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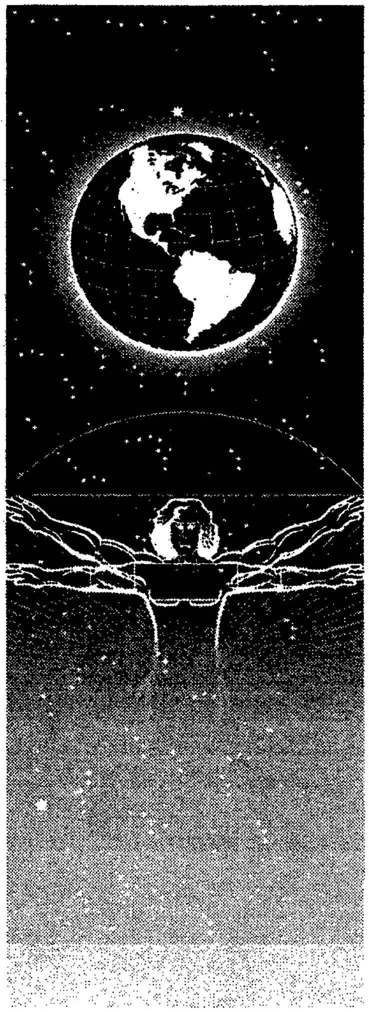

UNITED STATES AIR FORCE RESEARCH LABORATORY

Logistics Requirements for Space: On-Orbit Servicing (OOS)

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Final Report for the Period May 1998 to January 2000

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

ALBERT S. TORIGIAN, Lt Col, USAF
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Due to the unique mission requirements and anticipated costs of future satellites, the Air Force is investigating servicing its space assets on-orbit. This project examined current trends and technologies enabling on-orbit servicing (OOS), while concentrating on the logistics considerations for on-orbit support concepts. A cursory methodology to assess the need for OOS during acquisition is described. Technical and other limitations for OOS are identified. Satellite components that have the highest failure rates, low reliability, and components that may be expended prior to the end of system life are identified. Design reference missions are defined for several notional OOS missions.

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PREFACE

As the Air Force transitions to an aerospace force, the reliance on satellites and their capabilities has become increasingly critical to our warfighting capability. Due to economic and strategic necessity, future satellites may require fluids to be replenished or components to be repaired on-orbit. In fact, several Air Force satellite programs are considering on-orbit operations as support concepts for their systems. The term On-orbit Servicing (OOS) is often used to describe the activities associated with physically assessing or improving the state of a satellite in space. OOS ranges in complexity from remotely inspecting a satellite to replenishing its consumables to system upgrades and ultimately on-orbit repair. On-orbit servicing may fundamentally change space sustainment. No longer will entire satellites need to be replaced when they run out of fuel or need a component upgraded. This report examines current technologies and trends supporting OOS and the logistics implications that OOS may have on future space systems.

The principal investigator for this study was Fred R. Spates, PRC Corporation, Contract Number F04701-95-D-0013. This work was performed for AFRL/HESS and Space and Missile Center Plans and Programs Office (SMC/AXLX) under the Space Systems Acquisition Support (SSAS) II, Delivery Order 039, Logistics Requirements for Space.

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INTRODUCTION

The purpose of this study is to survey the Research and Development (R&D) technologies required to enable on-orbit servicing (OOS) of Air Force space assets and to assess the impact on space logistics of including on-orbit spacecraft servicing into logistics planning and operations. The overall goal is to provide the Air Force Research Laboratory, Deployment and Sustainment Division (AFRL/HESS) with a roadmap of technology developments and suggested demonstrations to validate OOS strategies for building a space logistics capability to accommodate Air Force missions.

OOS is work in space. The work, performed by men, machines, or a blend of both, relates to space assembly, maintenance, and servicing (SAMS) to enhance the operational life and capabilities of satellites. Emphasis in this research effort has been on the robotic servicing of Air Force next generation spacecraft, recognizing that the technology and strategies for OOS were developed in the early 1980's with National Aeronautics and Space Administration (NASA) leadership in the manned servicing of scientific satellites such as the Solar Maximum Mission (SMM) and the Hubble Space Telescope (HST).

The United States Air Force (USAF) initiated OOS spacecraft design studies, operational analysis and trades, and cost studies in the early 1980's. Over the last 10 years, Air Force and NASA ideas of on-orbit servicing equipment, infrastructure architecture, and needed technologies have started to merge in several areas – spacecraft modularity and design standardization are examples. While OOS is a relatively new element in the thinking of effective space operations and logistics, it is nevertheless appropriate to give increasing attention to the concept of spacecraft servicing as a possible way of decreasing the life-cycle costs of major programs.

Scope

This report addresses three major topic areas: development of on OOS decision support methodology; identification of consumables for candidate spacecraft; and development of an OOS concept of operations. In addition to these three areas, three additional areas were inserted into the report to enable completeness of results: gathering and categorizing mission, operations, spacecraft design, and infrastructure requirements; conducting preliminary maintenance analysis of candidate spacecraft; and development of logistics requirements and concepts. The interactive flow of this effort is shown in Figure 1.

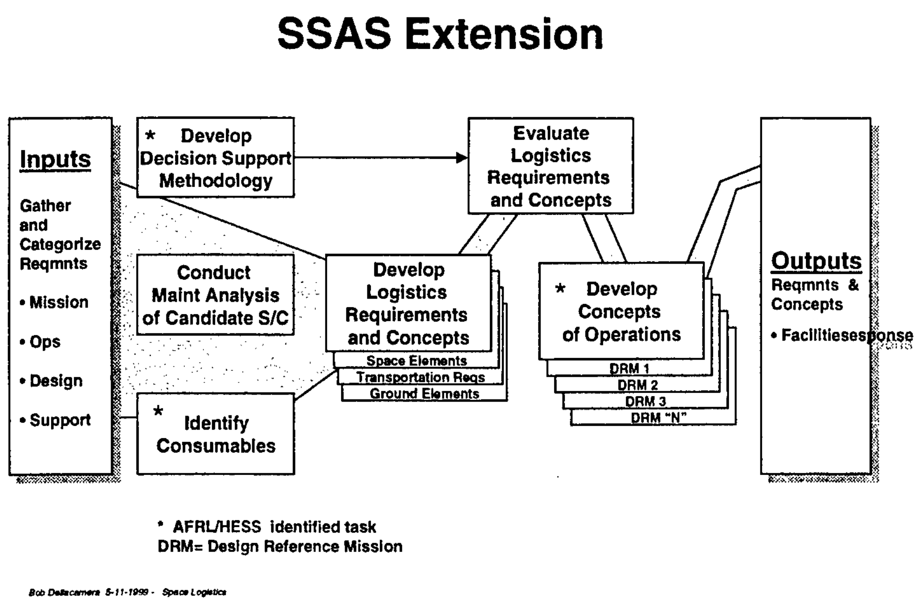


Figure 1 – Space Systems Acquisition Support (SASS) Study Plan

The development and sustainment of valuable space assets (Department of Defense (DOD), NASA, and commercial) requires that the assets be logistically supported by the timely assessment and improvement of their performance status. A broad range of maintenance and servicing techniques are potentially available to spacecraft designers and operators that could increase the spacecraft orbit lifetime and capability. This report highlights some of the future paths to sustainment that may be worth developing in the near and far term, which will impact military space systems for the next 15 to 20 years.

On-orbit servicing of Air Force space assets is an evolving process. Many space hardware items and operational techniques are presently in place to start extending the orbital performance and lifetime of Air Force, NASA, and commercial satellites. There appear to be no "show stoppers" as far as technologies, to the implementation of space logistics and a support infrastructure.

However, there are certain technology areas such as telerobotics hardware and control, autonomous spacecraft operations, and simulation and modeling techniques that, if developed to a higher level, will enhance or enable the eventuality of on-orbit servicing and space logistics. Technology needs are addressed in this report and a twenty-year prognostication was made.

AFRL is uniquely suited to conduct the identification, development and demonstration of servicing technologies. Attention to technology advances will bring new items or higher technology readiness levels enabling potential users to implement them more easily on their programs.

Figure 2 shows the relationship between technology development sources and AFRL, as well as with servicing, logistics, and infrastructure space operations. New and developed technology enables or enhances the logistics process, infrastructure and the servicing capability in two ways. First, better technology usually results in better economics when applying satellite servicing. This drives program costs down. Second, more program users or customers will opt for space logistics support, as the infrastructure becomes available and reliable.

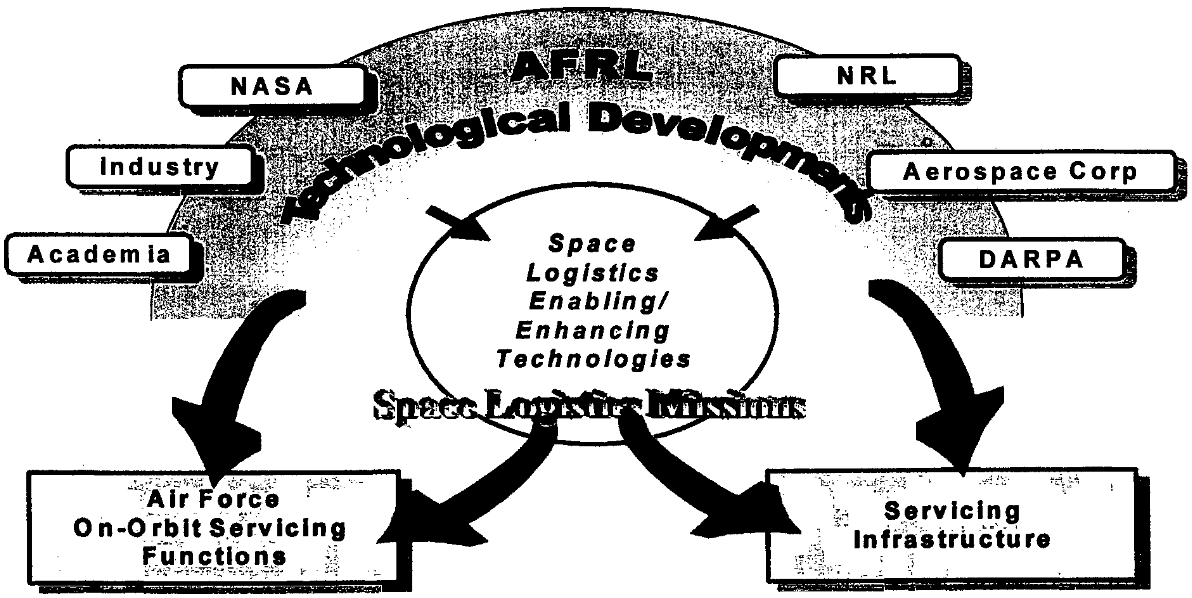


Figure 2– Relationship between Technology Development Sources and AFRL

A Servicing/Logistics Technology Plan needs to be generated that should contain a time-phased list of prioritized technology objectives to be attacked in the near future. This plan, which should be based upon user needs, provides the “big picture” so that AFRL can focus its resources on meaningful developments in an organized manner. The Plan should also identify longer-range needs so AFRL can plan for additional resources required to effectively develop new technologies. A document such as this Plan can be used to manage the R&D in this area and promote AFRL’s developments to potential users.

DEVELOPING A DECISION SUPPORT METHODOLOGY

This section attempts to generate an analytical model for use by space system developers, operators, and owners to answer the questions – **Should a specific spacecraft be designed to accept on-orbit servicing?**

In addition to a decision model, results of this effort can be used to evaluate logistics support concepts and methods of implementation. Some models on this subject already exist. This study effort selected the best features of existing models, generated new features, and packaged them into a standard analysis methodology that will work for various interested government agencies – especially the Air Force.

Approach

The strategy employed for this effort was to collect and analyze the inputs to a decision methodology structure for on-orbit servicing. Then the logistic support inputs and infrastructure requirements were determined from eight Design Reference Missions outlined in the section entitled Developing a Concept of Support Operations. The above was integrated into a Servicing Decision Methodology.

Because servicing costs is such a major part of the decision methodology, a life cycle cost model was generated that could be used generically or applied to specific programs.

Finally, serviceable spacecraft and servicer spacecraft design requirements were derived, again using the Design Reference Missions as important considerations, and a time phased technology status constructed to show the road map of servicing evolution.

This effort was broad in the scope of topics relevant to developing an OOS decision support methodology. The two factors that have the most influence on incorporating serviceability into a spacecraft program are the cost of servicing and the military mission need to improve a spacecraft capability and/or to extend its orbital lifetime. Therefore, economics and technology were investigated as the driving inputs to the methodology format.

Potential Benefits of On-Orbit Servicing:

On-orbit servicing could result in certain benefits to space programs. A list of potential benefits is shown below. Many of these tasks are program dependent. The degree to which benefits apply to a specific satellite program such as the Global Positioning system (GPS) and the Space Based Laser (SBL) depends on the satellite's mission, the national needs involved, and the servicing cost versus the value added to the satellite after it has received servicing.

- ***Extended Satellite Lifetime*** – Spacecraft modular designs will allow rapid on-orbit payload, subsystems, instruments, and component change-out at planned or at failure points in the mission, thus extending the useful lifetime of the spacecraft. On-orbit resupply of expendables (fuels, coolants, film, and batteries) will allow mission continuation. On-orbit final testing/checkout before release of the spacecraft by the launch vehicle will reduce the effects of "infant mortality" problems as experienced by the Landsat, Leasecraft, and Seasat satellites. The explosive rate of advancement in the early 1980s of payload electronics is slowing down. This slower rate of obsolescence is generating a need to get a longer lifetime out of a satellite. Another driving factor is the relative high costs of many of these satellites, further emphasizing the need for longer lifetimes.

- ***Enhanced Science from Satellite Payloads*** – Increased life of expensive Low Earth Orbit (LEO) scientific satellites and platforms requires on-orbit maintenance and servicing to get more science out of a satellite system. Typical experiment and instrumentation lead times will run 5 to 7 years in the future compared to the current 2 to 4 year on-orbit life. Retrieval (harvesting) and restocking of materials processing products from free flyers will allow long durations for experiments to be conducted on micro-gravity materials processing in space science. Payload or subsystem modules change-out at planned points in a space science program to introduce technology updates into the satellite will expand the scientific scope of the project. This is pre-planned product improvement. An example of this is HST, which has had its lifetime extended twice through servicing to allow for more scientific observations.

- ***More Mission Flexibility and Availability*** – Modular spacecraft design coupled with orbital servicing will allow easy change-out, repair, and upgrading of subsystems (power supply, communications, data handling, propulsion, etc.), components (solar arrays, booms, antennas, sensors, etc.), and payloads (optics, transponders, detectors, etc.). The changed modules could expand or alter mission objectives, scope of data acquired, or quality of information processed. Space replacement modules could be carried in the Space Shuttle on an orbital replacement unit carrier or stored at the Space Station or a space-based servicing depot.

- ***Improved Performance and Reliability of Critical - Periodic*** servicing will keep satellite performance at peak levels. Such planned on-orbit testing and servicing will be used to: calibrate payloads, trim thermal control on-orbit prior to spacecraft release from Shuttle, clean optical, solar array, and sensor surfaces, and ensure deployment of booms, antennas, and solar arrays. This will improve the performance of the space system and enhance mission reliability of critical components.

- ***Enhanced Military Mission Assurance*** – Orbital mechanics coupled with the demand for mission continuity may require on-orbit servicing with or from space-based facilities. Critical mission strategic operations, availability, and timing could depend on orbital servicing support. Consumable depletion time and the replacement interval impact overall constellation operations. As with NASA satellites, product improvement via modular replacements on military satellites at planned intervals could aid mission assurance.

- ***Reduced Life-Cycle Costs of Large, Long-Term Programs*** – Up to 30 percent of current spacecraft design is redundant to ensure reliability. We can probably reduce this factor in half with on-orbit servicing designed into the vehicle. Planned or contingency servicing costs may be lower than satellite replacement (fix the old rather than replace with a new spacecraft). Reduced space system ground integration and test time and cost is possible through modularity and standardization which would be incorporated into a serviceable spacecraft. On-orbit pre-ejection testing could reduce total system test costs. The realistic environmental testing in space could lower costs for appendage deployment qualification, command and data management operational assurance, electric power flow, propulsion readiness, thermal balance, and payload performance. The number of space and/or ground- based replacement spare satellites per constellation could be reduced and the number of launches during fleet operational lifetime could be reduced.

Decision Assumptions

The following assumptions strongly influence servicing decision methodology:

- ***Military Programs*** – The Air Force implementation of strategic programs (SBL, Space Based Radar (SBR), Next Generation Milstar and GPS, and possible operational micro satellites) will drive certain space assembly, maintenance, and servicing requirements; influence the space servicing architecture; and dominate the logistics architecture. In fact, a program such as SBL could be the DOD forerunner for space-based servicing.

- ***Launch Systems (Other than Space Shuttle)*** - Launch systems such as the Delta, Atlas, Titan, Evolved Expendable Launch Vehicle (EELV), reusable launch vehicle, Pegasus, Taurus, and Space Maneuvering Vehicle, could be available to support on-orbit servicing missions.

- ***Space Shuttle*** – The reusable National Space Transportation System, the Space Shuttle, built by Rockwell International under contract with NASA, will continue its successful performance of space missions. The next generation of Shuttle development will become a program reality resulting in block changes to the Shuttle with increased payload weight-to-orbit capability, lower launch and operations costs, longer on-orbit stay times, and better crew accommodation facilities for conducting servicing tasks at or near the Shuttle. The use of the Space Shuttle for on-orbit servicing would be only after DOD missions were manifested and whenever Space Station flights did not take precedence.

- ***Space Station*** – The International Space Station (ISS) program, now under development by NASA and a large industry contractor team, will be partially operational in space in the year 2000. The ISS, however, is going to benefit from satellite servicing itself with aid from the Shuttle, the Russian Progress and Soyuz vehicles.

- ***Orbital Maneuvering Vehicle (OMV)*** – An OMV is projected to be operational before 2007 to support space servicing missions into the first decade of the next century. It will strengthen the total capability of the National Space Transportation System (NSTS) and the Space Station. It is a vital link in the evolution from specialized spacecraft to flexible flyers.

➢ ***Astronaut Extravehicular Activity (EVA) Space Suits*** – NASA currently has upgrades planned for the next generation of astronaut spacesuits and related equipment. On-orbit EVA operations will include, but not be limited to, activities such as:
   - Satellite assembly, maintenance, and servicing on planned and contingency missions
   - Installation, removal, and transfer of Space Station or servicing warehouses, payloads, and satellite orbital replaceable units
   - Inspection and remedial repair and replacement of structural elements, solar panels, and thermal/meteor protective panels
   - Large structure erection and assembly

➢ ***Servicing Infrastructure*** - The space-based and ground servicing infrastructure total inventory will evolve with customer requirements and mission needs. Logistics architecture will be planned and incorporated into this infrastructure.

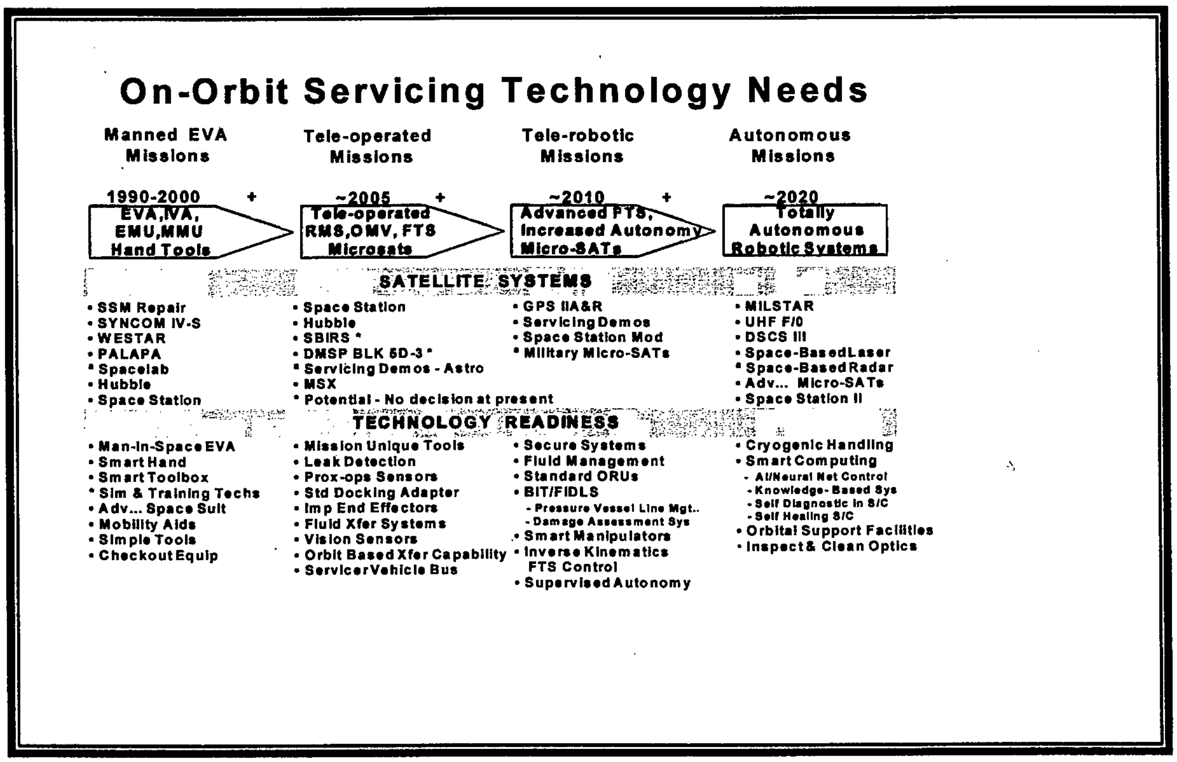


Figure 3 – On-Orbit Servicing Technology Needs

➢ ***Transportation Costs*** – since the largest portion of space servicing costs is the ground-to-orbit transportation costs, it is central to the economics of space operations that launch costs be reduced over the next fifteen years. It is therefore assumed that some parts of the National Launch System will be developed with a main thrust directed at lowering the dollars per pound to orbit costs.

➢ ***Manned/Robotic Structure*** – The near term space servicing activities (now to 2005) will feature labor intensive (manned EVA) on-orbit operations in low Earth orbits (LEO); but automation and robotic devices will gradually phase into mission operations. After the year 2010, space servicing will expand to Geo Synchronous Orbit (GEO) with heavy use of telerobotic hardware and automated work sites. 2010 is an arbitrary date. The phasing from manned to robotics dominated servicing missions will occur over about 5 years (2000 to 2005). However, even in the far term (after 2005) there will always be missions where human presence will be required to perform certain functions. Figure 3 illustrates the above.

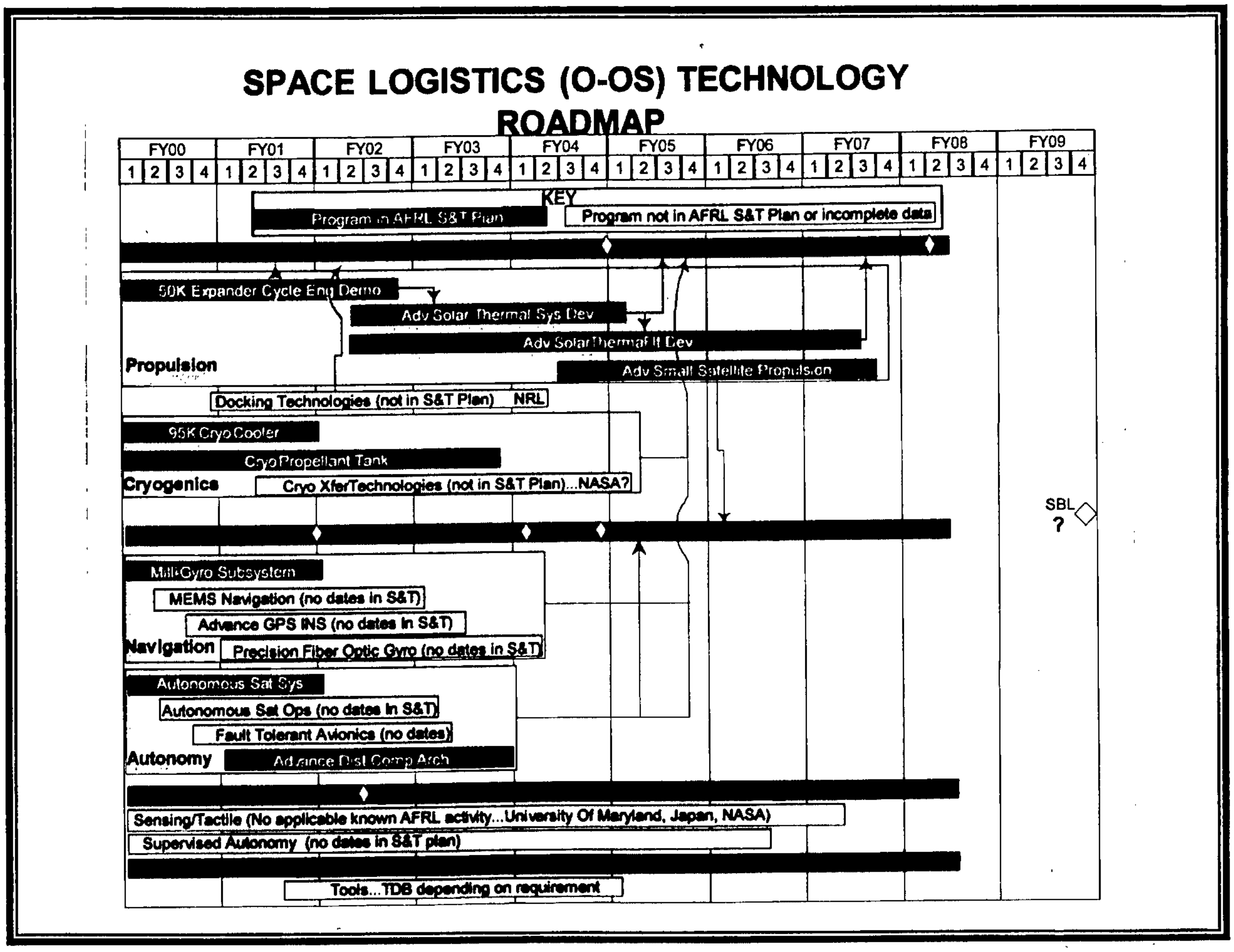


Figure 4 – Technology Roadmap for OOS

➢ ***On-Orbit Servicing Research Flow*** – Figure 3 is an assumption of how on-orbit servicing missions, robotic development, satellite systems, and technology readiness could flow from the present time to the year 2010. A technology road-map of the key research items is shown in Figure 4. Programs in the 1999 AFRL Science and Technology (S&T) Plan are shown in green; programs not in the 1999 S&T Plan are shown in yellow.

Servicing Decision Considerations

Planners and project managers will want to consider a number of parameters in arriving at a decision to implement or not implement space assembly, maintenance, or servicing. The important parameters are:

- ***Necessity*** – Is it absolutely essential for mission success?

- ***Satellite Mission Durability*** – This consideration is the "sine qua non" of servicing. If the basic mission of the satellite becomes obsolete before any benefit or extended service life is realized, then servicing to extend life has no merit.

- ***Required Near-Term Investment*** - It appears that, in the long term, space assembly and maintenance is highly cost-effective, however, there is a near-term question of affordability. There will not be offsetting cost savings during the buildup to an operational capability, and a national decision to invest in satellite servicing in the future has to be made.

- ***Guaranteed Space Assembly and Maintenance Availability*** – The servicing system must be sufficiently robust so there is no significant interruption in the availability of servicing or maintenance due to limited scope casualties.

- ***Total Life-Cycle Costs/Cost Effectiveness*** – Total life-cycle cost of a particular system may well be lowered if space assembly and maintenance equipment user charges are set artificially low, but the national viewpoint must consider full cost recovery for the development of the user equipment to properly assess cost-effectiveness.

- ***Technical Feasibility*** – We must satisfy ourselves that the planned equipment and mission scenarios are technically achievable. Assessment to date indicates that no fundamental enabling technology remains to be "invented".

