Program (a total of 15 satellites) and discussions with NASA-MSFC on their experience with the Shuttle main engine program. The cost of money was set at a 5% discount rate for LCC results.

A 10% uncertainty factor was assumed in all final result data for comparing the economic benefit of servicing. This defined a confidence threshold in the results to establish when a servicing benefit had been realized. This factor was generated by examining the correlation data from Task 1, and from an estimate of the input data uncertainty for the Task2 DRMs considered.

The baseline ground rule used to estimate Shuttle costs is based on a charge of $208M to launch 56K lbs to a nominal orbit of 160 nm, 28.5° inclination. This results in a $3714 per pound. Then for the various missions, a table look-up is used to determine the capacity for other than 160 nmi altitudes orbits, and a new dollar-per-pound factor is determined. The 33% manifest charge is included for all Shuttle payloads if the weight and length of the payload do not represent over 75% of the Shuttle capacity.

Space Station servicing related costs are mission dependant, but all payloads will require handling, monitoring, integration and testing prior to the servicing mission. During the mission staging period ORUs will be monitored by the Station Crew and it is expected that these operations will require continuous support by the Space Station Freedom (SSF) Data Management (DMS) and Communications subsystems. The servicing mission will require IVA crew support, Remote Manipulator System (RMS) handling time, and possibly EVA. The cost estimates include SSF Logistics Pallet Use $3,600/lb; DMS Services $6,600/hr; Communications Services $2,500/hr; RMS services $41,700/hr; EVA activity $123,000/hr; IVA activity $19,000/hr.

STUDY GROUND RULES

- All costs are in 1989 dollars

- Learning curve set at 100%

- Cost of money set at 5%

- A confidence threshold of 10% is used to evaluate the servicing benefit.

- System availability will be held constant.

  - Model will perform scheduled maintenance prior to failure

  - Model will simulate random failures and perform maintenance on demand

- Nominal Shuttle launch cost is $208M to 160 nm orbit

- Space Station Freedom (SSF) user charges for servicing missions are mission dependant, and vary between $10-30M It is assumed that the servicing mission will require IVA and EVA crew support, Remote Manipulator System (RMS) handling, and SSF support services during payload integration and test.

- Development costs of NASA servicing systems are paid by the NASA. A user fee only is charged to each program

  - Remote servicer user fee: $5M per mission

  - OMV user fee: $6M per mission

  - OTV user fee: $14.6M per mission plus fuel at $2100/kg

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SATCAV MODEL

SATCAV; a stochastic space mission life cycle cost & availability model was developed by Princeton Synergetics, Princeton, NJ, and has been used as the prime analytical tool in this study to generate program life cycle costs.

The model simulates launch and on-orbit operations associated with the initiation and continuing operation of a generalized space mission comprising multiple satellites with a multiple sensor capability. The model operates on an IBM PC microcomputer and utilizes a LOTUS 123 menu driven input/output system to create a date-file that is accessed by a FORTRAN Monte Carlo program that performs the computation.

SATCAV simulates satellite launch operations using expendable or recoverable launch vehicles and upper stages and takes into account the consequences of a set of defined failures in terms of cost incurring events and time delays. SATCAV simulates the random and wearout of a multi-sensor satellite determining when specific failures occur and when maintenance actions are required to respond to critical failures.

SATCAV encompasses alternative maintenance scenarios that include both ground and on-orbit spares. Both launch on-failures and launch in-anticipation of wearout failure alternatives are available. Different transportation scenarios may be selected for placement and maintenance flights.

SATCAV also considers subjectively selected uncertainties and develops cost, event, and availability statistics reports. It also develops a typical event timeline report.

SATCAV MODEL

- SATCAV; a stochastic space mission life cycle cost & availability model is the prime analytical tool in this study to generate program life cycle costs.

- The model simulates launch and on-orbit operations of a multiple satellite system with multiple sensor capability.

- SATCAV simulates satellite launch operations using expendable or recoverable launch vehicles and accounts for the consequences of a set of defined failures in terms of cost incurring events and time delays.

- SATCAV simulates the random failures and wearout of a multi-sensor satellite determining when specific failures occur and when maintenance actions are required to respond to critical failures.

- SATCAV also considers subjectively selected uncertainties and develops cost, event, and availability statistics reports.

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RESULTS SUMMARY

- ## AXAF:

  - All of the considered servicing scenarios showed to be cost effective over the expendable AXAF scenario. The expendable servicing system resulted in the lowest LCC

- ## POP

  - Platform servicing was not cost effective if total payload replacement is a requirement. A modified servicing strategy was defined to investigate when POP servicing would be cost effective.

- ## EP

  - The Expendable servicer demonstrated the lowest LCC. However, the Expendable servicer, Shuttle based servicer (FSS), and the expendable satellite scenarios were all within 5% in total LCC.

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TASK 1

REVIEW DATA FROM
EXISTING SERVICING STUDIES

TASK 1: PROGRAM SET

A number of previous servicing studies were evaluated. As a basis for information two payload models were utilized to formulate the candidate servicing scenario. These were the 1973 NASA Headquarters and the 1974 NASA-MSFC payload models. These two sources resulted in a combined 545 mission and 101 payload programs. The 101 programs was reduced in the final count to 14. The following methodology was used to reduce the number of programs into a manageable set to evaluate:

- Spin stabilized spacecraft were eliminated because of docking complexities

- Spacecraft with a recurring cost of less than $40M in 1975 dollars, and spacecraft with lifetimes less than 1 year were eliminated because servicing is unlikely to be cost effective on a low cost, short life satellite.

- Programs with launch dates before 1980 or those whose mission were complete, and would, therefore, generate little or no interest, were dropped as were one flight or duplicate missions.

Spacecraft cost data were not listed in the IOSS published documentation, as NASA had provided the cost data and felt that their release might compromise future procurement of the spacecraft. It was therefore decided to back out the cost numbers from the expendable program costs, which were given in the IOSS documentation in 1975 dollars. The expendable spacecraft program cost figures were obtained from the Integrated Orbital Servicing Study for Low Cost Payload Programs, Final Report, Volume II, Technical and Analysis, MCR-75-310, September, 1975, issued by the Martin Marietta Corporation, Denver, CO.

TASK 1: PROGRAM SET

- The following programs were evaluated during the study

  - The Integrated Orbital Servicing System (IOSS)

  - Spacecraft Assembly, Maintenance and Servicing

  - Satellite Servicing Working Group Studies

  - Communication Satellite Systems Operations (CSSO)

  - Geostationary Platform Bus Study (GPBS)

  - Defense Meteorological Satellite Program (DMSP) Block 6 study

- Criteria was established to reduce the total program set to 14, in order to maintain a workable number of SATCAV runs. The resultant program set is representative of spacecraft servicing programs that have a higher probability of being cost effective.

- The data presented in these studies has been transposed to a common data base and the costs normalized in 1989 dollars.

- Spacecraft costs were not explicit in IOSS documentation, therefore, cost numbers were backed out of the expendable program costs.

TASK 1 RESULTS

The summary chart tabulates the SATCAV model inputs for the satellite cost, launch costs, and repair mission costs, and the program life cycle costs. Each of the 14 programs are discussed in more detail in the final report. The overall program LCC cost for both the serviced and expendable case are shown so that the benefit of servicing can be established. In all but one case the benefit of servicing is positive. The metsat-L is a low cost LEO satellite with a significantly high repair mission cost. If the satellite is not designed for servicing, or if the servicing components represent a major percentage of the replacement cost, then the benefit of servicing is small.

The chart on the facing page compares the new SATCAV results with the previous study results. This comparison is made in terms of the servicing benefit percentage of each of the program. In most cases, the results compare very well, and are within approximately 5%. The AST-7, and AST-8 were separated by about 15%. In looking through the data it was found that the SATCAV model initiated many repair missions and replaced the spacecraft to achieve the mission availability over the life of the program. The number of servicing missions initiated is highly sensitive to the input reliability data, and the constant availability parameter assumed at the beginning of the study. It is difficult to quantify the exact nature of the failure between the old and new results, but if the initial study did not maintain the same level of availability as the present study, then that could cause the cost discrepancy. In general. the SATCAV model results correlate very closely to the servicing benefit predictions of the older studies.

