NAVAL POSTGRADUATE SCHOOL
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THESIS

SATELLITE SERVICING USING THE
ORBITAL MANEUVERING VEHICLE
IN LOW EARTH ORBIT

by

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June, 1990

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This thesis examines the concept of servicing and repair of satellites in low earth orbit (LEO) using the Orbital Maneuvering Vehicle (OMV). The emphasis is primarily focused on current polar orbiting satellites, however, it could be economically applied to any LEO in which sufficient numbers of satellites are located or where individual satellite cost/mission justify servicing. Significant increases in the cost effectiveness and operational flexibility of in-space systems can be realized when the capability to replenish consumable fluids, propellants and Orbital Replacement Units (ORUs) are incorporated into satellite design. ORUs can be placed in orbit using expendable launch vehicles (ELV), specifically selected to satisfy the mission need. Several suitable small payload, low cost boosters are now under development, with the attainment of operational status expected in the early 1990's. The concept calls for modular satellite design and deployment of a Space Based Support Platform (SBSP) to achieve complete effectiveness. New technology could be applied in the form of upgrades and on orbit modifications much more efficiently than the abandon and replace policy which currently exists for most satellite systems. The first four chapters provide background on the proposed concept, OMV and ELVs. Chapter V briefly describes several polar orbiting satellite systems providing mass summary breakdowns and current cost information. OMV payload servicing using the Flight Telerobotic Servicer (FTS) is then discussed. A comparison of estimated OMV satellite servicing costs versus satellite replacement for several missions is then tabulated. Conclusions and recommendations are then offered concerning the economic and operational benefits of concept implementation.

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Satellite Servicing Using the Orbital Maneuvering Vehicle in Low Earth Orbit

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

This thesis examines the concept of servicing and repair of satellites in low earth orbit (LEO) using the Orbital Maneuvering Vehicle (OMV). The emphasis is primarily focused on current polar orbiting satellites, however, it could be economically applied to any LEO in which sufficient numbers of satellites are located or where individual satellite cost/mission justify servicing. Significant increases in the cost effectiveness and operational flexibility of in-space systems can be realized when the capability to replenish consumable fluids, propellants and Orbital Replacement Units (ORUs) are incorporated into satellite design. ORUs can be placed in orbit using expendable launch vehicles (ELV), specifically selected to satisfy the mission need. Several suitable small payload, low cost boosters are now under development, with the attainment of operational status expected in the early 1990's. The concept calls for modular satellite design and deployment of a Space Based Support Platform (SBSP) to achieve complete effectiveness. New technology could be applied in the form of upgrades and on-orbit modifications much more efficiently than the abandon and replace policy which currently exists for most satellite systems. The first four chapters provide background on the proposed concept, OMV and ELVs. Chapter V briefly describes several polar orbiting satellite systems providing mass summary breakdowns and current cost information. OMV payload servicing using the Flight Telerobotic Servicer (FTS) is then discussed. A comparison of estimated OMV satellite servicing costs versus satellite replacement for several missions is then tabulated. Conclusions and recommendations are then offered concerning the economic and operational benefits of concept implementation.

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I. INTRODUCTION

A. GENERAL CONCEPT

The OMV is a reusable multimission spacecraft with a design lifetime of 10 years. The vehicle is built by the TRW Space and Technology group for the National Aeronautics and Space Administration (NASA). The spacecraft is constructed using modular design techniques to facilitate on-orbit repair and adapt readily to future modifications. Its primary missions include space station construction/resupply and logistics support for the Hubble space telescope. Current plans call for OMV launch from the Space Transportation System (STS) in 1994.

This thesis examines the issues and utility of the Orbital Maneuvering Vehicle (OMV) to conduct unmanned service and repair on satellites which are located in low earth orbit (LEO). The emphasis will focus on current United States polar orbiting satellites, with the potential to apply the concept to foreign and military satellite systems. The OMV is placed in a polar orbit, where it remains in a hibernation state until called upon to perform a mission. A small, modular storage rack which forms the basis of the space based support platform (SBSP) can be boosted with the OMV using the Titan IV expendable launch vehicle (ELV). [Ref. 1:Sec 3.27] The initial storage rack module provides logistic support, orbital replacement unit (ORU) and fuel storage capacity for the OMV, with the capability to be expanded as required at a later time. Periodic OMV resupply could be achieved by Titan, Atlas, Delta or Ariane ELVs. Upon receiving a servicing/repair mission, the OMV detaches from the SBSP and proceeds to rendezvous with the satellite requiring service.

Contingency resupply (individual ORU) could be accomplished using smaller ELVs such as Conestoga, Pegasus, Scout, or Delta [Ref. 2:p. 3]. The OMV would retrieve the ORU enroute to rendezvous the satellite to be repaired. Periodic replenishment of the OMV will be required. The frequency of replenishing will depend on the number, duration, and complexity of assigned missions. In the refueling, service or inspection missions, the customer is charged a fee commensurate with the mission and program logistical requirements. A mission which requires a contingency launch is coordinated with the OMV operations center.

A major criterion for evaluating this concept was to use primarily existing systems and platforms. Minor modifications will be required to configure the OMV for servicing and repair missions. Low cost ELVs and the Flight Telerobotic Servicer (FTS) are currently in prototype stages of development, with operational capability in the near future (2 to 4 years). [Ref. 3:p. 53] The FTS is a robotic device that can be tele-operated under the constant command of a human operator or run by itself under human supervision. The FTS was designed to assist astronauts in the assembly, maintenance, servicing, and inspection of the Space Station.

Development of a simple fuel canister will be required to periodically refuel the OMV [Ref. 4]. The cost to satisfy this requirement should be small, given that an existing ELV will be used to boost the payload.

The OMV is a long life platform, ten years or greater, with the capability to repair itself in the servicer configuration. Spare ORUs are maintained in a storage rack within the SBSP, along with other logistical needs. Refueling is accomplished through the use of an ELV equipped with an expendable fuel canister to minimize cost. The SBSP provides thermally controlled storage for ORUs, fuel and propellants, other consumables and storage for the FTS when not in use. [Ref. 2:p. 3]

OMV servicing/repair mission compatibility requires modular satellite designs, with standardized configurations to permit docking, refueling and/or replacement of defective ORUs using the FTS. This modular design concept has been incorporated into the OMV and Hubble Telescope. Funded by NASA, the OMV is currently scheduled for launch in 1994 to support the Hubble Telescope mission and, later, space station construction. [Ref. 5:p.7]

The number of countries capable of space operations has grown steadily in recent years. As a direct consequence, the number of satellites in orbit has increased, with France, Japan, and the European Space Agency (ESA) seriously challenging the United States in several critical areas. The competition from ESA has captured a 50% share of the western world's launch services market, while the U.S. space shuttle (i.e., STS) was grounded. [Ref. 6:p.28] In recent years, France

(Spot), Japan (MOS) and India (IRS) have placed their own earth observation satellites in sun synchronous polar orbits with ESA (ERS) poised to follow suit in the early 1990's, posing a further challenge. [Ref. 7:pp. 517-530] With a large commercial market share at stake for sensing earth resources and weather products, foreign nations have taken the initiative to develop their own systems. In contrast, the U.S. earth observation satellite program, Landsat, has experienced severe funding problems over the past few years. Only recently were funds restored, maintaining program integrity for the short term. Long term commitment questions still remain. [Ref. 8: p.30] Additionally, the U.S. supports two major meteorological satellite programs which provide data to a wide range of domestic, foreign, and military users.

The Soviet Union and China are also making bids to become serious competitors in the space market. With potentially huge commercial markets in the balance, other countries have moved rapidly to establish expertise in space operations. Maintaining leadership in space technology will return huge dividends in the future.

As funds continue to tighten from budget reductions, cost reduction measures must be found which will optimize and streamline programs without jeopardizing leadership and innovation. Extending the life of on-orbit systems is one way of reducing the overall cost of a program, with the possibility of conducting additional research and development (R & D) with excess funds. As new technologies are developed, they can be incorporated through on-orbit modification (i.e., ORU upgrade) much more economically than by replacing the entire satellite. The OMV servicer provides the flexibility for a ground station to respond rapidly to on-orbit repair/service situations at orbit inclinations and altitudes which are currently beyond the capability of manned operations. Manned polar space operations using the STS, have been postponed indefinitely. [Ref. 7: p.114]

The ability to service and repair satellites on-orbit could provide great incentive for the commercial market to utilize standard modular design techniques, which would ultimately result in lower unit costs through open competition.

Temporary loss of vital data and services provided by space based assets could be minimized. At the same time, implementation would increase the capital investment of the nation's space infrastructure with the potential to pioneer a new industry and reassert U.S. space leadership.

B. THESIS OBJECTIVE

The intent of the study is to investigate the feasibility of servicing/repair of satellites in polar orbit using the OMV in conjunction with various ELVs. The current practice of abandoning and replacing satellites is extremely costly. A more affordable and efficient use of assets may be realized by implementing a servicer strategy to extend the life of expensive satellites and offer a cost-effective means to upgrade or modify these assets on-orbit.

C. SCOPE, LIMITATIONS AND ASSUMPTIONS

For the purposes of comparison, current satellite systems are assumed to be capable of modular design and the additional cost of modular modification is not considered in total satellite costs. The study does not take into account the cost of ground station operations. The OMV servicer is assumed to be controlled from a ground station via the Tracking and Data Relay Satellite System (TDRSS). Non-catastrophic OMV and satellite failures are assumed. The current U.S. polar orbiting, earth observation satellite constellation is the primary group considered for the analysis. The OMV is assumed to be launched with a single module storage rack which serves as the basis for the SBSP. The study does not address the issues pertaining to orbital debris which would be generated by OMV on-orbit servicing/repair.

D. ORGANIZATION OF THE THESIS

The second chapter provides further background on the servicing concept and implications. A survey of satellites in polar orbit is presented. The factors relevant to satellite degradations, failures and design limitations are discussed. The issues and relative advantages/disadvantages of modular satellite design are considered. Lastly, components required for LEO satellite servicing are covered.

Chapter III provides a detailed view of the OMV in a servicer configuration. The physical characteristics and subsystems are described. Performance diagrams and capabilities are shown. Modifications to the preliminary NASA design for OMV servicer mission requirements are presented.

Chapter IV provides a survey of some current ELVs. A brief description of each with associated performance capabilities and costs are listed.

Chapter V covers current unclassified U.S. polar orbiting satellites, giving a detailed description of the mission, mass summaries and cost related data.

Chapter VI describes the on-orbit servicing process, detailing docking, and orbital insertion procedures. The FTS system is discussed in depth.

Chapter VII compares the cost of satellite replacement with the OMV service concept estimated costs for several polar orbiting satellites. The advantages and disadvantages of the servicing concept are then discussed. Conclusions and recommendations are then offered regarding the implementation of the OMV satellite servicing concept.

II. BACKGROUND

The total U.S. investment for the first three spacecraft of the Landsat program alone approached nearly one billion dollars in 1981 [Ref. 7:p. 532]. Since then, Landsats 4 and 5 have been placed in orbit with Missions 6 and 7 in the development/planning phase for mid-1990's launches. The National Oceanic and Atmospheric Administration (NOAA) polar orbiting program maintains two spacecraft continuously in orbit. Each satellite is designed for a two year operational life. Over 30 satellites have been placed in orbit since the meteorological program began in the early 1960's. [Ref. 7:p. 534] This group of satellites represents over one billion dollars invested as of 1985 (see Figure 2.1).

The Defense Meteorological Satellite Program (DMSP) managed by the U.S. Air Force (USAF) maintains two satellites continuously in sun synchronous polar orbits. The latest block 5D-2 satellites have a three year operational life. Over 30 DMSP derivative satellites have been launched since the mid-1960's, representing an estimated one billion dollars or more. [Ref. 7:p. 324]

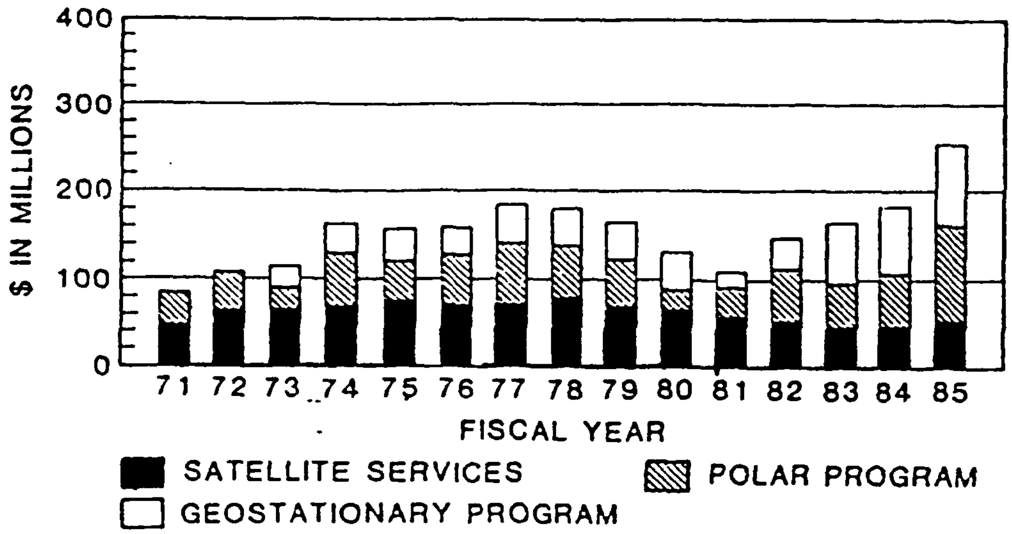

Figure 2.1 NOAA Funding by Program in FY 1985 $
[Ref. 9:p. 9]

A. CONCEPT DEFINITION

To reduce LEO space program costs and satellite degradations on-orbit, the operational life of the satellite must be extended and the capability to effect repair/upgrades must be established. Over the years, spacecraft costs have risen sharply. This situation has developed due to the requirement to deliver multipurpose satellite systems on-orbit, which drives builders to construct large, complex and expensive satellites. This in turn increases the cost to launch these systems. As a result, the number of satellites on-orbit and in the pipeline has decreased. Any deviation in the planned schedule can have a major impact. This was clearly illustrated in the case of the DMSP in the mid-1980's. where the U.S. was without a satellite for approximately 1 1/2 years. [Ref. 10:p. 12] Flexibility and expanded capability are extremely costly to achieve under these conditions, since replacement of the spacecraft is required to correct a deficiency in most cases. The ability to service, repair, or upgrade on-orbit would permit a high degree of program flexibility.

In most cases, ELV expenditures constitute nearly 50% of the satellite program hardware costs. [Ref. 10:p. 116] Reduction of launch costs will result in significant savings over the system life cycle. With the development of competitive relatively inexpensive ELVs such as Pegasus, Conestoga, the Liberty series and others, low cost access to LEO (on the order of $5 to $10 thousand/lb) will be possible with smaller payload capacities needed for repair missions (i.e., ORUs) [Ref. 10:p. 89 and Ref. 11:p. 14]. Using this capability in conjunction with OMV to perform satellite servicing, a fee is charged to the customer. The fee would include prorated costs for the OMV, propellant consumption, ground operations, OMV replenishment and profit margin. The cost of the ELV necessary to boost a particular ORU is borne by the customer and coordinated with the OMV operations center. The repeated expenditure for satellite construction and launch vehicles are thus minimized.

Once the necessary support infrastructure is in place, OMVs could be boosted as necessary to augment the existing fleet or as replacements for vehicles no longer serviceable. Using the payload capacity of larger ELVs, OMVs could be economically resupplied with fuel, consumables, and spare ORUs (see Figure 2.2).

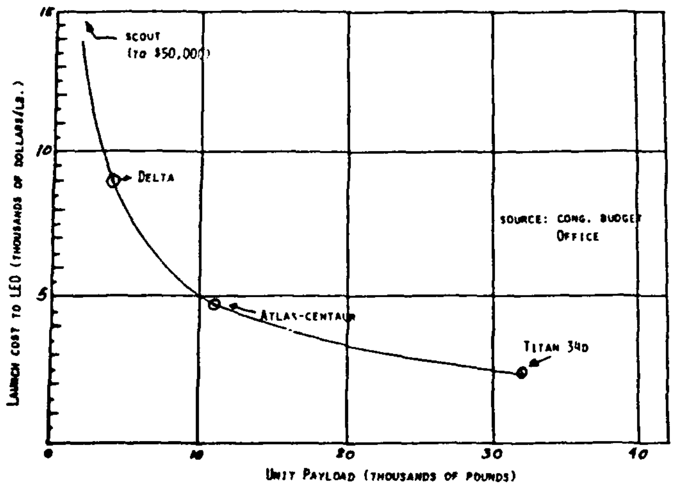

Figure 2.2 Effect of Vehicle Size on Orbital Transportation Cost
[Ref. 10:p. 264]

The ability to refuel on-orbit would also permit fuel versus payload trade-offs to be examined. The initial payload capacity of the spacecraft could be increased at the expense of a full propellant load. At a preselected point in the mission time line, the satellite could then be serviced to its full propellant capacity. Upgrades or other servicing could be performed concurrently.