Trends

Several trends provide impetus to servicing implementation because they make basic mission operational cost-effectiveness easier to achieve. These are:

- ***Satellite System Cost and Complexity*** - The trend from the earliest days has been for more complex, demanding missions, with increased spacecraft weight and complexity as a consequence. If the trend continues, basic affordability may come into question.

- ***Transportation Costs and Launch Costs*** – The trend has been towards a steady increase. The development of new systems such as the Heavy Lift Launch Vehicle, EELV, X-34, SMV, and STS II may reduce launch costs, but that is by no means guaranteed. The higher the costs of transportation, the more attractive the decision to service with space-based equipment becomes.

- ***Guaranteed Access to Space*** – If SAMS users must worry about whether access to their systems for servicing may be interrupted for lengthy periods, they might opt to pursue a different strategy and pay premium price for "silent spares" on-orbit.

- ***Non-DOD Users/Commercialization*** – NASA has, thus far, been the only user agency for satellite servicing and has demonstrated the operational feasibility and, to some extent, the economic benefits. The beginnings of commercialization can be seen, and as the lure of profit spurred the industrial revolution of the 18^{th} and 19^{th} centuries, so will the lure of profit spur the industrialization of space.

Key Cost Drivers

A number of items drive the total cost of any space system. Some operate uniformly on all applications to raise costs and are not discriminators in the decision relative to servicing. Other factors are both total cost drivers and cost discriminators, in that they act differently depending on the strategy chosen. The ten major cost drivers are:

- ***Satellite system complexity, size, and weight***
- ***Infrastructure costs***
- ***Infrastructure amortization base***
- ***Number of servicing events per mission***
- ***Transportation costs***
- ***Satellite replacement costs***
- ***Orbital Replacement Units (ORU) Costs (% of satellite)***
- ***Training costs***
- ***Technology development costs***
- ***Satellite weight/Cost penalties***
    - ***Reliability***
    - ***Serviceability***

Decision parameters, trends and key cost drivers are shown in Figure 5.

A top level CWBS for SAMS functions was generated. The upper two levels are shown in Figure 6. This CWBS identifies the cost cells associated with the major components of the Space Servicing and Logistics system. It differs from the CWBS shown in the companion Logistics Requirements Technical Operating Report in that the CWBS in the Logistics Requirement Report was developed to support the AFRL's On-Orbit Support concept developed by AFRL (Madison, 1999). As the system matures, some of the cells may shift from their present Figure 6 location and be placed under another major component. Note that the system is very large in number of hardware items and scope of operations. That is one reason the total OOS program will be created over a 20 year time period.

Decision Parameters
Mission Necessity
Mission Durability
Spacecraft Life Cycle Costs (LCC)
Infrastructure Investment
Servicing Equipment Availability
Launch/Transportation Availability
Technical Feasibility
Spacecraft Lifetime & Servicing Intervals

Key Cost Drivers
Infrastructure Costs
Infrastructure Amortization Base
Number of Servicing Events per Mission
Transportation Costs
Satellite Replacement Costs
ORU Costs
Training costs
Technology Development Costs
Satellite Weight/Cost Penalties

Trends
Increased satellite system cost and complexity
Increasing satellite operational life
Increased launch/transportation costs

Figure 5 – Satellite On-orbit Servicing Considerations

Cost Work Breakdown Structure (CWBS)

When completed, the CWBS will define the space assembly, maintenance, and servicing total system as it refers to all hardware, software, facilities and associated personnel and support services required.

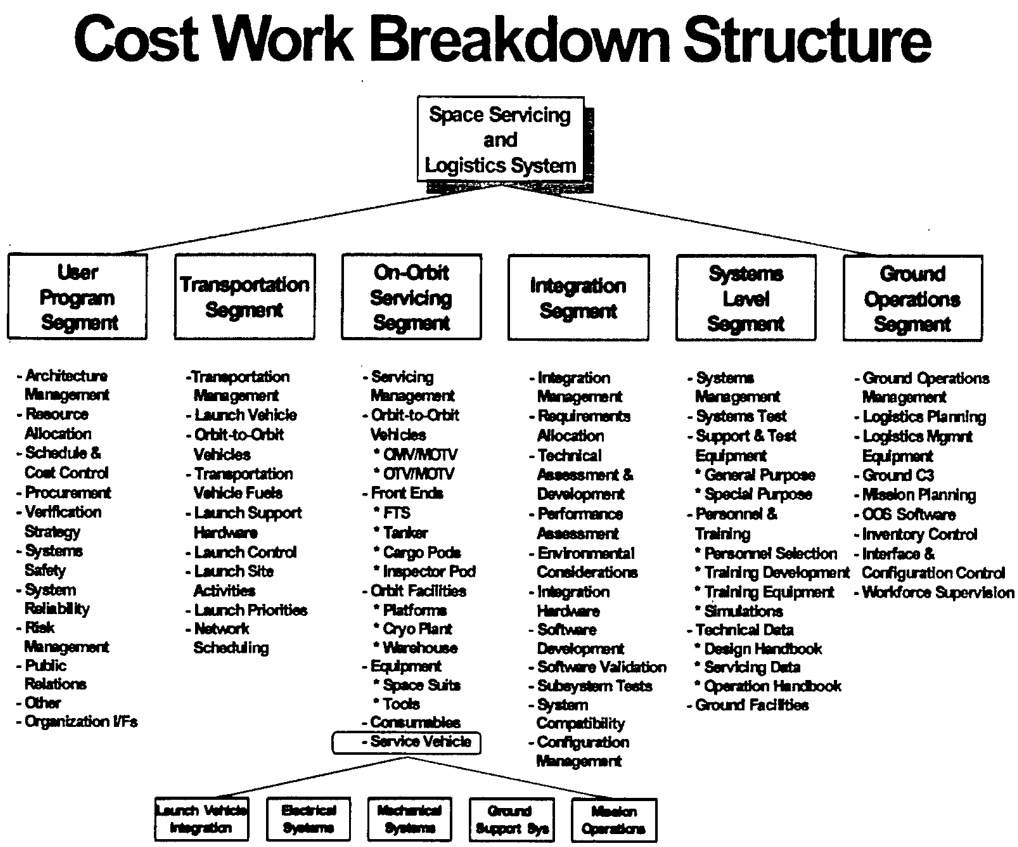


Figure 6 - Cost Work Breakdown Structure

Decision Model

In essence, the summary servicing decision model is simple. It integrates the above mentioned requirements, benefits, assumptions, decision parameters, trends, Design Reference Missions (DRMs), cost drivers, and WBS into a schematic structure shown in Figure 7.

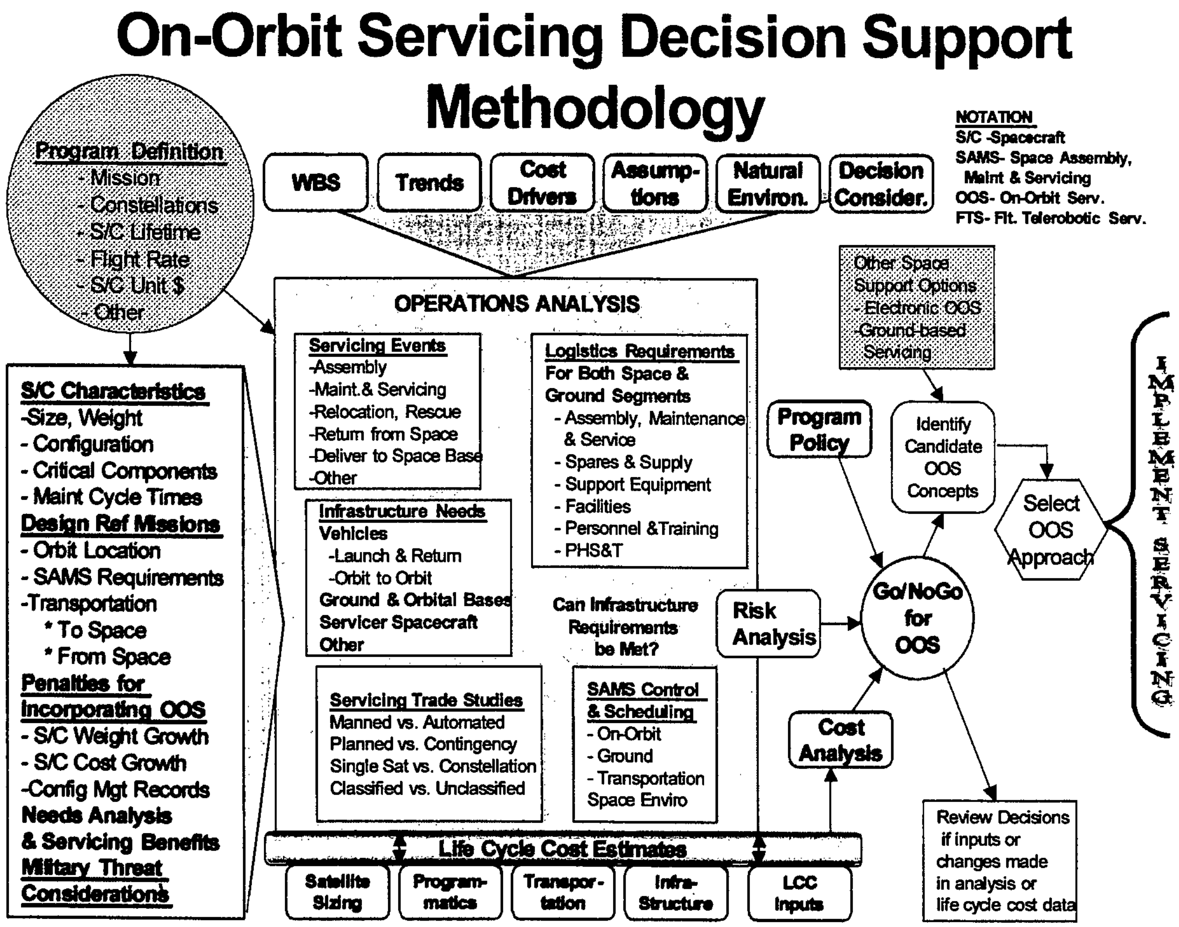


Figure 7 – Decision Support Methodology

Because many model inputs are qualitative, the model does not lend itself to a strict mathematical exercise. The many subjective inputs and assumptions are not in concert with the precision of a hard go or no go decision that one gets from the calculus of all number ingredients. Therefore, the model will need to apply engineering judgements and programmatic realities to the decision outcome.

With a go decision reached from model manipulation for a specific on-orbit servicing strategy, the decision will need to be run through a series of analysis that evaluate concepts such as: other on-orbit servicing strategies, risk, and policy compliance. This strategy will then compete with alternatives to such as: replace the spacecraft, use electronic work around and spacecraft redundancy, on-orbit spacecraft sparing, or ground based servicing.

To keep Figure 7 easier to read, we did not show all the inherent and feed back loops in the final decision process. It is the intent that the methodology as shown to be considered as generic to a wide range of military space satellite systems, i.e. communications, surveillance, early warning, navigation, weather, space science, and technology testing. Specific program offices such as SBL and GPS, to name two, will add their inputs to the model.

In summary, the methodology model allows the two major inputs, servicing costs and servicing benefits, to come together in a series of analysis and trades to allow decision-makers to have the full range of facts. If the decision is to not develop a specific space asset for servicing, the decision may not necessarily be final and can be reviewed if model inputs change.

Life Cycle Cost (LCC) Model

The one input to the decision methodology that has the most impact on SAMS implementation is the satellite program life cycle cost. Accordingly, a LCC overall block diagram was generated as the major input to the decision model. It is shown in Figure 8. The interaction of the various methodology elements, called modules, is indicated in the figure.

In developing the LCC block diagram, various cost models generated in the past 10 years were researched [1, 2, 3, 4]. Most of the servicing cost analysis work was performed from the 1983 to 1990 timeframe, the time when on-orbit servicing emphasis in DOD and NASA was at its peak. Not much has been published in the 1990s.

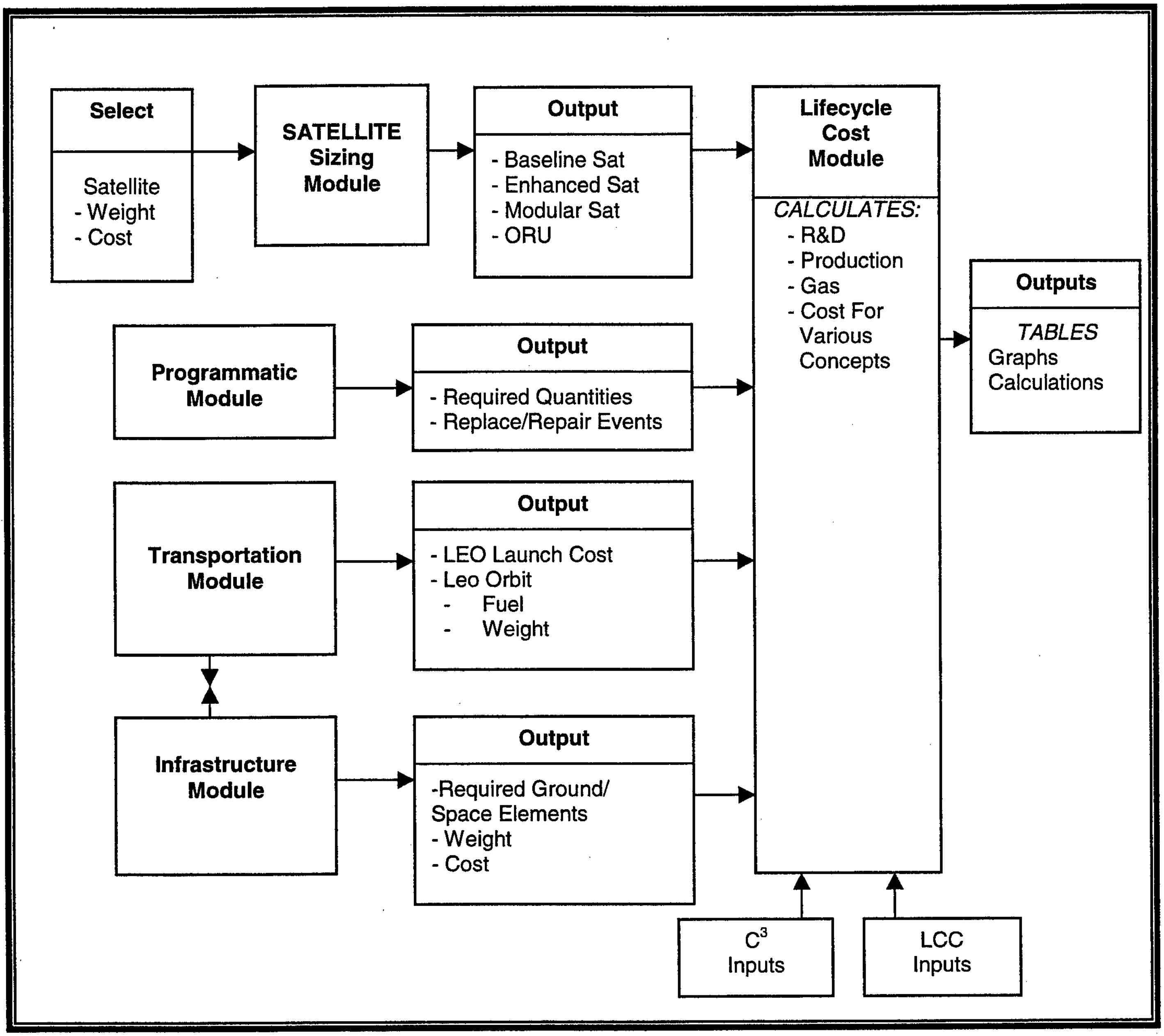


Figure 8 – Life Cycle Cost Model

- **Satellite Servicing Module** – The beginning step is to identify the satellite total cost (first unit cost) and total dry weight of the baseline satellite. Thus the user or analyst describes this information before applying the comparison methodology. Given this data, the user applies adjustments from the satellite-sizing module to obtain the cost (first unit) and weight of the baseline, enhanced reliability, or modular satellite at a more detailed subsystem level. This sizing module also provides the cost (first unit) and weight of the ORU. A diagram of the satellite-sizing module is shown in Figure 9. Its input is the total dry weight and first unit cost of a particular satellite using today's non-repairable or non-modular technology.

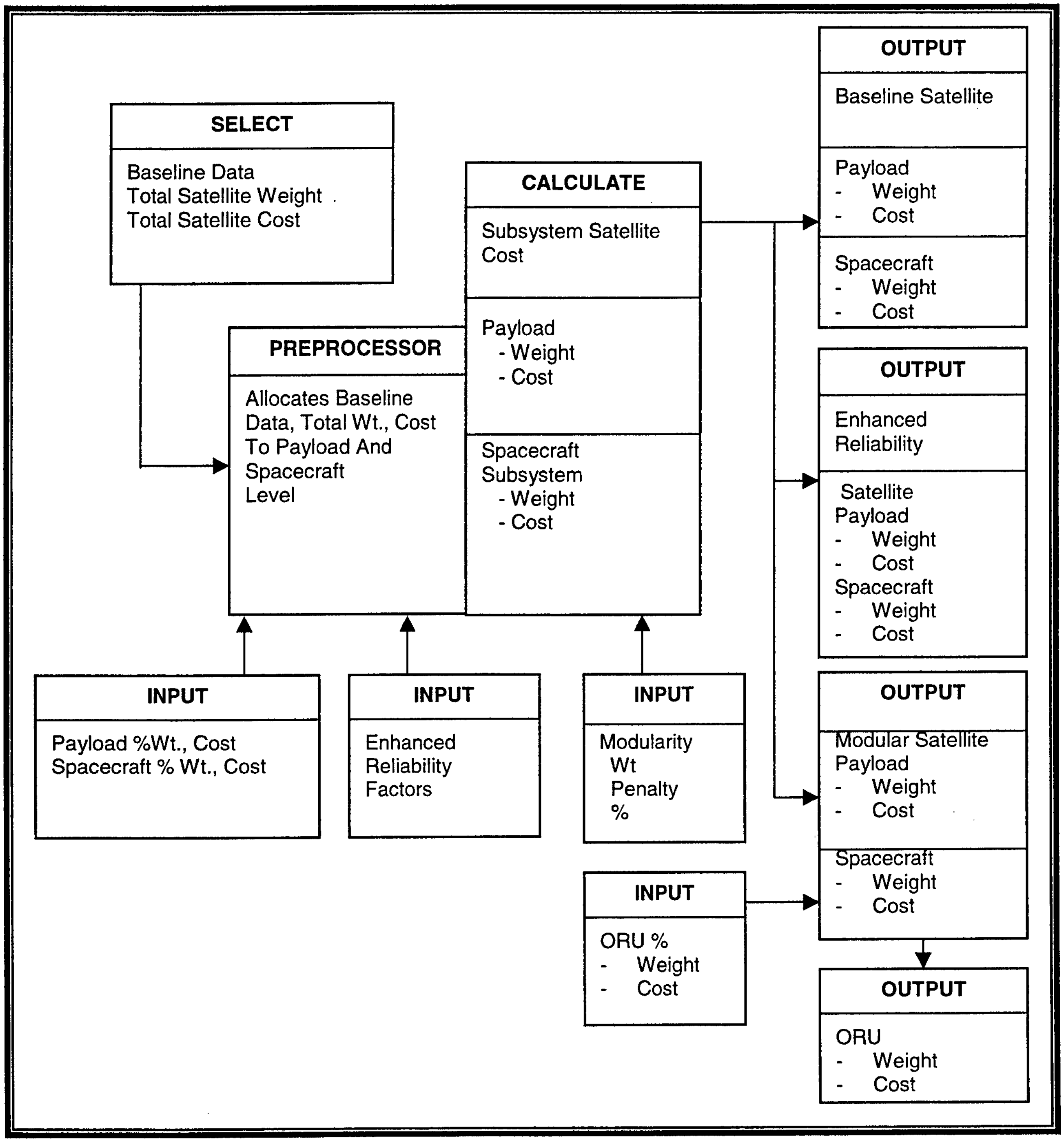


Figure 9 – Satellite Sizing Module

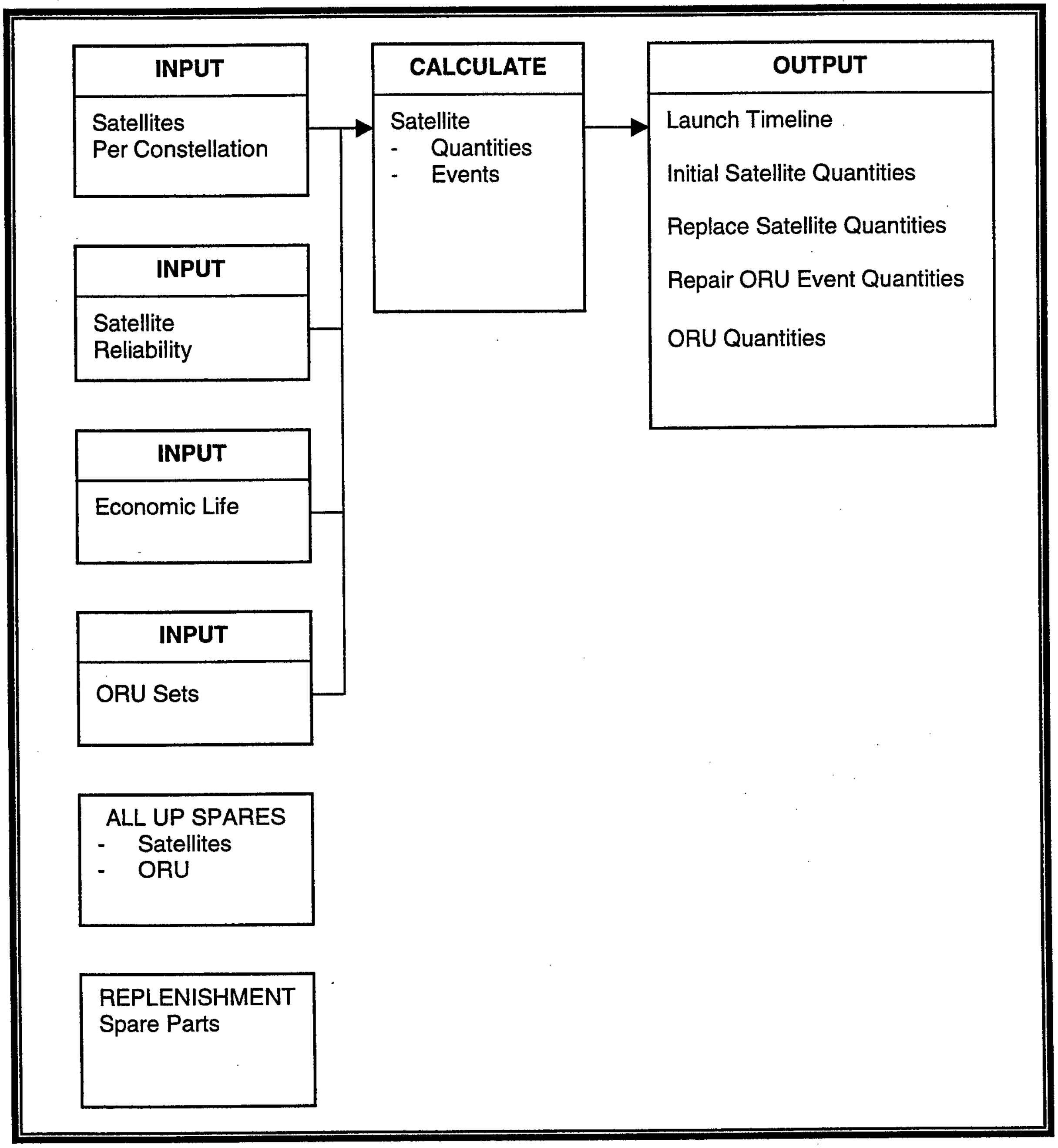


Figure 10 – Programmatic Module

- **Programmatic Module** – The programmatic module incorporates various quantity related inputs to determine the required output quantities, events, and timelines necessary for developing the satellite and ORU requirements for launch and orbital transfer vehicle manifesting. This module provides the satellite quantity information for the satellite system identified in the satellite-sizing module. Repair or replace events are identified based upon input satellite reliability and the economic lifetime of the analysis. The diagram of the programmatic module is shown in Figure 10. The purpose of this module is to calculate the various quantities required for the subsequent calculations in other modules (transportation and LCC modules).

First, the size of the constellation of satellites in the analysis must be specified. A value of one is baseline, so that the life cycle cost comparison between a single satellite under either replacement or repair strategies can be addressed.

Next, the time period of the economic analysis in years is specified. A value of 10 to 20 years is usually selected for system trade studies. This value of economic life does not automatically update the infrastructure life cycle, which must be calculated separately, but must be made consistent by the analyst.

Next, a measure of satellite reliability is incorporated. The number of failure events can be inputted for the 20-year lifetime. A value of zero means the original satellite constellation lasts the full economic lifetime. This value can be obtained from very rigorous off line reliability analysis of the specific satellite program under study.

The number of ORUs required in the economic lifetime (not counting spares) is treated as a single input variable. There is an ORU "set" in the basic repairable satellite and one for exchange at the first repairable event which occurs at the mean mission duration (MMD) time of the program life. The original set is brought back for refurbishment and the ORU set from this variable is used for the exchange. The use of a number greater than one implies that less refurbishment takes place.

The number of spare satellites (repairable and replaceable) which are needed in later LCC calculations is treated as a simple input in this variable. The initial spare ORU quantity is also a simple input number. The number of replenishment spare parts, expressed as a percentage, is used later in the production cost estimating relationships (CERs) in the LCC calculations. The programmatic module takes the input discussed above, calculates the necessary quantities and events, and outputs the items identified in Figure 10. Launch timelines are developed using the mean mission duration and economic life. Using this information about satellite constellation size, we can determine the number of replacement (i.e., non-modular) satellites, which must be launched in the initial constellation. The number of failure and repair events times the number of satellites in the constellation determines the number of replacement satellite events or ORU repair events. The number of ORUs is equal to the number of satellites in the constellation times the number of ORU sets required.

- **Transportation Module** – The transportation module develops the unit transportation (Earth to low earth orbit) cost for both repair and replace missions for the satellites and the necessary hardware required for each mission. A part of this calculation is the cost of the fuel for the reusable orbital transfer vehicle (ROTV) (when needed) to transfer from low earth orbit (LEO) to the satellite's final orbit for each mission type. This module obtains the weight information of the infrastructure elements from the infrastructure discussed next. The diagram of the transportation module is shown in Figure 11. The purpose of this module is to calculate the ROTV fuel costs for a reusable orbital transfer vehicle for various missions and to calculate the LEO launch vehicle costs. To arrive at both of the above values, weight manifests for the replace mission and repair mission are required. The ROTV fuel reserve is a simple input of fuel reserve in kilograms (pounds) of extra fuel over the mission requirements calculated below.