Program	Satellite Cost ($M)	Satellite Lnch Cost ($M)	Repair Kit Cost ($M)	Life Cycle Cost ($M) Non-Serviced	Serviced	Savings ($M)	Savings (%)
AST-5B	165.6	68.9	36.5	2553.1	1778.6	774.5	30
AST-5C	109.1	63.8	30.5	1420.5	1123.3	297.2	21
AST-7	210.7	118.9	41.3	3572.1	2277.7	1294.4	36
AST-8	57.4	219.4	36.2	2355.6	2277.4	78.2	3
AST-9A	168.2	83.9	36.8	3531.1	2177.3	1353.8	38
PHY-3B	100.2	236.1	41	2134.5	1904.6	229.9	11
NN/D-2B	76.2	130.5	43	3652.5	3227.4	425.1	12
NN/D-6	83	96.1	42.9	1675.3	1404.5	270.8	16
NN/D-12	91.2	136.2	34	4788.5	3250.9	1537.6	32
NN/D-14	87	57.8	26.1	3178.6	1854	1324.6	42
GEO PLATFORM	850	212	733	7488	6564	924	12
COMSAT	70	65.4	44.6	845	675	170	20
METSAT-L	40	60	45	681	717	-36	-5
METSAT-G	100	107.7	47.1	1273	1180	93	7

TASK 1 RESULTS
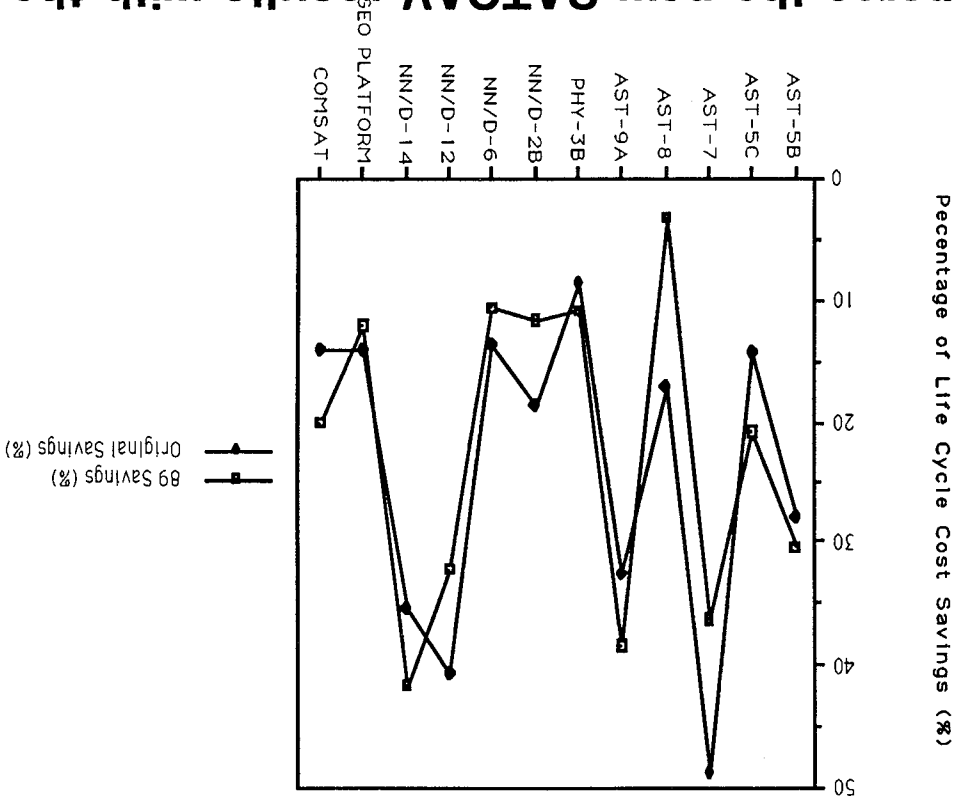
- This chart compares the new SATCAV results with the previous study results.

- The AST-7, and AST-8 were separated by about 15%. The SATCAV model initiated more repair missions and replaced the spacecraft to achieve the mission availability over the life of the program. The number of servicing missions initiated is highly sensitive to the input reliability data.

- Overall, the SATCAV model results are within 5% of the predictions of the older studies.

TASK 1 SUMMARY

The average benefit in the LCC costs due to servicing is 19.6%. This indicates that there is potential benefit in providing the servicing capability in certain satellite programs. However, the standard deviation of the results is about 14.4% indicating a large spread in the data. This leads to the conclusion that the benefit of servicing is not overwhelmingly conclusive and each program must be analyzed on a case by case basis.

Although the resultant data produced sizeable scatter, the trend indicates that the more costly the unit price of the satellite the more benefit there is to building in a servicing capability. The results indicate that the maximum cost benefit of servicing appears to be about 35% and that as the number of satellites increase, the benefit of servicing increases.

The cost of launching a servicing mission must also be considered. The results of Task 1 show that as the launch cost increase, the benefit of servicing decreases. However, all in all, the results track reasonably well with previous studies. It is clear that for some missions servicing will provide an overall cost savings.

TASK 1 SUMMARY

- Average savings in life cycle cost due to servicing is 19.6%

    - Indicates strong potential benefit due to servicing

- Standard deviation of above result is 14.4%

    - Indicates large spread in data

    - Servicing must be analyzed on a case by case basis

- Trend indicates that as the satellite unit cost increases, the benefit of servicing increases

    - Maximum benefit of servicing is approximately 35%

- As number of satellites increase, the benefit of servicing increases

- Trend indicates that as satellite launch cost increases, the benefit of servicing decreases

- Results of the 1989 analysis track previous results, thus validating the SATCAV model for new DRMs

TASK 2 AND TASK 3 COMBINED

Task 2 and Task 3 are presented together for each of the 3 DRMs examined. This increases the flow of the data from scenario development through analysis and results.

Task 2 Develop the servicing versus replacement scenario for each of the 3 design reference missions (DRMs). The DRMs developed were for the Advanced X-Ray Astrophysics Facility (AXAF), the Polar Orbiting Platform (POPs), and the Explorer Platform. In general, four basic missions were established. Expendable, Expendable Servicing, Shuttle Servicing and Space Station Servicing. Shuttle and Space Station Servicing were not considered for the POP.

Task 3 normalizes the economic data of the selected scenarios and analyzes the data in a parametric manner. The parametrics show the sensitivity effects on the LCC by varying either the satellite cost, reliability, servicer system cost or launch cost.

TASK 2/ TASK 3 COMBINED

Task 2: ANALYZE NEW DRMs

- Develop servicing and expendable scenarios
- Format cost mass and reliability data

Task 3: ECONOMIC ANALYSIS

- Use SATCAV model to generate program LCC
- Show sensitivity of reliability and cost components on overall LCC

Design Reference Missions Included: AXAF, POP, EP

SHUTTLE LAUNCH COSTS

The methodology for generating Shuttle launch costs can be quite ambiguous, and one gets a different answer depending who answers the question. A typical method uses the payload weight and length occupied in the Shuttle bay to establish a percentage of the total launch cost. If the weight (which includes cradles and supports) is a higher percentage of the total than the length component, then the cost is based on weight instead of length. And similarly, the cost is based on the length if the percentage of the Shuttle bay occupied is greater than the weight component. Additionally, if the percentage utilized is not greater than 75% of the Shuttle capacity (either weight or length, which is bigger) then a manifest charge, typically 33% of the payload launch cost, is added.

The individual NASA program offices do not recognize this cost as applied to their respective programs. They consider their manifest on the Shuttle as a secondary payload. In other words, they occupy excess Shuttle capacity, and therefore, the launch costs are not applied to their budget.

If this study adopted such an approach, the real cost comparison would be skewed to promote Shuttle-based servicing in all but polar orbits. Therefore, Shuttle launch charges using the methodology described above is used to generate a true cost comparison for the different servicing scenarios.

The baseline ground rule used to estimate Shuttle costs is based on a charge of $208M to launch 56K lbs to a nominal orbit of 160 nm, 28.5° inclination. This results in a $3714 per pound. Then for the various missions, a table look-up is used to determine the capacity for other than 160 nmi altitudes orbits. Then a new dollar-per-pound factor is determined. The 33% manifest charge is included for all EP Shuttle launches since the weight and length of the payload do not represent over 75% of the Shuttle capacity.

The weight estimates for all cradle and manifest weights were obtained from David Douds, GSFC.
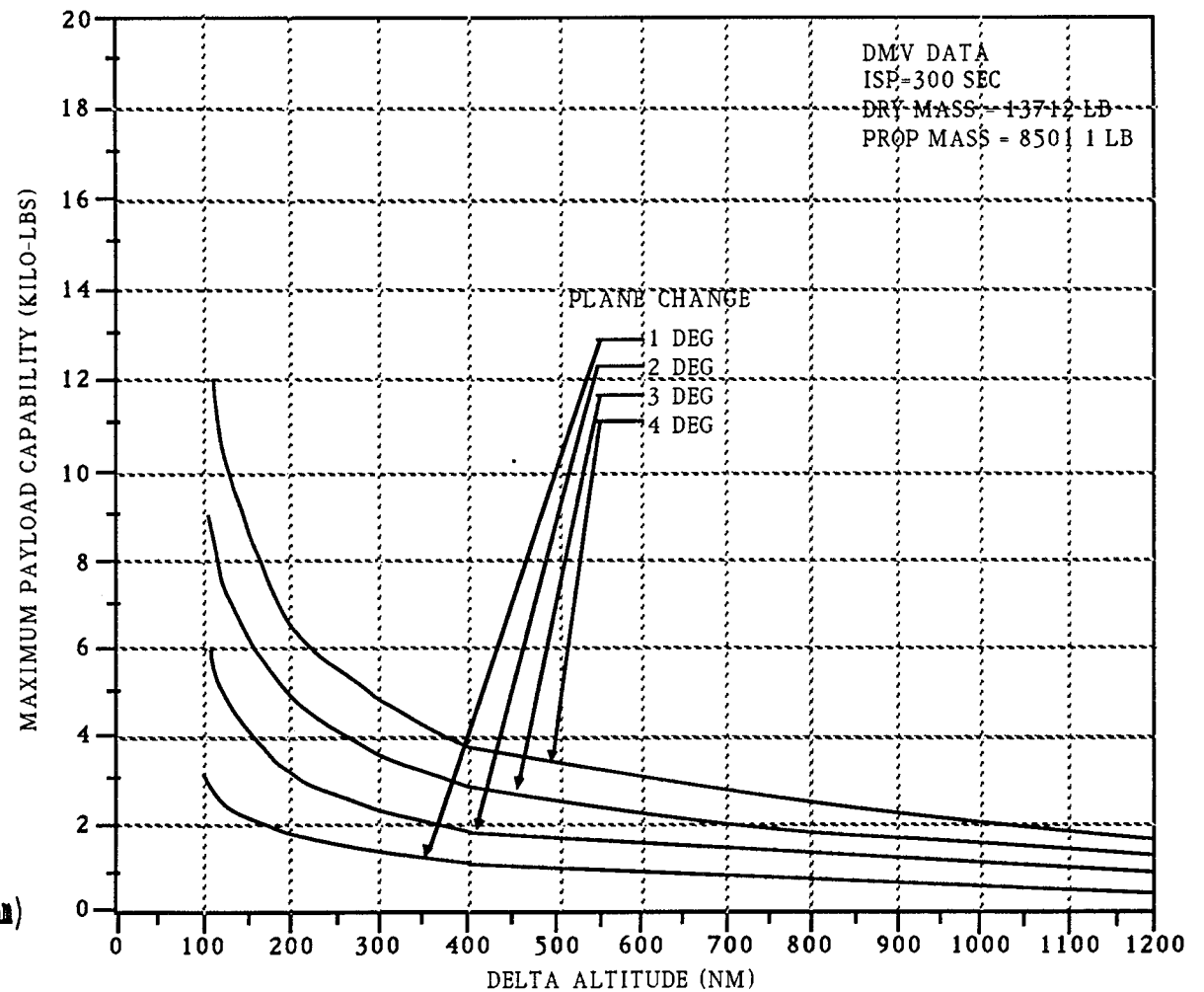
SHUTTLE LAUNCH COSTS