The primary advantages of on-orbit servicing are economy through reduced life cycle costs, flexibility, and the incentive to move towards standardized design procedures using ORUs which would result in increased system reliability. [Ref. 12:p. 9]

B. SATELLITES IN POLAR ORBIT

The U.S. maintains two operational weather satellite systems. The civilian program, NOAA, uses two satellites in sun synchronous polar orbits. The U.S. Department of Defense (DOD) maintains its own polar orbiting weather satellite system, DMSP, using two spacecraft in sun synchronous orbit. The Landsat system is operated by the Earth Observation Satellite (EOSAT) commercial partnership between Hughes Aircraft Company and RCA Corporation. Two Landsat spacecraft operate in sun synchronous polar orbit. [Ref. 7:p. 530]

Satellites in sun synchronous polar orbits cross the equator at the same local solar time each day. This feature facilitates data analysis by maintaining the same sun angle with respect to the ground location. Typically, two satellites are used to maintain morning and afternoon global coverage, viewing almost all the earth's surface twice every 24 hours, depending on altitude. Orbit inclination with respect to the equator ranges from 95 to 100 degrees. Orbits are retrograde circular or near circular, with altitudes varying from approximately 300 to 500 NM. Polar satellites considered for the study have inclinations which are between 97 to 99 degrees.

France, Japan and India currently maintain polar orbiting satellites, with plans to expand on-orbit assets. Canada and ESA are preparing to launch remote sensing polar platforms in the early 1990's (see Figure 2.3). Additionally, NASA is working with Japan, ESA and other nations including China to develop the first two unmanned Earth Observing System (EOS) polar satellites scheduled for launch in 1996 and 1998. [Ref. 13:p. 46] Funding of the EOS constellation is estimated at $15 to $30 billion over 15 years. The complete polar EOS system would total 4 platforms, with 2 platforms to be launched by NASA, 1 by ESA and 1 by Japan to provide frequent coverage of the entire earth. The first NASA platform is estimated at $375 million and will carry 19 earth monitoring instruments. The platforms will incorporate some modularity features and would have to be replaced at 5 year intervals, if a servicing capability is not available. [Ref. 14:p. 48]

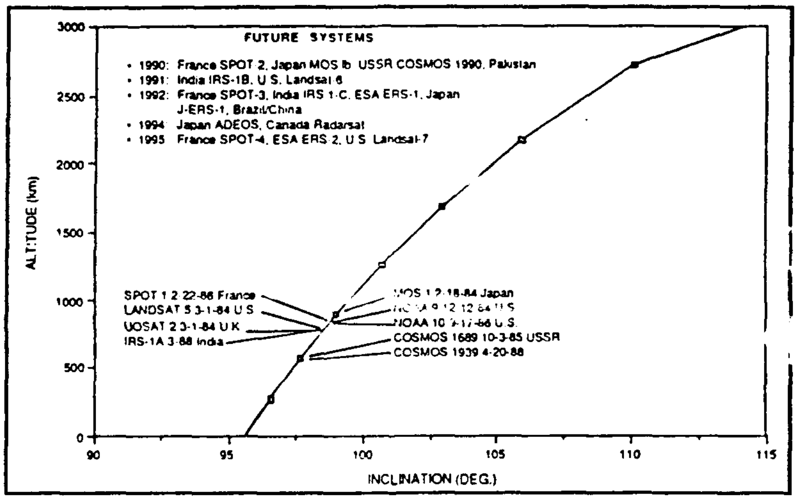

Figure 2.3 Sun-Synchronous Polar Orbiting Satellites
[Ref. 2:p. 3]

The commercial value of polar satellite derived products has been steadily increasing. In 1983, the failure of a command and data handling computer in Landsat 4 caused an estimated loss of $600,000 revenue per month. The French Spot imaging satellite revenue from data/product sales and receiving station fees totalled $3 million in 1986, $11 million in 1987 and $16 million in 1988. [Ref.

7:p. 522]. LEO polar satellites provide a wide spectrum of remotely sensed information which includes: [Ref. 15:p. 41]

- Mineral Resources
- Fire Detection
- Agriculture
- Weather
- Fisheries
- Pollution Monitoring
- Search and Rescue
- Border Surveillance
- Disaster Relief
- Cartography
- Earthquake Prediction
- Oceanography
- Hydrology
- Climatic Changes

C. CAUSES OF SATELLITE DEGRADATIONS AND FAILURES

The natural environment presents many of the most severe obstacles to the operation of a space system. The sun is the primary factor in affecting the region of space between the earth and sun. Energy, in the form of an outward flow of charged particles, is constantly being radiated by the sun and is known as the solar wind. Irregular and sudden changes in the intensity of the solar wind, lasting from a few minutes to several hours, are known as solar flares. The frequency and intensity of solar flares is closely related to the 11-year sunspot cycle. (see Figure 2.4) Solar energy directly influences the spacecraft through atmospheric heating, which increases the drag. The operational life of a satellite refers to the amount of time that the spacecraft performs its designed mission, while the orbital life refers to the time the vehicle will remain in orbit with no station keeping maneuvers to maintain orbit altitude.

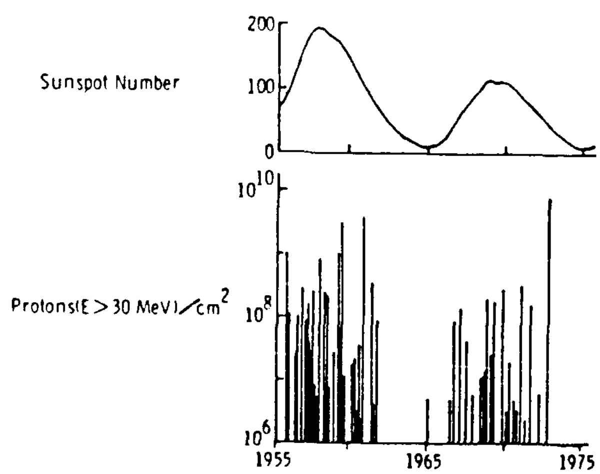

Figure 2.4 Solar Activity and Flare Proton Fluence
[Ref. 16:p. 64]

Although the atmospheric density at orbital altitudes is in most cases small, the lifetimes of LEO satellites are significantly affected by atmospheric drag [Ref. 17:p. 35]. A satellite in low earth orbit with no compensation for drag effects will constantly lose energy and altitude, ultimately reentering the earth's atmosphere. The orbital life of a satellite is a function of its altitude and ballistic coefficient. The ballistic coefficient depends on three factors: the spacecraft weight (W), frontal area (A) and drag coefficient (see Figure 2.5).

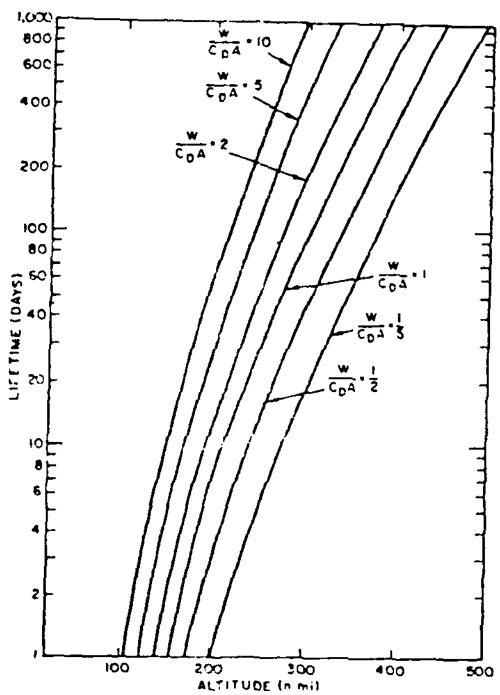

Figure 2.5 Satellite Lifetime as Function of Altitude
[Ref. 17:p. 39]

The 11-year solar cycle impacts orbital lifespans by changing atmospheric densities. Solar activity increases the effective density of the atmosphere through atmospheric heating, which effectively raises heavier gaseous components to higher altitudes creating increased drag on the spacecraft. To compensate for the drag effects, periodic expenditure of propellant is required to maintain satellite orbit altitude. In periods of heightened solar activity, larger amounts of propellant are required to offset increased drag. When the supply is exhausted, the satellite orbit begins to decay. Consequently, operational life is also a function of the launch date with respect to the 11-year solar cycle.

Solar cell damage and efficiency varies with altitude as shown in Figure 2.6. The primary gaseous components in the LEO region from 200 NM to 1200 NM are atomic helium and the much heavier atomic oxygen, with the helium layer above atomic oxygen beginning about 500 NM. Atomic oxygen collisions with a space vehicle are almost completely inelastic. [Ref. 16:p. 69] Typical collisions occur at relative orbital speeds of about 7700 m/sec. The highly reactive nature of oxygen, when combined with the extremely high impact velocities, causes material erosion on the spacecraft. Impingement of high energy solar radiation and atmospheric particles on spacecraft solar panels causes power output reductions over time. [Ref. 18:p. 152] The major types of radiation damage to solar cells are ionization and atomic displacement. Both the voltage and current output are affected. Increased activity as a result of the 11-year solar cycle causes additional damage.

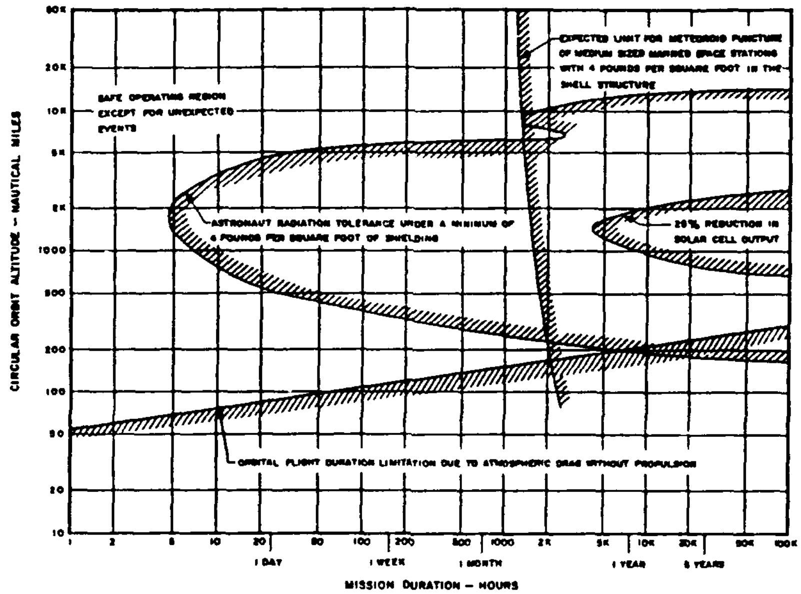

Figure 2.6 Solar Cell Efficiency Reduction Versus Orbital Altitude
[Ref. 18:p. 153]

Limited battery lifetimes have also impacted spacecraft mission capability. Because sun synchronous polar orbiting satellites spend approximately 35% of their orbit in eclipse conditions, battery performance for continuous operations is essential (i.e., remote sensing on earth's night side). Battery operations must be closely monitored to avoid exceeding the specified battery depth of discharge, limiting operations in eclipse conditions. Battery cell temperatures must also be maintained within a fairly narrow range to maximize cycle life. The development of high performance nickel-hydrogen (Ni-H_2) batteries have nearly doubled the cycle life of the widely used nickel-cadmium (Ni-Cd) battery, while adding a greater degree of complexity and cost. [Ref. 19:p. 1] The high energy capacity of silver-zinc (Ag-Zn) batteries is offset by relatively low cycle life (20-200) capability. [Ref. 20:p. 350] The nominal cycle life of a Ni-Cd battery is shown in Figure 2.7.

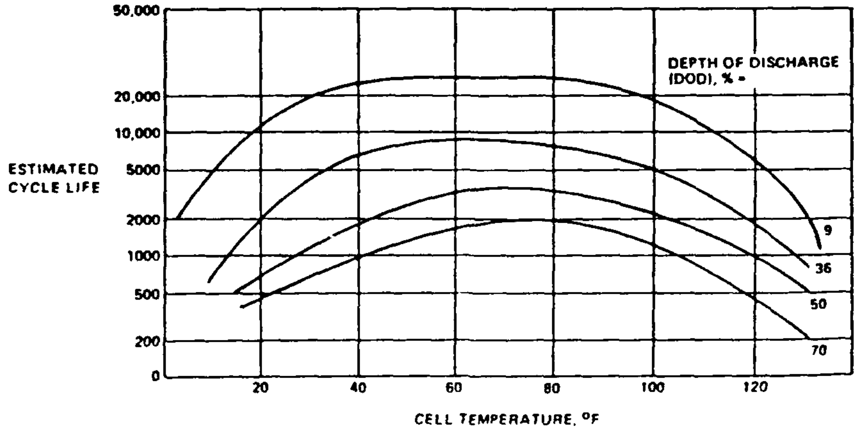

Figure 2.7 NI-CD Battery Cycle Life
[Ref. 20:p. 354]

Spacecraft data recorders, used for storing remote sensing information when the satellite is not in view of an earth receiving station, have been the cause of several recent mission degradations. [Ref. 21:p. 40] Although the number of receiving stations worldwide has grown, there are still not enough stations at key points around the globe to ensure continuous signal reception. Failure of the recording system precludes collection of important data which is outside the reception range of a ground station. Landsats 4 and 5 were designed to link data continuously via the TDRSS system, eliminating the need for data recorders.

However, due to operational problems with the TDRSS data link, Landsats 6 and 7 will again incorporate data recorders for on-board image storing.

Satellite remote sensing instruments have caused a number of missions to operate under less than full capability. Loss of a sensor often necessitates the procurement of the information from alternate sources, or in the extreme case, complete loss of vital data with mission replacement as the only solution. Table 2.1 summarizes the causes of mission degradation or failure for several polar satellites. [Ref. 7:pp. 523-537]

TABLE 2.1

SELECTED POLAR SATELLITE DEGRADATION/FAILURE CAUSES

SATELLITE	BATTERY	DATA RECORDER	SENSOR	ATTITUDE CONTROL	SOLAR ARRAY	POWER SYSTEM	COMMUNICATION SYSTEM
DMSP 2			X				
SPOT 1		X					
LANDSAT 1		X	X				
LANDSAT 3			X				
LANDSAT 4			X		X	X	
LANDSAT 5							X
NOAA 6			X				
NOAA 8	X						
SEASAT				X			

D. MODULAR SATELLITE DESIGNS

It is generally accepted that the easiest and most efficient on-orbit servicing requires modularization of a spacecraft into a number of easily exchanged ORUs (see Figure 2.8) [Ref. 22:p. 37].

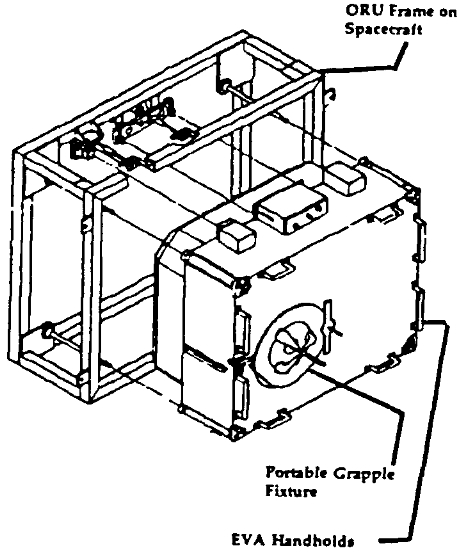

Figure 2.8 Orbital Replacement Unit
[Ref. 23:p. 1]

The fewer the ORUs, the easier on-orbit servicing becomes. The ease of on-orbit servicing must be balanced against the potential cost of replacing an ORU containing both failed and functional systems. The ORUs must be designed for easy insertion and removal using the FTS. Considerations here include alignment aids, interface verification and connection designs for power, thermal, fluid and communication services between the ORU and satellite core. [Ref. 22:p. 37]

Modular design of spacecraft to facilitate on-orbit servicing will increase design and development costs by an estimated 4%, with an estimated 8% per unit recurring cost increase for hardware according to a Martin Marietta study completed for NASA [Ref. 22:p. 38]. A serviceable design may also result in a heavier spacecraft, with a 5 to 10% weight increase per satellite estimated by many builders. Balanced against these increases would be the ability to replenish expendables, upgrade instrument packages and replace defective ORUs holding the downtime of a valuable satellite asset to a minimum. Individual ORU mass and cost would depend on the degree of satellite modularity and complexity.