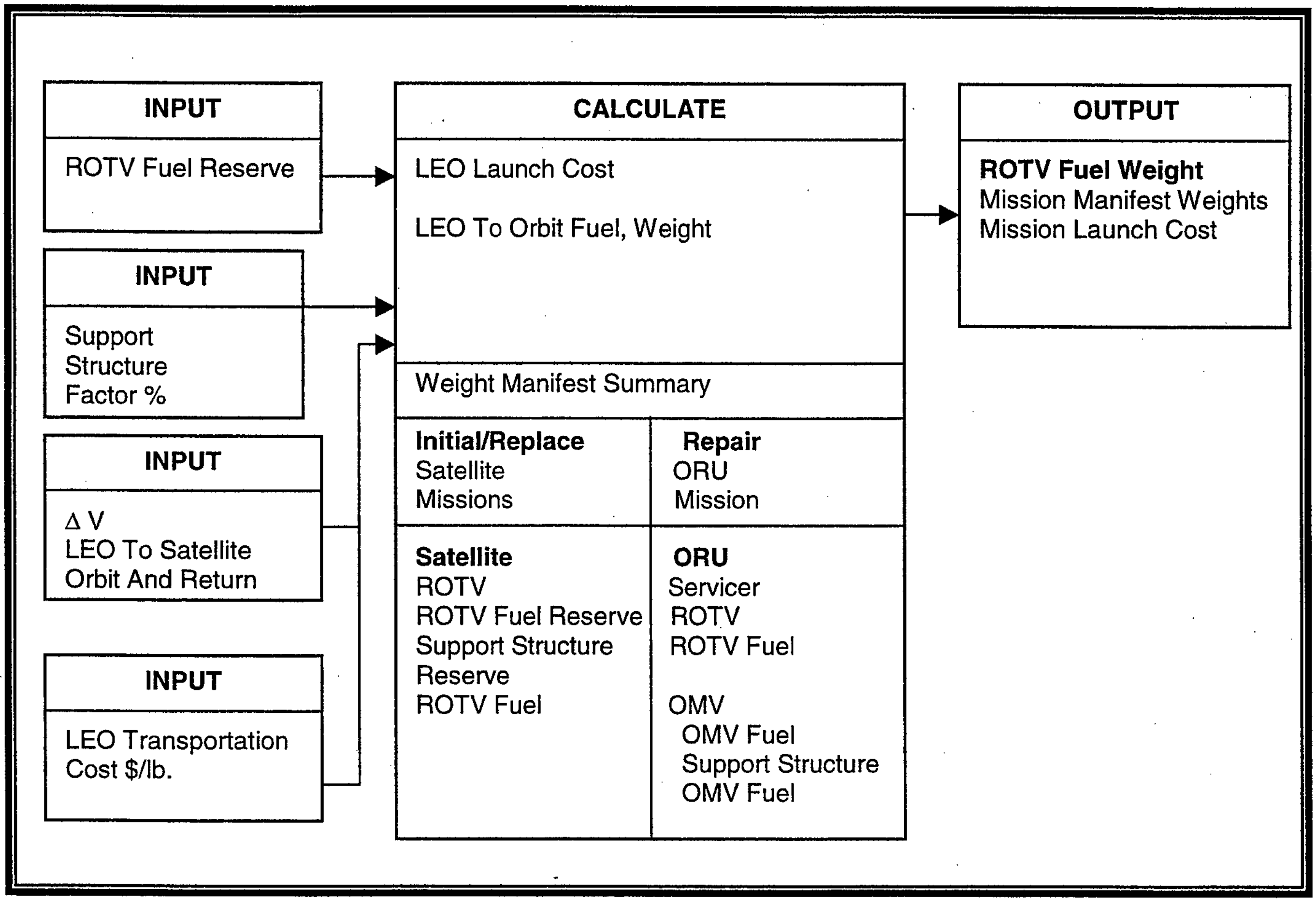


Figure 11 – Transportation Module

The support structure is an input percentage which is applied to all of the hardware (but not ROTV fuel) weight, which is manifested in ground launch the replace and repair missions. For satellite replace missions, this factor is applied to the satellite, ROTV, and ROTV fuel reserve weights. For ORU missions, this factor is applied to the ORU servicer, ROTV, ROTV fuel reserve, OMV, and OMV fuel. Note that this fuel does not have to be launched on the same mission as the hardware, but must be tracked for the specific mission. This fuel could be pre-positioned in space or launched on a separate launch vehicle.

The LEO launch costs are treated as a dollar per unit of weight, kilograms or pounds, cost to low Earth orbit. Specific launch systems could be identified by using unique values of $/kg ($/lb). However, the use of $/kg ($/lb) for launch cost eliminates the need for identifying the specific launch vehicle. This value was treated parametrically in the analysis.

The specific value of launch cost to LEO for a single satellite or ORU mission is the LEO $/kg ($/lb) times the satellite or ORU manifest dry weight to orbit. The ROTV fuel cost is treated as the $/kg ($/lb) for the refueling mission times the weight of the fuel. The methodology of using launch cost as dollars per unit weight assumes optimal manifesting, i.e., only the cost of the actual weight required on orbit is estimated even if the payload bay is half empty. If the launch cost were estimated using discrete dollars per launch, the launch cost would be higher than the $/kg ($/lb) approach since the cost of the entire launch vehicle would be charged even if its payload bay were half empty.

The output of this section produces the launch cost for satellite and ORU missions. The ROTV fuel cost is presented separately from the LEO launch cost due to its magnitude. It is a significant weight and cost consideration.

- **Infrastructure Module** – The servicing infrastructure is expensive and in the broadest sense consists of these elements:

  - ***Servicer Vehicle*** – an autonomous three-axis stabilized spacecraft with rendezvous and docking attachments and servicing modules with one or more robotic arms and stowage for replacement ORUs. It also has a fluid and gas transfer system and is adaptable to an OMV or OTV

  - ***Orbital Maneuvering Vehicle (OMV)*** – a remotely piloted or manned maneuvering spacecraft which can carry a servicing front end or a servicer vehicle and appropriate consumables and ORU modules for the satellite to be serviced. The OMV could be space-based.

  - ***Tanker Vehicle*** – a propellant carrier capable of mating to the OMV or OTV and carrying sufficient propellants to service multiple spacecraft on one mission.

  - ***EVA Space Suits and Related Hardware*** – astronaut EVA space suits with the environmental control backpack integrated. Hand held tools (some powered) to enable servicing tasks in situ or on a space platform.

  - ***Tender Platform*** – unmanned base for storage, spacecraft repairs, fuel depot, and inspection. Strategically placed for constellation or high traffic servicing.

  - ***Orbital Transfer Vehicle (OTV)*** – a reusable space truck remotely piloted or manned orbital transfer spacecraft/booster combination using cryogenic propellants. Used for extensive satellite repositioning (such as LEO to GEO). Servicer vehicle and supplies could be incorporated. Several types of Orbital Transfer Vehicles (OTVs) may be needed.

  - ***Man-Tended Platform*** – a solar orbit or GEO space-based station for space systems assembly, maintenance, or overhaul in the same orbit plane as the system to be deployed. Can support crew of up to 12 for a period of weeks. Important for constellation servicing.

- ***Small Inspection Vehicle (Microsat)*** – a very small remotely controlled spacecraft that can fly by and inspect an operational spacecraft. Short distance (about 100 meters) flight capability. Can also dock with a satellite to provide low power and small resupply fluids. Maybe dock with and drag a satellite to an OTV.

- ***Cryo Facility*** – a vehicle or platform for the on-orbit storage and handling of cryogenic propellants.

- ***Warehouse and Storage Facility*** – co-orbital warehouses with an OMV/satellite servicer system combination to service high altitude space assets between overhauls.

- ***Mission control*** – a manned or automated ground or space-based operations control center to provide the C3 functions for on-orbit spacecraft servicing missions.

- ***Launch Sites, Ground Facilities, Hardware, Equipment and Training Centers*** – essentially the ground logistics segment for on-orbit servicing missions. Integrates the above functions to insure the space segment infrastructure elements are properly utilized.

The infrastructure module provides the definition of the above various elements for servicing missions in terms of weight and cost. Each element will not be required for all missions, but each mission will require some of the elements. This module allocates the total life cycle cost (R&D, production, and Operations and Support (O&S)) to a per use cost for a given quantity of missions (amortizing quantity) over the satellite's lifetime. Thus, even though single satellite programs are analyzed, an attempt is made to allocate the infrastructure cost to other user programs and charge only a portion to a single mission. This is an important concept to this methodology. The diagram of the infrastructure module is shown in Figure 12. The infrastructure definitions and requirements are expanded in the section entitled Concept of Operations.

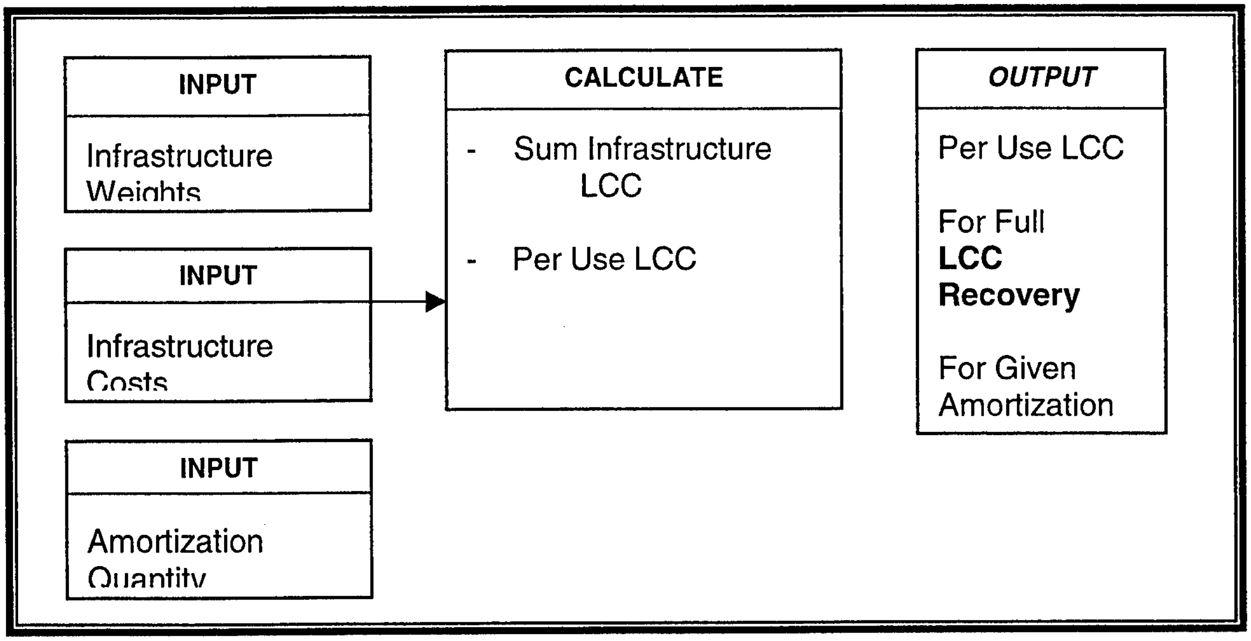


Figure 12 – Infrastructure Module

- **Life Cycle Cost Module** – The Life Cycle Cost module uses inputs from the integration services or communications, command and control (C3) element and LCC factors. It then calculates the various R&D, production, and O&S costs of the satellites, repair or replace quantities, transportation costs, and infrastructure use charges to obtain LCC estimates for each concept. The output of the methodology is in the form of printed tables of costs, graphical comparisons, and calculation results.

The LCC module is shown in Figure 13. The LCC module draws upon all other modules for input, as illustrated in Figure 8. This module uses factors and cost estimating relationships (CERs) to calculate the R&D and production cost of satellites and ORUs. Quantities from the programmatic module are used along with the unit infrastructure and transportation costs. These same quantities are used to obtain total C3 costs based upon a unit C3 cost which is input. Program level and management reserve costs are calculated as a percentage of the above totals. The costs are then row and column summed to give the life cycle cost by phase and by CWBS element for both replacement and repair cases.

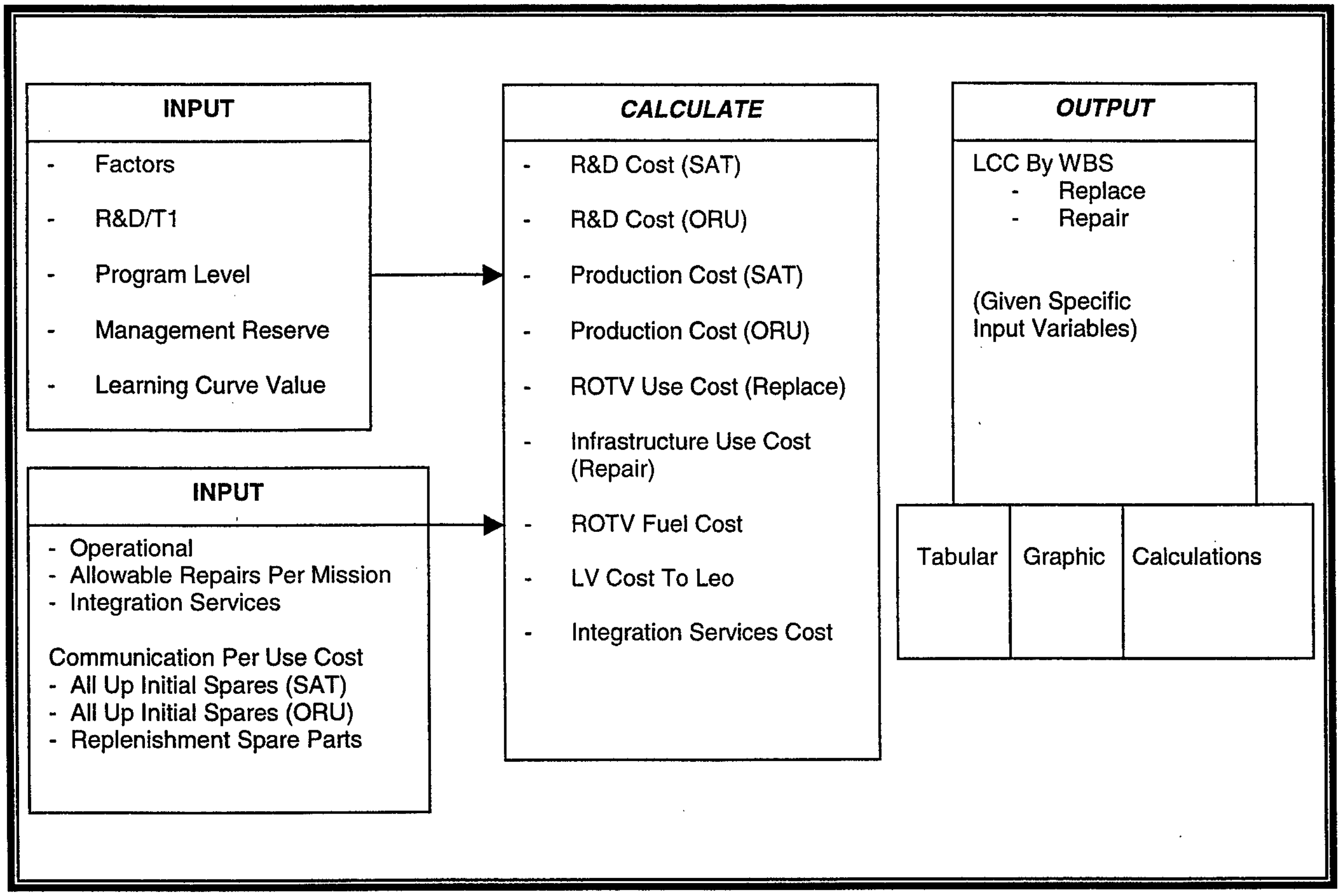


Figure 13 – Life Cycle Cost Module

Infrastructure Costs

The life-cycle cost of eleven infrastructure elements (Table 1) was generated based on the infrastructure life cycle cost assumptions listed below.

1. Over 20 years, the on-orbit servicing infrastructure will build up as requirements dictate and will eventually include the elements as shown in the left column of Table 1.
2. The life cycle cost (LCC) of each element consists of its development cost, unit cost, annual operational and logistics support costs and the cost of this operation and support costs sustained of 20 years at the same annual cost per year
3. LCC generated over a 20 year period with the dollars in millions on Table 1. Calculated in FY2000 constant dollars.
4. The hardware for the infrastructure elements developed and built by contractors.
5. A management reserve (risk) of 15% included during the acquisition of all element items.
6. While the accuracy of each individual life cycle cost estimate is important, the comparative accuracy of cost estimates are of primary concern to assure reliable determination of cost comparative ranking among the competing concepts.

7. Acquisition of space transportation systems is considered sunk, national asset costs, and NOT a SAMS cost included in LCC estimates. The cost can be stated as an additive cost for a sensitivity analysis using the government furnished data.
8. The operations and support costs of the space transportation system ARE considered SAMS costs, and are included in the LCC estimates.
9. The acquisition cost of existing C3 systems shall be considered sunk and not part of the SAMS system. The acquisition of any new C3 system required by SAMS shall be considered as a SAMS cost in the LCC analysis.
10. The operations and support cost for these C3 systems (existing and future) shall be included in the SAMS LCC analysis. Existing system estimates will be supplied as Government Furnished Information.
11. Cost of the acquisition, operations, and support of government communications and navigation satellites needed to support servicing missions are considered sunk, national asset costs, are not part of the servicing infrastructure LCC.
12. Cost of launch operations (not the cost of the launch vehicle) is included to place elements of the infrastructure into the proper orbit.

Table 1 displays the development, unit and operations costs for the eleven elements over 20 years. The total LCC for all elements totals $13.5 billion. This number was turned into a cost range of from $10.5 to $15.7 billion due to the lack of firmness in the dollar numbers estimated in the various columns of Table 1.

The cost of the individual elements of the servicing infrastructure was estimated based on the integrated inputs of the 1986-1988 servicing cost studies performed for the Air Force and extrapolated to CY2000 dollars using judgmental factors. The 20 year LCC of between $10.4 and $15.7 billion in CY2000 dollars is considered realistic for the servicing use modules employed and the assumptions applied. Additional point decision information for the infrastructure elements are required before a high confidence can be placed in any cost estimates for the elements.

Table 1 – Estimated Infrastructure Cost in Millions of CY 2000 Dollars

Infrastructure Elements	Initial Operational Capability	Development Costs	One Flight Article Production Cost	Annual O&S Costs	20 year O&S Costs	Total $M	Possible Range $M
Service Vehicle	2005	$325 M	$60 M	$50 M	$1000 M	$1435 M	1200 to 1600M
OMV	2005	$400 M	$110 M	$40 M	$800 M	$1350 M	1000 to 1500 M
Tanker Vehicle	2010	$350 M	$100 M	$20 M	$400 M	$870 M	600 to 1000M
EVA space suits	2005	$250 M	$190 M	$7 M	$140 M	$587 M	400 to 700M
ROTV	2015	$250 M	4190 M	$50 M	$1000 M	$2350 M	2000 to 3000M
Man Tended Platform	2010	$500 M	$200 M	$30 M	$600 M	$1330 M	1000 to 1500M
Micro Sat	2005	$90 M	$415 M	$44 M	$80 M	$189 M	100 to 300M
Cryo Facility	2020	$800 M	$200 M	$50 M	$1000 M	$2050 M	1800 to 2200M
Warehouse & Storage Facility	2015	$600 M	$150 M	$20 M	$400 M	$1170 M	900 to 1400M
Mission Control	2005	$180 M	$70 M	$25 M	$500 M	$775 M	500 to 900M
Launch site, Ground Facilities, Etc.	2005	$400 M	$150 M	$40 M	$800 M	$1390 M	1000 to 1600M
TOTAL $ MILLION		$4795 M	$1645 M	$336 M	$6720 M	$13,496 M	10,500 to 15,700M

It is estimated that a conservative number of infrastructure uses over the 20 year period, used for LCC will be 100. This is an average of five servicing missions per year. This is then the amortization quantity. Since these two items, infrastructure cost and amortization quantity, are relatively soft, they should be made variable within the cost model of Figures 8 and 12. For the baseline infrastructure cost of $13.5 billion (used on 100 program missions) the per mission cost is $135 million per use.

Sensitivity Analysis

A strategy for safe repair and/or servicing versus satellite replacement for various classes of space systems is based on the four input parameter categories of satellite, launch vehicle, infrastructure, and operations as depicted in Table 2.

Table 2 – Cost Effective Variables for Use in Sensitivity Analysis and Trade Studies

In-Put Variable – Satellite	Possible Range
Spacecraft weight, Lbs	2300 to 15000 (GEO & MEO) 2000 to 85000 (LEO)
Spacecraft costs	High and low values for LEO,MEO,GEO
Added to cost to make the S/C serviceable	2 to 8%
Modularity weight penalty	10 to 20%
Modularity cost	5 to 30% of total S/C cost
ORU cost	10 to 50% of total S/C cost
S/C development $/lb	25000 to 35000
Payload development $/lb	50000 to 60000
Constellation size	1 to 12 per orbit ring
Mean mission duration, years	2 to 15
Servicing interval, years	½ to 5
LAUNCH VEHICLE	
Launch vehicle type	NSTS, ELV, Orbit-to-orbit vehicle
Transportation cost to LEO, $/lb	600 to 6000
Transportation cost to GEO, $/lb	7000 to 10000
INFRASTRUCTURE	
Infrastructure location	Ground, LEO, MEO, GEO; 28 degrees to polar inclinations
Infrastructure 20 year LCC, $/B	10 to 15 (fuel capacity)
Amortization, total uses	50 to 200
Infrastructure use change	See Table 1
SPACE OPERATIONS	
Orbit extremes	LEO to GEO
Number of sats repaired per mission	1 to 5
Basing concept	Mostly space based
Servicing missions per year	12 to 20 post 2000

In general, the overall trends which make satellite maintenance and servicing appealing are similar for all generic orbit regimes considered (GEO, Medium Earth Orbit (MEO), and LEO). There are, however, differences in the magnitude of potential savings in the different orbital regimes due largely to increases or decreases in infrastructure required to access satellites and the absolute costs of the satellite in each regime. Following is a brief description of the trends, which make satellite maintenance and servicing appealing.

- ***Satellite*** - The satellite input variable category describes the characteristics of the individual satellite. The first satellite characteristic that favors the repair concept is high complexity and therefore high cost satellites. The second satellite characteristic is heavy satellites, which in most cases are also expensive. The third satellite characteristic is low cost orbital replacement units. This result will impact satellite compartmentalization and ORU design for modular satellites. The fourth satellite characteristic is that the satellite has relatively low mean mission duration. The more times a satellite needs to be replaced, the more the repair concept is favored. Thus, if high reliability can be assured at a reasonable cost, maintenance and servicing may not be worthwhile.

- ***Launch Vehicles*** – The characteristic within the launch vehicle category that favors the repair concept is low transportation cost. This is mainly because large payloads are required to be delivered to orbit for repair missions (just as for replacement missions) because of the large mass of hardware and fuel required for repair missions. Thus, transportation costs can be a big cost driver. At the same time, however, it is a big driver for replacement missions also. Thus, it is somewhat a relative issue. Even if transportation costs are high, repair missions may still be cost effective if other mission parameters override transportation costs.

- ***Infrastructure*** – The infrastructure input variable category represents the elements required to support repair missions. Low infrastructure LCC and a high amortization level favors the repair concept. Analysis shows that both GEO and MEO satellite could be repaired or serviced using the same infrastructure elements (including the same space node) which minimizes cost and operational complexity. DOD, NASA, and commercial satellite owners sharing such facilities could realize additional cost savings.

- ***Concept of Operations*** – The characteristic within the operations category which favors service and repair missions most is the capability to visit more than one satellite per mission. A huge economy of scale can be exploited for such missions assuming a sufficient number of satellites are available at a given time for such missions. Because of fuel limitations such missions are limited to co-planar satellites. This is not a prohibitive restriction for GEO satellites, since they are close to being co-planar because of the unique feature of this orbit. Several MEO satellite systems also have multiple satellites per plane, which can benefit from the multi-visit technique. LEO satellites, however, probably cannot benefit from such a technique because there are a limited number of assets in LEO and they are usually not co-planar.

Risk Management

Today's risk for spacecraft launch, flight to orbit, and on-orbit operations continues to carry a relatively high degree of uncertainty. Space insurance is one method the operators of commercial space systems use to mitigate the financial loss for mission failures.

Insurance as a means of dealing with risk should be only one approach in a much broader scheme of risk management. Where there is uncertainty, there is risk. To try to eliminate risk in space enterprise is futile. Risk is inherent in the commitment of present resources to future expectations. Risk is the probability and consequence of not achieving some defined program goal. Risk management is the process that encompasses the identification, assessment, tracking, control, and mitigation of program risks and results in overt actions to accept known risks or to make program adjustments, which avoid their potential consequences. Program risk elements are shown in Table 3 while Table 4 lists, by program phase, risk analysis applications. All major aerospace government agencies and aerospace contractors have their own risk analysis tools and techniques for managing technical, cost, and schedule risks for satellite programs. A risk management strategy must be established early and continually addresses throughout a program's life cycle.

Table 3 – Program Risk Elements and Associated Factors

Cost Risks	Schedule Risks	Technical Performance Risks
Competitive optimism Cost estimates ➢ Accuracy ➢ Uncertainty ➢ Timing Affordability ➢ Funding level ➢ Funding profile ➢ Contract type Quantity ➢ Number of spacecraft Customer uncertainty ➢ Need and urgency ➢ Funding level and profile ➢ Contract provisions Management control ➢ Monthly accounting ➢ Ongoing account tracking	Competitive optimism Schedule slippage ➢ Long lead materials or items ➢ Critical components ➢ Manpower availability ➢ Manpower/training requirements ➢ The marching army problem Quantity ➢ Number of spacecraft Customer uncertainty ➢ Need and urgency ➢ Funding level and profile ➢ Contract provisions Management control ➢ Monthly accounting Ongoing account tracking	Competitive optimism Spacecraft complexity ➢ Feasibility ➢ Producibility Technology ➢ Feasibility ➢ Uncertainty ➢ Obsolescence Engineering support ➢ Capability ➢ Availability ➢ Fragmented responsibility Quantity ➢ Number of spacecraft ➢ Overlapping development of interdependent projects Material procurement ➢ Availability ➢ Long lead ➢ Design changes Customer uncertainty ➢ Need and urgency ➢ Funding level and profile Contract provisions Management control ➢ Monthly accounting Ongoing account tracking

Table 4 – Risk Analysis Application by Program Phase

Phase I Concept Studies	Phase II Concept Validation	Phase III FSD	Phase IV Production
➢ Mission analysis ➢ Concept evaluation ➢ Trade studies ➢ Cost effectiveness analysis ➢ Risk identification ➢ Risk assessment ➢ Risk avoidance ➢ Risk control/mitigation ➢ Technology development planning for risk reduction ➢ Uncertainty in cost estimates ➢ Uncertainty in schedule estimates	➢ Requirements review ➢ Final design selection ➢ Technology selection ➢ Planning of activities for risk control/mitigation ➢ Program contingency	➢ Requirements review ➢ Management reserves ➢ Network & schedule planning ➢ Risk tracking and management ➢ Lessons learned	➢ Management reserves ➢ Network and schedule planning ➢ Risk tracking and management ➢ Change risk assessment ➢ Lessons learned

The first step, identifying the risks of on-orbit servicing missions, should be done at all levels of the project. Issues, such as which subsystems should be replaced versus repairable on-orbit, or how many layers of redundancy are to be built into certain systems, must be addressed. At a broader level, issues such as whether the design will permit alternative means of accesses to space, or how a crew might be rescued, are major concerns.

Once the risks are identified, they must be evaluated from two standpoints: how serious are the consequences and how likely are they to occur? The most serious risks must be dealt with to make them as improbable as possible and those with lesser degrees of severity must have their consequences accommodated in the least damaging manner.

The third step is to decide how to handle each identified risk. There are essentially four basic means of doing this: avoidance, reduction, transfer, or retention.

Avoiding is simply choosing to use another means of accomplishing an objective to avoid risk. However, as with any avoidance strategy, this also means missing the benefits associated with the riskier strategy, which may suggest using other risk management techniques.

Risk can be transferred by a number of means, including hedging, using surety bonds, incorporating, or subcontracting.

Finally, those risks, which are not avoided, reduced, or transferred, are retained. Retained risks include those, which have been reduced to an acceptable level, those with no identifiable means of risk management, and those, which may not have been identified.

Table 5 illustrates varying tradeoffs in implementing these approaches for a range of space risks. While the table is generally designed to illustrate reduced levels of risk from left to right, only when considered in a context of a complete system can a particular approach be evaluated as "better" than another.

Table 5 – Alternate Approaches to Handling Space Risks

Example of Risk	Approach A	Approach B	Approach C
Loss of subsystem unit(s)	Only existing unit	Ground spare exists	Second unit on-orbit, spare on ground
Serviceable system failure	Non-serviceable design	Serviceable design	Serviceable design and servicing system available
Launch vehicle unavailable	Dependent on single launch vehicle for initial launch and resupply	Dependent on single launch vehicle for initial launch, has backup available for resupply	Backup launch vehicle for both launch and resupply
Damage to system during resupply	Automated docking used	Docking with tether then pull in	System parked and picked up by teleoperated vehicle
Structural damage to module	Single hull material structure	Double hulled material	Composite hull
Communications loss	Multi-satellite network operating at maximum data rate	On-board recorders to cover one satellite out	On-board recorders plus separate satellite
Crew stranded	Original vehicle used for pick-up	Rescue-only vehicle attached	Launch and return vehicle attached or separate nearby facility accessible

Cost Benefits

Previous studies found that the nominal LLC savings of up to 33 percent could be obtained by using a repairable/serviceable satellite design for some systems. A few special cases indicated LCC savings of 30 to 50 percent. Other systems were found not to benefit at all from the serviceable concept. So on-orbit servicing is not for every program.