SPACE SYSTEMS/ LORAL

PROGRAM LAUNCH	ALTITUDE NM	MANIFEST PAYLOAD (LB)	WEIGHT CRADLE (LB)	$/LB	MANIFEST CHARGE %	SHUTTLE LAUNCH COST ($M)
Explorer Platform Servicing Mission • FSS, Shuttle In-situ	330	5500	10,900	4,643	33	101.3
Explorer Platform Servicing Mission • Shuttle/OMV	160	18,000	5,000	3,714	33	113.6
EP Servicing Mission • Shuttle / SSF	240	11,950	8,400	4,020	33	109

SSF SERVICING IMPLICATIONS

The chart below plots the waiting period between successive nodal alignments, as a function of the difference in altitude between the space station orbit and the AXAF orbit. If the space station is assumed to be located in a nominal 240 km orbit, then the differential altitude will vary between approximately 53 nm to 80 nm. This will result in a waiting period between successive nodal alignments in the order of 40 - 45 months. Due to this slow nodal drift, approximately 8.4° per month, a 15-20 day window of opportunity will exist to rendezvous and service the AXAF within a ±3° nodal bandwidth. The larger the nodal bandwidth the larger the window of opportunity, but the lower the transfer mass capacity. This window of opportunity estimate assumes that both orbits are at the same inclination. Initial orbit dispersions and second order orbit perturbations will result in inclination changes between the space station and AXAF. Given the workload on the Space Station crew, launch vehicle manifesting difficulties and potential for OMV failures, this imposes a severe constraint on Station based servicing.

SSF SERVICING IMPLICATIONS

SPACE SYSTEMS/ LORAL

Wait Time (mos)

Delta Alt. (nm)

MAXIMUM PAYLOAD CAPABILITY (KILO-LBS)

DELTA ALTITUDE (NM)

DMV DATA
ISP=300 SEC
DRY MASS = 13712 LB
PROP MASS = 8501 1 LB

PLANE CHANGE
1 DEG
2 DEG
3 DEG
4 DEG
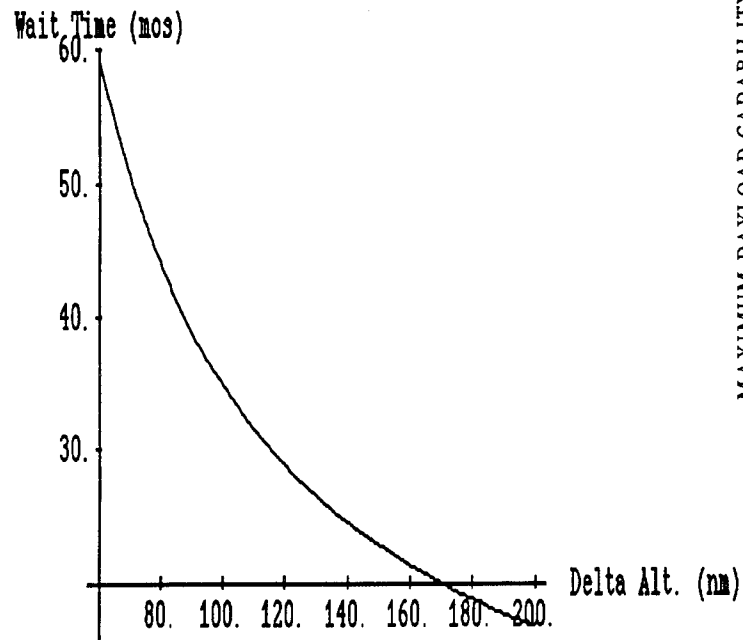
AXAF INTRODUCTION: SSES IMPLEMENTATION

This DRM represents one of the 4 great observatories. The AXAF mission is designed to collect astrophysical data over a wide range of the electromagnetic spectrum. The spacecraft is configured for a Shuttle launch to a 325 nm orbit. The spacecraft has no on board propulsion and over a 5 year period the orbit will degrade to 318 nm assuming nominal solar activity.

The AXAF spacecraft is designed for a 15 year mission with in-situ servicing every 5 years. During these servicing periods, it is expected that the servicing vehicle will perform a velocity maneuver to re-boost the satellite to a 325 nm orbit. The 5 servicing scenarios shown on the facing page were identified for further investigation. Prior to performing the economic analysis, the five candidate scenarios were evaluated to determine their relative performance. Each of the scenarios was ranked in terms of mission cost, risk and complexity. Once each of the scenarios had been ranked, a down select was made based on their relative ranking in terms of the these three factors. Two of the candidate scenarios involved Space Station Freedom (SSF) based servicing missions were eventually eliminated due to high servicing cost and window of opportunity servicing limitations.

Both of these SSF servicing scenarios involve the OMV, which has significant limitations due to the orbital mechanics of two satellites at different altitudes. The final report shows the constraints and capabilities of OMV servicing of AXAF from the SSF. The window of opportunity was limited to approximately 15 days every 45-55 months. This severe servicing constraint increased the preparation time, and cost, required on the SSF to assure that payload/servicer integration and test was complete when the launch window was available.

The ground based scenarios generally received higher marks. The remote servicing options were viewed to have the lowest complexity because of the reduced number of OMV operations. The ground based retrieval scenarios were seen to be the lowest in terms of risk because of the high level of human involvement in the servicing operations. Past experience on the MMS program has demonstrated the human ability to improvise and perform delicate operations that would be impossible for a robotic or telerobotic system to perform.

AXAF INTRODUCTION: SSES IMPLEMENTATION

Mission:	Astrophysics
Mission Duration:	15 Years
Constellation:	1 Satellite 28.5° X 325 nm orbit.
Launch Vehicle:	STS
Spacecraft Dry Mass:	30,000 lbs
Spacecraft Cost:	$525.0 M (FY 89)
Servicing Options:	Servicing at the Space Station utilizing OMV for retrieval
	Servicing in-situ utilizing a Space Station based SSS
	Servicing in the Shuttle bay utilizing the OMV for retrieval
	Servicing in-situ utilizing the ground based SSS
	Servicing in-situ utilizing the ESS

SATCAV COST INPUTS

The AXAF Phase B study indicated that the projected servicing interval was 5 years and the spacecraft would have a Ps of 0.44 at that time. With a Ps of 0.44, the SATCAV model predicted a much shorter servicing interval and since it was felt that the 5 year interval was in good agreement with past experience the Ps inputs were adjusted to 0.77 for the entire spacecraft. Since the spacecraft is designed to be almost completely serviceable, the Ps for the servicing mission was set to 0.88. This number is the combination of a probability of repairability of the spacecraft of 0.9 and Ps of the servicer of 0.98.

The costs shown have the most significant contribution to the resultant life cycle cost. The spacecraft and ORU cost inputs were derived from the AXAF Phase B estimates. Since AXAF is baselined for servicing, the non-serviced spacecraft cost was estimated to be 10% less than the Phase B cost. This figure was arrived at from the results of previous studies which indicates that the cost to design a serviceable spacecraft is approximately 10% greater than that of an expendable spacecraft.

The ORU charges were derived from the Phase B study cost estimates for the projected servicing mission payload compliment. The Satellite Servicing System (SSS) servicer costs were based on the standard OMV and SSS user charges of $6M per mission and $5M per mission, respectively, plus an additional $4M in crew training and operational expenses. The SSS launch costs were based on a STS launch. The ESS servicer costs were based on a recurring servicer cost of $30M plus $4M in crew training and operational costs. The ESS cost was derived from an internal study which determined that a low cost mission specific servicer could be manufactured for $30M, assuming that the design could draw on key technologies from previous programs such as the FTS, SSS and the OMV. The ESS launch charges were based on a Delta II launch.