The development of flexible, efficient solar arrays could permit degraded arrays to be replaced. One possibility is the use of flexible rollout type arrays stowed on a cylindrical drum. The concept was tested successfully in an experiment aboard an AGENA spacecraft in 1971 (Figure 2.9) [Ref. 20:p. 346]. The USAF has been funding research using gallium-arsenide cells which promise to be significantly more efficient (21.5% compared to 14.5% for silicon solar cells) [Ref. 24:p. 31]. Using the more efficient solar cells would permit the same power load to be provided using smaller, lower weight solar arrays. A flexible design feature would allow replacement arrays to be boosted using low cost ELVs in a folded configuration. Extension could be accomplished after attachment to the satellite by the FTS unit.

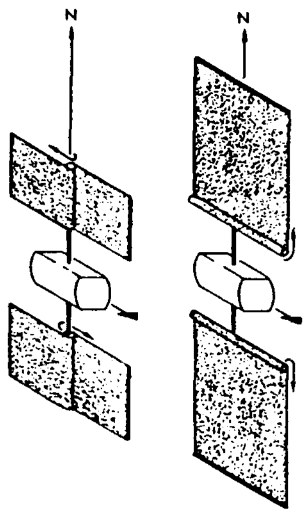

Figure 2.9 Flexible Rollout Solar Arrays
[Ref. 20:p. 345]

E. INSURANCE COSTS

Space insurance costs amount to a sizeable portion of total mission expenditures. Current satellite insurance policies require the customer to pay the insurer a specified amount for the total or partial loss of a satellite. Insurance which covers launch pad property, equipment and personnel also amounts to nearly $100 million for Titan, Delta or Atlas launches. [Ref. 25:p. 69] In the wake of the February 1990 Ariane failure, launch insurance rates are expected to increase to 20% or more of the spacecraft value [Ref. 26:p. 21]. Consequently, using low cost ELVs in conjunction with ORUs, which will in most cases amount to a fraction of the spacecraft cost, should significantly lower the amount of insurance required for launch and payload coverage. Insurance for the servicing/repair portion of the mission would still be needed.

An OMV servicing capability would permit insurance rates to be negotiated and specifically tailored to the insured's requirement. With an on-orbit servicing option, total and partial loss probabilities should decrease, resulting in lower overall insurance premiums.

It should be noted that the insurance issue does not impact U.S. government spacecraft, since all government payloads are self-insured. The potential loss to the government would be reduced if the spacecraft were serviceable in the event of failure. [Ref. 22:p. 50]

F. MANNED SERVICING OPERATIONS IN POLAR REGIONS

The Palapa and Westar satellite retrievals and on-orbit repair of Syncom IV-3 demonstrated that manned servicing operations using the STS was possible, with flights originating from the Eastern Test Range (ETR) at the Kennedy Space Center (KSC). Currently, STS operations are limited to orbit inclinations below 57 degrees for launches from the ETR, eliminating polar operations. STS launches from the Western Test Range (WTR) at Vandenberg Air Force Base can achieve polar orbit, however, shuttle facilities at the WTR have been placed in caretaker status for an indeterminate period of time. Reactivation would require time and serious consideration to the large funding requirement necessary to ready the WTR for STS operations.

Assuming that manned polar space activity were possible, the shuttle is restricted to approximately 300 NM in altitude with a standard loadout (see Figure 2.10), thus limiting the servicing mission to satellites below this altitude.

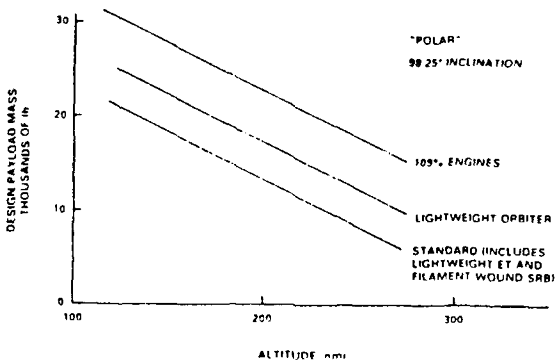

Figure 2.10 Shuttle Performance
[Ref. 16:p. 33]

Further, manned space operations significantly increase associated costs with respect of unmanned space flight. This is due to the hazardous environment in space, and the requirement to enclose man in an artificial environment. [Ref. 27:p. 40] Extravehicular activity (EVA) had been considered to repair and service Landsat 4 in 1984. It was calculated that a 5 to 6 hour EVA would be required to perform the mission, which included dangerous fluid transfers with man in the loop. Leakage or venting of a corrosive fluid onto the spacesuit pose serious risks to astronauts. Preparations for EVA missions include lengthy prebreathe and cabin pressure decrease periods to reduce nitrogen in the bloodstream, preventing nitrogen narcosis (i.e., the bends) when in the lower pressure spacesuits. [Ref. 28:pp. 44-53] Two person teams are usually required in the interest of safety.

Spacecraft in polar orbit spend about one-third of their time above 60 degrees latitude, and thus are exposed to greater radiation hazards [Ref. 16:p. 64]. Radiation hazards associated with polar orbits normally consist of trapped high energy protons, galactic cosmic rays, and the effects of the South Atlantic anomaly. High energy protons are the primary hazard to crews. The earth's magnetic field deflects nearly all solar particles in the region of low orbit altitude (150 NM - 300 NM), and low inclination (less than 60 degrees latitude) back into space. In polar regions, solar flare activity can have extremely serious consequences on manned operations. The sudden release of energy stored in the sun's magnetic field can accelerate charged particles to very high energies. Flare events are random and cannot accurately be predicted. Above 60 degrees earth latitude, the flare particles can stream all the way down to the atmosphere along the earth's magnetic field lines (see Figure 2.11).

Current spacesuit shielding does not provide adequate protection for large flare events. The occurrence of a solar flare would require immediate termination of an EVA and retreat to a safe haven aboard the STS. It is estimated that astronauts would have approximately 20 to 30 minutes to reach a protected location aboard the shuttle using the STS solar flare alarm system prior to the arrival of high energy

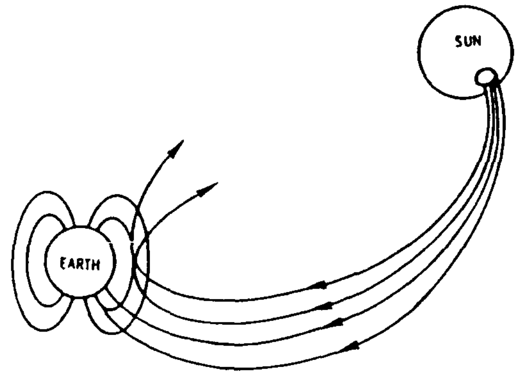

Figure 2.11 Solar Flare Particles Interaction with Earth
[Ref. 16:p. 63]

flare particles. [Ref. 29:p. 298] Manned polar operations clearly dictate that extensive precautions must be implemented to guarantee crew safety, whereas OMV satellite servicing eliminates the requirement for expensive man rated systems.

G. REQUIRED COMPONENTS FOR LEO SATELLITE SERVICING/REPAIR

Systems and subsystems necessary to perform on-orbit servicing and maintenance include: [Ref. 2:p. 2]

- OMV with Payload Kit
- Space Based Support Platform
- Ground Based Mission Control Center

- Expendable Launch Vehicles
- Flight Telerobotic Servicer
- On-Orbit Consumable Resupply Systems (i.e., ORUs, propellants, cryogenics, etc)

Implementation of an unmanned OMV servicing concept can be accomplished using several strategies. For the purposes of this study, a single OMV equipped with a FTS and storage rack is assumed to be available for multiple polar satellite servicing (Figure 2.12). Chapters III through VI outline the OMV, FTS, ELV, and satellite components of the servicing concept in more detail.

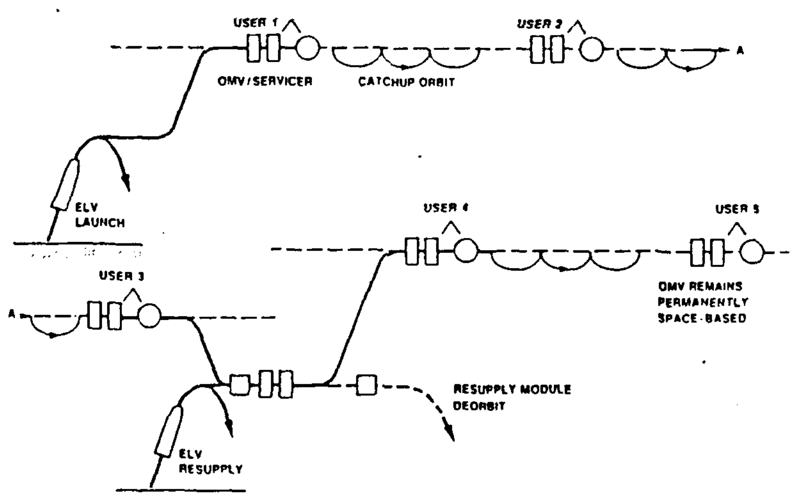

Figure 2.12 OMV Satellite Servicing
[Ref. 30:p. 19]

III. ORBITAL MANEUVERING VEHICLE

This chapter briefly outlines the NASA OMV design missions, provides a detailed description of the current OMV and required modifications for vehicle conversion to a servicer configuration.

A. MISSION

The OMV is a versatile, reusable, multimission, remotely operable vehicle with a design lifetime of 10 years over the course of 40 launches/landings aboard the STS [Ref. 31:p. 12]. The spacecraft prime contractor is the TRW Space and Technology group, supported by 37 subcontractors. Built for NASA, its primary missions include: [Ref. 32:p. 1]

- Spacecraft retrieval, reboost, deboost or viewing
- Spacecraft on-orbit servicing including refueling and component replacement
- Space station construction and logistics support
- Large observatory service (i.e., Hubble Telescope) from either space station or shuttle
- Experiment carrier for subsatellite missions

The OMV is currently adapted for launch aboard the space shuttle, however, a preliminary analysis was conducted to determine required OMV launch interfaces for Titan IV ELV compatibility. It was found that minor mechanical integration and ground/flight operation procedural changes will be required to adapt the OMV for Titan IV launch. [Ref. 1:Sec. 3.1] Additionally, the OMV would not require the use of an upper stage to reach the desired LEO altitude.

NASA plans call for the OMV to be placed in orbit by the space shuttle, and deployed using the remote manipulator arm. The OMV remains in space until refurbishment is required, where it is returned to earth by the STS orbiter. Permanent space basing at polar inclinations, where the STS is not expected to operate, is the most demanding scenario for the OMV, requiring repeated resupply by ELV. [Ref. 33:p. 9] By combining the technologies of space robotics (FTS) and on-orbit transfer of fluids with the mobility of the OMV, an unmanned resupply and servicing capability can be established.

The OMV's modular design enables self-servicing (with FTS) in nearly all situations, with the exception of catastrophic failures. The system incorporates a high degree of component redundancy such that no single failure will result in loss of the OMV mission. To conserve fuel and electrical power, the OMV can be placed in a hibernation state for up to 9 months. [Ref. 5:p. 24] This feature greatly enhances its utility and adds very little cost to the initial design by using existing technology. The spacecraft remains in a low power consumption state until receiving ground control activation commands when required to perform a mission. The *hibernation mode* calls for the OMV to be pointed at the sun for maximum solar cell output and minimum battery drain, and spin-stabilized to conserve fuel.

The first OMV is scheduled to be launched in 1994 to reboost the Hubble Space Telescope which had a launch date in April 1990. Other near-term missions include space station support, satellite retrieval, orbital debris collection, and spacecraft orbital transfers to orbits beyond the reach of the STS. Future possibilities include the capability to reach geosynchronous orbit to perform satellite servicing and return using an orbital transfer vehicle (OTV).

B. PHYSICAL CHARACTERISTICS

The OMV has a 15 foot diameter and is 56 inches in length, having been designed to occupy minimum space in the STS. Using the 15 foot dynamic payload envelope of the Titan IV ELV, polar insertion can be accomplished from the WTR. The OMV spacecraft incorporates a fully modular configuration that allows on-orbit replenishment of consumables and propellants, as well as replacement or upgrade of ORUs. The ORUs use a single-bolt attachment that permits change out by astronaut EVA or by the FTS. The design offers a high degree of reliability and maintainability. [Ref. 34:p. 8]

A fully loaded OMV in the NASA configuration weighs 19,900 pounds, including 9,000 pounds of usable bipropellant (monomethyl hydrazine/nitrogen tetroxide) for the variable-thrust orbit-adjustment engines, 1,180 pounds of usable monopropellant (hydrazine) for the Reaction Control System (RCS), and 165 pounds of usable nitrogen for the cold gas RCS. The cold gas system can be used for close proximity operations to reduce spacecraft contamination during final approach and docking maneuvers. [Ref. 32:p. 9] The OMV is composed of two separate modules; the Short Range Vehicle (SRV) which includes the RCS and avionics equipment and the bipropellant Propulsion Module (PM) (see Figure 3.1).

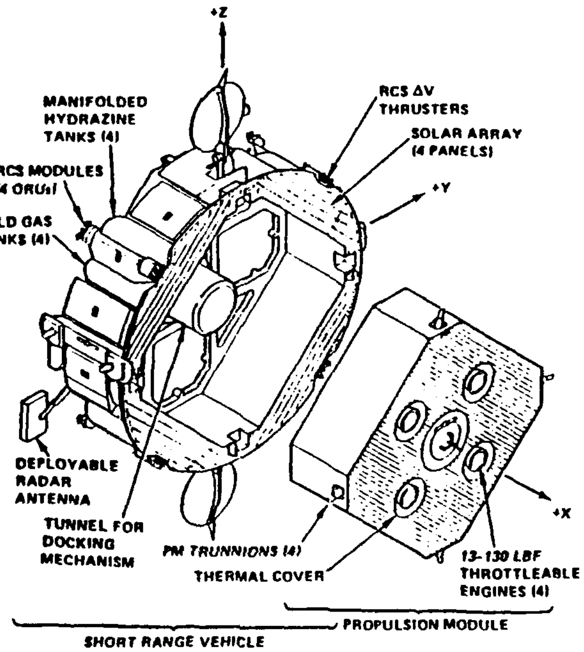

Figure 3.1 OMV Configuration Propulsion Module Side
[Ref. 30:p. 5]

1. Short Range Vehicle

The SRV is modular, containing 11 avionics and 4 RCS ORUs. All avionics and RCS subsystem ORUs mount on the SRV periphery (see Figure 3.2). Guide pins provide the positioning accuracies necessary for proper alignment and ORU insertion/removal.