It might be argued that the potential cost savings achieved by employing maintenance and servicing is not the driving factor in deciding whether to adopt a service and repair philosophy for future satellite systems. Percentage wise, the cost savings may appear to be marginal compared with the cost of developing and operating specific satellite systems. However, when applying these cost savings in a mission model sense across a number of satellite systems, the absolute dollar savings can amount to billions. The exact amount of potential savings depends on a number of variables including the mission requirements imposed on future systems. For example, servicing and repair options are more favorable to bigger and more expensive satellites. If satellite design lends to a "lightsat" design philosophy, little or no benefit could be gained from a maintainable design. In reality, some combination of both types of satellites will most likely be present in the inventory.

Cost benefit analysis shows that servicing provides substantial economic benefits using several scenarios. Sensitivity analyses indicate the impact of changing key cost assumptions. Even with the changes in the cost assumptions, the benefits of servicing still indicate LCC savings. Today there is a trend toward larger and more complex satellites especially for the NASA Great

Observatories science missions and Air Force surveillance missions (SBR). If this trend continues, the value of assets in space will increase. The prior results indicate that the cost savings due to servicing are increasingly larger as the satellites become larger and more expensive.

Figure 14 presents a comparison of replacement costs and servicing costs as a function of satellite size. The difference between the two cost curves represents the economic benefits of servicing. The satellite costs are based upon a weight-based cost estimating relationship (CER) for satellites of nominal complexity (i.e. $100 million unit cost for a 907 kg (2,000 lb) satellite). Using a CER for higher complexity satellites such as surveillance satellites would further increase the economic benefits. This figure illustrates increasing benefits realized as the satellites become larger and more expensive. The nominal case servicing cost curve represents the DoD only scenario and where ORU costs for the servicing represent 10 percent of the satellite costs. If the missions were reduced to 50 missions and the ORU costs increased to 20 percent of satellite costs, then the higher servicing cost curve results.

The impact of the high cost curve is to introduce a region where replacement is less costly than servicing. This occurs for satellites less than 907 kg (2,000 lb.). Thus, the importance of this curve is to indicate that a break-even point can occur at some point dependent upon the cost of satellites. The exact point at which the break-even point occurs depends upon the mission model and the servicing definition. Even though uncertainty will exist as to the exact point for break-

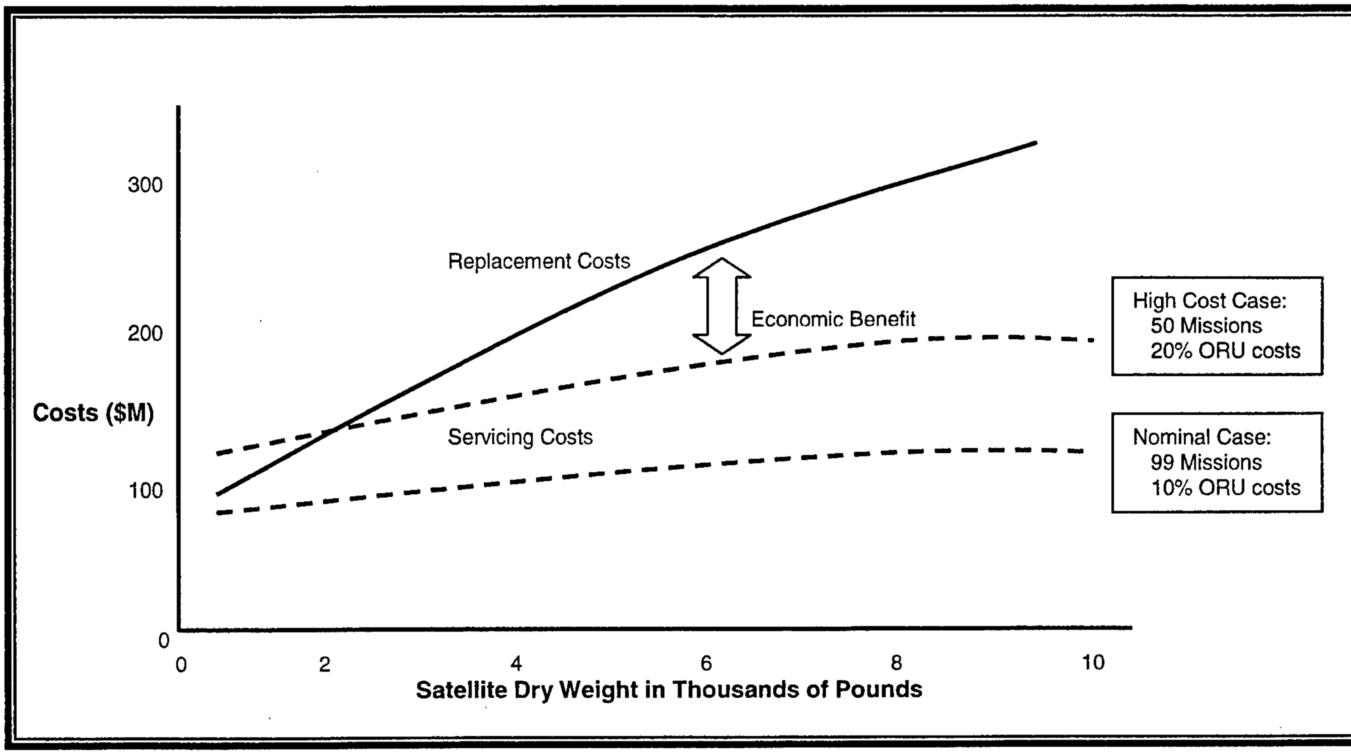


Figure 14 - Comparison of Replacement Cost vs. Servicing Costs as a Function of Satellite Size (Waltz, 1990)

even, the trend toward more complex, larger, and more expensive satellites leads to the conclusion that available servicing capabilities can substantially lower the total cost of the nation's assets in space.

Levels of Decision Making

Two levels of decision-making enter into the balancing strategy for implementing a national on-orbit SAMS capability. At the agency level (DoD and NASA) these questions will be asked:

- Is a SAMS capability mission enabling? Must we have it?
- How much near-term investment is required?
- What are the runout costs for putting the SAMS infrastructure in place?
- Can we recover development costs?
- Will international and commercial space users avail themselves and therefore pay a user charge for SAMS missions?
- How will a robust SAMS capability impact spacecraft insurance premiums?
- What standards must be mandated?
- Which programs will be asked to consider incorporating servicing into their satellite design and operations?
- Which programs will be commanded to incorporate servicing into their satellite design and operations?

When the question of "To service or not to service?" is presented to a typical System Program Office (SPO) director, this second level decision maker will probably ask a series of questions that go something like this:

- Does it cost me more this year?
- Does it help me get to first or next launch?
- Is servicing availability guaranteed?
- Will my project be charged to develop servicing hardware?
- Will my project have to share the infrastructure with other programs and thereby incur scheduling problems?
- Can I do my mission without on-orbit servicing?

If the answers are not favorable, the SPO director will undoubtedly seek to avoid servicing. Near-term money is always a problem and the development of a new satellite inherently contains sufficient challenges that the SPO director is not moved to undertake anything which doesn't help get to the main goal.

In the final analysis, cost alone should not be the final or only discriminator used to evaluate the military, civilian, and commercial utility of maintainable satellites. Chances are that if cost were the only parameter of importance, the United States would not have a civilian space program in the first place. Operating in space is an expensive undertaking. This is not to say that all cost issues should be completely ignored. Ideally, a balance must be reached between mission requirements and cost. The time has come to expand the scope of on-orbit servicing analysis to investigate other issues of importance. For example, quick turnaround repair missions could increase constellation availability by using pre-positioned space nodes containing appropriate ORU's. Satellite refueling systems could be used to replenish consumables on space test vehicles and/or operational satellites that may need periodic refueling (i.e., mission or maneuverability system tests). In addition, the overall survivability of space systems may be enhanced by ORU change-out and/or refueling, which provides another option to the ground-launched replacement and complete on-orbit sparing concepts. Once mission and cost data are evaluated together, sufficient information will be available to make hard decisions regarding the pros and cons of satellite maintainability. Such decisions probably should be reevaluated periodically as technologies evolve. It is expected that the concept of maintaining and servicing military satellites will be evolutionary rather than revolutionary.

Joint Investment

Space maintenance and servicing strategies can save money over the life cycle of some satellite systems. However, an investment in the infrastructure is required prior to achieving these savings. If NASA and DoD together make the decision to commit to an infrastructure or to maintenance concepts, which employ minimum infrastructure elements, many satellite systems would probably adopt the space repair and servicing concept. No one satellite user wants to have the first need (and thus cost) of the infrastructure development. However, the cost savings available through space repair and servicing, coupled with the mission enhancing possibilities mentioned above, could lead to a revolution in the way satellite systems are designed, produced, operated, and maintained in the future.

Serviceable Spacecraft Design Requirements

This section addresses the fundamental considerations in the design and support of spacecraft which can be effectively assembled and/or serviced on orbit. Spacecraft design requirements are presented and design steps suggested.

Maintenance Levels

The military concept of aircraft maintenance echelons on the ground is applicable to satellite servicing in space. In the military, the first echelon maintenance, the least complex level, involves elements designed for repair-by-replacement. These tasks can be accomplished in space by telerobotics, automation, or EVA. Second echelon maintenance relates to elements that are repairable or replacement but are not necessarily designed for servicing. The first and second echelon activities are performed at operational or training military sites. The third and fourth echelons of spacecraft maintenance today occur on the ground, but by the 2010 timeframe could occur in space. These activities are conducted at large maintenance and repair depots rather than in the field.

In level three maintenance, black boxes within systems are replaced, while in level 4, elements inside a box are repaired or replaced. The fourth echelon, servicing at the individual component or piece part level is the most complex,

We think that it will be very expensive to bring large satellites such as the SBR, SBL, and NASA's observatory-class satellites back to the ground for level 3 and 4 servicing. Past cost estimates for full refurbishment range as high as 60 percent of the original development cost of large (>30,000 lb) space systems. While the return of smaller, less complex spacecraft may be feasible, the economically practical approach to large-scale servicing is to *do it in space.*

Table 6 summarizes the above levels or echelons of maintenance or servicing. Space based level 1 servicing technology is available now via Shuttle crew EVA and could be ready for teleoperated servicing by 2005. Estimates of level 3 and 4 servicing availability would be 2010 to 2015 for level 3 and 2015 to 2020 for level 4. Obviously levels 3 and 4 capability will require space based work platforms (manned or man-tended), tanker vehicles, warehouse and storage facilities, and an orbit-to-orbit transportation system per Table 1.

Table 6 – Maintenance and Servicing Levels as Described by Military and Commercial Airline Organizations

Maintenance Level	Features
First Echelon "Flight Line" or "Field" Service	➢ Least complex ➢ Repair by replacement ➢ Space environment ➢ Tasks by EVA or automation ➢ Quick disconnect ORUs
Second Echelon "Hangar" or "Field" Service	➢ Intermediate complexity ➢ Repairable or replaceable elements – not necessarily designed for servicing ➢ Space environment, but sheltered facilities ➢ Tasks by EVA or automation, some AI support
Third Echelon "Depot" or space facility or space station service	➢ High level of complexity ➢ Black box replacement ➢ Sheltered, protected shirt-sleeve environment ➢ Major maintenance tasks
Fourth Echelon "Depot" or advanced space facility service	➢ Most complex ➢ Elements inside black box repaired or replaced ➢ Complete overhaul of spacecraft ➢ Refurbishment tasks ➢ Sheltered, protected shirt-sleeve environment

Spacecraft Servicing Design Assumptions

These are the major assumptions upon which to build an industry base of technology to enable the design and development of serviceable spacecraft:

- ➢ Within 5 years, the DoD and NASA may commit to servicing their space assets. Commercial operators will follow.
- ➢ Servicing of assets will start in low Earth orbit (Hubble Telescope and International Space Station are examples), then evolve to the servicing of satellites in polar orbits, later to high inclination orbits at medium to high altitude, and eventually to geostationary orbit.
- ➢ A transition will be made from manned EVA to remote (telerobotic and autonomous) servicing. See Figure 3.
- ➢ The DoD and NASA may initiate LEO proof-of-concept demonstrations in the next 5 years to enhance or validate driver servicing technologies.
- ➢ The DoD and NASA may by 2005 collaborate on a National On-Orbit Servicing Program to decide how to acquire the infrastructure and the technology needed to conduct servicing missions. A substantial National investment will be made in the next five years

in an orbit-to-orbit transportation (such as the old NASA/TRW OMV or the AFRL/VA SOV or the AFRL/VS SMV as well as telerobotic servicing systems such as the former Flight Telerobotic System.

- In the near future AFRL, NASA, and NRL will begin a joint effort to design and demonstrate an on-orbit refueling experiment.
- In the next three years efforts by DoD and NASA to incorporate an on-orbit satellite servicing facility or work bay on the International Space Station will be initiated.
- Around the year 2005, commercial communications satellite operators, especially those with large constellations in mid altitude-mid inclination orbits and at GEO will embrace on-orbit servicing as a life cycle cost saving strategy- thereby giving a big boost to infrastructure development.
- Around the year 2015, on-orbit servicing could be a worldwide customer based, commercial, privatized venture with private industry operating the infrastructure and performing the logistics tasks. They could lease the infrastructure from the U.S. government and charge the space system operators for their services.

We realize the above assumptions are aggressive, but a National on-orbit servicing program can't get started or prosper on today's business-as-usual format.

Serviceable Spacecraft Design Features

The program decision to incorporate on-orbit servicing into the operation of a spacecraft sets into motion certain approaches to design policy.

The general design features of military serviceable spacecraft are that the spacecraft must be: servicing-friendly in the automated mode, safe to service, and rugged enough to withstand the rigors of docking and handling by mechanical arms and fixtures.

A trend might be to design satellites within a given mission category such as communication, navigation, or surveillance with a common bus but a mission unique payload. Six items that could define the next generation spacecraft bus are: functional modularity, smart built in fault detection and test equipment, standardization policies, consumables replenishment (refueling), access to repair, and compatibility with the evolving space logistics architecture.

- Functional Modularity - allows major individual components or subsystems to be isolated from serial connections. This lends itself to ease of replacement.

- Smart Built - In Fault Detection and Test - Intelligence diagnoses and fault detection inputs the decision as what servicing functions are required. Computer aided self-testing capabilities enables mission operators to status the satellite ability to perform before and after servicing.

- Standardization - On-board intelligence, serial connections, and standard interfaces to the serial connections allow fast, automatic assimilation of new components into the bus by simply plugging them in. Other standardization applies to interface design of mechanical, electrical, thermal, and fluid components; docking adapters; grapple fixtures, alignment guides, and servicing tools; and interface documentation and drawings.

- Access to Repair - Safe design approaches are needed for servicing work platforms attached to the satellite, insuring no sharp edges or protrusions, allowable surface temperatures in the work area, and insuring the servicing operations do not physically interfere with solar arrays, instrument booms, deployed optics, and antennas.

- Consumables Replenishment - Replacement of consumables, including refueling ports and receptacles must be accessible, leak proof, and safe and matched to the servicer devices for liquid or cryogenic transfer.

- Logistics Compatibility - Design strategies must account for: spares and ORU on-board storage, accommodation of transportation pallets, satellite specific tool stowage, manipulator basing, transfer vehicles operations near or docked to the spacecraft, servicer vehicle docking, and configuration management and documentation considerations.

Servicing Strategy and Spacecraft Design

Once on-orbit satellite servicing has been established as desirable for a program, studies must be conducted, using the decision methodology previously described, to determine factors such as: systems architecture, level of modularity of the spacecraft bus and its payload, degree of reliability, frequency of servicing and what needs to be serviced during spacecraft expected lifetime, and level of commonality of systems or subsystems internal and external to the spacecraft's mission. Safety is inherent in the strategy and design process.

If the spacecraft is to be transported to another location before servicing starts, its structure must be capable of surviving the shock, acceleration, and vibration loads imposed by the transporter.

The spacecraft must be protected from contamination sources during all phases of the servicing process and the thermal environment must be maintained in a safe range throughout the operation.

Here are some investigations, analysis, or trades to be made to determine program servicing strategy and spacecraft servicing equipment integrated requirements:

Items requiring service on the spacecraft
Frequency of servicing and location of the servicing events
Servicing cost constraints (servicing cost versus spacecraft value)
Technology status of servicer systems
Concurrent engineering principles to be employed
Transportation to orbit and in-orbit transportation needs for both planned and contingency on-orbit servicing
Servicing support equipment required
Trades to determine what elements of the infrastructure should be program specific

and what elements should be rented or acquired from the general infrastructure inventory. For instance, the SBL program may find it more cost effective to have its own servicer.

Design approaches to the major interfaces of:

- Spacecraft bus to the ORUs
- Spacecraft bus to the robotic servicer system
- ORUs to the robotic servicer system
- ORUs to servicing tools, fixtures, and support equipment
- Existing and new ground support equipment to the spacecraft
- Spacecraft to the space and inter-orbit transport vehicles
- Spacecraft to simulation and ground crew training facilities
- Spacecraft refueling and other expendables replacement design concepts to the servicing tools and devices for these events

The program management philosophy should be to establish maintenance and servicing (M&S) requirements and responsibilities early in the spacecraft design schedule, and should include operators thinking in all design and development phases. M&S should be incorporated in all planning and program design reviews. Determining the servicing requirements for the spacecraft and its payloads is highly dependent on the engineering reliability index which is used as the planned interval to replacement, and on the maintenance philosophy (management decision) on the level of operational system reliability. Changes in these ground rules cause all logistics for uploads to be recalculated, and may influence whether or not a service vehicle is able to offer a satisfactory operational scenario.

Partitioning of Modular Spacecraft

Modularity is the keynote to spacecraft serviceability. Modularity in the design approach provides easy access and quick change-out to critical components but not all spacecraft components lend themselves to modular configuration. Examples are certain structures, electrical harness, antennas and solar arrays. These can be replaced or added to but probably on a case-by-case basis with unique requirements imposed on the design and hardware location.

The difference between DoD and NASA spacecraft, reflected in the considerations of survivability, security, and availability needs by military missions, causes the approach to modularity to differ but does not change the concept.

Modularity can improve the timeliness of ground integration and test of new or block change space systems. This has a potential cost benefit for a space systems program.

Figure 15 identifies the six principal engineering subsystem ORU modules carried on serviceable spacecraft. Earlier spacecraft programs did not have all of these ORU modules.

DATA MANAGEMENT

- Central Computer
- Central Computer Software
- Data Bus Controller
- Bus I/O Interface Unit
- Telemetry Formatter/Encoder
- Command Decoder
- Module Power Interface
- Module Thermal Controller
- Module Structure

ATTITUDE CONTROL

- Sun Sensors
- Earth Sensors
- Gyro Package
- Accelerometer Package
- Reaction Wheel Package
- Module Structure
- Module Thermal Controller
- Module Processor/Software
- Bus I/O Interface Unit
- Module Power Interface

RCS/PROPULSION

- Tanks
- Valves/Valve Drives
- Valve Drive Electronics
- Plumbing
- Thrusters
- Module Thermal Controller
- Module Structure
- Bus I/O Interface Unit
- Module Processor/Firmware
- Module Power Interface

Up/Downlink Communications

- U/D-Link Signal Processor
- U/D-Link Electronics
- Transec/Comsec
- U/D-Link Antenna
- U/D-Link RF Electronics
- U/D-Link Ant. Phasing Controls
- S-Band Omni Antenna
- S-Band RF Electronics
- Module Structure
- Bus I/O Interface Unit
- Module Thermal Controller
- Module Power Interface

CORE MODULE

- Core Structure
- Electrical Harness
- Master Data Bus
- Antenna Booms
- Deployment Mechanisms

POWER

- Solar Arrays
- Solar Array Boom/Drive Assemblies
- Solar Drive Electronics
- Solar Array Sun Sensor
- Batteries
- Power Control Unit
- Power Switching Unit
- Shunt Assembly
- Ordnance Electronics
- Bus I/O Interface Unit
- Module Thermal Controller
- Subsystem Structure
- Module Processor/Software
- Deployment Sequencer (EIA)

Figure 15 - Representative Module Partitioning

With fewer ORUs, on-orbit servicing becomes easier. However, ease of on-orbit servicing must be balanced against the potential cost of replacing an ORU containing both failed and functional systems. Transportation to and from space to support the servicing event must also be taken into consideration. Ideally, today's satellite ORUs should be designed for manipulation in both EVA and remote servicer modes; this includes considerations for grappling points, mass, and geometry. The ORUs should be designed for easy insertion and removal in both modes. The considerations here are for alignment aids, interface verification, and connection designs for power, thermal, fluid, and communication services between the ORU and satellite core.

Physical Characteristics of Orbital Replacement Units

Some designers advocate the development of standard size and shape ORUs for use across many spacecraft projects. In general, satellite requirements are sufficiently diverse and stringent to cause unique solutions to be incorporated in the resulting designs. Very little progress has been made in identifying common ORUs. The selection of common standard ORU geometrics should remain a long-term goal, but in the meantime, standard interfaces have a higher priority. Variable size and shape alone will not preclude standardized on-orbit servicing approaches, but they could make servicing and transportation less efficient.

Generally there are five categories of ORU geometry: rectangular of uniform size, rectangular of fractional sizes, rectangular but irregular size and shape, trapezoidal or pie shape, and free form. A summary of observations about each type is made in Table 7. In general, ORU designs from the three categories at the bottom of Table 7 are the most flexible and therefore the most useful to the satellite designer. The recommendation of one size and shape ORU or even a series of sizes and shapes as standards is not totally practical at this time, and would not be accepted by a majority of satellite designers. Efforts in this direction should be continued and encouraged.

Table 7 - ORU Geometry Comparisons

ORU Geometries	Pros	Cons
Rectangular Uniform Size	Allows Easy Stacking Of ORUs In S/C And Servicer Allows Structure Of S/C And ORU To Be Guides Possible Standard Module	Rectangular Assy Not As Efficient Fit In Shrouds Restricts S/C Designers
Rectangular 1,1/2,1/4 Size	As Above – More Freedom	As Above
Rectangular Irregular Size And Shape	More Efficient Packaging As Above – More Freedom	As Above
Trapezoidal Or Pie Shaped	Interfaces Well With Servicer As Above	Equipment Usually Less Compatible With ORU Shape
Free Form	Most Freedom, Widest range OF Answers To Thermal Problems	Requires Most Versatile ORU Stowage Racks

While the concept of satellite maintenance by ORU exchange is a conventional approach that has been explored extensively in theory and somewhat in hardware, it results in both design and cost penalties and advantages, in addition to simplifying servicing. Expendable spacecraft have an integrated design as diagramed in Table 8. Equipment shown in boxes in the figure is generally mounted to the inside surfaces of a very integrated and optimized structure. Thermal control is achieved by wrapping insulation around the entire assembly. The thermal control task is eased because some heat is transferred between equipment by radiation and conductivity through the structure.

Table 8 – Impact of Modular Satellite Design

Function	Integrated Design	Modular Design
ORU Access	Difficult	Simplified
Remote Servicing	Difficult/Impossible	Simplified
Structure	Optimized	Weight Penalty
Thermal Conditioning	Optimized	Weight And Complexity Penalty
Arrangements	Optimized	Constrained By Modules

Table 8 also presents a modular design used when the satellite is partitioned to include ORUs. Because the ORUs must be easily removable from the basis satellite, they must have their own independent structures separate from the backbone structure of the spacecraft. This results in duplicated or parallel structures and a weight penalty relative to an integrated design. Each ORU must be mounted to the satellite through a mechanical and structural mechanism that allows for, and eases, the exchange procedure. This interface includes alignment aids and accommodations fastening the ORU and probably a specific interface to match an ORU exchange mechanism. These features also represent a weight penalty over expendable designs. Such an interface design usually does not result in a large surface area of contact between ORU and satellite structure. As a result, it cannot be relied upon to provide a thermal conductivity path between ORU and satellite structure, unless new design and material techniques are developed.

Most ORUs removed from satellites during maintenance will be returned to Earth for test and refurbishment. For the foreseeable future, ORUs returning from space will do so in the Shuttle Orbiter payload bay. The ORUs must therefore be size compatible with a stowage rack or ORU carrier that can fit within that space. Later epoch transportation systems may relax that restraint. Eventually, some modules may be serviced at the Space Station and will have to be sized to pass through the applicable hatches.

A related subject that provides a similar limitation is the problem associated with the replacement of large deployable appendages such as antennas and solar arrays. These items are frequently much too large after deployment to be transported in reasonable sized stowage racks, or even the Orbiter cargo bay. They are launched in compact stowed packages and are deployed after reaching orbit. Mechanisms can be devised to restow most of these items, but the reliability of such devices after long exposures in space or after the deployed structure has been damaged is not assured. A technology that is receiving increasing attention at the Aerospace Corporation, at NASA centers (GSFC and JSC) at JPL, and at TRW and Lockheed Martin is inflatable structures. Future antennas, solar arrays, and sunshades may use this technology to reduce the stowage volume and weight. ILC Dover, Inc. is the industry leader in developing this technology.

ORU Sizing

The designs of 13 existing or planned satellites were analyzed by TRW in 1990 to determine their ORU characteristics as if the satellites were all designed for remote servicing. The steps in this were:

1. Data was collected from government and contractor documents
2. Each element of each satellite which might be configured as an ORU was identified
3. Thus, a total of 171 ORUs, for the 13 satellites, were listed
4. The mass, volume, and shape of each potential ORU were estimated
5. Adjustments were made to the characteristics of each element to account for the changes required to make it an ORU
6. Types and masses of potential resupply fluids were estimated for each satellite
7. Distributions were calculated for each physical characteristic
8. Each element, which might be configured as an ORU, was identified. Here some judgment was required.

All told, 171 elements were identified as potential ORUs on the 13 satellites.
TRW recommended the following <u>maximum</u> as guidelines for ORU sizing until firm user requirements are available:

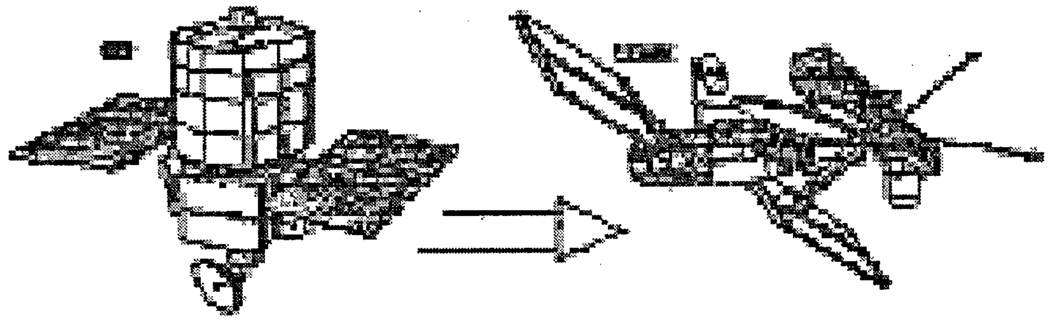
- Volume: 566 cubic meters (200 cubic feet)
- Mass: 567 kilograms (1250 pounds)
- Longest dimension: 254 centimeters (100 inches)
- Second longest dimension: 188 centimeters (75 inches)

Standardization

If modularity is the keynote to spacecraft serviceability, standardization is the thrust that makes it economically attractive. Standardization focuses on inter user servicing simulators, training methods, command and control functions and software, launch vehicles, orbit-to-orbit vehicles, and servicing tools and equipment. But the two standardization drivers that influence on-orbit servicing the most are standardized spacecraft hardware and standard interfaces both internal and external to the spacecraft.

Figure 16 shows an example of how modularity could evolve on spacecraft configurations. The spacecraft concept on the right side of Figure 16 shows an approach to design of future serviceable systems. Note the concept features a truss structure, accessible modules, refueling capability, deployable appendages, removable payloads, safing, self-diagnosis and testing autonomy, and on-orbit servicing accomplished interchangeably by either manned operations or robotic servicing.