SATCAV COST INPUTS

Expenditure	Cost ($M)			
	Expendable	SSS	ESS	EVA
Original Satellite Costs				
Satellite	525	583	583	583
Satellite Launch	169	180	180	180
Total	694	763	763	763
Servicing Costs				
ORU	N/A	289	289	289
Servicer	N/A	15	30	7.5
Servicing Launch	N/A	129	52	193
Total	N/A	433	371	490

- The ORU charges were derived from the Phase B study cost estimates for the projected servicing mission payload compliment.

- AXAF is baselined for servicing, the non-serviced spacecraft cost was estimated to be 10% less than the Phase B cost. This assumption was arrived at from the results of previous studies which indicates that serviceability increases the spacecraft cost by 10%.

- Expendable launch costs assumed Delta II launch vehicle

- Shuttle costs were extrapolated from a nominal Shuttle launch cost of $208M to 160 nm orbit

AXAF RESULTS

The facing page shows a summary of the results of the AXAF economic analysis. Shown are some of the key model inputs as well as the calculated number of satellites and number of repair missions required to perform the mission. The life cycle cost shown is the 5% discounted value. The numbers shown in the table are the average values calculated by SATCAV. The standard deviations on each of the life cycle costs is approximately 10% for all cases.

The output data indicates that 4.6 platforms are required for the expendable scenario, and that 1.4 platforms/3.0 servicing missions are required to maximize the overall availability over the 15 year mission lifetime. The interpretation of the number of platform or servicing missions, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers over a number of years. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end of life if a failure occurs. So if a failure does occur near the end of the mission lifetime, then a percentage of the replacement cost is spread over the remaining mission years.

It was considered a fair assumption that the EVA case could always be serviced, and therefore, only 1 platform would be required. However, for the expendable launched missions, the model used the probability of repair data ($Ps = 0.9$) to specify if a servicing failure could occur. Therefore, even though the system availability remained approximately unchanged, the complement of replacement missions to service missions were not identical.

AXAF RESULTS

Scenario	Satellite Cost ($M)	Sat. Launch Cost ($M)	Rep. Mission Cost ($M)	Rep. Launch Cost ($M)	Number of Satellites	Number of Repairs	Life Cycle Cost ($M)
Non-Serviced	525	169	N/A	N/A	4.6	N/A	2364
SSS Serviced	583	180	308	129	1.4	3.0	2039
ESS Serviced	583	180	323	52	1.4	3.0	1938
EVA Serviced	583	180	338	193	1.0	3.4	2116

- AXAF serviced with an expendable servicing system resulted in the lowest LCC.

- All of the considered servicing scenarios showed to be cost effective over the expendable AXAF scenario.

- The primary reason that the Shuttle based servicing scenario was not the most cost effective was due to the higher Shuttle launch costs.

- The SATCAV model assumed that EVA servicing would have a much higher probability of successful servicing over the robotic servicing scenarios.

AXAF PARAMETRICS

Once a baseline set of results had been developed for all three cases, 4 parametrics were examined to analyze the sensitivity of the results to the following parameters: Satellite cost, reliability, servicer cost, and launch cost. These parameters cover the major factors that determine the life cycle cost.

A satellite cost parametric depicts the effect of original asset cost versus the economic viability of servicing. In developing the parametric for this case, it was assumed that the satellite and replacement ORUs were affected by the same amount. The 25% variation was selected in order to provide a sufficient variation in the results to establish a pattern.

The reliability parametric was performed to investigate servicing strategies. The baseline spacecraft contained sufficient redundancy to provide a 5 year servicing interval. The satellite reliability levels were adjusted to model no redundancy and triple redundancy. In addition the spacecraft cost, mass and launch costs were adjusted accordingly.

The servicer cost parametric depicts the impact of the servicing system cost on the total program LCC. Initially the cost of the SSS was decreased by $5M and increased by $25M. Correspondingly the ESS costs were decreased by $5M and increased by $30M.

The launch cost parametric was included to determine the impact launch charges have on the economic performance of servicing. The launch charges were varied by +/- 20% to establish a trend. It is important to note that the percentage increase in launch costs were assumed identical for both the Shuttle and the ELVs.

The graph on the facing page shows the impact of servicer cost on the economic performance of servicing for both the ESS and SSS servicing missions. Since the goal of this parametric was to establish the amount users could afford to pay for servicing systems, it was decided to run additional cases where the servicer cost was tripled and quadrupled for both servicing systems. The plot clearly shows that servicer system cost can be increased significantly before the benefit of servicing becomes questionable. The approximate standard deviation of the results has been drawn on the graph to illustrate the maximum costs of the servicing systems. Reading from the graph it can be seen that the maximum users fee for the SSS is about $60M and the maximum servicer cost is approximately $125M.

The primary difference in costs between the ESS and SSS servicing mission is the launch vehicle. Since the launch vehicle is a major contributor to servicing mission cost, a second plot of the parametric 3 data is shown to illustrate the effect of servicing mission cost on the economic performance of servicing. The X axis of the plot is "Repair Mission Cost" which is composed of the ORU costs, the servicer cost and the servicing mission launch costs. The chart shows that the break even point for servicing is with a servicing mission cost of $475M. This means that the sum of the three mission cost components must be less than or equal to $475M for servicing to be economically viable.

AXAF PARAMETRIC
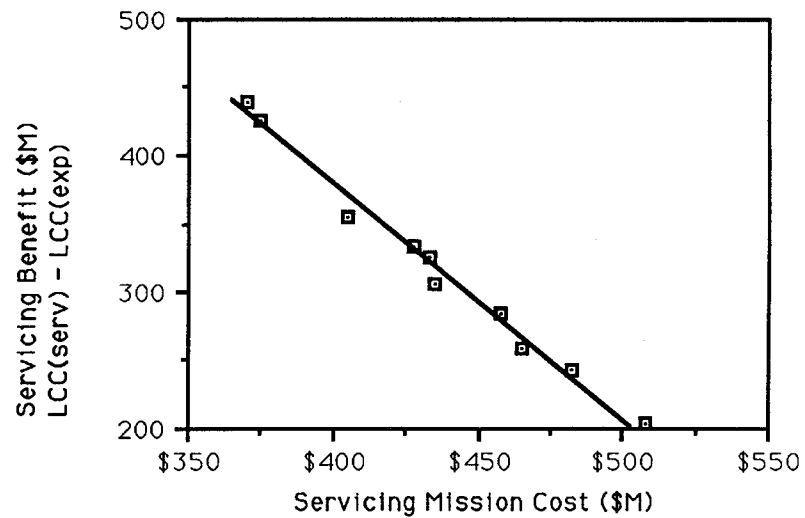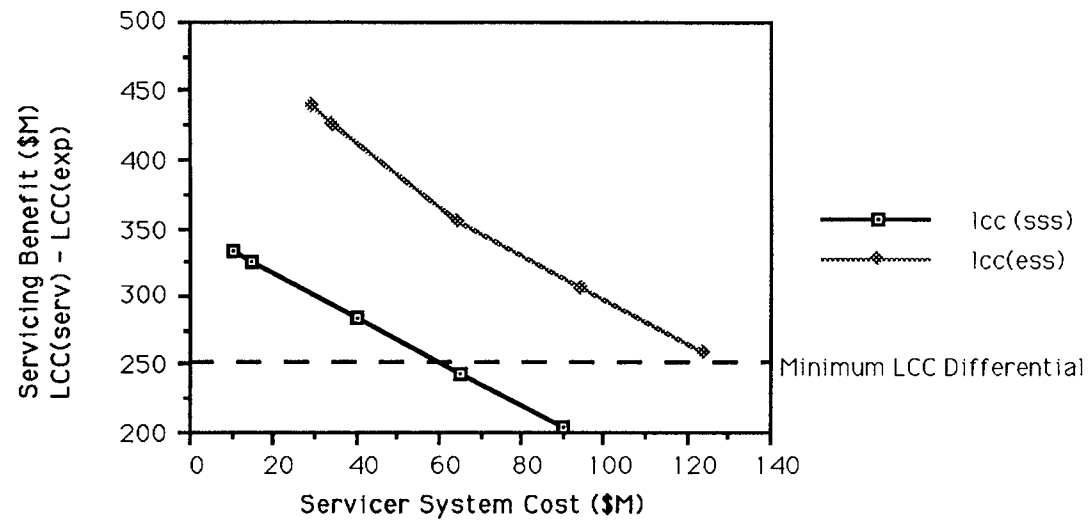
AXAF SUMMARY

The study examined many servicing options and compared the total LCC to a similar expendable spacecraft which are replaced rather than serviced. The study narrowed the option field down to ESS, SSS, and EVA based servicing options. It was determined that servicing through the space station resulted in higher cost, and the risk to the mission success was unduly jeopardized by the short window of opportunity, and the long waiting periods between successive servicing windows.

The three servicing options all proved to be cost effective over an expendable AXAF. The ESS costs were derived from an in-house preliminary study, as no funded ESS study currently exists. It is felt that the technology for a mission specific-simple ORU replacement robotic system will be available during the mission time frame. However, the costs were based upon the timely development of the SSS and OMV programs. Although the OMV funding has been eliminated, it is our opinion that a similar program with a limited scope should be initiated to fill the gap. We make this recommendation based on the potential LCC saving resulting from this study, and many other reputable studies.

AXAF SUMMARY

- The data indicates that an Expendable Servicer results in a potential LCC savings of 18% ($426M) over an expendable AXAF.