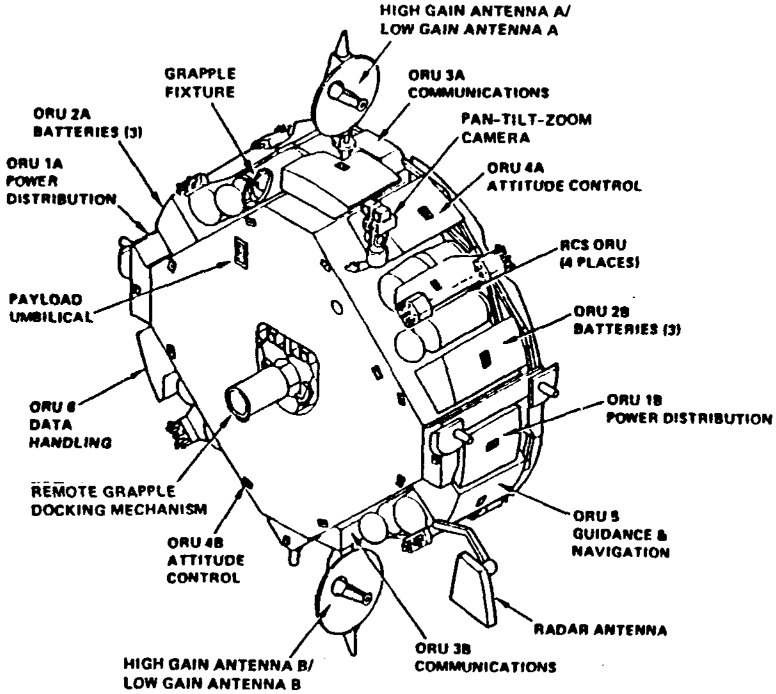

Figure 3.2 OMV Configuration Payload Side
[Ref. 34:p. 9]

The SRV is designed to perform as a stand alone system in support of space station assembly and space shuttle missions with small mass payloads and low maneuvering requirements. The SRV's propulsion system is independent of the propulsion module. The SRV uses 4 RCS modules, which consist of 28 monopropellant (hydrazine) thrusters rated at 12 lb-force each and 24 cold gas thrusters (rated at 5 lb-force each) uniformly spaced around the vehicle. [Ref. 31:p. 15]

2. Propulsion Module

The four main engines and bipropellant are contained in the replaceable PM. The entire PM is an ORU which permits on-orbit bipropellant resupply through module change out [Ref. 32:p. 9]. There are no fluid interfaces between the PM and SRV. Plug type fittings are used to connect electrical power and command data links. Once depleted, the PM is returned to earth for refurbishment and reuse via the shuttle. Successful replacement of a fully loaded PM has been demonstrated using the space shuttle's remote manipulator arm and by astronaut EVA at the Marshall Space Flight Center. [Ref. 5:p. 16]

The PM's four variable thrust engines (13 to 130 lb-force) provide approximately 90 percent of the total impulse capability of the OMV. The wide range of thrust available is required to ensure that sensitive payloads can be transported without causing damage. Accelerating forces of not more than .002 g are needed for Hubble Telescope servicing missions and operations in which large solar arrays or delicate instruments are involved. [Ref. 5:p. 12]

The PM is used where large orbit altitude/plane changes are needed, or movement of large payloads is necessary. The OMV has the capability to complete plane changes of up to 6.5 degrees or approximately 1,000 NM altitude changes (see Figure 3.3).

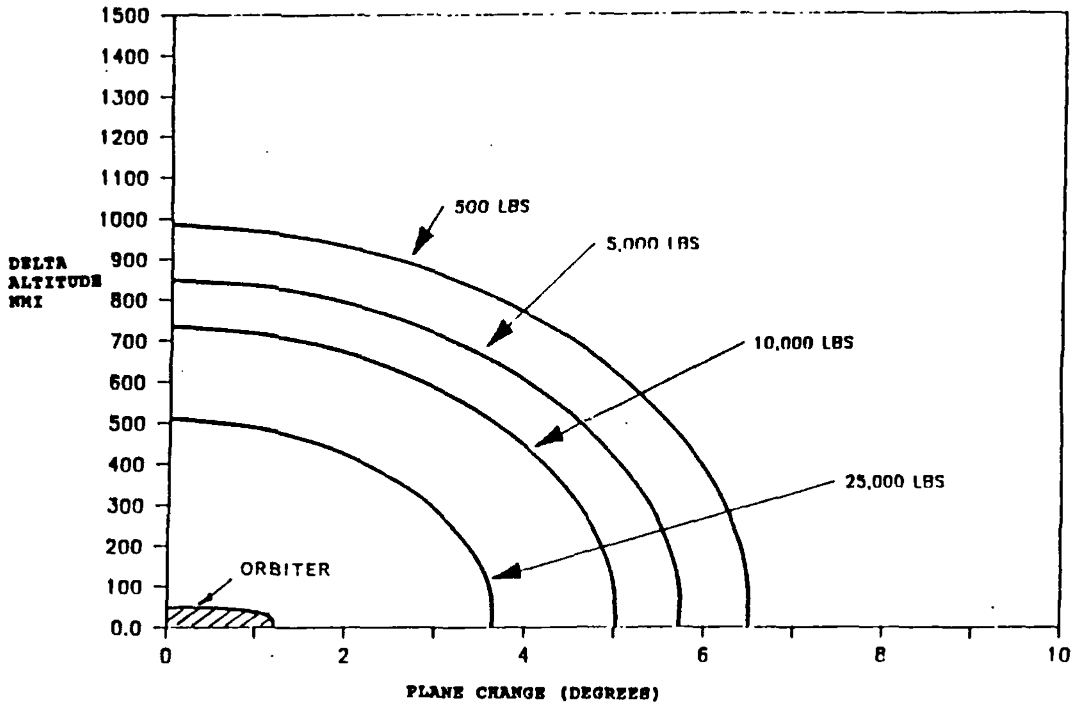

Figure 3.3 OMV Payload Deployment Performance
[Ref. 34:p. 16]

OMV altitude change performance is a function of payload mass (see Figure 3.4). Some specific examples include: [Ref. 5:p. 7]

- Capability to retrieve space telescope (25,000 pounds) at 130 NM above base (120 NM) for servicing and redeploy to 130 NM above base then return.
- Deliver a 3,500 pound payload to 340 NM above base, deploy and return with a 1 degree plane change each way.
- Transfer 50,000 pound logistic module from 160 NM base and deliver to space station at 270 NM, then return to base.

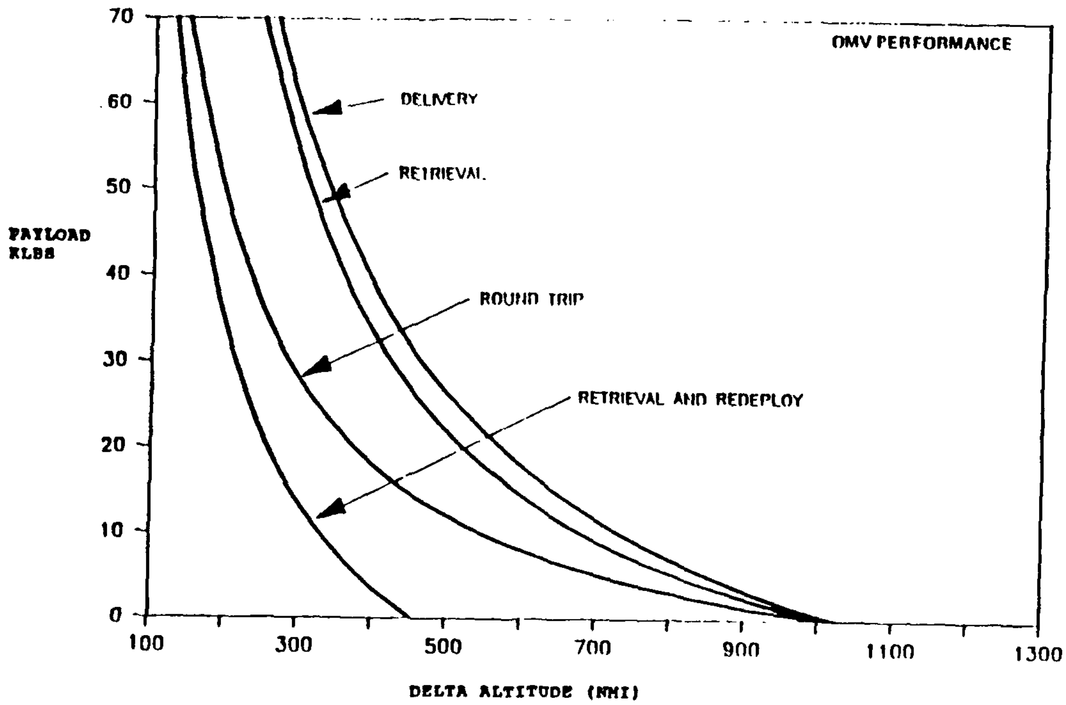

Figure 3.4 OMV Delta Altitude, NM
[Ref. 34:p. 17]

C. THERMAL CONTROL

The thermal control subsystem operates using a completely passive design. Multi-layered insulation blankets cover all non-radiative surfaces and propellant tanks. Thermostatic heaters are provided on propulsion components and critical avionics for under-temperature protection. All avionics ORUs use variable-conductance heat pipes coupled to radiator surfaces. [Ref. 5:p. 20] Each ORU is thermally insulated to facilitate on-orbit ORU changeout.

D. POWER

The OMV uses batteries to provide primary electrical power, with solar cells as the secondary source. The requirement for this arrangement is driven by the fact that the original design specifies short duration, high power consumption missions. Since the OMV is maneuvering, it cannot always maintain the correct sun angle for solar array use. Further, any payloads must be powered and maintained in the correct attitude orientation regardless of OMV orientation. [Ref. 5:p. 21] The current OMV design consists of 6 rechargeable 220 ampere-hour Ag-Zn batteries, that can provide sufficient power for an envisioned 7-day maximum mission. Recharging is accomplished by reorienting the OMV solar array (mounted aft on SRV) towards the sun. Solar array power can be used to supplement battery power on some missions. The solar array design end-of-life (EOL) output capacity is 500 watts [Ref. 31:p. 21].

E. GROUND CONTROL

The primary control of the OMV is accomplished from a ground station using the two-way TDRSS data link. Communication is accomplished using S-band channels which are fully redundant, and can handle high digital data rate (1 megabit per second) transmissions required for pilot-mode video and target viewing. The OMV conducts autonomous docking up to the final approach point (at 1000 ft), where the ground based pilot assumes manual control. Provisions for placement of a control console aboard the space shuttle have also been examined. [Ref. 31:p. 21]

The Ground Control Console (GCC) equipment provides for near real-time pilot control functions, and routine spacecraft monitoring and control. [Ref. 5:p. 19] Two GCCs are arranged side by side to provide close pilot-copilot interaction. The console receives and formats OMV telemetry data for display to the pilot and up links command signals.

The GCC provides video, text and graphic display for all telemetry data. During the final approach and docking maneuvers, the pilot controls the OMV by using a series of controls which are similar to those found in aircraft. A three second command signal time delay exists as a direct result of using the TDRSS data link. The majority of the time delay is a function of data formatting requirements, rather than link delay. It has been determined by simulation and full scale model testing that pilots can compensate for the three second delay with the proper training. The system has been successfully evaluated on both cooperative and non-cooperative (tumbling) satellites. The NASA GCC will be located at the Johnson Space Center. [Ref. 5:p. 13]

F. NAVIGATION AND DOCKING

Navigation and spacecraft attitude information are provided by the Global Positioning System (GPS), a rendezvous radar set, an inertial measurement unit (IMU) and a set of sun and earth sensors. These systems are used to permit autonomous docking to a range of 1,000 feet from the target spacecraft with an onboard computer. [Ref. 33:p. 2] Two modes of guidance are provided, orbit change and auto-rendezvous.

The OMV can attach to payloads and other spacecraft using one of two methods. The Remote Grapple Docking Mechanism (RDGM) provides the complete functional capability to capture and release on-orbit, by remote command, a payload containing a NASA standard grapple fixture. The RDGM also contains electrical power and data interfaces between the payload/satellite and OMV to enable alternate control through OMV GCC. [Ref. 35:p. V1P1-31]

The second attaching method uses a Three Point Docking Mechanism (TPDM) to mate the OMV with a payload/satellite. The system provides a structural and electrical interface between the OMV and the satellite/payload fitted with a flight support system docking interface. [Ref. 34:p. 26] The TPDM adaptor has three latches mounted on a ring at 120 degree intervals to secure the payload. The TPDM provides the complete functional capability for capture and release on-orbit by remote command. Both methods use a system of 2 video television cameras, lights for night operations and on-board electronics to allow the pilot to control OMV docking from the GCC.

G. MODIFICATIONS FOR ORBITAL SERVICING MISSION

The OMV in the NASA configuration is primarily a battery powered, short mission duration vehicle which is designed to be serviced at the space station, shuttle, or on the ground [Ref. 1:Sec. 3.3]. In order to perform extended duration (10 years or more), polar satellite servicing, a number of modifications are required. Conversion of the OMV from a battery powered to solar powered vehicle with the addition of a front end "kit" (FTS and Storage Rack) appears to offer the most flexible and cost effective solution. The alternative calls for OMV battery replacement at nine-month intervals using ELVs, with the possibility of extended battery charging periods. For the purposes of the study, the solar powered vehicle with a servicing kit will be examined.

Specific subsystems requiring modification are the electrical power, including solar array and batteries, thermal control, radiation protection and the addition of an integral front end kit consisting of a storage rack and FTS.

1. Power

The OMV in a servicer configuration requires an average 750 watts (W) for OMV operation, 450 W for the FTS and 800 W for battery recharge, totalling 2,000 W of power required. [Ref. 33:p. 31] The current NASA OMV with Ag-Zn batteries and solar array which provides battery charging is insufficient to meet the demands for remote satellite servicing. By converting the primary OMV bus power source to solar energy with batteries providing auxilliary power higher degrees of flexibility are available for extended duration servicing missions. Battery usage becomes necessary only during eclipse and non-sun oriented operations. The high energy Ag-Zn 7 kilowatt-hour (Kw-hr) batteries (one, plus one redundant spare) can require up to a six-week charging period with the current solar array. Replacement due to the relatively low cycle life would be necessary after nine months by ELV resupply. By changing to long life, faster charging Ni-Cd or Ni-H_2 battery types, extended duration (10 years or more) lives are possible. Although initially more expensive, long term cost savings result from decreased replacement and ELV resupply requirements.

The Ni-H_2 battery is lighter and can operate at a higher depth of discharge than comparable Ni-Cd batteries. Using an existing flight qualified, 1.6 Kw-hr Ni-Cd or 2.2 Kw-hr Ni-H_2 battery results in a requirement for six Ni-Cd or three Ni-H_2 batteries respectively including one redundant spare for each type. [Ref. 33:p. 32] Both types can be encased as modular ORUs for OMV compatibility. The high number of cycles required for the servicing mission (over 58,000 per 10 years) limits the depth of discharging for both battery types. Ground testing of Ni-H_2 battery has demonstrated a capability of over 40,000 cycles in ground testing, whereas flight experience with the Ni-Cd battery is more extensive. Allowable depth of discharge is 25% and 40% for the Ni-Cd and Ni-H_2 battery types respectively. Battery characteristics are summarized in Table 3.1. [Ref. 33:p. 105] The Ni-H_2 battery offers long-term cost and weight savings over the Ni-Cd arrangement.