Now **Future**



- Modularity
- Accessibility
- Instrument Repair
- On-Orbit Check Out
- Tools, Fixtures, Test Procedures
- Flight Support Structure

- Modularity
- Accessibility
- Refueling Capability
- EVA Deployable Appendages
- Standard Interfaces
- Autonomy/Self Test
- Interchangeable Manned Or Robotic Servicing
- Payload Change-out

Figure 16 - Serviceable Spacecraft Design Features

Candidate ORUs and Components for Standardization

The TRW and Lockheed SAMS study of the mid 1980's identified six spacecraft ORU modules and nine subsystems or components modules that were found to offer substantial benefits through fit, form, and function standardization. The ORU modules candidates are:

1. Communications and data handling
2. Attitude control
3. Thermal
4. Structure, particularly the basic bus
5. Electric power
6. Propulsion

Component candidates for standardization are:

1. Batteries
2. Power control unit
3. Inertial reference unit
4. Reaction wheel
5. Earth sensor
6. Payload electronics
7. Magnetic-torque
8. Sun sensor
9. Thruster pressurant tanks
10. Fuel pressurant tanks
11. Drive control units

Standard Interfaces

Typical interface items in each of the functional areas are listed in Table 9.

Table 9 – Typical Candidate Standardization Items for Spacecraft Functions

Mechanical	
ORU container interface, including alignment	ORU, size and weight
Satellite grasping/berthing	Flight releasable grappling fixture
Robotic end effector exchange system	Robotic end effector
Tool interfaces	Standardized tools
Tethering devices	
Multi-mission modular spacecraft, module structure assembly form and fit	
Electrical	
Panel mount and in-line connectors	Robocon subminiature electrical connectors
Low force connector pins	Connector mate/demate tool
Tool interfaces	Cable tie wires
Satellite and servicer power buses	
Fluids	
Automatic refueling coupler	Automatic umbilical connector
Robotic fluid coupling	Universal refueling interface system
Leak detection techniques	Tank gauging techniques
Optical	
Cameras and mounts	Access envelope and viewing angles
Lighting	Fiber optic connectors and cables
ORU status indicator	ORU inspection techniques
Label and color coding, NASA Std 3000 and Fed-Std 595A (combined with automatic vision identification, such as bar code labels)	
Thermal	
Replaceable thermal insulation panels	Insulation thermal resistance
Conductive ORU to satellite interfaces	Convective ORU to satellite interfaces
Test methods with space ratings	
Data Communication	
Communication control architecture and protocols	Data Formats
Laser communication wavelengths	Warning/messaging signals
Servicer data buses	Satellite data buses

Servicer Spacecraft Design Requirements

The Spacecraft that provides M&S to one or more operational space systems (satellites, space stations, other) is called the servicer. There are usually three parts to a servicer system:

- A robotically operated servicer spacecraft which is essentially a spacecraft bus that provides basic servicing functions
- A robotic manipulator system which performs the actual M&S

- An equipment marshalling depot which stores orbital replacement units, (ORU's), consumables, and special servicing equipment. While the depot could be ground based, analysis has shown that cost and time benefits could be realized of space basing in some cases.

Conceptually, the servicer spacecraft can be small (even micro-sat size), medium, or large depending on the complexity of M&S it performs, as well as the number and location of the operational space systems to be serviced on a single servicer mission. The servicer could be ground or space based and be part of a general infrastructure inventory or be "owned" by a specific program such as the GPS or SBL. Trade studies must be performed for each separate Air Force and NASA program to determine which of the above has an economic and operational advantage.

Servicer Configuration

The servicer spacecraft should employ a modular structure which houses the robotic manipulator system and its subsystems and components in separable modules. This equipment should have a quick change-out capability in order to accommodate several types of robot manipulator functions to meet various M&S mission requirements. This change-out could occur at a space-based man-tended platform or on the ground. A single bus module can house all of the internal subsystems and support a docking system. A description of an example of servicer functions and hardware is given on Table 10 [5].

Table 10 – Key Characteristics of an Example Servicer (AIAA Paper 99-4473)

Spacecraft Subsystem	Characteristics
Attitude Determination and Control System (ADCS)	• 3-axis stabilized • Star Tracker • Inertial Measurement Unit • (16) one pound- force thrusters
Command and Data Handling (C&DH)	• Command Telemetry Control Unit (CTCU) contains two 1750 processors, memory and data handling • Command decoder and telemetry formatter
Communications (COMM) System	• Space Ground Link system (SGLS) transponder • Downlink: 32 kbps standard • (2) Omni-directional antennas
Electrical Power System (EPS)	• Power Control and distribution Unit (PCDU) • 45 sq ft GaAs body mounted solar arrays on payload modules • (20) NiCd "F" Cells (6.3 Amp-Hrs) in bus module • Worst case: 90 minute orbit, 36 minute maximum eclipse time
Ground system	• Space Ground Link System (SGLS)
Thermal control	• Passive thermal design with heaters • Adiabatic interface to satellite during servicing • Satellite thermal design is not impacted by the addition of a payload module
Mechanisms	• Launch vehicle separation with Marmom clamp • Payload module separation accomplished with low shock separation devices (such as shape memory alloys) • Other mechanisms include docking/grappling, and star tracker covers
Orbits and Trajectories	• Parking orbit of 200 nmi, circular LEO • Hohman transfer to higher altitude using 2 delta-V maneuvers
Propulsion	• Mono-propellant for delta-V burns, attitude control, maneuvering • 4 – 10 lbs delta-V thrusters, mounted on bottom of bus module • 16 – 1 lbs ACS thrusters
Structures	• Modified LEO satellite "box" design • Advanced lightweight composite materials • High modulus graphite fibers/cyanate ester resins

In addition, servicer vehicles must provide the space and volume to carry ORUs, consumables, and any special M&S equipment. Docking systems on the servicer will probably have to be mission and robotic manipulator specific. For this reason, servicers should be capable of accommodating several types of docking systems, with the ability to change-out between servicing sorties. Hall [6] contains an excellent description of the high, medium, and low capability servicer concepts for servicing GPS spacecraft.

Servicer Concept

Servicer vehicle designs have been under study by government and industry organizations for the past decade. Preliminary servicer concepts are depicted in figures 17 and 18.

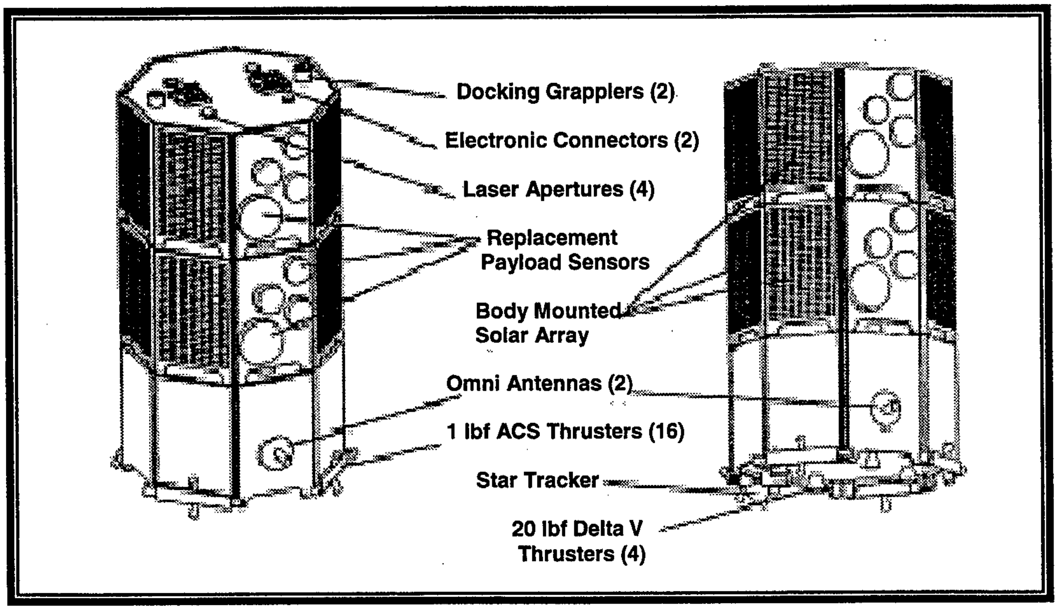


Figure 17 – Servicer Concept, NRL-SMARD program, 1998

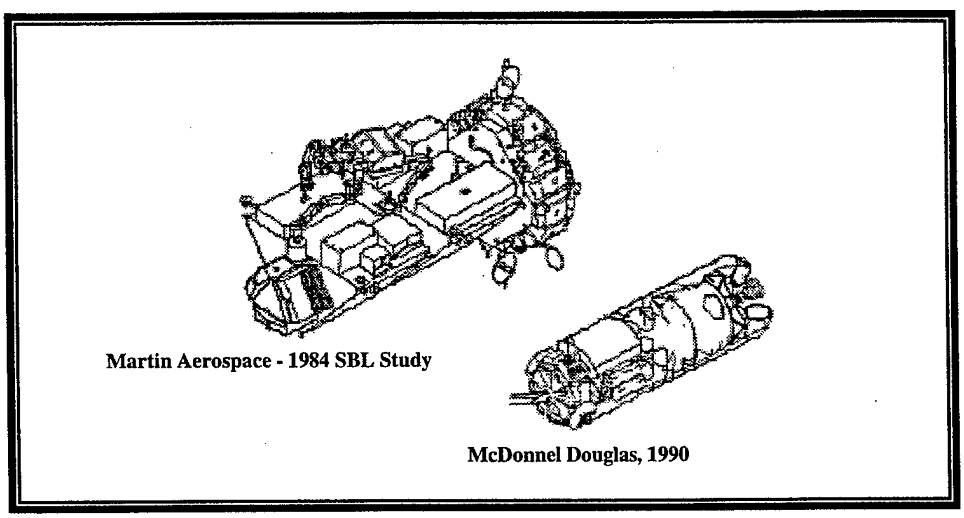


Figure 18 – Martin and McDonnell Douglas Servicer Concepts

Note in the TRW and McDonnell Douglas concepts, the servicer vehicle was propelled by the OMV while the NRL and Martin concepts employed integral propulsion.

Docking System

The NRL Spacecraft Modular Architecture Design (SMARD) study in 1998 developed rendezvous and docking techniques that can be applied to on-orbit servicing [7].

Rendezvous Maneuvers – In a three axis stabilized mode, the Servicer maneuvers using GPS navigation from its transfer orbit to a target area at 100 meters range from the satellite to be serviced.

- The spacecraft, equipped with a GPS receiver, downlinks its position and attitude to the Space Ground Link System (SGLS), which uplinks them to the Servicer command receiver.

- The servicer, also equipped with a GPS receiver, compares the spacecraft coordinates to its own, and uses autonomous rendezvous algorithms to maneuver to the target.

- The Servicer downlinks its position coordinates to SGLS periodically for ground support supervision, so the maneuver can be aborted at any time.

Docking Event

SMARD considered two basic types of docking systems for the Servicer: teleoperated and autonomous.

Teleoperated docking systems use video imagery, a remote human operator, and "joystick" controlled maneuvering. Digital cameras mounted on the servicer provide a view of the docking operations, which is downlinked, to a ground based operator. Joystick operation is linked to the attitude control system to control the position, attitude, and rates of the servicer. Without use of a Tracking and Data Relay Satellite Systems (TDRSS) data link, the docking maneuvers need to be time coordinated with limited ground contact windows (about 17 minutes contact time per revolution of period 106 minutes). Because this amount of time is believed to be insufficient for docking the servicer to the satellite, a costly TDRSS link would be necessary if a teleoperated docking system was to be implemented.

The autonomous docking system which SMARD baselined for the Servicer incorporates a laser ranging system, body-mounted grappling mechanisms, and a manual override feature. The laser ranging system determines range and attitude of the satellite docking interface relative to the servicer and fed this information to the attitude control system. Grappling mechanisms located on each of the two payload modules are used for mechanical connection of the Servicer to the satellite docking interface. The autonomous docking has a manual override feature, which allows ground-based personnel to abort the service mission at any time during the autonomous rendezvous and docking maneuvers.

A laser ranging system is required as part of the autonomous docking system for the Rendezvous and Docking (R/D) servicer. At 100 meters range from the satellite docking interface, the Servicer will use the laser ranging systems to determine position and attitude (relative to the satellite). From 100 meters down to 10 meters, a laser pulse ranging system will be used; and from 10 meters down to zero, a fine tracking laser ranging system will be used.

A fine tracking laser ranging system is used within 10 meters of the satellite's docking platform. It uses three one-milliwatt laser transmitting apertures, aligned in the same geometry as the target retro-reflectors. This technique allows the determination of precise range to one millimeter and attitude to about 0.1 degrees.

Docking interface on the satellites need to provide for permanent structural support of payload modules, coupling to propellant and pressurant lines, connection to electrical power system, connection to both digital and fiber optic data buses, and connection to various harnesses from individual replaceable components. Grappling features of docking mechanisms can be located on the servicer spacecraft to minimize the complexity of modifications to satellites.

In early 1999 the Aerospace Corporation published a report for the Space Based Laser grouped docking mechanisms into six different categories, depending upon the method of docking [8].

- **Centroidal.** Docking system located along the mating crafts' centroids, typically with some sort of docking book attached.

- **External Enveloping.** Relies on some kind of extensions from the chaser spacecraft to surround the target spacecraft and force it into a docking position.

- **External Grasping.** Grasps the spacecraft at discrete points on its periphery, as opposed to external enveloping which indiscriminately grasps the spacecraft as it presents itself.

- **Internal Expansion.** Uses a device that expands within a receptacle on the target spacecraft.

- **Peripheral.** Characterized by unobstructed central area that could be pressurized for passage.

- **Hybrid Systems.** Combines features, typically docking and latching, to achieve a rigid dock.

Examples of existing docking concepts within the six categories are shown in Table 11.

Table 11 – Docking Systems Assessment (Aerospace Corp TOR-99- (1019)-3)

Category	Concept	Pros	Cons
Centroidal	Probe and Drogue (Soviet Union's Soyuz/Soyuz and Soyuz/Salyut, US Gemini and ISS	Good capture High attenuation Good alignment capability	Complex Weight High development costs
	Multi-finger claw (never flight tested)	Low weight	Low rigidity Low attenuation High development costs
	Cable Snare (US's Space Shuttle Remote Manipulation System (RMS)	Simple design Low weight Low cost	No attenuation Low rigidity
External enveloping	Inflatable arms Space bola Compliant arms Split basket Multi-segment arms Snare	Good capture High attenuation Good alignment capability	Low rigidity Complex Weight High development costs Not for docking
External grasping	Joined telescopic arms (Never flight tested)	Good capture High attenuation Good alignment capability	Low rigidity Complex Weight High development costs Not for docking
Internal expansion	Telescopic arms	High attenuation Good alignment capability	Low rigidity Complex Weight High development costs
Peripheral	APDS (Soviet Union's Mir/Shuttle and Apollo/Soyuz, Russia's part of the ISS)	Good capture High attenuation Good alignment capability Low cost	Complex Weight
	Common berthing (US's part of the ISS)	Experience High rigidity	
Hybrid	MSAS (ESA's DBS, TRW,s ABM, Japan's ETS-VII)	Low weight Good alignment capability	Low rigidity No attenuation Complex High development costs

Robotic Manipulator

Robot arms allow manipulation of large components for spacecraft assembly, removal of failed ORUs and replacement of new ones from the servicer inventory, positioning of the spacecraft to be servicer inventory, positioning of the spacecraft to be serviced to optimal angles, assist in the refueling operations, and alignment of spacecraft booms sensors, solar arrays, and antennas.

Two design concepts are shown on Figure 19. Option 1 is a high performance, two-arm system; option 2 is a single arm, lower cost system for servicing events of low complexity.

The robot manipulator system (options 1 or 2) interfaces directly with their servicer structure and the spacecraft being serviced.

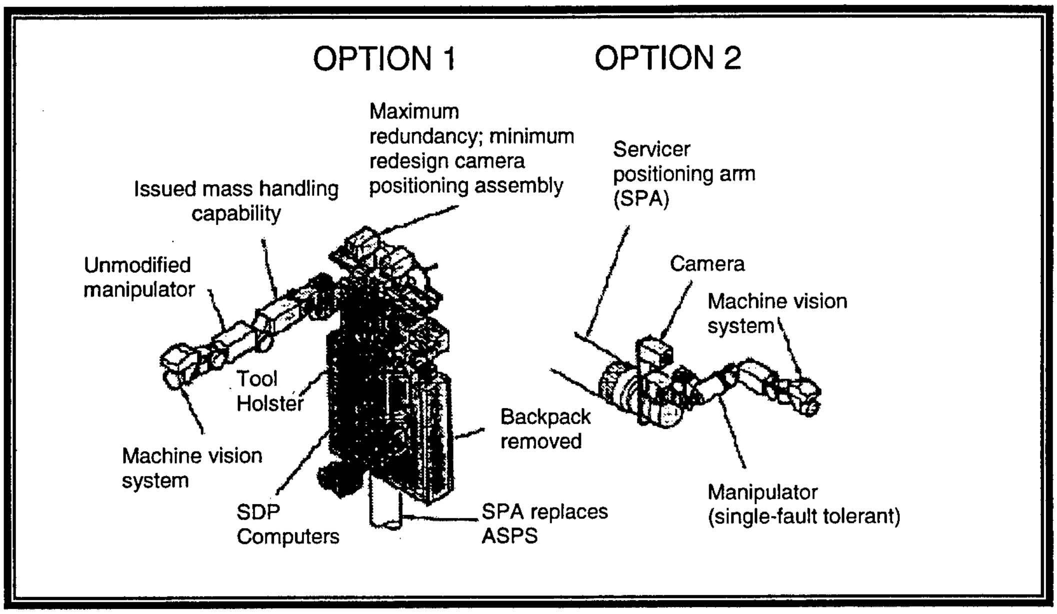


Figure 19 – Example of Robotic Manipulator, One and two arm configurations

Design and cost trades are necessary to define robot manipulator capabilities for:

- Number of arms and their reach and accuracy
- Degrees of freedom – probably 7 Degrees of Freedom (DOF)
- Mass moved or held by arm(s) – probably 50 to 3000 lbs
- Type of imaging system (sensors, Television, software)
- Thermal control requirements
- Communications requirements
- Data management requirements
- Electrical Power requirements
- End-of-arm tooling
- Attachment stabilization and positioning needs

- Degree of system autonomy
- Other

A single arm system can handle simple ORU change-outs but a two arm system will be needed for assembly operations. Two arms enable operational redundancy.

Micro-Satellites as Servicers

Micro-satellites as part of the logistics infrastructure, Figure 1.5, for on-orbit servicing and inspection are under study at the Aerospace Corporation, the AFRL at Kirtland AFB, and probably other places. Their application to servicing missions for the SBL, SBR, GPS, and GEO comsats is discussed by Dr. Rich Madison, formerly of AFRL Space Vehicles Directorate (AFRL/VSDD), in his 1998 unpublished document "Modular On-Orbit Servicing (MOS) Concept Definition and Descriptions."

Used in conjunction with an OTV, micro-sats could be employed to:

- Replace position sensitive sensors on GPS
- Inspect and remove contamination from SBL mirrors, also provide fuel replacement to SBL in a battle situation

The number of micro-sats needed for OOS depends on the inspection and servicing needs of operational spacecraft in the constellations of Air Force space systems. As a minimum one small and one large micro-sat per OTV might be sufficient. A GEO based OTV could employ a microsat to inspect the number of GEO assets or to provide faster response to GEO emergencies.

Because of its number of spacecraft in the SBL system, say for example 32 satellites (4 rings, 8 satellites per ring), the program is likely to have a high demand for servicing. One OTV per ring, each with several large micro-sats could be deployed near SBLs that were or are involved in a conflict. The micro-sats could replace fuel tanks on battle involved SBLs and clean the optical equipment on SBL used in peace-time missions.

Micro-satellites will probably be configured to be mission specific. They could be designed to dock with a part on the next generation Air Force spacecraft after traveling a short distance (about 100 meters) from an OTV, Servicer vehicle, or warehouse platform. Attaching an ORU to the front end of the micro-sat permits docking to the spacecraft to service and plug in that specific ORU. The micro-sat could also serve as a platform for a micro-robot, a free flying inspector, or a short distance tug.

Micro-sats are small, by definition (50 to 300 lbs), but they still employ a high degree of sophisticated technology. They will require subsystems such as: a docking mechanism; sensors for determining attitude, position, velocity, cameras; a docking port with electrical fluid, and thermal connections; data storage and processing (software, computers); communications; attitude control; propulsion; and a structure that allows interface with an OTV, servicer, platform and launch vehicles.

The use of micro-sat impacts space logistics strategies and inventory. More about this is discussed in Section III.

Decision Support Methodology Conclusions

The task, Develop Decision Support Methodology, was broad in scope in that we examined the inputs and outputs of a structured logic to determine if on-orbit servicing should be designed into specific spacecraft. To this objective, on-orbit servicing: benefits, penalties, costs, technology and the support infrastructure were investigated. Major conclusions are as follows:

GENERAL

1. There is a renewal of government and industry interest in on-orbit servicing of space assets. The assembly and servicing accomplishments of the International Space Station and the Hubble Space Telescope provide a hardware benchmark as to the issues, technology, costs and benefits of on-orbit servicing. Both the Air Force and the Navy have recently completed on-orbit servicing studies and are planning additional activities in this area.
2. Four things are central to building a solid logistics roadway for on-orbit servicing

- Economic evidence that on-orbit servicing can be a cost savings alternative to satellite replacement
- Consistent ability to access space systems with a servicing capability
- Ability of the space systems to be serviced
- Ability to create a National Standards Policy and Plan which accommodates the requirements of DoD, NASA, and commercial organizations.

Specific

1. On-orbit servicing could result in benefits to the SBL project:

- Allow for a higher performance spacecraft
- Extended mission duration
- More mission flexibility
- Upgrade of spacecraft and payload
- Improved performance and reliability of critical components
- Lower launch weight with on-orbit refueling
- Lower launch weight with on-orbit assembly
- Reduced life cycle cost up to 30% depending on the specifics of a given program

2. Early design decisions influence the assessment methodology and cost effectiveness of on-orbit servicing:

- Availability of low-cost transportation – Earth to orbit and Orbit to Orbit
- Reduction of cost of existing/projected government launch systems
- Development of a servicing infrastructure
- Projected transition of manned to robotic servicing
- Parallel development of technologies required for on-orbit servicing

3. Key cost drivers for on-orbit servicing development, deployment, and operations

- System complexity
- Infrastructure costs
- Servicing interval
- Number of spacecraft servicing events per servicer mission
- Technology development costs
- Launch costs
- Spacecraft replacement costs
- ORU costs
- Spacecraft weight/cost penalties to incorporate on-orbit servicing into SBL design.

Space-basing most of the infrastructure can save costs and increase response time. Trade studies needed to verify specific benefits to programs. Modularity is the key to spacecraft serviceability; standardization makes it economically feasible

- Design and development of a servicer vehicle should parallel the design and development of the satellite to be serviced
- Micro-satellites may have an important niche in the logistics and servicing infrastructure
- Infrastructure technologies effort on autonomy, robotic systems, teleoperations, and simulation and modeling should start as soon as possible to enable unmanned servicing missions of Air Force assets such as GPS and SBL to become operational in the next 10 years. Flight demonstrations of these and other technologies should start in the next five years.

IDENTIFYING SPACECRAFT CONSUMABLES

Objective

The objective of Task 2 was to list, define, and categorize those items or components on space systems that will need replacement or replenishment before the spacecraft end of life [9,10,11].

Task Approach

The strategy used for this task was to review the products consumed by a spacecraft during its orbit mission and analyze how they might be replaced on-orbit by a servicer vehicle system. This task collected the consumables data; a concept of operations design reference mission was then developed (as DRM No. 2) in Task 3 to indicate the logistics involved in their replenishment.

Consumables

The major products or components considered to be a replaceable item on a spacecraft are fuels, solar arrays, and batteries. Fuels were emphasized in this study as they have great influence on extending the useful lifetime of a space system.

For the most part consumables relate to the spacecraft's propulsion system, which perform a variety of tasks essential to active missions in all orbits [12]. These include:

- Orbital Maneuvering – ability to move from an initial parking orbit to an escape trajectory or insert into a final mission orbit.
- Orbital Maintenance – ability to maintain a specific orbit against drag and other perturbations, or phase the orbit to maintain proper angular separation in a constellation of satellites – such as GPS or SBL or Globalstar.
- Attitude Control – ability to rotate the spacecraft to reorient sensors or dump momentum, especially beyond LEO where magnetic torquing and gravity gradient stabilization are not realistic options.

The Space Based Laser spacecraft, planned for initial on-orbit operational deployment in 2020, uses consumable reactants to operate it's hydrogen fluoride laser payload. The SBL consumable considerations are discussed later in this section.

Propellant System Options

A list follows of propellant system options considered in this study:

1. Cold-gas – uses the energy of a gas stored at high pressure, which is accelerated to high velocity through a nozzle.
2. Chemical system – uses the energy inherent in chemical bonds released through catalytic action or combustion to produce high temperature exhaust products, which are then expanded out of a nozzle to high velocity.
   - Storable liquid – mono-propellant (hydrazine) catalytically decomposed to produce a superheated gas or bi-propellant (hydrazine and nitrogen tetraoxide) which produce a hypergolic chemical reaction on contact. Storable implies non-cryogenic.
   - Solid – combines oxidizer and fuel into single, solid propellant.
   - Hybrid – typically uses a solid fuel with a liquid oxidizer.

3. Nuclear system – uses the intense heat generated by nuclear fission (or fusion) to heat and inert reaction mass to high temperature. The mass is then expanded out a nozzle to high velocity.
4. Electric system – uses electrical energy to accelerate a reaction mass through electro-thermal, electromagnetic or electrostatic means, to high velocity.
   - Resistojet – electrical resistance heating of a single propellant (hydrazine or nitrogen)
   - Pulse plasma thrusters – uses an electric current to ablate a solid propellant (Teflon) creating a plasma, which is accelerated, in an electromagnetic field.

Propulsion Technology Option Costs and Resupply Amounts

The cost analysis below was reported in Information Source No. 1 above. The data shows the relative costs of each of the propulsion propellant technology options.

- Cold gas – mass and volume costs were very high, time costs were high; integration and logistics costs were low; and the technical risk, power and safety costs were very low.
- Solid – integration costs were very high; mass, safety and logistics costs were moderate; volume costs and technical risk were low; and the time and power costs were very low.
- Bi-propellant – safety and logistics cost were very high; volume and integration costs were moderate, time costs and technical risks were low; and the power costs were very low.
- Mono-propellant – safety and logistics costs were very high; mass, volume, and integration costs were moderate; time costs and technical risk were low; and power costs were very low.
- Hybrid – technical risk was high; integration costs were moderate; mass, volume, time, and safety costs were low; and power costs were very low.
- Hydrazine Resistojet – time, power, safety, and logistics costs were very high; mass, volume, technical risks, and integration costs were moderate.
- Water Resistojet – time and power costs were very high; technical risk was high; mass, volume, and integration costs were moderate; and safety and logistics costs were very low.
- Pulse Plasma Thrusters – time costs were very high; technical risk was high; power and integration costs were moderate; and mass, volume, safety, and logistics costs were very low.

In the late 1980's, TRW and Rockwell International studied spacecraft fluids needs and fluid transfer requirements. A total of 16 fluid types were identified as necessary for various resupply missions. They are:

1. Aerozine – 50 (MMH/N_2O_4)
2. Ammonia (NH_4)
3. Argon (gas)
4. Carbon Dioxide (gas)
5. Helium (gas)
6. Helium (liquid)
7. Monomethylhydrazine (MMH)
8. Nitrogen (gas)
9. Nitrogen tetraoxide (N_2O_4)
10. Oxygen (gas)
11. Oxygen (liquid)
12. Helium (super fluid)
13. Hydrazine (N_2H_4)
14. Hydrogen (liquid)
15. Water H_2O
16. Xenon

The following resupply amounts in pounds for several consumables are given below. These data are from Rockwell International from their satellite resupply work in 1985. The numbers from 1995 to 2001 are from the Rockwell data; the authors predicted numbers for the period 2001 through 2010.