- The SSS option results in a potential LCC savings of 13.7% ($325M) over an expendable AXAF.

- The EVA option results in a potential LCC savings of 10.5% ($248M) over an expendable AXAF.

- Reliability has a major effect on the benefit of servicing; it effects both frequency and cost of servicing mission. The LCC cost results from a unique combination of redundancy and servicing.

- The parametric study has shown that if servicer costs are higher than the stated baseline, servicing could still remain cost effective. The exact value is dependant on the servicing scenario.

- The data supports the conclusion that SSF-based servicing is not cost effective.

  - The servicing window of opportunity from SSF is less than 3 weeks, with approx a 4 year waiting period before nodal alignment.

  - This severe constraint will result in longer lead time planning to ensure the window of opportunity is not missed, thus increasing servicing related costs.

POLAR ORBITING PLATFORM APPROACH: SSES IMPLEMENTATION

The current US POP Program consists of three EOS-A platforms and three EOS-B platforms. These platforms have a 5 year mission life to provide continuous Earth observations for 15 years. EOS-A series of platforms will support a payload of 3,000-3,500 kg, and provide 6 kW total power output. The design life of each platform is limited by the expected lifetime of the Earth observation sensors. EOS-A platforms are scheduled for replacement at 5 year intervals, but are being designed for servicing if an effective means becomes available during the life of the mission. EOS-B platforms are envisioned to be similar in design to the EOS-A platforms, but with a modified payload complement. It is the objective of the SSES to model, as close as possible, the current POP architecture, and to investigate servicing options that would directly compare with a replacement platform strategy.

The approach is to investigate the expendable and serviceable alternatives for EOS-A Platforms. No attempt has been made to evaluate EOS-B platforms due to the limited data available. It was also assumed that the cost trends generated for EOS-A platforms would be representative for EOS-B as well.

One expendable scenario and two serviceable scenarios are presented in this study. Many architecture studies have been performed (see references) in the past to evaluate the benefits of various servicing options. The two most recommended servicing options were chosen for the baseline servicing options in this study: The Add-On Active Carrier; and the Active Carrier with robotic exchange capabilities. It was assumed that each of these servicing options have the capability to rendezvous and dock with the POP. In other words, the POP will not be required to de-orbit for servicing.

The Atlas II launch vehicle was selected over the Delta II launch vehicle to carry the servicer to orbit. The decision was based on the recommendations of the Hixson Report, May 1990. This study did not undertake a packaging analysis and trade study to justify this selection. The Hixson Report found that the Atlas II could provide a much higher percentage of serviceable payload than the Delta II.

The payload servicing strategy assumed the "replace at design life" method. All science instruments were assumed to have a 5 year design life with a probability of success of 0.85. If however, the model triggers either a launch or on-orbit spacecraft failure, a replacement platform or servicing mission is initiated.

POP APPROACH: SSES IMPLEMENTATION

- The POP-SSES will investigate serviceable and expendable cases of the Eos-A platform series. No attempt has been made to cost the Eos-B platform system.

- Each scenario has been defined using available data, and by assumptions when data was not available.

MISSION	Earth observation of global change events
ORBIT	705 km, sun synchronous, 1:30 pm nodal crossing time.
LAUNCH VEHICLE	Titan IV Initial Placement Atlas II Servicing
MISSION LIFETIME	Total: 20 years On-orbit: 15 years
PLATFORM R COST	$700M
SERVICING OPTIONS	1. Active Add-on Carrier 2. Active Carrier with Robotic Exchange System

GENERAL POP ASSUMPTIONS

Servicing of the platform is limited to expendable launch vehicles, as no capability exists for Shuttle launches to near-polar orbits.

The Titan IV launch vehicle is assumed for initial launch and placement of the platform, and the Atlas II series launch vehicle is assumed for the launch of the servicing missions. The Atlas was the recommended servicing launch vehicle, as mentioned previously, to maximize the percentage of science payload serviced.

The ideal method of treating failures would have been to ascertain accurate POP reliability and planning data, and to translate this data into a strategy consistent with model inputs that would trigger a servicing mission when a specific threshold was reached. This threshold could be defined as a specific sensor failure, a combination of sensor failures, or a bus failure. Two problems prevented this approach from being implemented; An existing strategy with consistent probable failure data, and a SATCAV model limitation. Although some probability of failure data was available in the D. Hixson report (POP Servicing Study, Final Report, May 7, 1990), no strategy for specifying what series or combinations of failures should trigger a servicing mission.

The model was originally designed for identical servicing missions, and therefore, is not capable (without model modifications not funded in this study) of triggering servicing missions specific to different sensor failures. Since the maximum expected lifetime of the sensors was 5 years, the servicing mission was designed for that specific servicing scenario. An overall system reliability number of .75 P(s) at 7.5 years, specified by Chris Scolese, Eos Project Office at GSFC, was used.

GENERAL POP ASSUMPTIONS

- No STS servicing capability to polar orbit

- Atlas II launch vehicle assumed for servicing missions

- 5 year engineering development period

- System level reliability of .75 @ 7.5 years was assumed

  -- science payload: 0.85

  -- Platform bus: 0.88

- The repair mission assumed a 5 year expected lifetime for all science instruments. If a failure occurred prior to the 5 year intervals, the model would initiate a repair mission.

- The SATCAV model is designed for only one definition of the repair mission. The SATCAV model servicing criteria will initiate a repair mission when a specific combination of system failures occur. However, we were not able to ascertain a servicing strategy which prioritized sensors to determine what combination of failures can be allowed before a servicing mission is initiated. Therefore, system level reliability was assumed.

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POP BASELINE INPUT COSTS TO SATCAV MODEL

The baseline costs for the POP scenarios are shown below. Most of the cost data has been extracted from the Hixson report (May,1990), and some modifications were made with input from Chris Scolese, GSFC.

When a failure occurs, either total platform replacement or a repair mission is initiated. Total replacement is always assumed in the expendable scenario, and only assumed for the serviceable scenarios if the platform can not be serviced. A 90% repairability factor is assumed to account for the probability that the platform cannot be serviced. The repair mission consists of a servicer and launch vehicle. Since the model is restricted to identical repair mission costs, and a total of 3 servicers are required to replace the entire payload complement, a complete servicing mission must include three launches and three servicers to replace the entire payload. To account for the reliability effects of 3 servicing launches per servicing mission, the launch vehicle reliability was adjusted from .98, as agreed in the mid-term report, to 0.94.

Instrument and platform spares are not input into the model. The method by which the model accounts for the cost of spares is when a failure triggers a replacement or repair mission to meet the mission lifetime.

The baseline costs for the Add-On carrier serviceable option were increased over the expendable case to allow for the added development and hardware modification costs. GE Astro Space has concluded that 2 Add-On carriers could be accommodated by the existing platforms without significant design modifications. Previous packaging studies discussed in the Hixson Report have concluded that 3 Add-On carriers would be necessary to replace the entire POP instrument payload. As a result of the additional design analysis and hardware modifications necessary to support at least 3 Add-On carriers, the NR cost of the platform for the Add-On scenario was increased by 50% and the recurring cost by 10% over the expendable platform.

The baseline costs for the Active Carrier, Robotic Exchange serviceable option were increased over the expendable case to allow for the added development and hardware modification costs to incorporate the robotic system. Although the current platform design is being designed for servicing, it was not known whether this includes the necessary scarring to accommodate the Robotic Exchange System (RES). Therefore, the NR cost of the platform was increased by 20%, and the recurring cost by 10%. Platform integration costs for both of the serviceable options were assumed to be 20% higher than the expendable platform .

The WTR pad modifications was a point of some controversy. The $500M was verified by D. Hixson and included in the POP Servicing Study Final Report. It was however, a questionable line item according C. Scolese, GSFC. The question still remains unanswered whether the Polar Platform Program would bear the total cost of such a modification in the year 2000 time frame. An in-house decision was made to implement the full $500M in the baseline scenario, but show in the parametrics, the scenario without the charge.

POP BASELINE INPUT COSTS TO SATCAV MODEL

	Expendable NR ($M)	R ($M)	Add-On NR ($M)	R ($M)	Robotic Exch NR ($M)	R ($M)
Initial Placement						
Platform	241	237	361.5	260	289.2	260
Instrument set	579	300	579	300	579	300
Platform Integration		62		74.4		74.4
Payload Integration		100		100		100
Total Replacement Hardware Cost		699		734.4		734.4
Servicer						
Active Carrier Servicer			50	31	50	31
Serviceable Inst. set				100		100
ORU's				50		50
PL Integration				20		20
Platform Systems				23		23
Robotic Each Syst					100	30
Robot Integration						12.8
WTR Pad Modifications			500		500	
Total Servicer Hardware Cost		0.0		224.0		266.8

POP RESULTS COST SUMMARY

The results of each of the POP scenarios are summarized below. The results indicate that servicing does not appear cost effective given the assumptions and baseline input costs. The total discounted LCC of the Expendable scenario is $3652M in FY89 dollars. The nearest serviceable option is $4342M, an increase of $690M. The difference in the total discounted LCC between the two serviceable scenarios (Add-on carrier and Robotic Exchange carrier) is small, approximately 1.6%. A 10% confidence factor was established at the beginning of the study to indicate a significant benefit of servicing. A servicing benefit below this threshold was only considered a potential benefit given the uncertainties in the input data and the calculated data.