The current OMV solar array can provide only 650 W of power, which is used primarily for battery charging. The add-on solar array size is based on the average power demands of the OMV and FTS. The solar array, mounted on the

TABLE 3.1

OMV BATTERY OPTIONS

	Ni-Cd	Ni-H_2	Ag-Zn
Capacity (Kw-Hr)	1.4	2.2	7.0
Allowable Depth of Discharge	25%	40%	80%
Number	6	3	2
Total Weight (lb)	536	342	290
Number of Cycles	≈ 20,000	≈ 40,000	≈ 20-200

SRV, is 37 square feet (sq ft) in area. The solar array required for an OMV servicer using silicon cells is 200 sq ft. [Ref. 33:p. 34] This can be accommodated by adding deployable paddles or fold-out wings to the present design (see Figure 3.5). Using higher efficiency gallium arsenide (Ga-As) solar cells requires approximately a 167 sq ft array area. Solar array end-of-life output is 2 KW [Ref. 33:p. 105]. Solar array characteristics are summarized in Table 3.2. [Ref. 33:p. 106]

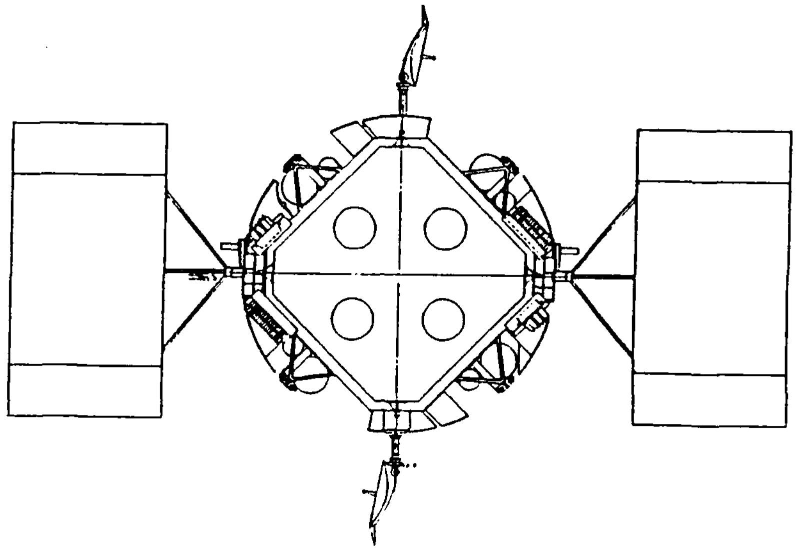

Figure 3.5 OMV Solar Array Configuration
[Ref. 1:Sec. 3.3]

TABLE 3.2

OMV SOLAR ARRAY OPTIONS

	SILICON	Ga-As
Area (sq ft)	200	167
Weight (lbs)	230	221

2. Thermal

Degradation of thermal surfaces in LEO polar orbits is significantly greater than in the lower inclination orbits (60 degrees or less). The propulsion module aft-face and thermal surfaces on the ORUs must be able to survive an acceptable amount of on-orbit degradation over a 10 year period. The baseline NASA OMV has the capability to last three years in low inclination orbits using silver-teflon tape. Beyond this point the thermal operating range will degrade, ultimately leading to component failure. To extend thermal protection to components over the 10 year period, silver-quartz second surfacing mirroring is used. [Ref. 1:Sec. 3.9]

3. Radiation Shielding

Extended duration OMV polar servicing missions necessitate increased radiation protection over the baseline NASA vehicle. The long term (10 year) exposure to high energy protons, cosmic rays and effects of the 11-year solar cycle will exceed the 10,000 rad total dose design limit. The original NASA design projected low inclination, 6 to 10 day missions between 160 NM to 300 NM. Additionally, any missions which reach approximately 1200 NM in polar orbit enter the inner Van Allen radiation belt (peak radiation flux is at 1800 NM). [Ref. 1:Sec. 3.9] Operations within this region may require additional shielding to extend vehicle life to 10 years or more. Using the TRW total radiation dose model, additional shielding material required for a 10 year, natural environment, Geosynchronous

Earth Orbit (GEO) would add 367 lbs to the OMV weight. [Ref. 1:Sec. 3.9] An extended duration LEO polar orbiting vehicle shielding requirement can be approximated by using the GEO shielding figure as a first estimate. The actual polar shielding requirement will be less than that of the highly saturated radiation environment found at GEO altitudes. [Ref. 29:p. 14]

4. Propulsion

Using the NASA version OMV, the bipropellant propulsion module, RCS hydrazine (N_2H_4) tank ORUs and gaseous nitrogen (N_2) ORUs are designed for shuttle on-orbit or earth based replacement. Using bi-directional fluid flow couplings, consisting of interconnects, control valves and command telemetry avionics, the OMV is provided with an interface to receive propellant/fluid resupply via ELV and to transfer fluids/propellants to a user spacecraft. [Ref. 33:p. 61] The fluid couplings necessary to mate with the user satellite are added to the baseline OMV remote grapple docking mechanism. (see Figure 3.6) For a servicer OMV equipped with a s age rack and FTS, a manifold is used to route the fluid transfer kit to the front face docking post.

Use a of bi-directional fluid transfer kit eliminates the requirement for costly propulsion module replacement and ORU changeout. Resupply fluid and propellant canisters are used to replenish the OMV servicer tanks.

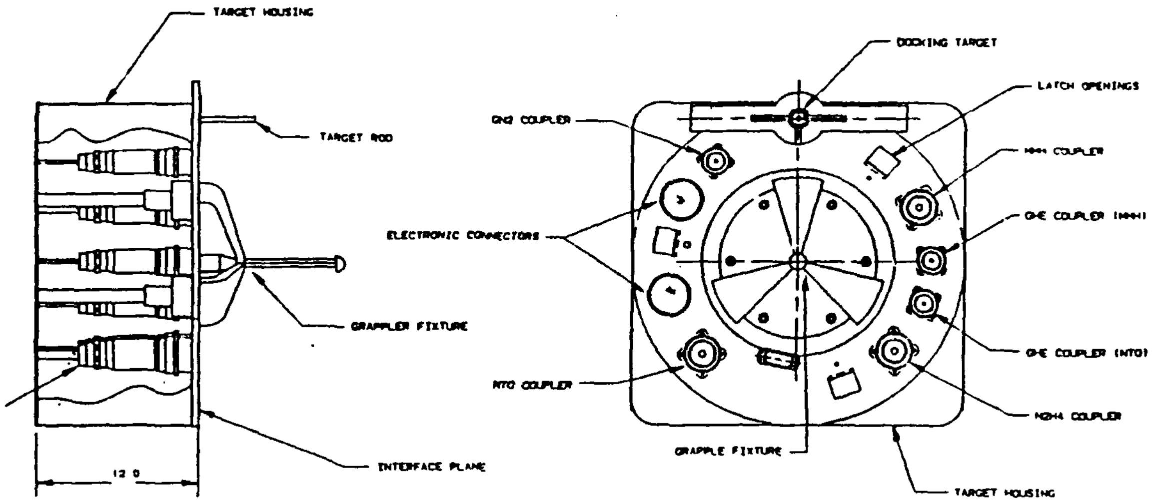

Figure 3.6 User Spacecraft Fluid Coupler Mechanism
[Ref. 33:p. 72]

5. Storage Rack

The rack module serves as the OMV's logistics storage center for ORUs, propellant and other consumables. Additional modules could be boosted during opportunity or dedicated launches. Expansion to a fully functional SBSP would require the platform to have its own power, thermal and stabilization systems to maintain SBSP attitude and temperature control when detached from the OMV. [Ref. 4] With a SBSP, a single or multiple OMVs can be furnished with spare propellant, ORUs and other necessary consumables. The SBSP is placed at an altitude which minimizes round trip OMV servicer travel distance. The decision to fund the development of an operational SBSP would depend on the number of satellites and/or platforms which are available for servicing. For the polar orbiting constellation, the number of satellites may appear to be low, however, a SBSP permits ready access to all assets for preplanned product improvements (P^3I) and other modifications to particular satellite subsystems. [Ref. 36:p. 11] Cost savings would result from the ability to use larger ELVs for ORU resupply, which reduces the on-orbit cost per payload pound, and permits large scale replenishment transfers to a SBSP. Storage rack weight is estimated to be 1,193 pounds. [Ref. 30:p. 107]

6. Flight Telerobotic Servicer

In June 1989, Martin Marietta became the phase C/D prime contractor to build a FTS system for use by NASA in assembling the U.S./international space station [Ref. 3:p. 53]. The FTS attaches to the storage rack, forming the front end servicer kit for the OMV (see Figure 3.7).

The primary purposes of the FTS are ORU change out and fluid line connection/disconnection. These manipulation tasks do not require much dexterity and could be performed by single or double arm manipulation. For example, the change out of ORUs of the type used in the OMV design requires the use of a universal servicing tool (UST). For ORU removal the tool loosens a single attachment bolt and subsequently removes the unit after locking on an H-shaped bracket. [Ref. 33:p. 37] For the purposes of this study, the dual arm FTS system is assumed.

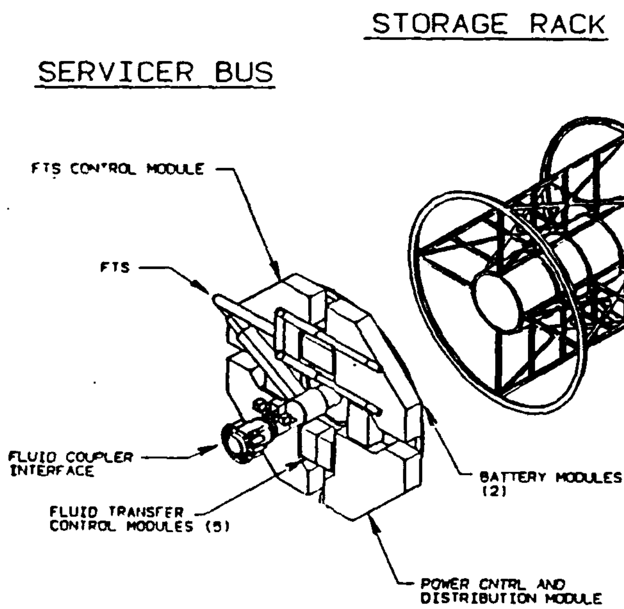

Figure 3.7 OMV Servicer Kit
[Ref. 30:p. 31]

The FTS has two manipulators, each with seven degrees of freedom (DOF). It also has one five-DOF attachment stabilization and positioning system mounted on a compact body. Other equipment mounted on the body includes two Ku-band antennas, a camera positioning assembly with two video cameras and holsters for storing tools.

The manipulators are teleoperated and controlled in seven DOF. Although six DOF are adequate to perform all tasks in free space, the seventh permits the FTS to reach around obstacles and avoid contact with the worksite (see Figure 3.8). [Ref. 37:p. 15] Main arm reach is 14.5 feet. Two cameras are mounted

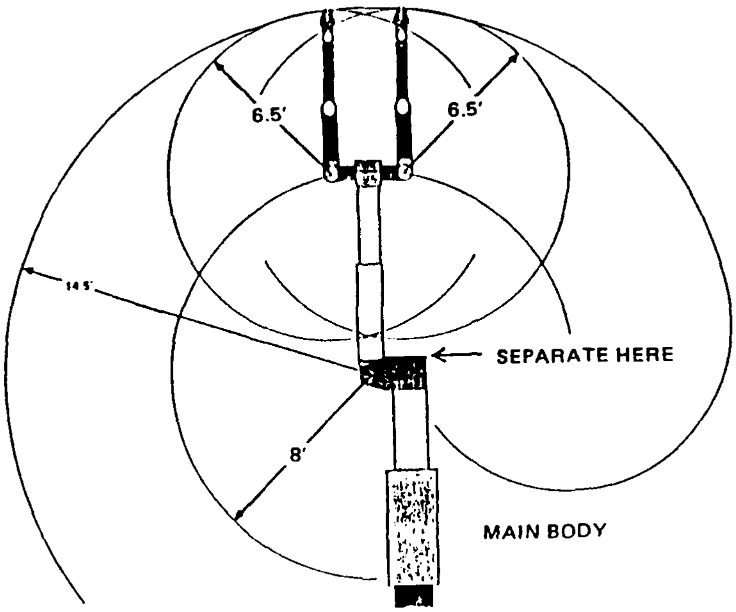

Figure 3.8 FTS Work Volume
[Ref. 30:p. 25]

at the "head" of the telerobot for general task viewing, and a camera is mounted at each wrist for close-up viewing.

Telerobot safety is a major design consideration. The FTS is two-failure tolerant to preclude collision with the host satellite or space station. The software looks at the manipulator's position, and compares it with the boundaries established for the manipulator. [Ref. 37:p. 18] If the boundaries are exceeded, the manipulator is automatically de-energized and an alert is sent to the operator. The FTS system mounted on the OMV is subject to the three-second feedback time delay resulting from the TDRSS control link. Further, OMV command bit rates are limited to one kilo bit per second (kbps), which is far below the 400 kbps requirement needed for full human feedback control operation. Direct control from the GCC is thus limited to extremely low frequencies, comparable to the very slow command sequences used when controlling the OMV docking approach to a target satellite. [Ref. 33:p. 46] To prevent control instabilities due to the large signal feedback time delays when operating under manual control, the FTS is programmed to perform manipulator tasks autonomously under human visual supervision using the video camera system. Manual override becomes necessary only when a malfunction or manipulator boundary alert occurs. [Ref. 4]

The FTS will have the capability to operate indefinitely in the thermal environments encountered in low earth orbit [Ref. 37:p. 18]. FTS weight and power requirements based on a recent NASA study are approximately 575 lbs and 450 W respectively [Ref. 33:p. 106].

7. Summary

The OMV servicer kit (i.e., solar arrays, Ni-H_2 batteries, storage rack, FTS) including fluid transfer system and contingency margin totals 4,110 pounds. (see Figure 3.9) The total launch weight of the servicer kit, including 3,000 pounds of usable hydrazine and 3,200 pounds allocated for ORUs is 10,749 pounds. [Ref. 33:p. 106] Adding 327 lbs for radiation shielding, the total OMV servicer configuration launch weight is 30,976 lbs.

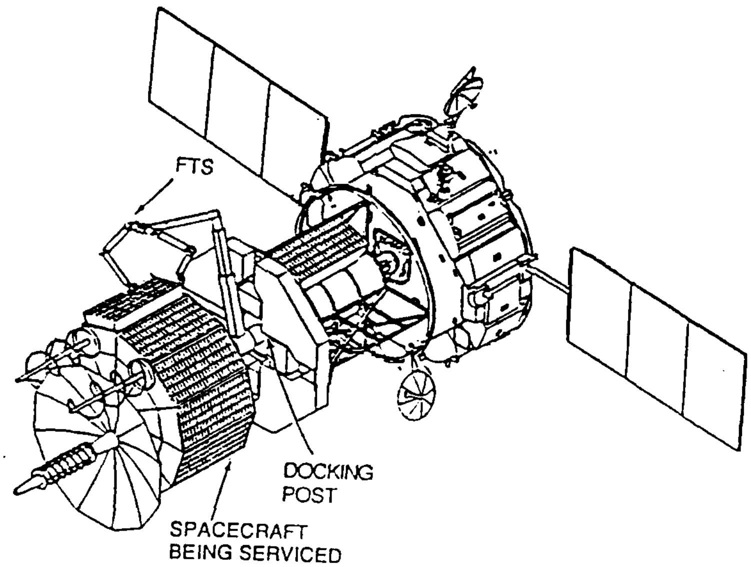

Figure 3.9 Operational Servicer Design
[Ref. 30:p. 33]

IV. EXPENDABLE LAUNCH VEHICLES

This chapter provides a brief survey of selected ELVs that would be used in support of OMV satellite servicing. Other competing ELVs with similar capabilities can be used as well.

A. TITAN IV

1. Description

The Titan IV ELV is manufactured by Martin Marietta Astronautics Group and was designed to duplicate space shuttle payload capabilities [Ref. 38:p. 15]. The launch vehicle is an improved version of the highly successful Titan III. The Titan IV launch vehicle consists of a two-stage liquid propellant core with two strap-on solid rocket motors (see Figure 4.1). [Ref. 39:p. 141] It is capable of single or dual payload missions to LEO. Payload fairings (with no upper stage) are 66 feet long and 15 feet in diameter. [Ref. 1:Sec. 3.1]

It will be able to place 32,160 pounds into a circular 100 NM polar orbit from Vandenberg AFB. The Hercules Corporation is currently developing solid rocket motor upgrades for Titan IV which, when placed into service, will boost polar payload capacity to 41,400 pounds. Western test range Titan IV launch capability

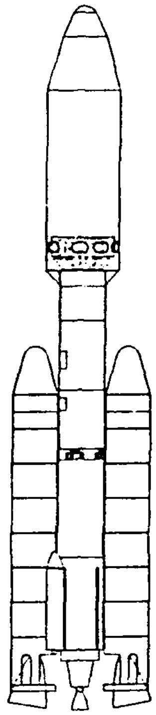

Figure 4.1 Titan IV (No Upper Stage) with OMV Payload
[Ref. 1:Sec. 3.1]

is expected to be available in 1990 from complex 4E [Ref. 40:pp. 32-34]. The USAF has issued a request for proposals (RFP) for the initial work to modify one additional WTR launch pad (complex 6) for Titan IV compatibility, which was previously developed as a space shuttle facility. The option to pursue the development of a new Titan IV pad (complex 7) at the WTR is also being considered should complex 6 conversion prove to be unfeasible. [Ref. 41:p. 13]

The converted intercontinental ballistic missile, Titan II, can boost a 3000 lb payload into a 100 NM polar orbit. Using existing strap on motors, this capacity can be increased to 7,000 lbs. Titan II launch facilities are currently available at Vandenberg AFB (complex 4W). Approximately 55 Titan II launchers still remain in the inventory. [Ref.7:p. 380]

2. Servicing Mission

The Titan IV is used to boost the OMV servicer, spare ORUs, SBSP modules and provide OMV logistic replenishment. Titan II will be used to launch future Landsat spacecraft.

3. Cost

The cost for each Titan IV launch is calculated to be $105.5 million, not including the payload [Ref.40:p. 33]. Titan II launch costs are approximately $24.6 million [Ref. 7:p. 379]. Launch cost estimates do not include upperstage or insurance costs.