Table 12 – Consumable Resupply Amounts (Rockwell International, 1985)

NASA	**1995-2001 (lbs.)**	**2001-2010 (lbs.)**
Hydrazine	22000	50000
Liquid Helium	6000	15000
Water	45000	170000
Xs-Methane Mixture	200	800
Commercial		
B1-Prop (H_2O_4)	20000	65000
Hydrazine	3500	10000
DoD		
Bi-Prop (N_2O_4/A/50)	295,000	700000
Hydrazine	63000	130000
Liquid Helium	10000	21000

Space programs that could investigate on-orbit consumable replenishment are the SBL, GPS, SBR, Iridium, Globalstar, and SBIRS (low).

Space Based Laser Consumables

The Air Force SBL program is in the early stages of system architecture definition so the present numbers associated with SBL consumables will be subject to change as the spacecraft move through subsequent phases of development.

The primary mission of the SBL is to provide surveillance to detect and negate, in the boost phase, ballistic missiles in defense on CONUS, Hawaii, Alaska, and in defense of U.S. forces, interests and allies in various theaters. Its secondary mission includes surveillance of space and near earth, and space defense and control.

The SBL program consists of a space-based constellation of 20 to 50 satellites for a full operational capability system. These satellites will operate in an orbit of between 800 and 1600 kilometers at about 60 degrees inclination. For purposes of this study, we assumed a SBL constellation of 32 satellites in four orbital planes, eight satellites per plane. The initial deployment will start in 2020. Other assumptions include:

- SBL spacecraft design life: 7 to 10 years, degradation after 5 years
- Mean mission duration: 5 to 12 years
- Servicing interval: 5 to 10 years, depending on the war fighting time of each satellite
- Servicer vehicle capability: 1 to 4 SBL's serviced per flight
- The baseline SBL platform is 28 feet in diameter and 105 feet in length. Vehicle weight is between 65000 and 80000 lbs.

<u>SBL Consumables:</u>

1. Baseline spacecraft propulsion subsystem is a monopropellant system using 5535 pounds of hydrazine with helium pressurant tanks. The propulsion subsystem performs both final launch insertion and on-orbit maneuvers which include maneuvers to maintain and re-orient the space vehicles altitude; maintain orbital altitude by providing drag make-up; and providing the coarse pointing control during laser operations. Orbital circularization is required to provide the boost to transfer from the elliptical drop-off orbit to the desired circular orbit.
2. The Alpha laser device reactant storage and supply assembly stores the hydrogen fluoride laser reactants as cryogenic gas ($D_2/H_e,H_2$) and ambient gas (NF_3) at high pressure. The weight of the reactants is 13425 lbs.

Table 13 – Laser Reactant Summary (AFBMDO CARD report, 1995)

REACTANT	TOTAL FLUID WEIGHT (MG)	STORAGE TEMP (K)	STORAGE PRESSURE psia
NF_3	4.98	300	2800
D_2	0.13	80	6500
H_2	1.52	80	6500
H_e	0.66	80	6500
N_2H_4	0.56	300	350
TOTAL	**7.85**		
Laser Run Time = 300 seconds			

Logistics Factors for Replenishing Spacecraft Consumables

There are many consumables that might need to be replenished in the life of a space system. For unmanned systems fluids, pressurants and gasses are typical items that can extend the life of future spacecraft. For manned systems there are additional items that can be described as life support consumables. These include food, hygiene and comfort items.

For unmanned systems, propellants and fuels dominate replenishment requirements. Accomplishing this type of servicing requires many accommodations and on the ground and in space. Also extensive logistics-oriented procedures must be developed and administrated by dedicated logistics providers whose goal will be to make these operations efficient and economical.

Infrastructure for Replenishing Consumables

There are basically three capabilities that a support infrastructure needs to replenish consumables: production, transportation and dispensing facilities and equipment. These capabilities are required for any logistics system. For space, these translate into an infrastructure that consists of a production site that may or may not be in proximity to the launch site. Launch sites must have equipment and facilities to store, handle and load potentially dangerous materials. A transportation capability must also exist which consists of terrestrial and space transportation resources. On Earth, normal delivery methods such as trucks, trains and ships perform their traditional function of getting consumables to the launch site.

With the amount and dangerous nature of these consumables there is a need to raise the level of safety procedures to assure safe and timely delivery to meet operational requirements. To be economical, the launch vehicle itself and the system and procedures that operate it must be optimized for replenishing space consumables. Transportation is the big-ticket item of a support infrastructure.

Finally, orbital facilities that can dispense the consumables to operating spacecraft are required. Currently there is no space infrastructure and refueling will be staged from the ground, on an *ad hoc* basis, in the near future. There is simply not enough need to justify implementation of a support infrastructure.

With the advent of space station operations there will be an orbital capability that could be used to stage consumables in space. When the space station reaches operational ability, it will generate significant consumable replenishment by itself, so there will be enough earth to orbit and return traffic to justify establishing a support infrastructure. If the station takes on the marshalling point role, there would also be a need to be orbit-to-orbit transportation in the form of space tugs and tanker spacecraft.

Fluid Replenishment Technologies

There are many accommodations that need to be made to enable consumable replenishment. Current ground capabilities at launch sites can support limited logistics resupply. For fluids and gasses, tanker capabilities for the launch vehicle and any orbital transportation are required. There have been many technologies postulated but few have been developed to real hardware and none have been certified for flight. Many of the technologies to do this exist and have been proven for terrestrial applications. Refueling requires a significant technological development effort to ensure safety during operations. Fail safe technologies that ensure separation of hypergolic fluids need to be highly developed and proven before being applied to operational programs.

Tank containment technologies will be needed for in-space facilities and transportation. Fluid coupling technologies that assure that the right consumable goes in the right place on each spacecraft need to be developed. There are several companies that have concepts for and actual hardware available to connect two spacecraft together and transfer fluids. From these technologies, systems must be synthesized and developed to be as fail safe as possible in operations.

After the coupling accommodations are resolved, fluid transfer technologies must be developed, verified and applied. Typical transfer technologies include pumping techniques, pressure transfer and tank replacement. It is expected that there will not be a single transfer technique that will be applicable to all types of transfer. Hypergolic, monopropellant and cryogenic materials require vastly different techniques for transfers. All techniques must be developed to practice and certified for use in operational situations.

Another technology that is applicable to cryogenic fluids is re- liquefaction machinery. The shelf life of cryogenics in the space environment is limited simply due to the limits of insulation capability. Re-liquefaction will eventually be required for long duration space ventures.

Applying automation to the fluid replenishment process can payoff by reducing cost and increasing the reliability of replenishment operations. Smart front-ends for tankers that can assess accurately when couplings are made secure and safe are needed. Automation used for replenishment must have highly reliable operation, benign failure modes and many workarounds, to assure safe operations and successful replenishments.

With the high value of unmanned spacecraft and the safety requirements of manned spacecraft, it is expected that both automation and manned operations will be needed in replenishment operations.

Below is a comprehensive list of refueling technologies These items listed are not all mature and will require some development to be at operational technology readiness level 8. But they are important to spacecraft refueling missions:

1. Leak detection and repair
2. Refueling hardware: EVA, robotic and blended
3. Fluid management
4. Cryo material handling
5. Fluid transportation tanks and vessels for launch vehicles and orbital facilities
6. Fluid transfer
7. Variable set-point regulators and relief valves
8. Monopropellant catalytic vent life with long burn times and high concentrations of noncondensible gases, and pulsed operations
9. Pressurant solubility effects during fill
10. Contamination control during venting
11. Adiabatic compression heating in surface tension tankage
12. Automatic fluid couplings
13. Resupply mechanism to make and break the fluid coupling
14. Tank quantity

15. Oxidizer burner and fuel burner that can accept high concentrations of noncondensible gasses, and pulsed operations, especially a burner that can handle both simultaneously or separately
16. Separation of gas vapor from liquid during venting (required for ullage exchange and vent/fill re-pressurize transfer methods to be effective)
17. No-vent fill

Remarks

A design reference mission for replenishment of consumables (DRM #2) is outlined in Task 3 of this study. This DRM describes one approach to replenishing propellants. It is not intended to be the ultimate answer for all refueling situations or a one size fits all. It is intended to illustrate the length and breadth of the effort involved for fluid resupply in space.

DEVELOPING A CONCEPT OF OPERATIONS

Overview- Concept(s) for Support Operations (CoSO)

It is important to realize that there is not one concept of support operations for all types of space servicing. Each operating system has its own unique support requirements and implementations, and there are several "Best" solutions that depend on the capabilities of an available support infrastructure. One way to address these requirements during the study phase is to formulate CoSO based on a Support Design Reference Mission (SDRM). SDRMs allow for analysis and optimization of both the primary, or operational, and support missions. This method allows the sub-optimization of individual operations and logistics tasks against a particular mission or multiple task missions, through the use of trade studies.

Realistically, there is little chance that a service mission will be dispatched from the ground for one service action. The cost would be prohibitive. Because of economic constraints, servicing missions that are staged from the ground will be configured with as much capability as possible.

On the other hand, if space logistics resources are in compatible orbits, there is more of a chance that single task and ad hoc missions could be conducted. The mix of manned and robotic solutions for servicing missions will vary as to the maturity of technology and operational needs.

In either case, the nature of space operations has matured in that programs are no longer Research and Development oriented. Many programs both military and commercial consist of many identical satellites and long mission durations. If one looks at terrestrial analogs there is no long-term operating system on earth that doesn't require some support or tending. Sooner or later as more orbiting systems are deployed, a space logistics infrastructure will be needed. Major users of space should help shape this evolution so that they can reap the benefits of space logistics to reduce the cost and increase the effectiveness of their programs.

Options for Spacecraft On-Orbit Servicing

While the subject of this report is servicing and maintenance in space, there are alternatives to on-orbit servicing that must be considered. Many of these techniques are or have been standard operating practices in the current and past space programs. For future systems, all techniques must be considered in the cold light of cost and effectiveness so that the best solution is selected and implemented. Below are some of the techniques that can be considered as a starting point of our discussion:

- Design out the need for servicing entirely for the life of the spacecraft. This could be done using two basic methods. (1) Design for short missions and replace prior to expected failure; (2) Design and implement enough redundancy to obviate the need for servicing and maintenance for the entire mission life.
- Launch a replacement spacecraft as, or if required. In effect, the total spacecraft is an Orbital Replacement Unit (ORU).
- Retrieve a spacecraft, and bring back to earth, where the hardware is serviced or refurbished and subsequently re-launched.
- Reconfigure functions electronically, by telemetry to correct individual element failures. Deactivate the spacecraft in response to a critical or final failure, in preparation for shutdown and deorbit.
- Place a reserve satellite in a strategic orbital location, so that it can be moved into position to replace a failed satellite easily, quickly and economically.
- Establish on-orbit capabilities to service, maintain and replenish, hardware, software and consumables.

After several DRM/ CoSOs are developed, requirements and concepts that are common across several systems will evolve. Analysis will indicate where infrastructure development effort should be placed, and indicate an optimum mix of infrastructure elements that can support each system properly. The CoSO is excellent reference for current and potential users to ascertain the operational cost of future systems and how they can take advantage of space servicing to improve the economic, effectiveness and schedule aspects of their program.

Military Satellites Population Predictions

Mr. Marco Caceres, Space System Analyst of the Teal Group, Fairfax, VA, provided this estimate of the satellite market from 1999 to 2009 in phone conversation with Don Waltz on August 16, 1999.

The Teal Group views the market as being relatively flat over the 1999-2004 time period with an average of 29 satellites launched annually. This number will begin to increase to between 30 and 35 each year by 2004.

The Teal Group forecasts that about 299 military satellites will be launched worldwide during 1999-2009. The total satellites launched worldwide during this period is estimated to be 1446, so military vehicles accounts for 21%. They say the value of the 299 military satellites will be approximately $35.0 billion, not including launch costs which are estimated to add another $13.0 billion – making a total of $48.0 billion.

The 299 military satellites are separated in six different types: reconnaissance and surveillance, technology development, navigation, early warning, communications and meteorological and earth resources. Table 13 shows the number of units, related percent of market, and dollar value. Of these six categories, reconnaissance and surveillance satellites will account for the largest number, 81- worth a total of $16.5 billion.

Table 14 – Type Of Military Satellite and Dollar Values, 1999-2008

Type of Satellite	Number of Units	Percent of Market	Dollar value ($B)
Communications	47	16	5
Early Warning	42	14	10
Meteorological and earth resources	6	2	0.5
Navigation	51	17	2
Reconnaissance and surveillance	81	27	16.5
Technology development	72	24	1
TOTAL	**299**	**100**	**35B**

Trends Worldwide

Roughly half the world's military satellites will be from the U.S. DoD is currently launching 10-11 satellites per year. This rate will increase. The Russians are now launching 15 military satellites annually. That rate will slowly decline. The remaining number of military satellites will come from Europe, China, Israel, Japan, and perhaps Chili.

Following a flat period during 1999-2003, the military satellite market should take an upward turn in 2004. This growth will be attributed primarily to two U.S. programs that will start launching satellites at about that time; the Surveillance, Targeting, and Reconnaissance Satellite (Starlite), and the Space-Based Infrared System-Low (SBIRS-Low).

Starlite will be a system or at least 20 small reconnaissance satellites. The program sponsored by the Air Force, DARPA, and National Reconnaissance Office (NRO), will give definition to NRO's Future Imagery Architecture (FIA) program to reduce the size and cost (by at least half) of next-generation spy satellites – a process that should start bearing fruit around 2006-2007. It could serve as the model for DoD's small satellite development effort, in much the same way the Discovery, New Millennium, and Small Explorer programs have for NASA.

Meanwhile, launches of SBIRS-Low satellites are expected to start by 2006. This proposed Air Force system of 20-30 small LEO early warning satellites would be the follow-on to the Defense Support Program (DSP) satellites. The program has been on a tight schedule calling for a first launch in 2004, but this target date clearly appears unrealistic.

NAVSTAR GPS is the largest and most predictable military satellite program for the foreseeable future. Replenishing the system has begun again, and this process will continue well into the next decade.

In 1997 the Lockheed Martin-produced Block 2R satellites began replacing the NAVSTAR GPS Block 2 and Block 2As launched from 1989 to 1996. These Block 2R replenishments will continue for another three years, as they are needed.

Teal projects that perhaps another 10 Block 2Rs will be launched, assuming that delivery of the new Boeing-produced Block 2Fs begins more or less on schedule around 2001-2002. They do not anticipate launches of Block 2Rs past 2002.

The Air Force remains committed to a Block 2F procurement of 33 satellites, despite having canceled (for funding reasons) its proposed buy of three Block 2Fs in Fiscal Year (FY) 00. This contract with Boeing – the largest satellite procurement ever by the Pentagon – should keep the NAVSTAR GPS constellation operational through at least 2025, particularly if the new satellites achieve anywhere near their design lifetime of 15 years.

<u>Past 2009</u>

Predictions of what will happen after 2009 remain speculative. Much will depend on how the NRO proceeds with its FIA program and how much the Air Force comes to rely on commercial satellite systems. Clearly, DoD is placing great emphasis on finding creative alternative ways to meet its satellite service needs in order to save money.

The Pentagon probably will continue to use commercial satellites as much as possible, thereby reducing the pressure to develop its own systems. This will help keep the numbers of new dedicated military satellites launched down to a minimum.

The Teal Group also thinks decision-makers will realize that, ultimately, deploying large numbers of small satellites will be costlier than expected. Note that the primary reason for adopting this strategy has less to do with overall cost savings and more to do with reducing per-mission risks. In other words, DoD wants to avoid losing $1-billion spy satellites on a failed launch, as it did last August with DSP Flight 19.

The need to lower satellite costs will lead DoD to adopt new concepts such as placing multiple and diverse payloads on each system. This concept, called the Global Multi-mission Support Platform (GMSP), is already under investigation by the Air Force. The idea is to find compatible payloads that can be placed on the same platform without having their sensors interfere with each other.

Assuming it receives the necessary start-up program funding in its FY01 budget, the Air Force aims to launch its first GMSP satellite during 2007-2009. If this occurs, there is a good chance that the number of individual satellites launched annually by the military will start dropping off sharply around 2008.

Space Based Laser (SBL) Program

Separate from the Teal Group's projections above, the Litton PRC study team has been collecting SBL launch and servicing mission information from the SBL Architecture Contractors. Meetings were requested with TRW, Lockheed-Martin and Boeing. This resulted in productive exchanges of non-classified, non-proprietary information with TRW and Lockheed-Martin during multiple meetings. This information will be correlated and presented as an appendix of this report after the Air Force releases it to Litton PRC.

Information to date indicates the SBL system will consist of between 20 to 50 satellites deployed, starting in 2020 in low Earth orbit of about 1600 Km at 60 degrees inclination.

Both TRW and Lockheed-Martin are investigating a variety of SBL constellation possibilities. One estimate by Lockheed Martin shows a 32 satellite SBL constellation, within 4 planes and 8 satellites per plane. A TRW constellation consists of 36 satellites, within 18 planes and 2 satellites per plane. Each company is looking at a 20 per year, for 20 years, lifetime for the SBL program starting with launches in 2020.

One Lockheed Martin analysis goes on to indicate:

- 36 SBL launches from 2020 through 2044, 24 years.
- 5 launch failures during the 36 launch, however 1 of the 5 spacecraft was recovered with a servicing Orbital Transfer Vehicle and returned to operation. That means 32 operational spacecraft.
- 117 satellites serviced from 2024 through 2044 or an average of 5.85 Sats serviced per year over these 20 years.
- 2.7 SBL's serviced, average, on each of the 43 servicing missions over these 20 years.

With above as a model, it would appear that some sort of a servicing plan, versus satellite replacement, would prove to be of economic benefit for the SBL program.

For example, if the SBL is a 20-year program with 32 operational satellites, that is 640 operational satellite years. If each SBL were designed for a 7-year lifetime (without servicing), 91 spacecraft would be required to provide the 640 satellite years. At a price of $1B/sat that is a total program cost of $91 Billion. Now if the 43 servicing missions were conducted at $500 million per mission, that is $21.5 billion. A savings of $91.0B-21.5B = $69.5B is realized with servicing. This $69.5B saving would be reduced by the amount the SBL program would be charged for use of those elements of the logistics architecture and support that they used. But even if the architecture "rental" charges were $30B over the 20 year program, the savings would still amount to $69.5B-30B = $39.5 B over total spacecraft replacement. Launch costs were not included in the above analysis.

Non Military Satellites

Teal Group information estimates a world wide total of 1446 satellites will be launched from 1999 to 2009. If 299 of these are military as discussed above, that leaves the non-military satellite population at 1147. Of these, 893 will be commercial communications satellites and 40 will accomplish commercial proprietary work. The remaining 254 satellites will be civil systems composed of science, earth resources, technology development, and weather satellites. One third of all the 1446 satellites will be U.S. systems.
The 1446 satellites, world wide, launched from 1999 to 2009, are summarized below:

Table 15 – Estimate of future satellite deployment, (The Teal Group, 1999)

SATELLITES	**NUMBER**
Military Satellites	299
Non Military Satellites	1147
Commercial Communications	(853)
Commercial, Other	(40)
Civil-Science, Earth Resources	(254)
Tech Develop, Comm, Weather	
TOTAL	**1446 satellites**

Most of the 853 commercial comsats will be in mid to high inclination Earth orbit constellations or else positioned at Geosynchronous Earth orbit (GEO). It would seem, that an on-orbit servicing infrastructure placed to support these constellations and at GEO would find a good market for their capabilities for on-orbit refueling, ORU change-out, or product improvement [13].

Derivation of Space Logistics Support (SLS) Requirements

SLS requirements flow from the projected mission models of potential users of a space logistics infrastructure. Primary requirements are a summation of known user needs. Then logistic requirements are either derived or intrinsic in any combination that delivers logistic support where and when needed as depicted in Figure 20. As more missions are analyzed, common logistics requirements emerge and become the basis for the Space Logistics System or Infrastructure.

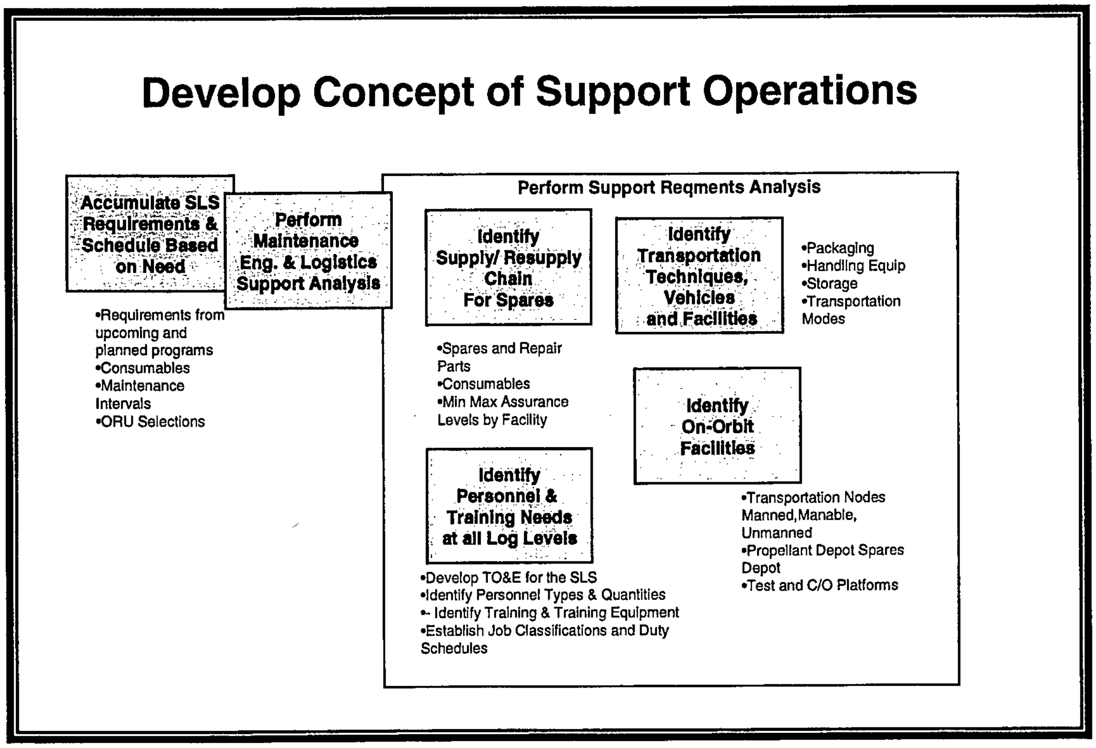


Figure 20 – A Support Requirements Analysis Precedes the Concept of Support Operations

It is important to examine as many potential space infrastructure users as possible. The more space logistics support users that can be found, the less overhead costs each must bare. The support infrastructure will be large and probably outlast most of the operational systems it will support. To be a viable operation, the infrastructure will have to constantly evolve with new capabilities to support each new system. The cost of these services should generally decrease as the population of logistic service user's increase. Economy results from sharing baseline services like transportation, facilities and others. Also, as the traffic increases, reusable transportation systems become viable and economical. The domino effect of the increasingly capable infrastructure is that users have access to capabilities they don't have to develop, operate or maintain. Users just buy and schedule infrastructure services.

Future space mission models indicate that US and other government users will not necessarily be the technology leaders or the have the highest numbers of space objects in the future. Commercial and foreign users will dominate the market for space logistics services in a few decades. These entities will have to be profitable, so servicing will flourish if it lowers cost of employment and operation. Since cost and effectiveness are so important, it makes sense that these services be provided by commercial entities, to allow competitive procurement of space maintenance services. Commercialization will accelerate reduction of these costs in to the affordable range. Typically, space transportation and maintenance support companies, are the type of entities that could evolve.

Commercially provided servicing will be beneficial to all space users, including the military, since support technologies and capabilities need not be developed, by individual programs or agencies. Servicing can simply be applied to military systems, paying only what is used and not the development of redundant capability. The Infrastructure Relationship chart, Figure 21, shows that significant effort can be off loaded to a logistics infrastructure that was previously absorbed by the operating systems.

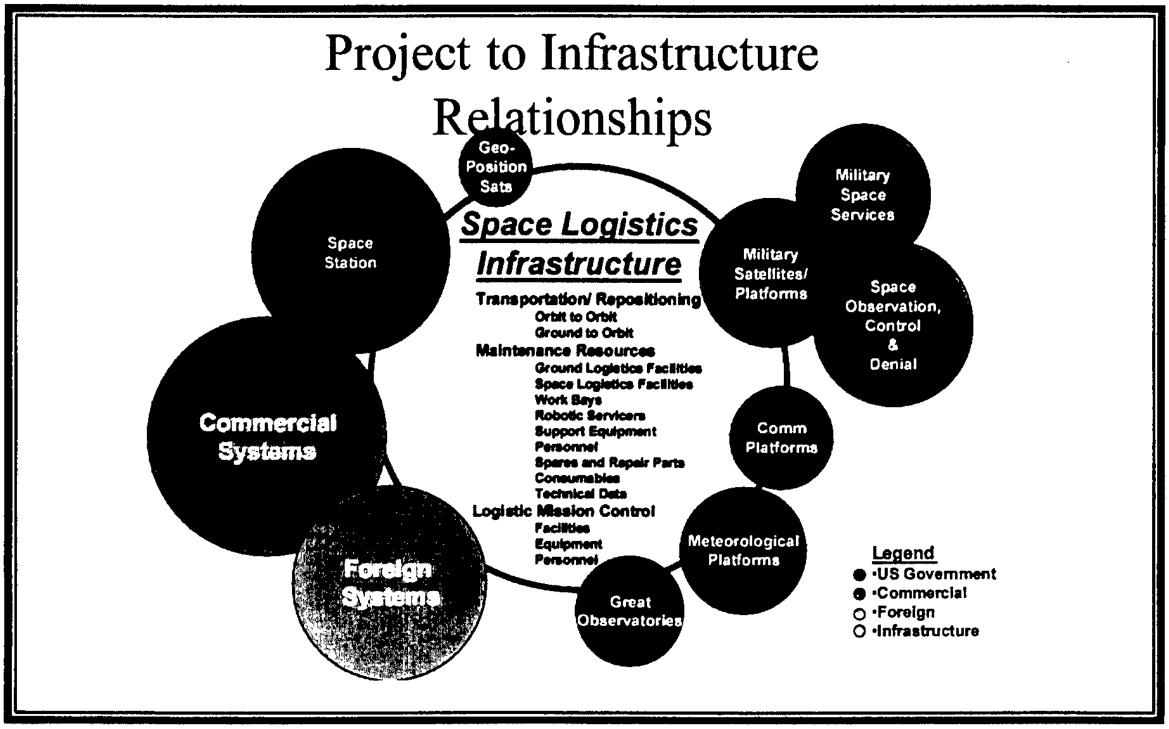


Figure 21 – The Logistics Infrastructure can be used to Jump-start New Programs

After a service infrastructure becomes established, on schedule space transportation should be part of the capability. Thus, new military systems would be able to use lower cost transportation and space logistics utilities that might enable or enhance their mission, for the price of a "Ticket-to-Ride".

Evolution of a Space Logistics Capability

Capabilities that the infrastructure should have are depicted in Figure 22. It shows significant effort by logisticians from the outset of programs: A common misconception in the past has been that logistics support effort doesn't start until the operational program and hardware efforts are well along. With the emphasis on systems engineering established in the 1960s, it became evident that operational support requirements should be considered from the outset of programs. This allows design decisions to be made that will assure that the system will not only perform, but be operable as well.