The output data indicate that 4.6 platforms are required for the expendable scenario, and that 1.5 platforms/3.1 servicing missions are required to maximize the overall availability over the 15 year mission lifetime. The interpretation of the number of platform or servicing mission, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end-of-life if a failure occurs. So if a failure does occur near the end of the mission lifetime, a percentage of the replacement cost is spread over the remaining mission years.

The LCC costs spans a 20 year program time frame; 5 years of development, and 15 years of active on-orbit performance. If a failure occurred during launch, a new platform was launched. If a payload or platform failure occurred, a servicing mission would be attempted in order to maintain system availability for the full 15 year mission life. The serviceable platform assumed a 90% factor for a successful servicing mission. No degradation of that factor was assumed after a successful servicing mission. If the platform could not be serviced, then a new platform would be launched.

The serviceable scenarios have included a one time nonrecurring cost of $500M to modify the WTR for Atlas launch capability. The possible exclusion of this line item has been examined in the parametric analysis. When this NR WTR cost is removed the total discounted LCC difference between all three cases is approximately $260M, or 6.8%.

POP RESULTS COST SUMMARY

SPACE SYSTEMS/ LORAL

	INPUT DATA				OUTPUT DATA		
	Satellite Cost ($M)	Sat Launch Cost ($M)	Servicing Mission Cost ($M)	Servicing Mission Launch Costs ($M)	LCC ($M)	# SAT	# Servicing Mission
POP 1 (Exp)	699	250	N/A	N/A	3652	4.3	0
POP 2 (Add-On Carrier)	735	250	224	75	4342	1.5	3.2
POP 3 (Active Carrier Robotic Exchange)	735	250	267	75	4412	1.5	3.1

- **3 servicing missions are necessary to replace the entire instrument set**
- **Expendable platform is the most cost effective solution**
- **Add-On Carrier and Robotic Exchange Carrier are within 2% of each other. Too close for a meaningful conclusion.**
- **If the WTR NR cost is removed from the POP 2 and POP 3, then all three scenarios are within 8%, which is below the 10% confidence threshold defined at the beginning of the study.**

POP SERVICER COST PARAMETRIC

The graph on the facing page illustrates the impact of repair cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that if servicing the entire payload is required, then the platform replacement is more cost effective. The baseline servicing kit cost for 3 servicing missions is $626M, and the replacement cost for the Expendable and Robotic Exchange option is $699M and $735M, respectively. In addition, the launch costs for a servicing mission (3 Atlas launch vehicles) is estimated at $225M, versus the replacement platform launch costs of $250M (Titan IV). Clearly, these numbers do not give the servicing option much chance of being cost effective.

To obtain some useful comparisons with the following parametrics, a modified servicing mission has been defined. The rationale was to reduce the number of servicers required per servicing mission. This was accomplished by assuming only 2 Atlas launched servicers would be required per servicing mission. This will reduce the total payload replaced, but it will also show the the potential benefits that servicing can produce. The following modifications were assumed.

- $240M payload replaced

- $100M ORUs

- $40M Payload integration

- $60M Active Carriers

- $30M Robotic Exchange System

- $20M Platform Systems

- $10M Robotic Integration

The following parametric charts will show the potential servicing benefits of both the baseline and modified repair kits.

The $500M WTR pad modification costs have not been included in the following parametrics. It was mentioned earlier in the text, that it was not clear from the available information whether this represented actual cost to modify the WTR for Atlas launches or if the POP program would be charged the entire cost of such a modification. The decision was made to include the cost in the baseline analysis, but to eliminate it from the parametric analysis.

POP SERVICER COST PARAMETRIC
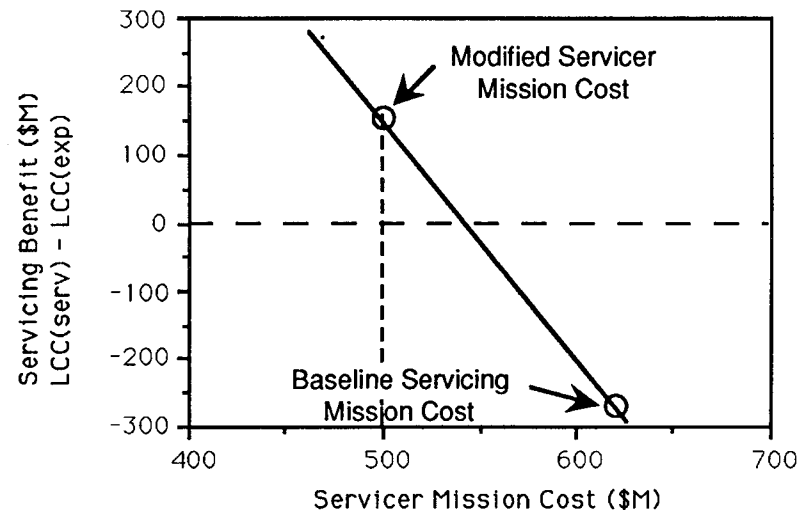
- **This chart shows the potential benefits that servicing can achieve as a function of the servicing mission cost.**

- **The Baseline servicing mission which consists of 3 Atlas launches for replacing the entire payload is not cost effective as defined (ie. $626M).**

- **A modified servicer mission which consists of only 2 Atlas launches indicates a potential $150M LCC savings. This however, does not replace all of the science payload.**

- **Further benefits can be achieved if Servicer or ORU costs can be reduced.**

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POP SUMMARY

The results indicate that servicing is not cost effective given the assumptions and baseline input costs. The total discounted LCC of the Expendable scenario is $3652M in FY89 dollars. The nearest serviceable option is $4342M, an increase of $690M. The differences in the total discounted LCC between the two serviceable scenarios (Add-on carrier and Robotic Exchange carrier) are small, approximately 1.6%.

There are three main contributors which undermine the cost effectiveness of POP servicing scenarios. The first, is that the cost to repair the platform is just as expensive as to replace it. The second, is that the costs of three Atlas launch vehicles, which are required to completely replace the payload complement, is on the same order as the cost of a single Titan IV platform launch, and thirdly, the $500M NR cost to upgrade the WTR for Atlas launches.

The parametrics shows that servicing becomes cost effective when the servicing ground rules are changed. First, the $500M WTR pad modification costs were not included in the parametrics. Then, a change in the servicing mission reduced the number of servicers required per servicing mission. This was accomplished by assuming only 2 Atlas launch vehicles and servicers would be required per servicing mission. This will reduce the total payload replaced, but it will also show the the potential benefits that servicing can produce. Although this is a very simplistic methodology, and cannot be directly related to the effect on system availability, it still provides a reasonable basis to understand when servicing POP becomes cost effective.

POP SUMMARY

- The Baseline results found that if total payload replacement is a requirement, then platform replacement is more cost effective than servicing.

- In order to replace the entire payload set, three servicers and launch vehicles are required. This drove the servicing mission costs to the same order as the platform replacement costs.

- The Add-on carrier and Robotic Exchange servicing scenarios were very close in total LCC. However, the number of Add-on carriers required for complete payload replacement cannot be accommodated by the existing platform design.

- The parametric study showed that:

  • The trend of launch, servicing mission, and platform replacement costs were highly dependant on the ratio of the servicing to platform replacement cost.

  • Servicing the POP could be cost effective if servicing mission costs were reduced.

EXPLORER PLATFORM APPROACH: SSES IMPLEMENTATION

The current EP consists of the Multi-mission Modular Spacecraft and a platform equipment deck (PED) to support various science payloads. The MMS supplies the entire EP with power, attitude control, communications and data handling. Mission specific support equipment can be mounted into available PED modules.

The First EP mission will support the Extreme Ultraviolet Explorer (EUVE) which will be launched by a Delta II launch vehicle. After completion of its mission (approximately 3.5 years), a second payload such as the X-Ray Timing Experiment (XTE) will be launched by the STS. The Explorer satellite will be retrieved, and the EUVE payload will be exchanged on-orbit with the new science payload.

It is the objective of the SSES to model the current EP architecture and to compare the servicing strategy with an expendable platform and other servicing options.

The approach is to investigate and compare the economic benefits of expendable and serviceable alternatives for the EP. One expendable and four serviceable scenarios are presented. Each option assumes initial launch of the EP on a Delta II launch vehicle with the EUVE payload. Then, whether or not the scenario is expendable or serviceable, a replacement payload like the XTE is assumed. The STS serviceable options include, Shuttle retrieval of the EP at 330 nmi, Shuttle launch to 160 nmi and OMV retrieval, and Shuttle to SSF where the new payload is integrated to the OMV. The last servicing option utilizes the Expendable Servicing System (ESS) launched on an expendable launch vehicle.

EP APPROACH: SSES IMPLEMENTATION

- The approach is to investigate STS and expendable servicing options for the Explorer Platform and compare with individual and expendable platforms.

MISSION	Science, Astrophysics
ORBIT	330 nmi, 28.5° inclined, nominal
LAUNCH VEHICLE	Delta II Initial Placement STS, Delta II Servicing
MISSION LIFETIME	Total: 11 years On-orbit: 7 years
PLATFORM R COST	$98 M
SERVICING OPTIONS	1. Shuttle-based 2. Shuttle/OMV 3. Space Station Freedom /OMV 4. Expendable Servicing system

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GENERAL EP ASSUMPTIONS

The platform and experiment probability of success data was not available. In-house assumptions were made. A P(s) of 0.92 was used for the EP bus at a 10 year mission life, and 0.96 was used for the experiment at a 3.5 year mission life.