B. ATLAS

1. Description

General Dynamics has been working on a commercial Atlas program since the early 1980s. The current Atlas 1 version uses a two stage liquid propellant core [Ref. 39:p. 179]. The new Atlas 2 launcher will feature enhanced performance by incorporating optional strap on-boosters. Availability is planned for 1991. [Ref. 7:p. 370] The large payload fairing is 30.8 feet long and 12 feet wide, with a medium size fairing (25 feet x 9.6 feet) available. Both Atlas 1 and 2 launchers are fitted with the Centaur upper stage motor for GEO payload insertion. The Atlas1 and 2 launchers without the Centaur upper stage are known as versions J1 and J2 respectively. Atlas J1 can place 6,100 lbs into a 100 NM polar orbit, while Atlas J2 will be capable of boosting approximately 7,000 pounds into a 100 NM polar orbit, without the use of strap on boosters. [Ref. 42] Currently, only Atlas E (see Figure 4.2) through H launchers are certified to operate from the WTR using launch sites 3E/W. [Ref. 7:p. 371] The Atlas E can boost approximately 2,400 lbs of payload to a 100 NM polar orbit. As of April 1990 only seven boosters remain in the inventory for future missions. Modification of existing WTR Atlas launch facilities could be accomplished to provide enhanced polar orbit insertion capability. [Ref.42]

2. Servicing Mission

The Atlas E through H launcher is used to launch the NOAA and DMSP series polar weather satellites. Additionally the Atlas ELV can be used in conjunction with OMV logistic support.

3. Cost

Launch cost for the Atlas 1 is $40 million. Launch price includes $500 million third party liability insurance. [Ref. 39:p. 180] Since the Centaur upper stage is not required for polar servicing missions, launch cost for Atlas J1 would be reduced to approximately $20 million [Ref.42].

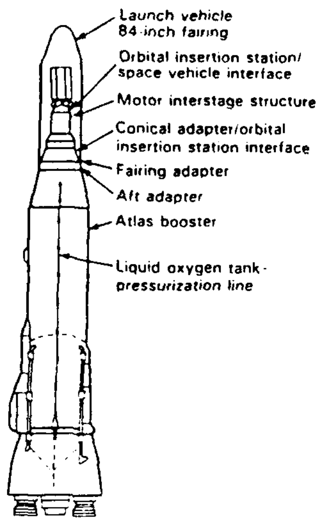

Figure 4.2 Atlas E
[Ref. 39:p. 177]

C. DELTA

1. Description

The McDonnell-Douglas Astronautics Company Delta launch vehicle has been a NASA space workhorse for 27 years. Over the past 9 1/2 years, reliability has reached nearly 98%. The current Delta II ELV uses a hybrid first stage, liquid second stage and solid upper stage. Additional strap-on solid motors are available (see Figure 4.3) for heavier payload launches. Payload fairing is 27.8 feet long and 8.3 feet wide. The use of 10 feet diameter fairings is under investigation for future

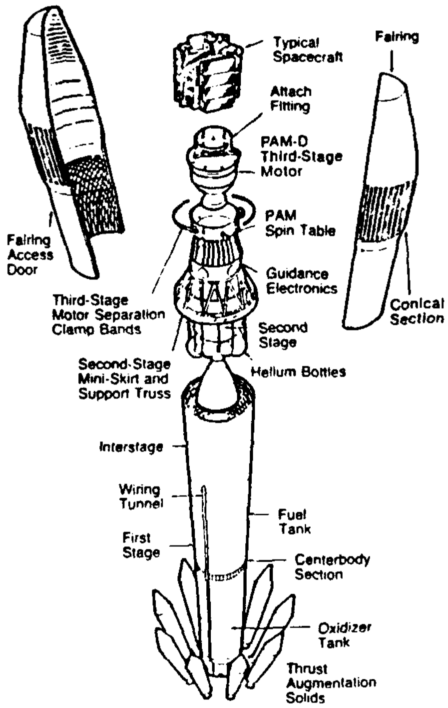

Figure 4.3 Delta II Launch Vehicle
[Ref. 7:p. 383]

missions. The Delta II (Model 6920) is capable of boosting a 6,670 pound payload into a 100 NM circular polar orbit. The new version model 7920 will have the capability of placing up to 8,420 pounds of payload into the same orbit. (see Figure 4.4) [Ref. 10:p. 253] Delta II launch facilities from the Eastern and Western Test Ranges are currently available.

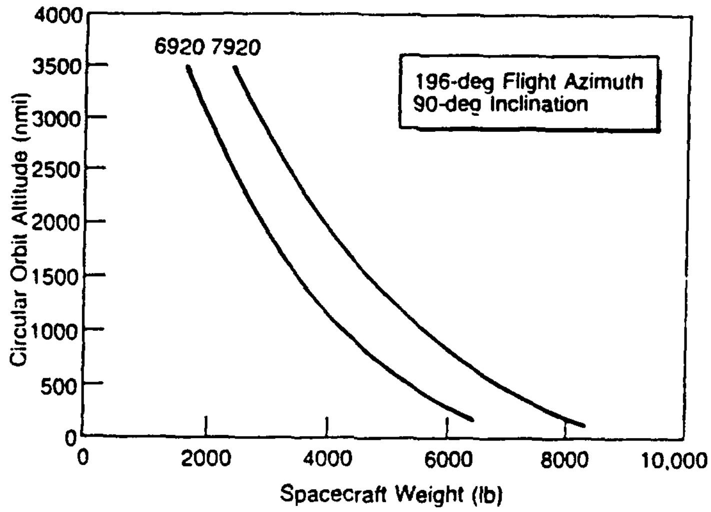

Figure 4.4 Delta II Two Stage Performance
[Ref. 10:p. 253]

2. Servicing Mission

The Delta II is used to place the Landsat series spacecraft into polar orbit. Additionally, the Delta II can be used to support OMV refueling/logistics and SBSP module insertion.

3. Cost

Delta II space launches range in price from $35 to $50 million. [Ref. 39:p. 181] For the purposes of this study, a $40 million figure will be used.

D. SCOUT

1. Description

Designed and developed in the late 1950s by NASA, and LTV Missiles and Electronics Group, Scout's first launch was in July 1960. [Ref. 39:p. 217] Over the past 20 years, the reliability rate has exceeded 98%. The Scout G-1 uses a 4-stage solid propellant motor. The fairing can support a payload which is 4.9 feet long and 3.2 feet wide. (see Figure 4.5.) [Ref. 39:p. 340] The G-1 model can place a payload of 485 pounds into a 100 NM circular polar orbit (see Figure 4.6). Launch facilities are located at the Wallops Flight Facility (WFF), Virginia, Vandenberg AFB, California and NgWana Bay (San Marco Facility), Kenya, Africa.

As of June 1988, only seven Scouts remained in the inventory to satisfy requirements through the 1990s. Although Scout production has terminated, the possibility of line re-opening has emerged. This will be contingent on the requirements of NASA's small Explorer program studies and a private venture LTV Corporation and an Italian business group in anticipation of a growing microgravity payload market in the 1990s. [Ref. 7:p. 372]

2. Servicing Mission

The Scout G-1 is used to boost small payloads such as ORUs, cryogenic fluids or other special equipment as required by the user satellite.

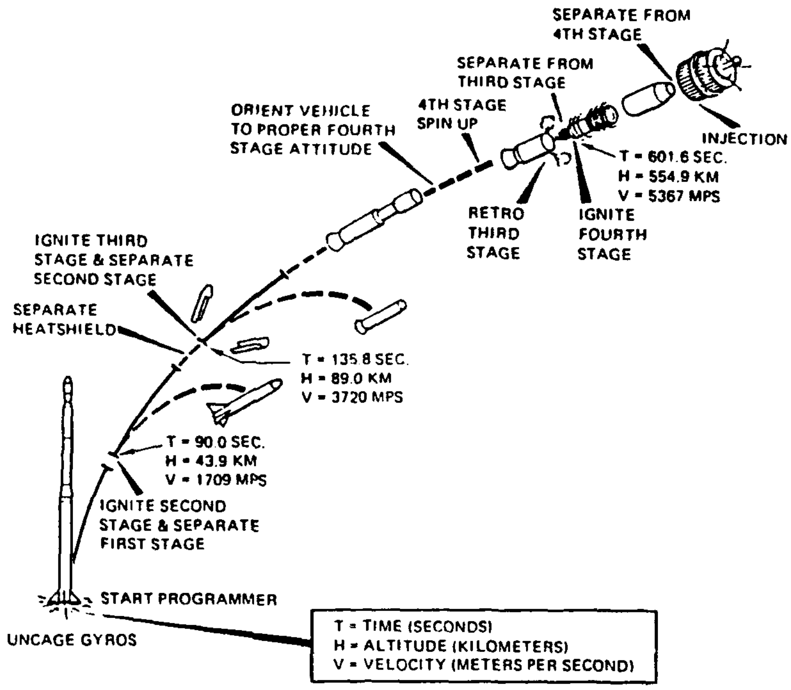

Figure 4.5 Scout Launch Vehicle
[Ref. 7:p. 373]

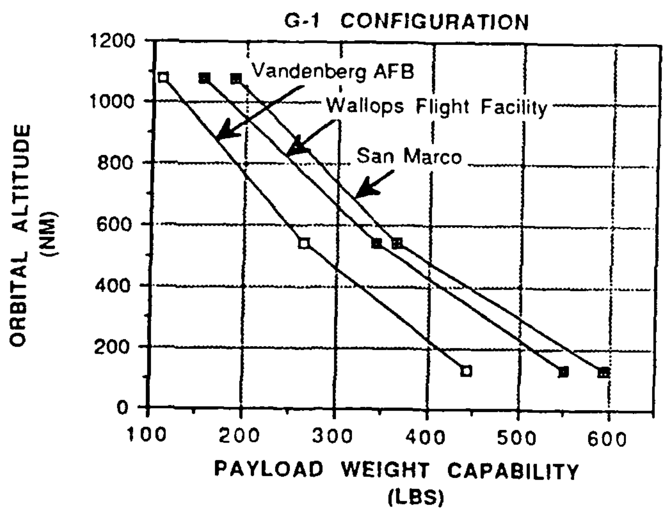

Figure 4.6 Scout G-1 Payload Performance
[Ref. 39:p. 233]

3. Cost

Launch cost for the Scout G-1 is $15 million. [Ref. 40:p. 238]

E. PEGASUS

1. Description

The Pegasus vehicle was privately developed and equally funded by the Orbital Science Corporation (OSC) and the Hercules Aerospace Company. The commercial venture is aimed at attracting customers with small payload insertion requirements in LEO. The booster is designed for horizontal launch utilizing a conventional wing to provide lift (see Figure 4.7). [Ref. 31:pp. 27-30]

The Pegasus is 49.2 feet long, has a 22 -foot wing span and is 50 inches in diameter. Designed to be carried under the right wing root of a B-52 aircraft, the Pegasus is launched from an initial altitude of 40,000 feet. The booster then uses a three stage solid-propellant motor to achieve orbit. The payload section is 6.3 feet long and 3.8 feet wide. Although presently restricted to military aircraft launch, commercial aircraft adaptors are expected in the future. [Ref. 31:p. 4]

The Pegasus is capable of placing an 850 pound payload into a 100 NM circular polar orbit (see Figure 4.8). The first successful Pegasus flight was completed in April 1990.

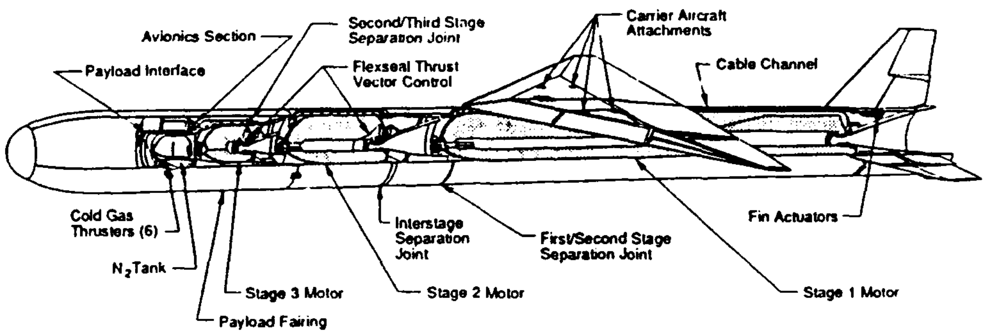

Figure 4.7 Pegasus Launch Vehicle
[Ref. 31:p. 33]

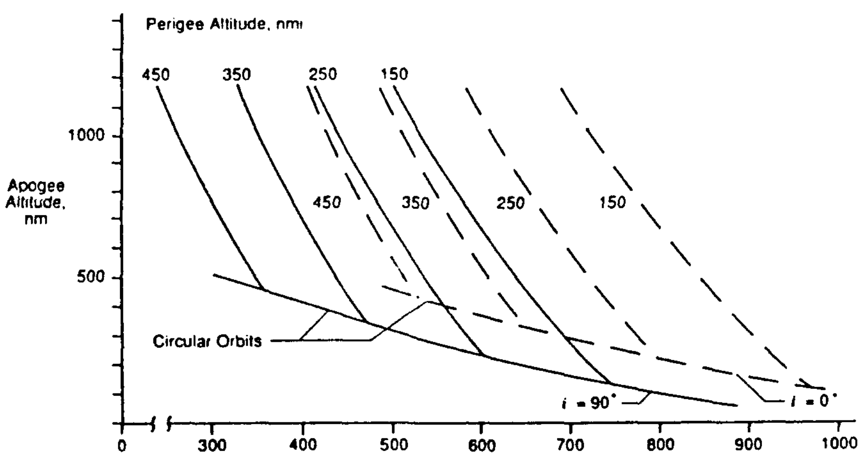

Figure 4.8 Pegasus Payload Performance
[Ref. 43:p. 23]

2. Servicing Mission

The Pegasus is used to boost ORUs, small mass consumables and other special payloads which may be required.

3. Cost

Launch cost for the Pegasus is approximately $10 million. [Ref. 44:p. 51]

F. SUMMARY

Table 4.1 summarizes selected ELV characteristics.

TABLE 4.1

ELV CHARACTERISTICS

VEHICLE	PAYLOAD TO POLAR ORBIT (100 NM)	SERVICING MISSION	INVENTORY STATUS (as of Apr. 90)	COST (in FY-90 $)
TITAN IV	32,160 lbs	OMV launch /resupply	Operational	105.0 M
TITAN II	3,000 lbs	OMV resupply	55	24.6 M
ATLAS J1	6,100 lbs	OMV resupply	IOC* (1991)	20.0 M
DELTAII	6,670 lbs	OMV resupply	Operational	40.0 M
SCOUT G1	485 lbs	ORU launch	7	15.0 M
PEGASUS	850 lbs	ORU launch	IOC* (1990)	10.0 M
* IOC- Initial Operating Capability				

V. POLAR ORBITING SATELLITES

This chapter briefly describes current U.S. polar orbiting satellites. Satellite system mass breakdown, launch vehicle and cost information is also provided. The DMSP, NOAA television infra-red observation satellite (TIROS) series and Landsat spacecraft are launched with an inclination such that the final orbit is sun-synchronous. This means that the orbital plane of the satellite precesses 360 degrees in 365 days (about 1 degree per day). This precession is mainly due to the non-spherical nature of the earth. Precession of the orbital plane at this rate keeps the orbital plane orientation the same with respect to the Sun, with two equatorial crossings occurring at the same local time each day per orbit. Thus, a satellite may be termed to be in a morning, noon, or afternoon orbit depending on this orientation. [Ref. 45:p. 1-1] In general, most polar orbit inclinations are between 95 to 100 degrees, depending on the operating altitude (see Figure 5.1). The combination of precession of the orbital plane and rotation of the earth produces an apparent westward motion of the satellite ground track. Exact repeat cycles occur at approximately 15 to 17 day intervals depending on satellite altitude and inclination.