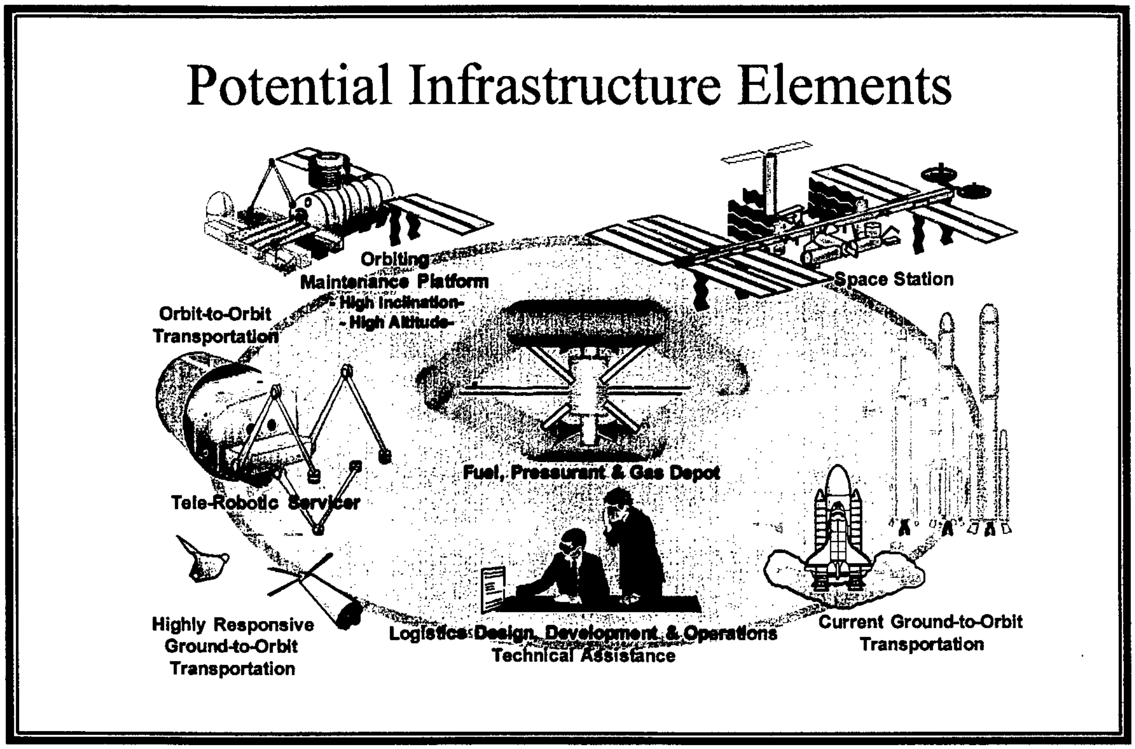


Figure 22 – Infrastructure Elements Provide a Roadmap to Space

During a design and development phase, existing and pending logistics capabilities should be considered during trade studies that are done for the operational system. Logistic Support Front End Analyses, as applied to new programs, begin to formulate operational planning and logistics support requirements for an evolving space system as shown in Figure 23.

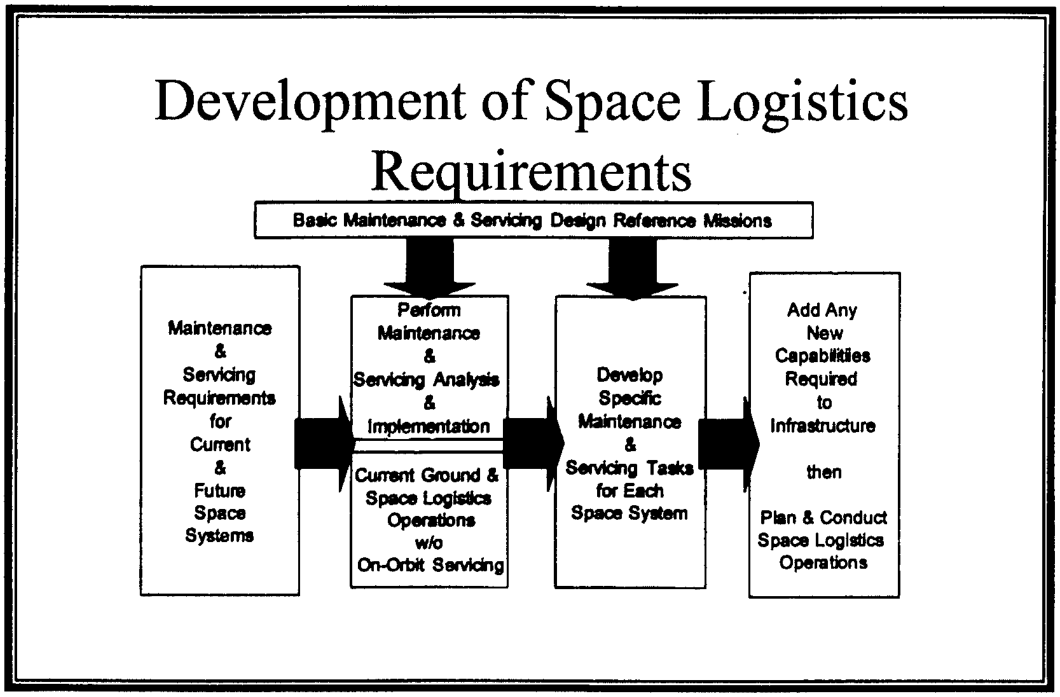


Figure 23 – Logistics Support Requirements are an Amalgamation of the Support Requirements for all Systems that may be supported

Since the primary space system is evolving at the same time as the infrastructure, trade studies will indicate what, where and when different capabilities will be needed. Since there many common services that space logistics can provide there is a good possibility that some program costs can be avoided entirely and effort focused on the primary mission. Logisticians that work these front-end trades and analyses can be critical to the success of the prime program.

As an illustration of the impact logistic support can have on the early stages of a program servicing hardware accommodations kits could be developed, produced standardized and certified. If satellite designers and users include these items on their spacecraft it will assure compatibility with a logistics infrastructure. Figure 24 shows a sampling of the types of hardware that would be available in a servicing accommodation kit.

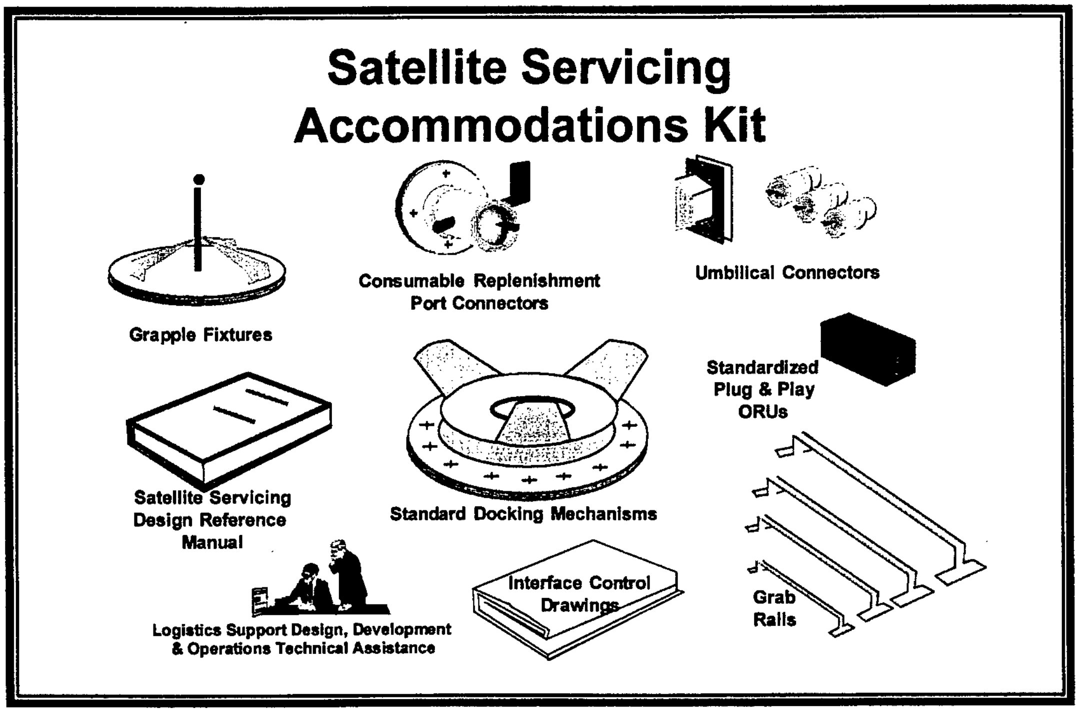


Figure 24 – A Satellite Services Accommodations Kit can Aid Satellite Developers

An accommodation kit transcends the design and development phases and can be the first operational hardware procured, since no special development is required. In effect, it can jump-start hardware development and eliminate redundant design and development effort.

During an Implementation Phase there are many logistics products to design, produce and test. These include maintenance plans, spares & repair parts, support and test equipment, training courses and equipment, maintenance facilities, etc. When a space logistics infrastructure is in place, new products and services need to be introduced into its inventory control system. Implementation effort includes certification of service, configuration management, training, introducing new hardware/software into the logistics system, establishing usage rates for consumables, establishing new logistic facilities, etc.

During deployment phase the logistics infrastructure has to provide service and maintenance to elements of a system as it begins operations. Space systems sometimes take many months or years to deploy, so partial system support must be in place at the outset of the deployment effort. In logistics vernacular, it is usually termed Pre-operational Interim Support. The final support structure is usually defined at this point and it's simply an effort to coordinate the deployment of the logistics system slightly ahead of the operational systems.

During the deployment phase, the logistics system supports testing activities. This is often a dress rehearsal for full operations and allows final tweaking of the support system and infrastructure. Also, the logistics system has to respond to the demands of new systems during this infant mortality or burn-in phase. Typically maintenance actions, spares, and consumable usage are much higher during this period than for a steady state operational period.

The operational phase usually sees a constant refinement, taking place in the logistic system. Min/max levels are refined for equipment, spares and consumables. Maintenance and servicing activity will show where logistic resource levels can be adjusted for the real world. During extended space operations, it is conceivable that: Pre-Planned Product Improvement (P^3I), Preventive Maintenance Programs and Technology Insertion missions will be done. These efforts can be very significant efforts and important in long-lived space missions.

As stated previously, the space logistics system will probably outlast several generations of operational space programs. To provide effective logistic support, requires that the configuration and technology of the servicing infrastructure at least maintain compatibility and some times anticipates needs of "Customers".

Support Design Reference Missions

Maintenance and logistics planning consists of a series of "What/ If" exercises, and trade studies, where operational support needs are anticipated and a strawman solution is offered. One way to initiate this work is to develop individual roadmaps for basic or single-function logistics type missions. This way single purpose missions can evolve and be optimized on their own. A basic structure and elements are a good starting point for application to current and new systems. We have dubbed these basic SDRMs. So far we have identified eight basic missions, they are:

1. Space Inspection
2. Replenish Fuels, Pressurants and Gases
3. Repositioning/Space Transportation
4. Remove old systems and debris from orbit
5. ORU Replacement of failed components
6. Assemble large spacecraft or orbital facilities
7. Realignment/Recalibration
8. Decontamination

These basic SDRMs are the essence of space logistics actions. For actual implementation of servicing missions it may be wise to combine two or more SDRMs to garner maximum value. Figure 25 shows the elements that will be used to build the logistics infrastructure.

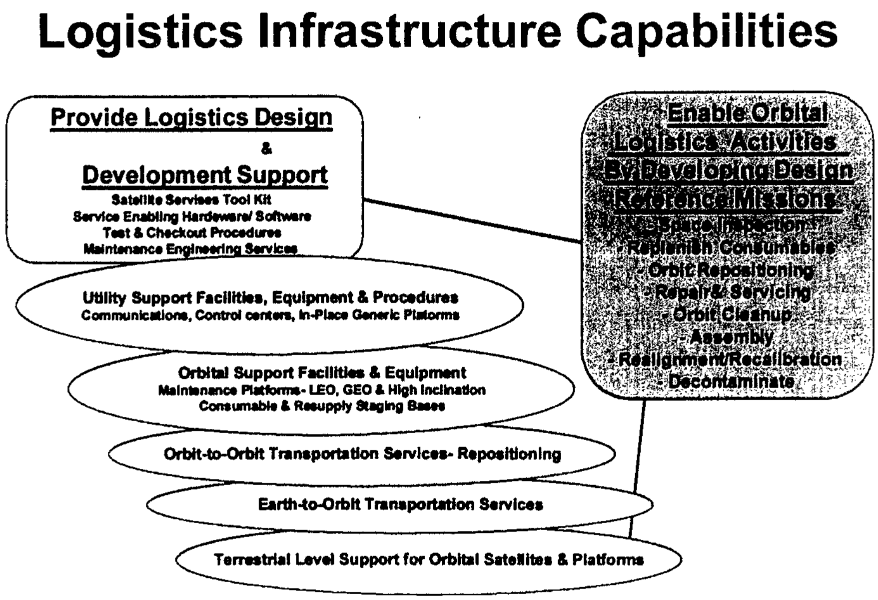


Figure 25 – A Full Complement of Logistics Support Capability Provides a Vibrant Infrastructure

Below are descriptions of each identified SDRM. SDRM descriptions include: What can be done, how it can be accomplished, and some variations of the basic missions. This information will provide heuristics to space logistics implementers so that they can focus more effort on their operational mission scenarios.

No order of priority or importance is implied to the sequence of SDRM presentation. The SDRMs are basically independent and can be mixed and matched for specific applications.

Space Inspection SDRM

There are many variations possible for the satellite inspection mission. Any selection starts with the type of inspection required, and what basic launch vehicle is to be used. There are many variations to the launch requirement from a dedicated launch to staging many "Inspectors" in orbital marshalling points or including micro-satellites on the operational spacecraft itself. Inspection requirements such as resolution, fidelity, proximity and duration are important factors.

Typical questions that need to be addressed in analyses are: Is a direct ascent to intercept trajectory, which gives a few seconds of viewing, is sufficient? Or; is a co-orbital mission, that allows longer stay time in the vicinity required? What type of inspection is required? Visual/Satellite Condition? Infrared? Radiation? Leak Detect?

There are many variations possible for this mission that depend on the inspected vehicle, multiple mission task groupings, urgency and economics. An infrastructure mix that supports inspection missions tends toward expendable Inspector vehicles. This is because the sensing devices tend to be relatively small and inexpensive. The product of an inspection mission is data that can be sent to the ground for processing and dissemination. So inspector vehicles are not necessarily "used up" and are ripe for multiple inspections. Limits here might be simply a matter of propulsion lifetime and maneuverability. Launch and positioning cost dominate inspection missions.

Variations

Assess Damage/ Deterioration:

1. Visual inspection- Single Sat Inspector, Assess Damage:
2. Visual/ IR/ Spectrograph Multiple Satellites
3. Assess the nature of any potential threat satellite or object

Direct Ascent Mission-

This type of mission might be staged from a military base similar to the proposed F-15 Anti-Satellite weapon of the 1980s. The inspector vehicle should use the certified round concepts common to anti aircraft missile technology. These vehicles are not treated like a complex weapon system but rather like bullets. They are manufactured using form, fit and function standards at the subsection or component level. They are given a comprehensive production test that certifies that the section will perform its function with high reliability for an acceptable length of time. After assembly either at a depot or at the using location using simplified mechanical means that do not disturb the certification of the section, the sections can then be certified as a "round".

Once the missile becomes an entity, it is integrated to the launch system. When an all systems test is passed satisfactorily, this constitutes certification of the system for operation. Confidence in a high level of readiness diminishes over time, due to the reliability aspects of the hardware. To bring the inherent availability back to an acceptable level at the systems or subsystem, tests are repeated. When this is done, the section is re-calibrated to a standard and so the whole vehicle retains its certification. Once the re-calibration period is determined, testing is done repeatedly until the vehicle is used for a mission or an anomaly is detected. If the direct ascent inspector system ever gets to be routine, this approach to operations is a way to achieve it.

The direct ascent approach requires significant mission planning and precision due to the relative velocity differences between the inspector and the orbiting vehicle. If the mission is not orbital, only short view time is available, as crossing velocities are high. The tendency will be toward "Pico-satellite" implementation.

Orbit Considerations – Direct ascent vehicles are basically capable of sub orbital missions All azimuths are accessible but mission windows are extremely short. Limited use is likely for direct ascent inspection missions, as the cost factor will tend to be high for the payoff. One study asserts that a 35-pound satellite can be placed in LEO by direct assent, although other authoritative experts think this is difficult to accomplish. 35-pound satellites do not provide much inspection capability in the current or foreseen state of the art. These micro-sats therefore would have be extremely low cost, and fill a niche role for space inspection missions.

Co-orbital Mission – Staged from government range or dispatched from space base. Long orbital dwell times are attainable. Larger inspector vehicles that could enable multi-spectra missions are probably favored. Lag time to inspect is likely be considerable using Hohman Minimum Energy Orbit Transfers. Space-based mini-inspectors could be collocated at maintenance and replenishment platforms to avoid costly travel up and down through the earth's gravity well. Reusable OMVs/SMVs are natural vehicle types for orbit-to-orbit transportation in these missions. Using a standard-shareable-reusable propulsion system would minimize the cost of dedicated propulsive system development and manufacture.

Product – Images and data via data link.

Orbit Considerations – Orbit insertion or storage is economical if within +/-10 to 15 degrees of inclination. Delta-v required for inclination plane change is very high. Delta –v for altitude change is much less. Staging "Inspectors" at say 0, 30, 45, 75 and 90 degrees LEO would provide all azimuth coverage. Multi use inspection spacecraft can bring mission costs down substantially. A fast up/ slow down mission can give response with minimal expenditure of resources.

Replenish Fluids Consumables and Pressurants SDRM

Replenishing resources would be an asset for many satellite families, although there are few with current servicing provisions. (E.g.. GPS, DSP, Milstar, KH Series). Consumables like: mono methyl hydrazine, nitrogen tetra-oxide, liquid hydrogen, liquid oxygen, liquid helium, carbon dioxide, argon, water, ammonia, Aerozine 50, and fluorine bearing compounds.

All replenishment missions require some sort of co-orbit, rendezvous and docking capability. Servicers must have some dexterous elements that can carry out servicing and maintenance tasks. Such a craft will be high value enough that it needs be used for more than one service activity to achieve economical operations.

Listed below are six typical replenishment tasks:

1. Replace Batteries (Primary cells)
2. Replenish RTG fuel
3. Replace solid propellants
4. Replenish Fluids: Propellants, pressurants, cryogens and coolant
5. Resupply Life support consumables: Food, water, respiratory gases, agents and hardware.
6. Replenish data storage media. Examples are photographic and magnetic media.

Fluid resupply functions integrate very well with other servicing missions. This allows for costs to be shared for common operations like, transportation, rendezvous and docking, guidance and control and thermal control. Servicer spacecraft require fluid & pressurant transfer capabilities. (Pumping techniques, bladder tanks, exchange tanks, post delivery reactants . . .). Technologies for cryogenic transfer have been postulated but not yet developed. Servicer and Operating Spacecraft both require ports to establish an interface, This interface should be secure but with tolerance for misalignment. Fail safe fueling techniques need to be developed tested and implemented.

Multiple Satellite refueling scenarios could benefit from an orbiting consumable dispensing facility to be economical. A facility like this will need to have a resupply line back to the ground itself in order to be effective. Once this orbiting facility gets to a substantial size, it may no longer be feasible to have the refueled spacecraft change orbits to rendezvous and dock to refuel. This opens the door for mini-sat tankers that move between the space depot and spacecraft transporting and dispensing consumables on an as needed basis. Space basing maintenance resources parallel terrestrial logistics levels of maintenance; Organizational (Mini-Tanker Insitu Refueling), Intermediate (Consumable Marshaling Point, and base for Mini-Tanker) and Depot (ground facilities and transportation to keep a marshaling point supplied.) If the logistics infrastructure commits to mini service vehicles, it enables other maintenance activity, as well as, through the use of other types of front ends or accessories (Inspectors, remote test and checkout equipment, robotic ORU exchange tools).

Product: Refueling service that extends the useful life of spacecraft

Single Sat:
Dock and connect fluids — Tends to favor Appliqué Technique

Multiple Sats:
Dock and connect fluids — Tends to Orbiting Service Platforms

Orbit Considerations – Same inclinations as "Inspector". Servicing the servicer makes easy access to space a requirement. This places requirements on an infrastructure to replenish consumables at the staging base. Reliable rendezvous and docking capabilities are critical to mission success. Mission "up" and mission "down" configurations of the servicer will be different due to changes in spacecraft mass. This in turn will change the orbital dynamics as well.

Reposition and Space Transportation SDRM

Decay time for spacecraft in circular or other high-energy orbits tends to be longer than elliptical orbiting spacecraft. As such a de-orbiting system needs to be used to accelerate the fall from orbit after the spacecraft's mission is finished. It is not desirable to simply destruct spacecraft, as that technique can cause an increase in debris (larger number of smaller objects) in the orbit, so there is a shotgun rather than a bullet hazard. Large objects need to be moved to an orbiting facility or, decelerated to achieve destructive reentry. These actions require rendezvous, capture and applying delta-v. Theoretically, an explosion ahead of the spacecraft track could lower orbital velocity but there could be excess energy applied and the risk of fratricide will always be there. An OMV/SMV could provide this function if properly equipped.

There is a current scenario that a repositioning capability could be used if it was available. The DSP 19 mission was left in an improper orbit that made it impossible to carry out its mission. The propulsion system simply did not operate for the prescribed time. Nothing else is wrong with the system, it's just in the wrong place and it doesn't have any propulsion capability to overcome this situation.

If an OTV was available with enough ISP to bring the satellite to its proper orbit it must have at least one other accommodation to carry out a servicing mission. The DSP spacecraft has no way to grapple or lock onto the vehicle. The servicing agency would have to work hand-in-hand with the satellite manufacturer to develop a docking system and perhaps modify the performance of the OTV to ensure that the spacecraft will be delivered to the proper orbit safely.

Over the years there have been several efforts to define and develop a multiple use orbit transfer capability [14].

Orbit Considerations – Same inclinations as "Inspector". Accomplishing a de-orbit burn, then releasing the object and burn so that the de-orbiter remains in orbit, thus saving the servicing spacecraft for another mission (An OMV model). There is another approach that could be used, and that are to use previously orbited insertion stages that have reuse capability, to apply the required delta-v. Candidate upper stages for these roles are: Delta, Titan Launch Dispenser and IUS.

Variations:

Adjust Spacecraft Orbit:	
Dock and move sat	Emergency or Planned Mission
Deploy Multiple Satellites:	
Dock and dispense	Planned Mission
Capture and Return Satellite	
Dock, Deorbit (Ground)	Emergency and Planned Missions
Capture move to Service Facility:	
Dock, Adjust Orbit	Orbital Maintenance Resources
Salvage Existing Satellites	
Dock and Move to Platform	Orbital Maintenance Resources

<u>Remove Old Systems and Debris from Orbit SDRM</u>

There is a need for removing small and particle size debris from low and medium altitude circular orbits. These items are hazardous to operating satellites in the same altitude; even though the mass may be small the relative velocities of any contact could be extremely high and cause considerable damage. This mission lends itself to a space based "sweeper" system that could be deployed in bulk and deployed as the need arises. One way to accomplish this mission would require a deployable array that can clean up orbital tracks effectively. There are proprietary concepts formulated but not developed, to do this job effectively.

Generally these sweepers take the form of relatively inexpensive expendable devices that simply absorb particle-sized debris like a sponge takes on water. For them to work they have to expand to a large size once in the required orbit. Their missions are short as when the surface area becomes large the orbital drag increases and the sweeper de-orbits quickly.

To make this approach feasible, operators must get these sweepers to orbit in the most economical manner possible. Perhaps piggybacking multiple brooms on the primary launch vehicle, the satellite itself or, on other launches, using big dumb boosters, or high rate launch concepts. In any case space-basing multiple expendable brooms seems to be indicated. Direct assent would be ineffective, as the orbital dwell time of a circular orbit is required to achieve maximum effectiveness.

For larger objects such as: Spent motor cases dead satellites and major pieces of satellites; a more purpose-built debris remover may be required. It could be envisioned as a specialized front-end attachment for an OMV or OTV that would grab the object and de-orbit or carry it to a safe location. The intact objects might already have grapple points for robotic arms that could be used for this purpose, as well. For broken pieces a snare or net type device might be the best solution.

For either version of this SDRM spaced-basing may provide significant cost and responsiveness advantages.

Orbit Considerations – Inclination not critical, orbital altitude is the driving factor. Orbit life times are short and cleanup effectiveness is accomplished through proliferation, with multiple expendable "Sweepers". Devices simply reenter the atmosphere at the end of their mission, so no disposal procedure is required

ORU Replacement SDRM

An ORU is a spacecraft item, the replacement of which constitutes organizational maintenance, repair, or product improvement update. The physical characteristics of ORU were discussed in Task 1, Development Decision Support Methodology. *In situ* ORU repair implies exchange but that may not be the actual implementation. Automation-based ORU Exchange requires a relatively smart Servicer with significant robotic capability. Multiple tool use, several degrees of freedom, sophisticated manipulator system(s), and module parking ports are examples of the capabilities required. These capabilities basically replicate functions of man-based EVA Servicing. ORU Exchange also requires significant accommodations on the spacecraft itself to allow servicing. "Solar Max" type ORU exchange would be impossible with current and planned space automation. To affect that repair required removing and replacing a score or more of not captive mounting and connecting screws and nuts. It was considered way outside the capabilities of manned EVA Servicing at the time. An adept and extremely well trained astronaut did it through sheer determination with conventional tools.

An additional use of ORU replacement is to implement spacecraft improvement. By exchanging ORUs, it is possible to increase a spacecraft's capabilities like power generation, storage and control, thermal control and data storage and transmission capacities, utility capacity. And even manned modules as requirements evolved. This pre-planned product improvement (P3I) technique is easily implemented if the spacecraft is design for it.

Spacecraft with robotic ORU Exchange capabilities should have significant accommodations built in. Quarter turn captive fasteners, bayonet and breech lock connections go a long way to reducing the complication of robots used to accomplish successful maintenance. Robotic servicers must have substantial maintenance related capabilities, as well as, enough intelligence and flexibility to accommodate anomalous physical situations.

Another way to accomplish ORU Repair is to use the "add-a-module" or appliqué technique, which is like installing redundancy, after the fact. It requires spacecraft buses that can isolate failed modules electrically and accept functional information from the new module in a different position. Current and future data busses have this inherent capability, but physical accommodations need to be added in the form of attachment ports that allow for inserting new modules and for providing thermal control capabilities if required. A derivation of this approach is to use "Plug and Play" technique for inserting new subsystems and technologies.

The robotic servicer that implements appliqué type maintenance needs most of the sophisticated capability that the ORU Exchange technique requires. A concept of a robotic servicer is shown in Figure 26. This type of sophisticated capability is generic enough that it could be shared with other missions along with the cost burden. Thus multi task missions would make more economical sense. Single task missions might be economically staged from an orbiting service platform using Mini-Sats.

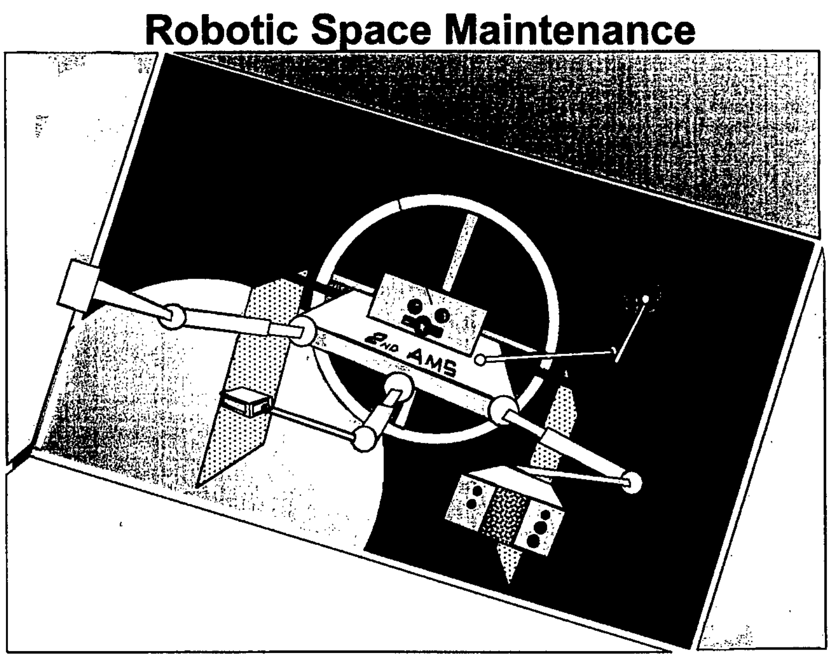


Figure 26 – Many ORU Exchange Technologies and Elements are already Available

Almost all, future generation spacecraft above the size of the Microsats can be designed to incorporate modular on-orbit servicing features. This is especially true if the Air Force, NASA, and civil spacecraft developers, implement a variety of payloads that are configurable to support missions like communications, early warning, reconnaissance, surveillance, meteorological, earth resources, positioning, navigation and pure science.