For Modelling purposes, the platform and cumulative experiment expected lifetimes were not equal. The MMS has a 10 year design life, but not all of the experiments to fully utilize that capability have been defined, so the model executed just a single experiment replacement. The experiment titled, "Exp #2" is a simulation of the XTE payload, but no cost data was available, so a generic payload was assumed. The assumption on costs for the Exp #2 was assumed to be 1.2 times the EUVE experiment costs. Now, the implication of not modelling the Explorer Platform as a 10 year on-orbit program will not effect the accuracy of the servicing versus expendable platform comparison. The input to the SATCAV model only allows a single servicing mission definition. Therefore, the expected lifetime for both experiments was selected to be 3.5 years. The system mission lifetime ran for 7 years instead of 10 so that multiple servicing missions would not be triggered. The only implication by this modelling assumption is that since the MMS has a 10 year design life, no failures of the MMS would likely result.

The assumption was made, and accepted by MSFC, that the exclusion of Shuttle charges to NASA programs, because they are considered secondary payloads, would not accurately compare the servicing versus the expendable scenarios. This is mainly due to the fact, that most expendable satellites are launch on Expendable launch vehicles, and serviceable scenarios are serviced with the STS. Therefore, to compare scenarios with consistency, Shuttle launch costs were included. The chart to follow fully explains the Shuttle launch cost assumptions.

Some servicing versus expendable scenarios decrease the cost of the expendable satellite relative to the servicing one to try and adjust for the fact that a serviceable satellite is 10%-15% more costly to design and build. That assumption was not used for EP because MMS is an existing design that has flight history. The assumption was made that it would be more realistic of a comparison to compare all options with a common satellite bus.

GENERAL EP ASSUMPTIONS

- The experiment expected lifetime is 3.5 years
- A four year engineering development period prior to launch
- Delta II launch Vehicle for initial EP placement and expendable servicing missions
- EP spacecraft bus reliability 0.92 with a 10 year expected lifetime
- EUVE and Exp #2 reliability of 0.96 with a 4 year expected lifetime
- The NR and R cost of Exp #2 is 1.2 times that of EUVE
- The Shuttle launch charges are based on a sliding scale based on launch weight relative to launch capacity to orbit. The secondary payload approach is not considered
- The baseline EP is used for all servicing options. No platform discounting is applied, even for the expendable platform scenario.

EXPLORER PLATFORM SATCAV INPUT COSTS

The input data for the EP has been acquired from two sources. Rudd Moe, Satellite Servicing Manager, GSFC, supplied the nonrecurring and recurring data for the MMS modules and the EUVE payload. Saroj Patel, MSFC supplied the remaining data. The data was converted into FY89 dollars. It was assumed for experiment #2 that the nonrecurring and recurring cost would be increased by 20% over the EUVE payload.

For all of the serviced and non-serviced scenarios, the same platform and platform costs are assumed. This is consistent with the philosophy that whether the platform is expendable or serviceable the same platform, as currently designed, would be used. Therefore, the same launch vehicle would also be used for initial placement of the platform. This reduces the cost comparison to the cost of the servicing mission and related launch costs relative to the platform replacement costs.

The following chart itemizes the major recurring cost inputs to the SATCAV model. In the expendable EP case, a replacement platform and payload is launched instead of servicing. It was assumed that for all repair scenarios that one MMS module (C&DH) would be replaced. The C&DH was assumed since tape recorders have a limited lifetime.

The Flight Support System (FSS) consists of three cradles which serves as an on-orbit servicing platform and provides mechanical and electrical interfaces between the EP and the shuttle. The FSS is utilized only for the in-situ Shuttle based servicing scenario. In the Shuttle/OMV servicing case, it was assumed that the servicing modules would be stored on the servicer which is integrated to the OMV on the ground. In the Space Station Freedom servicing scenario, the servicing payload is transported as cargo in the Shuttle to the SSF.

The servicer and OMV costs were based on standard SSS and OMV user charges of $5M and $6M, respectively. The ESS servicer costs were derived from an internal study to develop a mission specific servicer. The $20M recurring cost and $7M NR assumes the design could draw on key technologies from previous programs such as the FTS, SSS, and OMV.

Space Station user fees were derived from in-space service and labor task estimating parameters obtained from S. Patel, MSFC. These charges include on-board EPS, DMS, Comm, astronaut services for up to 10 days, and SSF storage for up to 30 days.

Crew training costs assume such items as planning, procedures, and crew activity planning of personal and facilities. Also included, is mock-up, simulator design and construction costs required to adequately train the astronauts.

EXPLORER PLATFORM SATCAV INPUT COSTS

EXPLORER PLATFORM	NON RECURRING	QTY	RECURRING
EUVE	68.4	1	28.5
MMS	18.4	1	69.5
MACS	6.5		12.2
MPS	4.5		8.4
C&DH	7.4		13.1
SOLAR ARRAY & SADA			6.3
STRUCTURE			11.2
ODC			3.4
PROPULSION			5.1
TDRSS ANTENNA			4.0
FLT SOFTWARE			3.6
MISSION EQ DECK			2.2

SERVICING COSTS	EP2	EP3	EP4	EP5
EXPERIMENT #2	34.2	34.2	34.2	34.2
EXPLORER PLATFORM C&DH MODULE	13.1	13.1	13.1	13.1
FLIGHT SUPPORT SYSTEM	6.0	---	---	---
FSS LAUNCH SUPPORT	2.2	---	---	---
USER GSE	1.7	1.7	1.7	1.7
SERVICER USER FEE	---	5.0	5.0	22
OMV USER FEE	---	6.0	6.0	---
CREW TRAINING	5.0	5.0	7.5	---
RMS/EVA	1.5	1.5	1.5	---
SPACE STATION USER FEE	---	---	7.0	---
	63.7	66.5	76.0	71

EP BASELINE LCC RESULTS

The following chart summarizes the LCC results for all expendable and serviceable scenarios. The total discounted LCC ranged from $409M for the ESS servicing scenario to $455M for the Space Station based servicing. The expendable servicer system (ESS) was the most cost effective from a bottom line cost stand-point. However, it was only 3.5% better than the expendable scenario, and 4.9% better than Shuttle-based servicing scenario. The level of confidence in this result cannot be very convincing due to the maturity of the cost inputs for a program (ESS) that is not very well defined. A more fundamental observation for the ESS scenario is the drastic difference in servicing system launch costs (ie. Delta II versus the Shuttle launch).

This study uses a 10% confidence threshold of the difference in total LCC to make conclusive comparisons. Such a comparison can be made for ESS versus the servicing scenario utilizing the SSF. The total differential LCC is $46M, and the 10% threshold is $41M-$45M; therefore, SSF-based servicing would not be cost effective relative to expendable servicing. However, the results of the other scenarios are to close to make conclusive recommendations.

The output data indicate that 2.5 platforms are required for the expendable scenario, and that 1.1 platforms/1.3 servicing missions are required to maximize the overall availability over the 7 year mission lifetime. The interpretation of the number of platform or servicing mission, as shown below, is the modelling implementation of spreading the costs of a new platform or servicers. No modelling techniques are incorporated to stop the implementation of a new platform or servicer near end-of-life if a failure occurs. If a failure does occur near the end of the mission lifetime, then a percentage of the replacement cost is spread over the remaining mission years.

EP BASELINE LCC RESULTS

	INPUT DATA				OUTPUT DATA		
	Satellite Cost ($M)	Sat Launch Cost ($M)	Repair Cost ($M)	Servicing Launch Costs ($M)	Discounted LCC	# SAT	# Repair Missions
EP 1 (Exp)	98	55	N/A	N/A	424	2.5	0
EP 2 (Shuttle)	98	55	63.7	101.3	430	1.1	1.3
EP 3 (Shuttle/OMV)	98	55	66.5	113.6	447	1.1	1.3
EP 4 (Shuttle/SSF)	98	55	76.0	109	455	1.1	1.3
EP 5 (Exp. Servicer)	98	55	71	55	409	1.1	1.4

- **The Expendable servicer demonstrated the lowest LCC**
- **However, scenarios EP1 and EP2 and EP5 were all within 5%, which is below the established 10% confidence factor**

SERVICER COST PARAMETRIC

The graph on the facing page illustrates the impact of repair mission cost on the relative economic benefits of servicing. The differential LCC is the difference between the indicated servicing option versus a corresponding expendable spacecraft. When the differential LCC is below zero, it indicates that a non-serviced, replacement spacecraft scenario is the most cost effective.

The plot shows that servicing is marginally cost effective for the Expendable Servicing System (ESS), with a break even servicer cost of approximately $80M. The baseline servicer cost for ESS was $54M. The break even point for Shuttle based servicing is much lower than the ESS case, approximately $50M. The primary reason is the much higher Shuttle launch costs which significantly impact the total LCC.