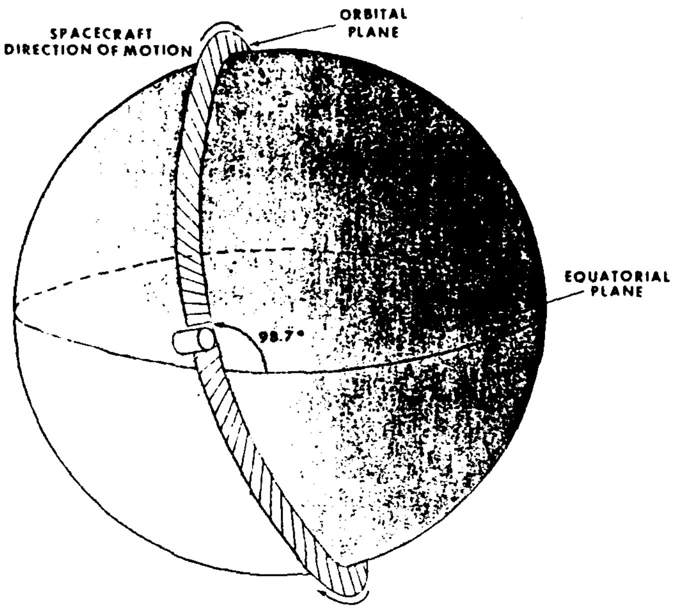

Figure 5.1 Typical Polar Orbit
[Ref. 46:p. 6-2]

A. DMSP

1. Mission Description

The mission of the DMSP is to provide global meteorological data to the Service Commanders in support of worldwide military operations, both strategic and tactical [Ref. 45:p. 57]. The program is managed by the USAF's Systems Command, space Division in Los Angeles AF Station, CA . The space segment consists of two satellites in 450 NM sun-synchronous polar orbits (inclination 98.77 degrees) with an orbital period of 101.4 minutes. This equates to 14.2 orbits per day. One satellite is placed in a morning orbit (0730 local time descending node) and one in a noon orbit (1200 local time ascending node). [Ref. 45:p. 1A-1]

Real-time weather data is transmitted directly from the spacecraft to Air Force and Navy ground terminals, and Navy aircraft carriers located throughout the world. Meteorological data is also transmitted to selected ground sites. A store and playback mode is also available to provide satellite information on areas which do not have ground receive sites for direct downlink. [Ref. 7:p. 269]

The current block 5D-2 satellites have a three year operational life and orbital life of approximately 80 years (see Figure 5.2). Each satellite is equipped with a visible/infrared scanner, microwave imaging sensor, microwave temperature sounder, electron spectrometer and electrostatic ionosonde sensor. [Ref. 7:p. 271]

The sensors measure ocean surface wind speed, ice coverage and age, precipitation, cloud altitude and water content, storm movement and surface moisture. Additionally, upper atmosphere electron and proton levels are monitored to aid radar and long-range radio operators.

The block 5D-2 satellite was constructed using some modular components to facilitate on-orbit repair [Ref.7:p. 271]. Approximately 5 block 5D-2 vehicles remain in the inventory at this time. An improved block 6 satellite is expected to be launched in 1998 [Ref.7:p 299]. The spacecraft is built by the General Electric Astro-Space Company, assisted by three subcontractors.

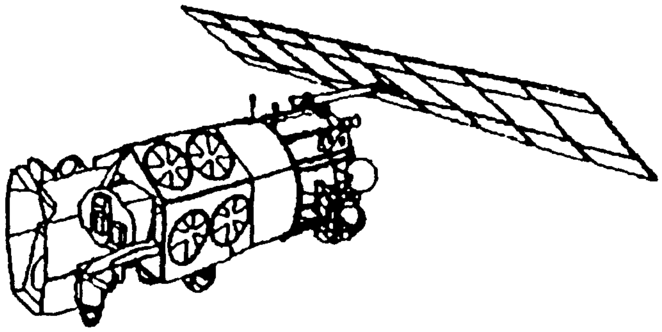

Figure 5.2 DMSP Block 5D-2 Satellite
[Ref. 47:p. 57]

2. System Mass Breakdown

The DMSP Block 5D-2 launch weight is approximately 3,200 lbs. The spacecraft has a beginning of life (BOL) on-orbit mass of approximately 1,820 lbs and uses hydrazine propellant for reaction control and propulsion [Ref. 7:p. 271]. The on-orbit satellite mass summary breakdown by individual subsystems is shown in Table 5.1 [Ref. 47:pp. 55-57].

3. Launch Vehicle

DMSP Satellites are launched using the ATLAS E-H launchers from the WTR at Vandenberg AFB, CA [Ref. 42].

4. Mission Cost

The cost of each DMSP satellite is approximately $65 million [Ref. 10:p. 17]. Under the assumption that an unshared ATLAS launch is required, the total mission cost per satellite is estimated to be $85 million.

TABLE 5.1

DMSP MASS SUMMARY BREAKDOWN

SUBSYSTEM	WEIGHT (LBS)
Structure	558.3
Thermal	50.5
Propulsion	37.9
Electrical	465.6
Command & Control/Communication	98.3
Attitude Control	127.7
Payload	374.9
Apogee Motorcase	106.1
Satellite BOL Mass	1,819.1 lbs

B. NOAA

1. Mission Description

The mission of the NOAA satellite program (current series TIROS-N) is to provide global meteorological and environmental data required to support both the operational and experimental portions of the World Weather Watch Program. [Ref. 48:p. 13] NOAA operates two command/acquisition ground stations at Wallops Island, VA and Fairbanks, Alaska in support of satellite operations. An additional ground station at Suitland, MD is used to record incoming satellite data for central processing and dissemination. [Ref. 49:p. 44] The space segment consists of two sun-synchronous satellites at an altitude of approximately 450 NM (see Figure 5.3). Orbit inclination is 98.9 degrees. The orbital period is approximately 102 minutes, resulting in 14.2 revolutions per day. One satellite is injected to provide a morning pass (0730 local time on the descending node), while the second provides an afternoon pass (1430 local time on the ascending node) [Ref. 49:p. 4].

They are the principal source of data for 80% of the globe that is not covered by conventional data collection means. Over 120 foreign nations , and 1,000 schools, private institutions and others receive NOAA satellite imagery. The current NOAA-10 and 11 spacecraft have a 2 year operational life and a 350 year orbital life. [Ref. 7:p. 534] Each satellite is outfitted with a high resolution radiometer, operational vertical sounder, space environment monitor, data collection and platform location system, and a search/rescue transponder. The satellites measure

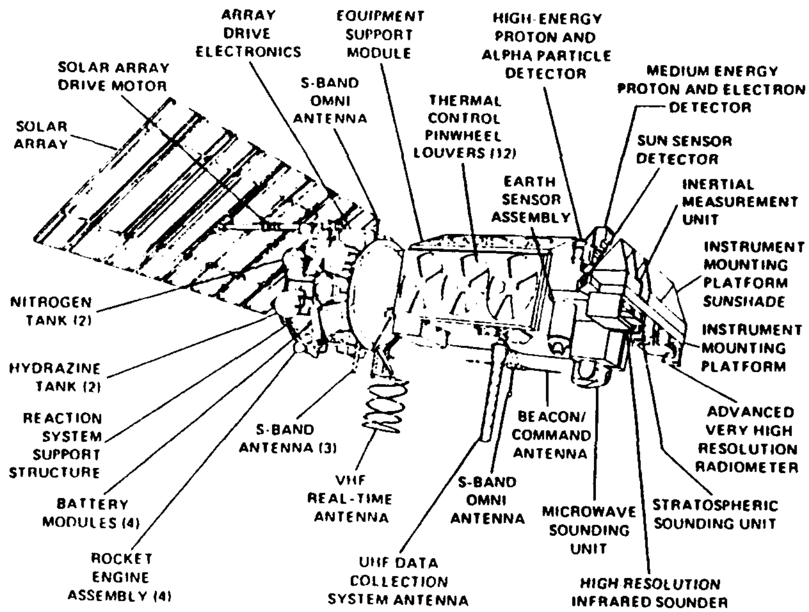

Figure 5.3 NOAA Tiros-N Series Spacecraft
[Ref. 48:p. 13]

temperature and humidity in the earth's atmosphere, surface temperature, cloud cover, water-ice boundaries, and proton/electron flux densities near the earth. [Ref. 47:p. 6] The spacecraft is manufactured by the General Electric Astro-Space division, based primarily upon the DMSP satellite design [Ref. 7:p. 533].

2. System Mass Breakdown

The NOAA 11 satellite launch weight is approximately 3,725 lbs. The spacecraft has a BOL mass of approximately 2,240 lbs and uses hydrazine propellant for station keeping maneuvers. The on-orbit satellite mass summary breakdown by individual subsystems is shown in Table 5.2. [Ref. 47:p. 139]

TABLE 5.2

NOAA TIROS-N MASS SUMMARY BREAKDOWN

SUBSYSTEM	WEIGHT (lbs)
Structure	405.3
Thermal	63.8
Propulsion	216.4
Electrical	522.5
Command & Control/Communication	322.3
Attitude Control	125.9
Payload	474.9
Apogee Motor Case	106.1
Satellite BOL Mass	2,237.2

3. Launch Vehicle

NOAA satellites are boosted using the Atlas E/F launchers from Vandenberg AFB, CA [Ref. 7:p. 535].

4. Mission Cost

The estimated cost of a current NOAA satellite is approximately $44 million [Ref.7:p. 535]. The total mission cost per satellite is $64 million, assuming a single satellite launch.

C. LANDSAT

1. Mission Description

The Landsat program is designed to provide near global land remote-sensing imagery. The imagery has greatly enhanced the ability to monitor and understand the dynamics, character and structure of the earth's land surface [Ref. 49:p. 156]. The EOSAT commercial entity assumed program control from NOAA in 1984. The transfer of the program to EOSAT was the beginning of a 10-year effort to commercialize Landsat products. The space segment currently consists of two spacecraft, Landsats 4 and 5 (see Figure 5.4). Both satellites are located in circular sun-synchronous polar orbits at an altitude of approximately 380 NM. Inclination is 98.2 degrees. Landsat 5 equatorial crossing occurs at 0945 local time, with a 16-day repeat cycle and a 1490 NM ground track separation at the equator. Landsat 5 became the primary spacecraft after multiple malfunctions affected Landsat 4's performance in October 1987. Landsat 4 was maneuvered to a higher altitude in an effort to continue operations until Landsat 6 becomes operational in 1991. Landsat spacecraft have been designed for a three-year operational life. [Ref. 7:p. 528] The main body of the spacecraft is comprised of NASA's standard Multimission Modular Spacecraft (MMS) and the Landsat instrument module. The system integrates the attitude control, power, communications and data handling, and propulsion subsystems in a standard configuration. It was developed by the Goddard Space Flight Center to support

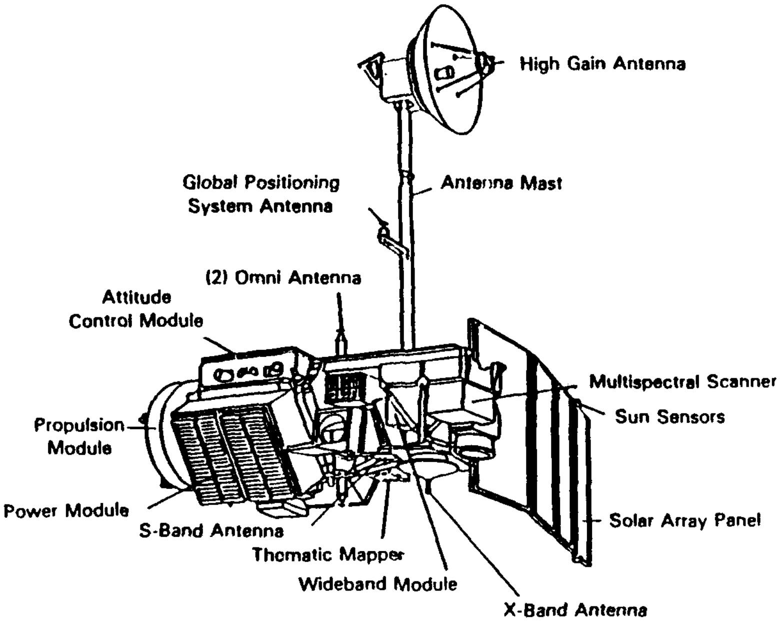

Figure 5.4 Landsat 4/5
[Ref. 47:p. 161]

many spacecraft missions, providing lower costs through economies of commonality and quantity purchases.

The satellites use a Thermatic Mapper (TM) and a Multi-Spectral Scanner (MSS) as primary sensors. Real time TM data is available via access on the TDRSS network. Over 14 foreign nations have installed ground receiving stations for Landsat data. The high quality imagery obtained from the Landsat spacecraft has had a major impact on management of the world's three major resources; food, energy and environment. [Ref. 7:p. 531] Current funding difficulties may result in a coverage gap in the late 1990's, when the Landsats 4 and 5 are expected to cease operating. The improved Landsats 6 and 7 will feature a five-year design life and improved sensors. Additionally, the vehicles will again use data recorders which had been previously eliminated. The spacecraft are built by the General Electric Astro-Space Division.

2. System Mass Breakdown

The Landsat 5 launch weight is approximately 4,449 lbs. The spacecraft has a BOL mass of approximately 4,284 lbs and uses hydrazine for on-orbit station keeping. The spacecraft component mass summary breakdown is shown in Table 5.3 [Ref. 47:pp. 64-65].

TABLE 5.3

LANDSAT MASS SUMMARY BREAKDOWN

SUBSYSTEM	WEIGHT (lbs)
Structure	330
Thermal	13
Propulsion	738
Electrical	591
Command & Control/Communication	299
Attitude Control	453
Payload (Includes Instrument Module)	1,860
Spacecraft BOL Weight	4,284

3. Launch Vehicle

Landsat spacecraft are launched using the Delta II (MOD 3920) ELVs from the WTR [Ref. 47:p. 63]. Landsats 6 and 7 will use the Titan II ELV for orbital insertion commencing in 1991 [Ref. 7:p. 530].

4. Mission Cost

The cost for Landsat 4 was $60 million in 1984 [Ref. 50:p. 16]. The estimated cost due to inflationary increases is approximately $70 million in 1990 dollars. Using an unshared Delta II launch, total mission cost would be approximately $110 million.

D. SUMMARY

Table 5.4 summarizes polar satellite characteristics.

TABLE 5.4

POLAR SATELLITE CHACTERISTICS

SATELLITE	INCLINATION	ATTITUDE (NM)	LAUNCH VEHICLE	# OF SATELLITES ON-ORBIT	TOTAL COST PER SATELLITE LAUNCH (in FY-90 $)
DSMP	98.77°	450	Atlas E-H	2	$85 M
NOAA	98.90°	450	Atlas E/F	2	$64 M
LANDSAT	98.20°	380	Delta II	2	$110 M

VI. SATELLITE SERVICING WITH THE OMV

A. ORBITAL INSERTION

The OMV was designed for orbital insertion using the space shuttle. Range safety restricts ETR launches to less than 57 degree inclinations for direct insertion [Ref. 1: Sec. 3.1]. Since STS operations from the WTR have been deferred indefinitely, an ELV is required to boost the OMV into polar orbit.

The best suited available ELV to satisfy this mission is the Titan IV. The Titan IV has ETR and WTR launch capability and a payload dynamic envelope of 15 ft which is the same as the STS. The Titan IV with no upper stage has a payload capacity of 32,160 lbs to a 100 NM circular polar orbit. The total OMV servicer weight is 30,976 lbs, leaving over 1,000 lbs of excess payload capacity. Electrical and mechanical interface requirements between the OMV and Titan IV were found to be feasible following a detailed investigation conducted in 1988. [Ref. 1: Sec. 3.1]

1. Electrical

The NASA OMV has an electrical umbilical connector to maintain electrical power while in the STS cargo bay. The same interface can be retained by using the STS side of the umbilical for the OMV subsystems which must be energized during the launch phase, such as the IMU and certain ground control circuits, showed that the OMV batteries can supply the necessary power. Based on these requirements, no electrical connection between the OMV and Titan IV are necessary. Consequently, no OMV electrical hardware interface changes are required. [Ref. 1: Sec. 3.1]

2. Mechanical

An adaptor is required to mechanically attach the OMV to the Titan IV. Using a square adaptor design, the OMV is supported at four evenly spaced points to provide direct and relatively short paths between the load and reaction points. Removal of the OMV trunnion and keel pins (required for space shuttle operations) is necessary to establish the proper payload fairing clearance. The pins exceed the payload allowable dynamic envelope by 7.75 and 8.5 inches respectively. The pins could be reinstalled by on-orbit EVA permitting STS retrieval, should manned polar operations become possible at a future date. The OMV is integrated to the Titan IV payload fairing with the PM face down. This permits the solar array panels to be stowed as shown in Figure 6.1. [Ref. 1: Sec.3.2] The arrangement allows the OMV servicing kit to be placed on the SRV payload side with no restrictions, well within payload fairing length restrictions.