Four features that will define the next generation spacecraft busses are: Plug-and-play modularization, functional modularity, automatic fault detection and isolation and one or more docking ports [15].

One or more ORUs in the form of modules for spacecraft functions like data management, attitude control, Reaction Control System/ propulsion, communications, electric power and core structural elements would, in the context of this SDRM, be delivered on a servicer vehicle to the spacecraft to be serviced. While docked, the ORUs would be telerobotically transferred from the servicer to the spacecraft.

Other spacecraft elements such as payloads, sensor packages, instrument clusters, and deployable booms can also categorized as ORUs.

Variations:

Exchange ORUs and Repair surface:

LEO/GEO	Planned Mission

Exchange ORUs and Refuel:

LEO/GEO	Planned Mission (P3I)

Exchange ORUs and Refuel Multiple Sats

LEO/GEO	Emergency Mission

ORU change-out details:

There are many events that are common to any servicing mission, be it an on-orbit assembly, maintenance, or servicing task. They are listed below in the sequence that they should be performed. This example is for ORU change-out, but the list holds true for refueling, surface restoration, decontamination, realignment, and re-calibration, as well.

The sequence shown below assumes the servicer spacecraft is space-based, has the proper ORUs aboard and its own propulsion or access to an OMV type vehicle.

Typical Pre-ORU change-out events

1. Close-in maneuvering (pre-approach)
2. Satellite inspection
3. Spacecraft stabilization (as required)
4. Final approach and docking
5. Position recognition, initialization
6. Spacecraft deactivation or safing, as required
7. Electrical power, command and control, data interface connections
8. System interrogation and fault isolation
9. Integration of servicer and spacecraft control functions (as required)
10. Worksite preparations, covers removed, debris collected and stored
11. Install support equipment

ORU Exchange Events:

One or more ORUs are removed from the servicer and properly installed on the spacecraft being serviced. Autonomous docking and ORU exchange is shown graphically. Neutral buoyancy tank tests conducted by McDonnell Douglas (now Boeing) and TRW in the SAMS Study indicated that roughly 40 minutes would be required for supervised for typical ORU robotic removal and replacement.

Post ORU Exchange Events:

Once servicing is complete, a series of events are required before the serviced spacecraft returns to normal operation and the servicer leaves. These events are listed below:

1. Systems interrogation / checklist
2. Return work-site to operational status
3. Disconnect external power, command & control, and data.
4. Separate and standoff
5. Inspect spacecraft, power up and checkout operation
6. Close-in maneuvering (post standoff)
7. Evaluate, capture and stow maintenance generated debris
8. Servicer departs
9. De-install support equipment

The first step, above, systems interrogation and checklist, is an inspection that determines if the servicing operation was successful, or if it caused maintenance induced failures. If operations are not normal, a decision needs to be made as to whether to try to correct the problem or to leave the spacecraft and return at a later time. The latter could occur if the required ORUs or tools are not available on the servicer spacecraft.

Orbit Considerations – Co-orbit with serviceable spacecraft. Rendezvous and docking required. Mission up and Mission down may have different servicer spacecraft configuration (e.g. Center of Gravity, size and/ or mass).

Space Assembly of Large Spacecraft or Facilities

The world is in the midst of the largest space construction project right now, the International Space Station. Multiple missions are just the beginning of the complexity and effort. Designing for space assembly is not a trivial task, as it requires:

1. Design and manufacture individual elements that can be integrated in orbit.
2. Identify and integrate orbital and terrestrial transportation and other logistic needs
3. Identify, organize and train teams to accomplish all the tasks.
4. Design procedures for launch assembly, service and operations to complement the hardware.

5. Identify and implement the ground support resources for implementation and operations.

The 30+ missions for the space station assembly are interspersed with dedicated logistics missions that bring up service and maintenance resources that will allow for maintaining operations while the station is being completed.

On a smaller scale the postulated Space Based Laser could be a two-part mission with the possible addition of loading fuels after assembly and during its lifetime. There are two designs for the SBL:

One that would be launched fully assembled, on the largest launch vehicle in the inventory, and another that would be assembled in orbit. For this mission a smaller satellite is not and can't be made as capable as the larger assembled satellite using present and foreseen technology. For some missions size is an important and/or enabling factor. Several previous missions that were postulated by DoD and NASA were candidates for on orbit assembly.

For DoD, the Neutral Particle Beam Weapon System that was part of the Strategic Defense Initiative (SDI) required four missions just for assembly and regular visits to replenish consumables.

NASA programs that included assembly tasks were 25kw Space Platform, 100 meter Telescope and the GEO Shack. These programs postulated servicing and maintenance techniques and effort that enabled spacecraft installation and operation in the orbital environment.

If these programs had proceeded to deployment and operation phases, the logistics infrastructure required for servicing, maintenance and space assembly would have evolved twenty years ago.
An additional use of Space Assembly is to implement spacecraft improvement with techniques like Add-a Module. This approach was postulated in NASA's Space Platform program. The plan was to simply add docking ports, utility capacity. And even manned modules as requirements evolved. It is conceivable that the Space Station will be very different at its 20th anniversary through the use of this P3I technique.

Typical Space Assembly Tasks:

1. Unload components or assembly elements from transportation vehicles
2. Transfer components or assembly units by .OMV, special tug or with crew using an MMU.
3. Position components into assembly sequence
4. Temporary restraint/ holding of components during assembly
5. Attach components to assemblies/subassemblies through mechanical means (Bolting/latching, bonding and welding)
6. Install electrical power and distribution systems and components
7. Install command, control and data systems
8. Assemble piping distribution systems

9. Install electrical power systems and components. Power units, fuel tanks, batteries and RTG for example
10. Assemble/deploy appendages (Solar arrays, radiators, antennas, sensors, booms and payloads)
11. Attach subsystem modules. (Propulsion, propellant tankage, attitude control and communications)
12. Attach special equipment (Covers/protective shields, thermal insulation, hand rails and restraints for future servicing visits and docking adapters)
13. Align and calibrate (Structures, subassemblies, appendages, instruments and sensors)
14. Initial operation or startup tasks such as complete systems checkout and functional testing.

Products: Large scale space objects in various orbital locations performing complex operations while being economically viable.

Orbital Considerations: Most assembly projects tend to be in high energy orbits (LEO Circular and GEO). The key is to make the assembly orbit readily accessible for the ground with reliable transportation. It may eventually evolve that large satellites may be assemble in LEO no matter where the eventual operational altitude be. Orbit transfers, in plane, can enable missions that end up in the radiation belts and beyond.

Prognostication: As space assembly infrastructure matures, the tendency to assemble smaller satellites will evolve. With the economies realized by using high-rate shared transportation and on-orbit assembly, the cost of placing several small payloads to orbit would be less than the cost of dedicated large launch vehicles. Also, when space assembly and servicing becomes routine, it will minimize the need for extensive ground integration effort, which can further reduce life cycle costs.

Realignment/ Recalibration SDRM

On satellites that have optical elements or are concerned with accurate data throughput, the possibility of needing Realignment and/or Recalibration is foreseeable. To accomplish these tasks during operations it is expected that significant adaptive or adjustment capability is already part of the spacecraft systems. Thus this function can be done remotely in most cases. However there are some cases where *insitu* alignment and calibration may make sense.

Realignment: After a replacement of an element of an optical chain, almost any system of this type needs to have its alignment checked. There is just one way of not having to do this that I know of and that is to replace the entire optics chain to a non-critical surface. This would allow alignment in the controlled environment of the lab or manufacturer on the ground. The nature of optical maintenance is basically remove and replace or add an element as was done to the HST. This kind of activity would require a visit by or to a servicing capability.

If the visit is to a service facility any optical alignment equipment should be available to the servicer locally. Collimators and reference equipment are some types of additional support equipment that might be needed for alignment.

If a servicer visits the spacecraft, it is probable that extraordinary equipment will not be there, without extensive preplanning, prepositioning and preparation. Remote alignment using earth (Ground reference marks) or space references (Star formations or Stars) might be used. Adjustments would be done by the servicer or by the spacecraft itself if there were adaptive optics aboard. Usually, adaptive optics can normalize minor anomalies by using either mechanical or electronic manipulations.

Recalibration: Calibration connotes reference to a primary or secondary standard. As envisioned for satellites it is expected that reliance on reference standards will be minimized. The most probable calibration parameters are Color, Voltage, and Frequency.

Color is mostly used in optical systems. Ground references are usable for the visible spectrum as the reference color is known and the atmospheric effects have been characterized. For UV and/or IR calibration known references from extra terrestrial sources may be used. Using "Friendly" launches as tests could help calibrate surveillance satellites.

Decontamination SDRM

Most spacecraft suffer a degradation of some sort during the life of its mission. A common type of degradation is contamination, either from the space environment and/or from the expulsion of propellants and other consumables from the spacecraft itself.

Some of the surfaces that typically suffer lower performance due to contamination are: Optics, mirrors, solar arrays, radiators and even some types of insulation.

Decontamination activities can involve several techniques like wiping, applying solvents, applying heat or re-coating surfaces. All of these tasks require that the decontamination device be at the surface needing treatment. A servicing spacecraft must rendezvous and dock with the contaminated vehicle and be able to place whatever decontamination tool in the proper location to do the job. Depending on the uniqueness of the contamination that needs to be removed, it may be that the responsibility of the servicing system is simply to position a proprietary decontaminating device provided by the operational program.

Formulating the Concept of Support Operations for a Space Logistics Infrastructure

Based on the future planning of commercial, government and foreign space users a logistics support infrastructure can enable or enhance space systems by providing maintenance services. A concept of this infrastructure is shown in Figure 26.

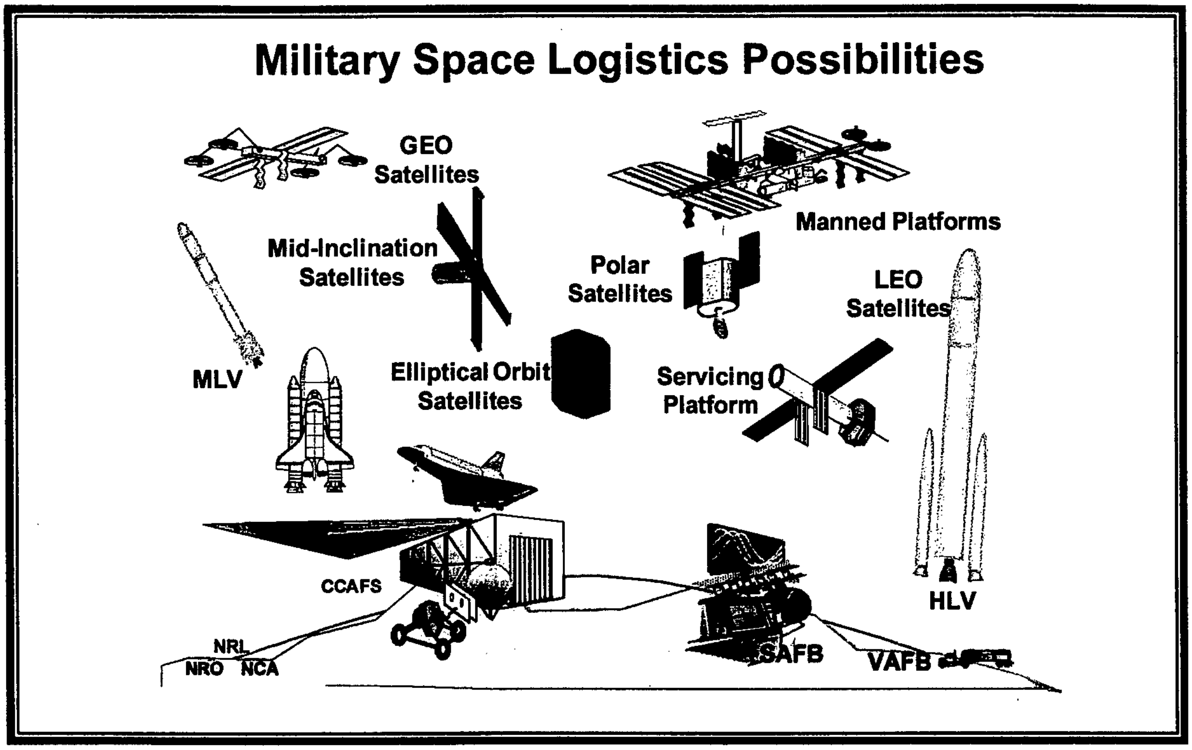


Figure 27 – Space Logistics Capabilities are often Imbedded in Individual or Combined Projects

This graphic shows not only the space side of space logistics but some of the ground elements as well. Space elements should dovetail with the ground elements, to be effective and economical. The existing Air Mobility Command (AMC) ground Logistics capabilities like Launch vehicles, launch sites, launch/landing cargo integration, spares and consumable depots, ground support equipment, as well as, personnel to operate and manage this maintenance and servicing effort are perfectly suited to support a space infrastructure. All that is really needed is for the space element to be treated as a gateway to all the space systems that require servicing. Space Logistics plans, policies, technologies, tasks, projects and organizations can be just like air-breathing systems.

In the space sector elements like: Orbit Transfer Vehicles, robotic servicers, fuel depots, servicing platforms and a command and control system dedicated to logistics missions and operations will need to be developed. These two basic areas need to be seamlessly integrated as far as operations are concerned in providing services to operational spacecraft and constellations.

Requirements Derived from Space Users

Space user requirements indicate requirements from a space logistics infrastructure. These requirements take several forms and each contributes to different parts of planning and implementation.

- Traffic projections from commercial, government and foreign space users provide indications of the volume of "Saleable" logistics services that a logistics infrastructure could supply.
- Types and quantities of logistics resources required to enable or enhance their missions indicate nature of "Saleable" logistics services that a logistics infrastructure could supply.

- Awareness of available enabling and/or enhancing services that a support infrastructure could provide through early logistics interaction.

Currently, operational systems planners are underestimating the potential capabilities available from a space logistics system. They are coming up with the same old solutions based on old concepts and inefficient transportation systems. There is a need for a logistics entity to lead operational systems and establish space logistics as a way to break the logjam. This forms a path of least resistance by allowing users to buy or rent a service and not have to develop and maintain the capability themselves.

Space Logistics Implementation is Phased to Support Customer Scheduling

The agency that develops and runs the Space Logistics infrastructure is projected to have many opportunities to supply products and services. According to the latest mission traffic models for the next ten years, there will be 299 military and 1,147 other satellites will be launched. The military satellites alone are valued at $35 Billion, NOT including launch costs. If maintenance and servicing can extend the life of the systems at reasonable cost, it will attract considerable attention. There are multiple long duration military systems in the development and planning phases, some of which will have their missions enabled or enhanced by including space assembly, maintenance and servicing. Many commercial space systems for communications, earth viewing, positioning and eventual space manufacturing will need logistics services to maintain their capabilities that their customers will depend on.

Design for Maintenance and Servicing Assistance

If a commercial space logistics infrastructure anticipates this growing business, it will influence spacecraft designs of potential customers. As was shown back in Figure 4, using a satellite servicing accommodations kit for interface hardware can save spacecraft developer's significant funds in the implementation phases of the program. The items shown are installed on the spacecraft side of the interface to assure perfect matches to those on the servicer. Using this hardware will save costs in the operational phase because the service provider will not have to make special accommodations when providing properly outfitted spacecraft, service.

A space logistics organization, whether commercial or government, should have logistics engineering expertise within their organization that spacecraft developers can use to help design and planning for operations. Eve though the personnel are important, there should be proven Interface control and design for maintenance documentation available that saves additional time and effort.

Application of Space Logistics Capabilities to Military Space Programs

There are several military space systems on the horizon that are considering space logistics support to not only enhance their missions but to enable them. Properly used and applied, space logistics services reduce life cycle costs. On large constellations with multi-decade missions the yearly cost savings from using space logistics to meet availability requirements becomes very significant. Below are examples of military space systems that could benefit from space logistics support.

Figure 27 depicts a support concept for a space constellation as is projected for a space-based laser system. Here servicing is done on a periodic basis. In order to maintain operations. The servicing effort could take the form or replacing consumables and change-out of limited life items. Also, if faults can be detected at a ground facility and repairs can be done by ORU replacement this activity can be done as well.

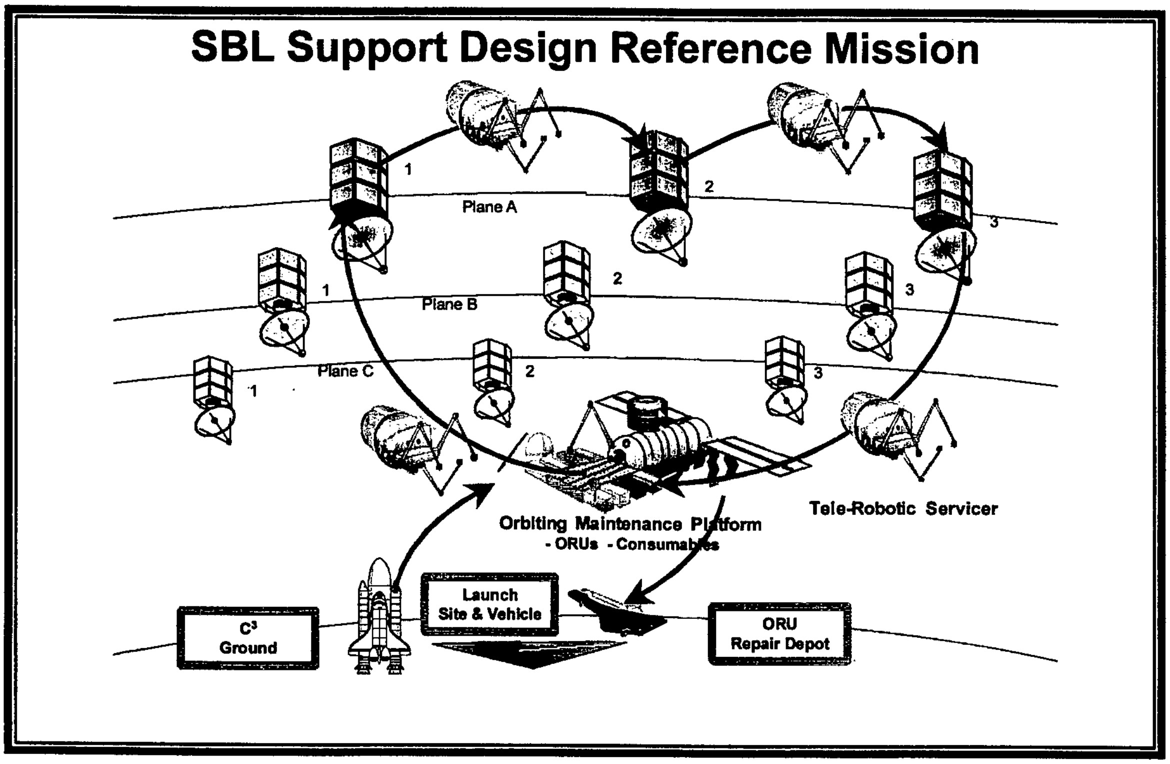


Figure 28 – Common Infrastructure Elements can be applied to Many Systems

This particular servicing approach is postulated to be done on an orbital ring basis as transportation costs are minimized. Here in a ring with three satellites the servicer can move to each with relative ease probably accomplishing the same sequence of events at each.

Another projected program, GMSP, has the potential for truly economical space operations. This project could provide enormous benefits when using a multi payload platform:

1. Users are provided power, communication, attitude control/ station keeping and thermal control as utilities that they don't have to develop or maintain.
2. SPO Personnel only have to develop their own payload system. This allows program developers and operators to focus all their effort and cost on their primary mission and equipment
3. Tenants on a GMSP are assured that their payload is compatible with the space logistic system.

These factors allow users to buy what satellite services they need and no more. If one abstracts any mission, even a military mission, to its essence most payloads would thrive on a multi-payload space platform. Figure 28 shows a concept of a generic platform.

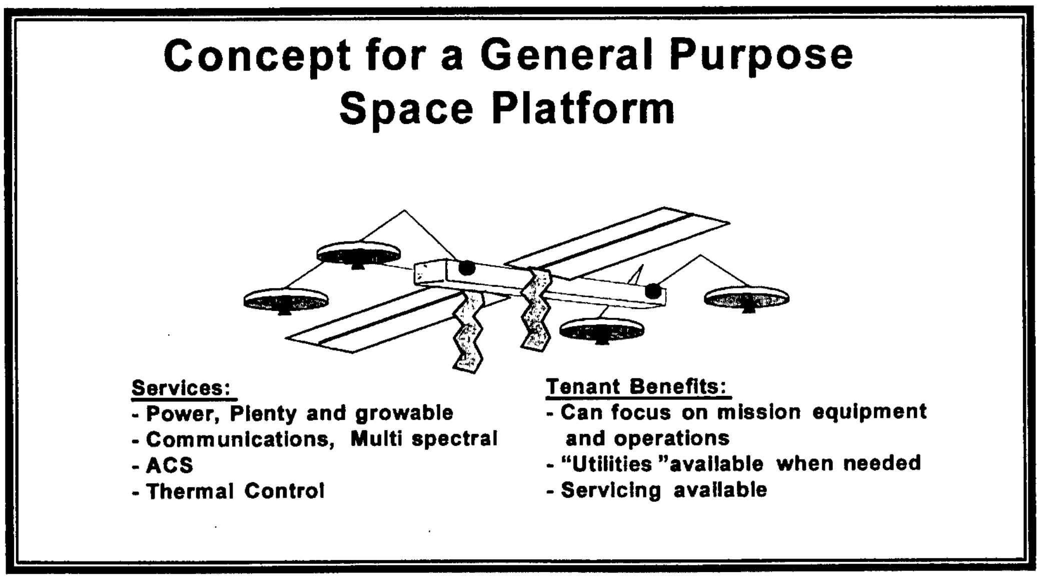


Figure 29 – General Purpose Platforms are More Economical Users When They are Serviceable

Space Platform concepts have been postulated from the outset of the space program. Space Station itself is a major multi-function space platform, NASA had a multi-payload Platforms postulated in the 1960s though the 1980s. The selling point of this type of facility is that it would be visited regularly and services were readily available.

Issues Yet To Be Addressed

- Establishing Elements of the Space Logistics Infrastructure
- Ownership and Operation of space logistics facilities
- Economics and flow of user fees
- Control methods, degrees of autonomy for servicing spacecraft
- Control centers (Brick and Mortar, Equipment/ Software, Procedures /Protocols)

Supporting Tasks

- Gather and categorize Requirements- The logistic infrastructure is only valuable if it responds to the needs of potential "Customers", as such current and project Mission, Operational, Design and Support requirement form the basis for the entire study.
- Conduct Maintenance Analysis of Candidate Spacecraft- At least a cursory but traditional front-end maintenance analysis of each spacecraft identifies maintenance and support requirements.
- Develop Logistics Requirements and Concepts- with Maintenance, Support and Consumable requirements in hand planning for the Logistics Infrastructure can be done. The space support infrastructure can be categorized in three areas: Space elements. Transportation requirements and elements and Ground elements.

Outputs of this Study are expected to be preliminary infrastructure requirements and concepts that have been examined for feasibility, applicability and economic sense.

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ACRONYMS

50 (MMH/N_2O_4)	Aerozine
ABM	Alternate Berthing Mechanism
ACS	Attitude Control System
AFRL	Air Force Research Laboratory
AFRL/HESS	Air Force Research Laboratory, Deployment and Sustainment Division ()
AMC	Air Mobility Command
APDS	Androgynous Peripheral Docking System (Apollo/ Soyuz Program)
ASPS	Automatic Servicing Position System
BIT	Built in test
C^3	Communications, command, and control
CCAFS	Cape Canaveral Air Force Station
CER	Cost Estimating Ratio
CONUS	Continental United States
CoSO	Concept for support operations
CWBS	Cost Work Breakdown Structure
D_2	Deuterium
$D_2/H_e,H_2$	cryogenic gas
DARPA	Defense Advanced Research Projects Agency
DBS	Docking & Berthing System
Delta V	Change in velocity
DoD	Department of Defense
DOF	Degrees of Freedom
DMSP BLK 5D-3	Defense Meteorological Support Program Block 5D-3
DRM	Design Reference Mission
DSCS	Defense Space Communication System
DSP	Defense Support Program
EELV	Evolved expandable launch vehicle
EMU	Extravehicular unit
ESA	European Space Agency
ETS-VII	Engineering Test Satellite-7
EVA	Extra vehicular activity
F/O	Follow-on
FIA	Future imagery architecture
FIDLS	Fault identification diagnostic system
FTS	Flight telerobotic system
FY	Fiscal Year
GEO	Geosynchronous Earth orbit
GMSP	Global Multi-mission support platform
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
H_2	Molecular Hydrogen
H_2O	Water
He	Helium

HLLV	Heavy lift launch vehicle
HLV	Heavy Launch Vehicle
HST	Hubble Space Telescope
I/O	Input/output
ILC	ILC Dover, Inc.
INS	Inertial Navigation System
IR	Infrared
ISS	International space station
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KH Series	Classified Satellite Series
lbf.	pound-force
LEO	Low Earth orbit
Litton PRC	Litton Planning Research Center
LLC	Life cycle cost
M and S	Maintenance and Servicing
MD	McDonnell Douglas
MEMS	Micro-Electrical Mechanical Systems
MEO	Medium Earth orbit
MILSTAR	Military, strategic, tactical, and relay
MLV	Medium Launch Vehicle
MMH	Monomethylhydrazine
MMU	Manned maneuvering unit
MSAS	Maneuvering Satellite Attach System
MSX	Multi Servicer Experiment (now Space Maneuvering Vehicle)
N_2H_4	Hydrazine
N_2O_4	Nitrogen tetraoxide
NASA	National Aeronautics and Space Administration
NF_3	Nitrogen Fluoride - ambient gas
NH_4	Ammonia
NRL	Naval Research Laboratory
NRO	National reconnaissance office
NSTS	National Space Transportation System
O&S	Operations and support
OMV	Orbital maneuvering vehicle
OOS	On-orbit servicing
OPS	Operations
ORU	Orbital Replacement Unit
OTV	Orbital transfer vehicle
PALAPA	Indonesian Satellite (Indigenous Word)
PHS&T	Packaging, Handling, Storage and Transportation
P3I	Pre-planned product improvement
R&D	Research and Development
R/D	Rendezvous and Docking
RLV	Reusable launch vehicle
RMS	Remote maneuvering unit

ROTV	Reusable orbital transportation vehicle
RTG	Radioactive thermoelectric generator
S&T	Science and Technology
S/C	spacecraft
SAFB	Schriever Air Force Base
SAMS	Space Assembly, Maintenance, and Servicing
SBIRS	Space-based infrared system
SBL	Space Based Laser
SBR	Space Based Radar
SDI	Strategic Defense Initiative
SDP	Space Defense Program - evolved to SDI/ Star Wars
SDRM	Support design reference mission
SGLS	Space ground link system
sinequa non	An essential condition, indispensable, absolute pre-requisite
SLS	Space logistics support
SMARD	Spacecraft Modular Architecture Design
SMC	Space and Missile Command
SMM	Solar Maximum Mission
SMV	Space Maneuver Vehicle
SOV	Space Operations Vehicle
SPA	Servicer positioning arm
SPO	System Program Office
SSAS	Space Systems Acquisitions Support
STS	Space transportation system (Space Shuttle)
SYNCOM IV-S	SYNchronous COMmunication satellite- 4- S-Band
TDRSS	Tracking and Data Relay Satellite Systems
U/D	Up/down
UHF	Ultra high frequency
UHF F/0	Ultra High Frequency Follow / On
US	United States
USAF	United States Air Force
UV	Ultraviolet
VAFB	Vandenberg AFB
VSD	Vehicle Systems Directorate
WBS	Work breakdown structure
WESTAR	WESTern Union Communication Satellite
Wt_3	Weight
Xfer	transfer