EP SERVICER COST PARAMETRIC
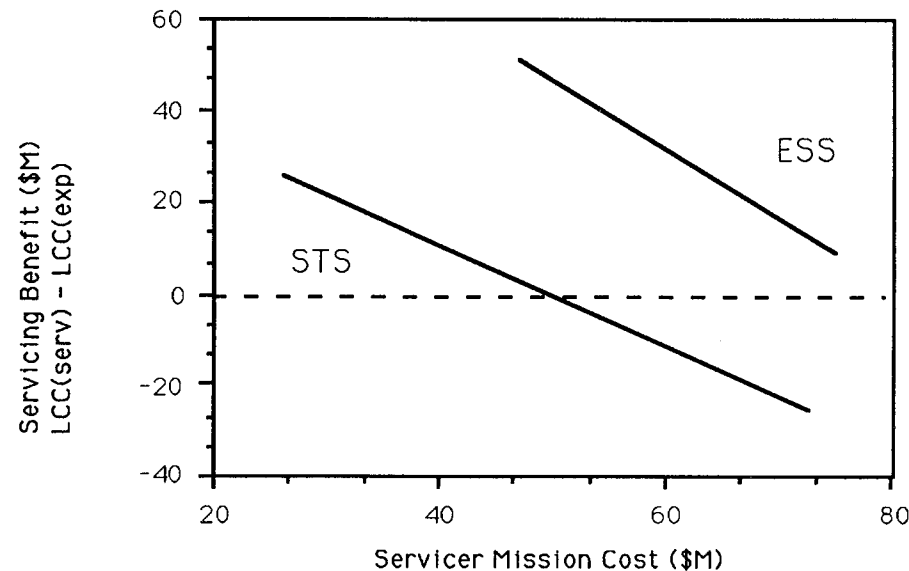
- The LCC benefits for each of the servicing options are shown as a function of EP servicing mission recurring cost by varying both the nonrecurring and recurring costs

- The ESS servicing option shows LCC savings benefits over the expendable scenario for servicing costs below $80M

- Shuttle based servicing becomes cost effective over the expendable scenario when servicing costs are below $50M.

- The lower slope STS curve results from fact that launch costs represent a higher percentage of the total LCC than the ESS case

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EXPLORER PLATFORM SUMMARY

The expendable servicer system (ESS) was the most cost effective from a bottom line cost stand-point. However, it was only 3.5% better than the expendable scenario, and 4.9% better than Shuttle-based servicing scenario. The level of confidence in this result cannot be very convincing due to the maturity of the cost inputs for a program (ESS) that is not very well defined. A more fundamental observation for the ESS scenario is the drastic difference in servicing system launch costs (ie. Delta II versus the Shuttle launch).

Typically, these studies use a 10% confidence threshold of the difference in total LCC to make conclusive comparisons. Such a comparison can be made for ESS versus the servicing scenario utilizing the space station. The total differential LCC is $46M, and the 10% threshold is $41M-$45M; therefore, SSF-based servicing would not be cost effective relative to expendable servicing. However, the results of the other scenarios are to close to make conclusive recommendations.

The parametric analysis generated some important, but not terribly surprising trends. It was shown that as servicer costs decreased, the benefit of servicing increased. They also showed that as the platform cost increased, the benefit of servicing increased. The launch cost parametric indicated that if the Shuttle launch costs could be reduced by 15%, then a break even point for Shuttle-based servicing would occur relative to the expendable platform.

Although it was stated that no conclusive recommendations could be made to rank the top three scenarios, the parametrics do allude to a few important observations. First, with the current Shuttle costs it is almost impractical to achieve a 10% servicing benefit over the expendable scenario. And second, the only reason that the ESS trends are so encouraging over the Shuttle-based servicing option, is because of the launch cost disparity. So although the parametric trends indicate where the break even points appear, the value of the Shuttle launch costs are the single most influential factor as to how the results appear.

EXPLORER PLATFORM SUMMARY

- The total LCC for all the EP scenarios ranged between $409M and $455M, a 10.6% difference. The 3 most cost effective scenarios were within $21M; the Expendable servicer ($409), the Expendable platform ($424M), and the Shuttle based servicer ($430M).

- The results do not indicate a clear advantage for either the servicing or expendable scenarios. However, the data supports the conclusion that SSF-based servicing is not cost effective, and has a much higher probability of increased costs if on-station delays occur.

- The SATCAV model results are highly dependent on reliability data to estimate failure probabilities. Since no data was available, the accuracy of the results is suspect. However, the relative difference is still representative since most of the same hardware was assumed for all mission scenarios.

- The parametric study trends indicate that as repair and launch costs are reduced, the benefit of servicing the platform increases. And as the total spacecraft system cost increases, the benefit of servicing also increases, as long as the servicing costs are significantly lower than spacecraft replacement cost.

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NEW DRM COMPARISON TREND

This summary chart comparing the three DRMs is an attempt to quantify a parameter that will be representative of new servicing missions. In sifting through the mass of data that this study generated, we felt that the ratio of servicer with launch costs to replacement satellite with launch costs captured the most influential parameters of a typical servicing mission. The differential LCC cost is the difference between the serviced spacecraft LCC and the unserviced spacecraft LCC. The data points for each DRM represent the scenario of greatest servicing benefit. In the case of the POP, two cases are shown since the baseline cases did not show any servicing benefits. The modified POP scenario represents a servicing mission in which not all of the science payload is replaced. For more detail see the POP parametric section.

The chart indicates that for systems with ratio value of less than 80% a servicing benefit exists. The lower the percentage of servicer to replacement cost, including launch costs, the greater the potential servicing benefit.

An attempt was made to expand this chart to include data from task 1. Although the overall trend was consistent with the new DRMs, the scatter in the data was quite large.

NEW DRM COMPARISON TREND
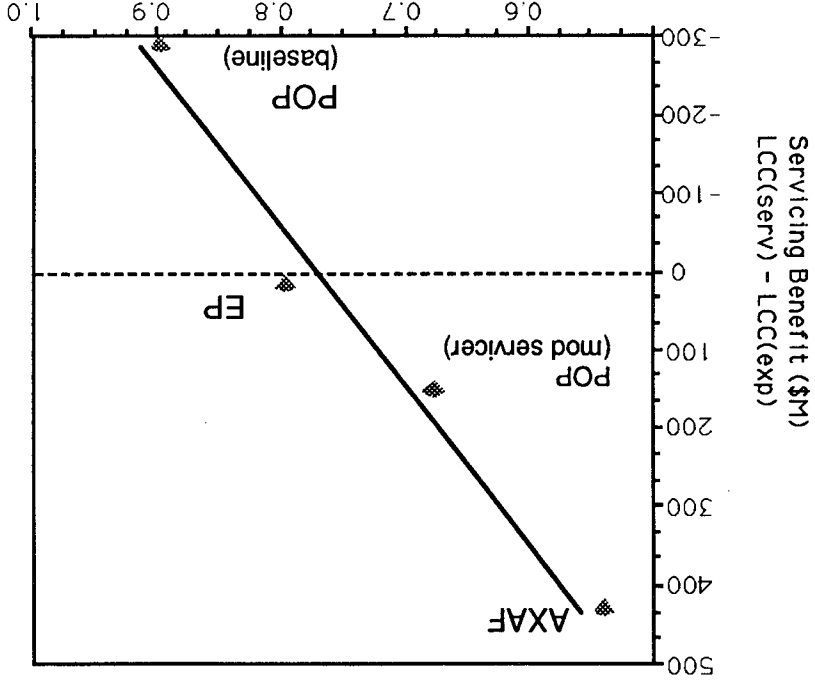
Servicer w/Launch Cost-to-Spacecraft w/Launch Cost Ratio

- It was found that the ratio of servicer to replacement cost, including respective launch costs, is a good parameter to indicate the potential benefit of servicing.

- The approximate break even value of this parameter occurs between 75-82%. The lower the percentage of servicer to replacement cost, the greater the potential servicing benefit. This trend should be considered a good indicator for the design of new servicing missions.

SSES SUMMARY

- Task 1 reviewed 14 old NASA servicing studies, and analyzed them with a common set of servicing and economic parameters.

  - The average savings in life cycle cost due to servicing is 19.6%.

  - The results of the 1989 analysis track previous results, thus validating the SATCAV model for new DRMs.

- Task 2 and Task 3 defined 3 DRMs: AXAF, EP, and POP. Each DRM examined the Expendable satellite versus Expendable Servicing, Shuttle Servicing and SSF Servicing. Shuttle servicing to polar orbit for the POP was not an option.

  - The data supports the conclusion that SSF-based servicing is not cost effective.

  - The servicing window of opportunity from SSF is small, and the waiting period before nodal alignment is large. This results in longer lead time planning to ensure window of opportunity is not missed, thus increasing servicing related costs.

  - Shuttle launch costs, as calculated, were significantly higher than the corresponding expendable launch vehicle. This factor greatly reduced any potential servicing benefits.

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SSES SUMMARY (con't)

SPACE SYSTEMS/ **LORAL**

DRM RESULTS

- **AXAF:**

  - All of the considered servicing scenarios showed to be cost effective over the expendable AXAF scenario. The expendable servicing system resulted in the lowest LCC

- **POP**

  - Platform servicing was not cost effective if total payload replacement is a requirement. A modified servicing strategy was defined to investigate when POP servicing would be cost effective.

- **EP**

  - The Expendable servicer demonstrated the lowest LCC. However, the Expendable servicer, Shuttle based servicer (FSS), and the expendable satellite scenarios were all within 5% in total LCC.

15. Supplementary Notes

16. Abstract

Previous studies have shown that satellite servicing is cost effective; however, all of these studies were of different formats, dollar year, learning rates, availability, etc. Therefore, it was difficult to correlate any useful trends from these studies. This study was initiated to correlate the economic data from our studies into a common data base, using a common set of assumptions. A selected set of existing funded programs were then analyzed to provide an independent analysis of the servicing options and potential economic benefits.

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