3. Thermal

The temperature inside the payload launch fairing (PLF) is controlled by air conditioning on the launch pad and therefore does not present a problem for any OMV hardware. The OMV experiences free molecular heating after the PLF is

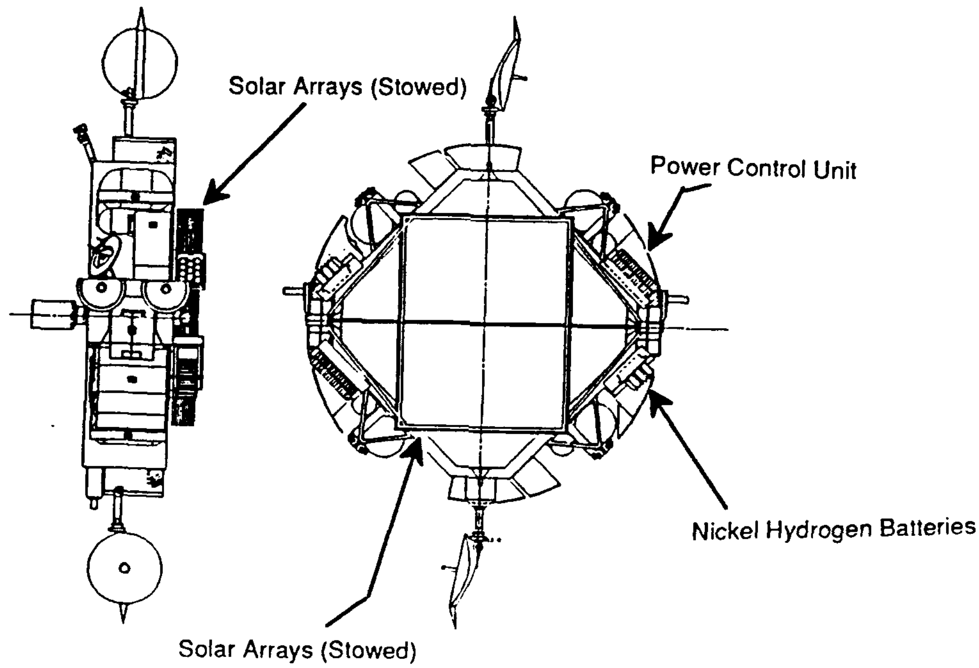

Figure 6.1 OMV Solar Array Launch Configuration
[Ref. 1:Sec. 3.3]

jettisoned. Since this heating rate is below that of the on-orbit environment, there is no impact to the OMV design. [Ref. 1: Sec. 3.1]

4. Structural

The structural limit loads of the Titan IV have a 1.25 factor applied to the design values, while the man-rated STS requires a more stringent 1.4 factor. All of the Titan IV launch environments (i.e., acoustic, acceleration loads, vibrations and shock) are either similar to or less severe than the STS launch environments.

After orbital injection, solar panel extension occurs, followed by OMV ascent to its operational altitude (300 to 500 NM).

B. PAYLOAD STABILITY

A stable payload or user satellite is required for successful docking to the OMV servicer. Current specifications permit the OMV to dock with an object rolling at 2.8 degrees per second relative to the docking axis or .5 degrees per second for a tumbling target. [Ref. 42: p. 7]

C. OMV DOCKING OPERATIONS

OMV docking to an ORU payload or user spacecraft will be operated by remote control from the ground, or possibly the space station, by a pilot using television monitors and on-board radar. The ground or space based pilot commands the vehicle through the TDRSS link.

1. Rendezvous

The problem of principle concern in polar orbiting satellite servicing and resupply is to establish cost-effective rendezvous and docking procedures for servicing a constellation of satellites [Ref. 51: p. 1]. The orbital insertion point of ELV resupply modules and/or ORUs should be as close to the OMV servicer position as possible, to minimize the fuel requirement for retrieval. The OMV maneuvers to establish an orbit to dock with a user satellite. The ORU or resupply module launch is coordinated so that recovery can occur while the OMV is enroute to a user satellite, minimizing total fuel required for the operation. OMV plane change magnitudes for rendezvous with the polar orbiting spacecraft under consideration are on the order of 1 to 2 tenths of a degree. This greatly reduces the propellant required to conduct servicing operations.

The OMV uses an inertial navigation system and one of two GPS receivers to determine orbit change parameters, based on an earth-centered coordinate frame. The GPS receiver enables OMV position knowledge within 470 ft and velocity within 1.4 ft per second. Auto-rendezvous to a point near a target spacecraft or payload can be accomplished from a separation distance of up to 4.5 NM by means of the rendezvous radar. [Ref. 5: p. 21] The OMV acquisition radar maximum range is 4.5 NM with a ± 20 degree field of view [Ref. 31: p. 43]. Range data is provided from 4.5 NM to 100 ft. Once the target has been acquired by the radar tracking system, the OMV begins a pre-programmed docking approach. In this phase, the OMV performs all orbit change and trim maneuvers required to bring the vehicle to within approximately 1,000 ft of the target. Manual pilot control via the GCC takes place at this point for the final approach and docking. (see Figure 6.2.)

The OMV is programmed to execute a collision-avoidance maneuver in the event of two critical component failures, in either the automatic or manual operating modes. If the failure is sufficient to disable the OMV while in the automatic operation mode, the vehicle automatically transitions to its space-basing

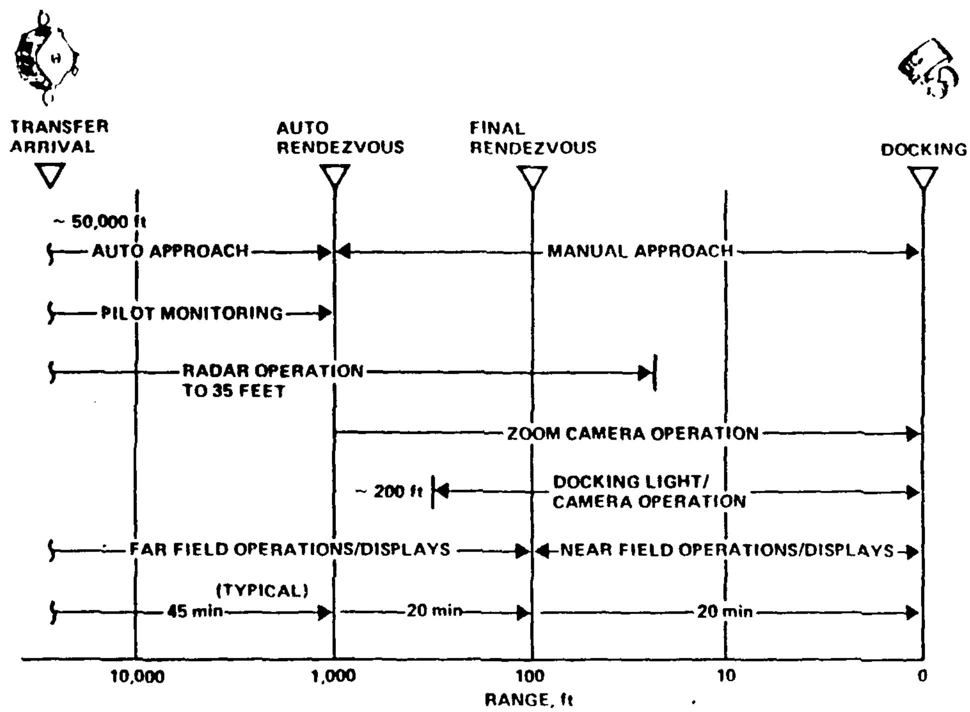

Figure 6.2 OMV Proximity Operations and Docking
[Ref. 34:P. 19]

mode. In the manual operating mode, the OMV executes a reverse thrust maneuver to back away from the target satellite or payload. These safety features ensure OMV and target satellite/payload safety. [Ref. 5: p. 12] A representation of the OMV servicer control process is shown in Figure 6.3.

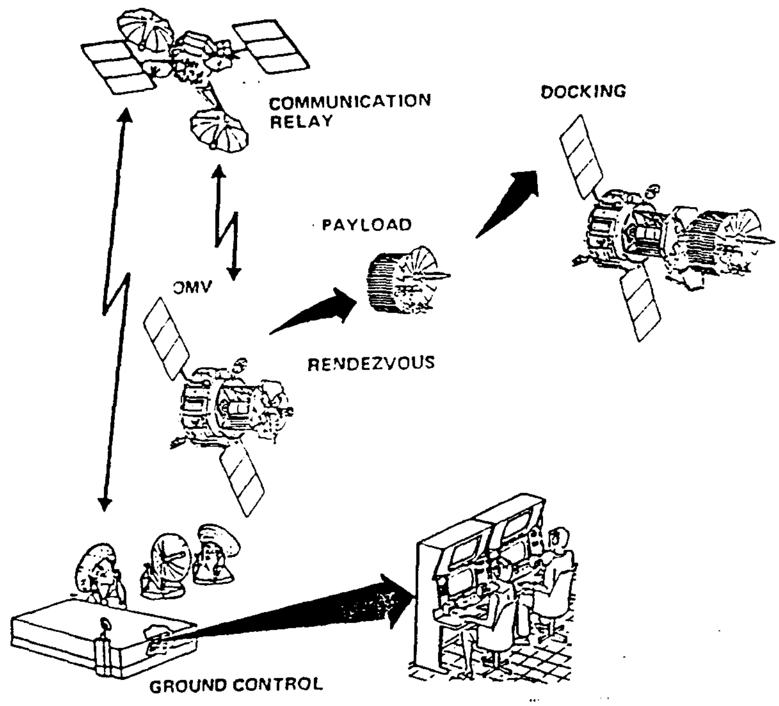

Figure 6.3 OMV Servicing Control
[Ref. 34:p. 12]

D. DOCKING MECHANISMS

The OMV can be fitted with either the NASA standard remote grapple or three point docking mechanisms. This study assumes that a RGDM configuration is used. The mechanism is centrally located on the face of the OMV servicer kit, and contains all electrical and fluid connections for on-orbit servicing requirements. (see Figure 6.4.)

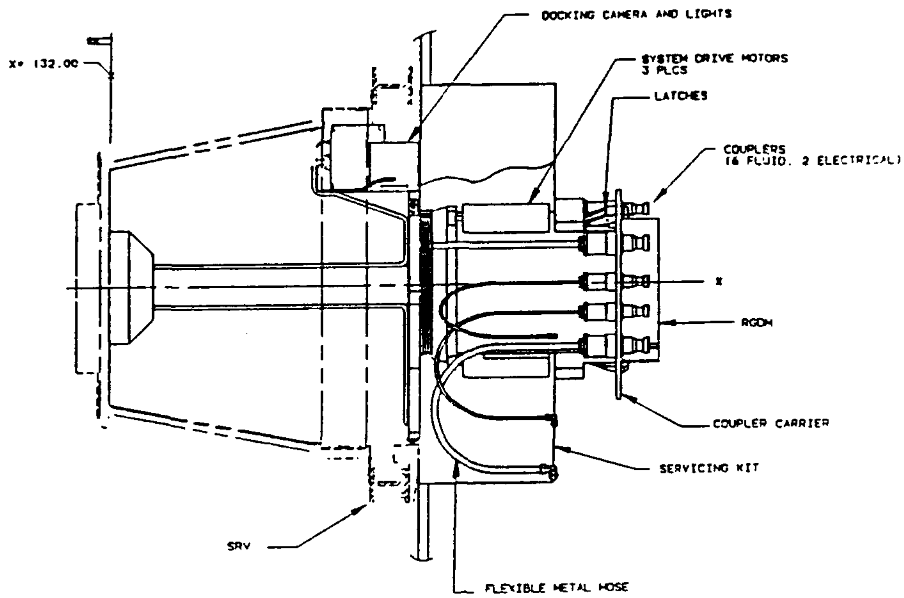

Figure 6.4 RGDM Fluid Coupler Mechanism
[Ref. 33:p. 71]

The fluid coupler design includes six couplings (two bipropellant, one hydrazine, one gaseous nitrogen and two gaseous helium) mounted on a ring carrier surrounding the RDGM. Electrical system connections are also provided. Initial alignment and mating occurs during docking, and final coupling engagement with the user spacecraft is accomplished by driving the carrier ring to its final mated position with three drive motors. The design provides latches to lock the system in the mated position as an added point of restraint to the 1,200 lb RDGM restraining force. User satellites would require at least one integrated RGDM fluid/electrical connection point for on-orbit servicing. Additional grapple fixtures may be needed to provide the OMV servicer access to locations which cannot be reached from the primary attachment point (see Figure 6.5).

To provide the pilot with a visual aid necessary for docking and attachment, a grapple target is painted on the user satellite or payload. The pilot maintains specific orientation with respect to the target while closing the distance to the target satellite for final docking.

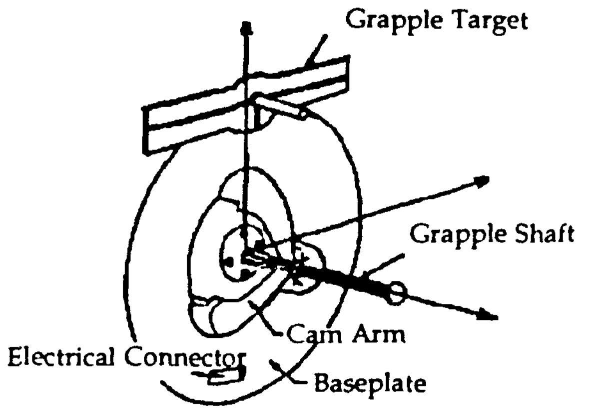

Figure 6.5 Satellite Grapple Fixture
[Ref. 23:p. 6]

E. SERVICER MANIPULATION TASKS

The manipulation tasks required to be performed by the FTS do not require a high degree of dexterity, however, a simple ORU removal/replacement procedure is necessary. Using the ORU change-out method incorporated into the OMV as a representative example, a single universal servicing tool (UST) is needed. For ORU removal, the tool loosens a single attachment bolt and subsequently removes the unit after locking on an H-shaped bracket at the access opening. The tool blade is inserted into the access hole extending through the ORU body to turn a lead screw that fastens or unfastens the module to the structure below (see Figure 6.6). To install an ORU, the process is reversed.

The H-shaped interface plate at the top of the module is held by the two UST prongs in the process of attaching or detaching it to or from the spacecraft structure. [Ref. 33: p. 37] Robot manipulator tasks necessary to gain access to ORUs, such as the removal/relocation of thermal covers is assumed to be within the capability of the robot. [Ref. 33: p. 99]

Replacement of fluid tanks would require a complex sequence of instructions for the handling of attachment bolts and fluid line connectors. This type of FTS operation is considered impractical for most servicing missions, unless the supply tank is an integral part of an ORU which is designed for one-step modular removal or replacement.

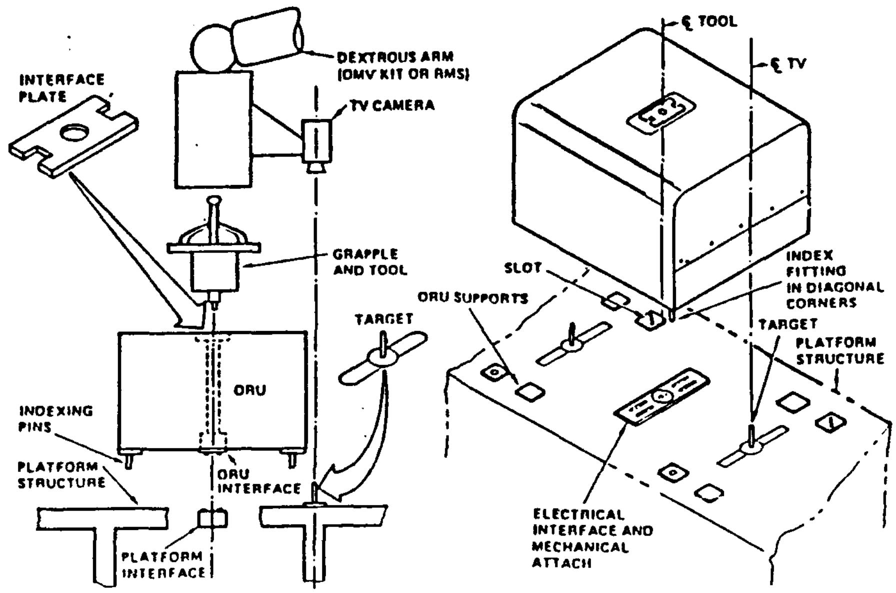

Figure 6.6 ORU Change-out Method
[Ref. 33:p. 38]

F. USER SPACECRAFT INTERFACE REQUIREMENTS

1. Mechanical

User spacecraft interface provisions and operational status during servicing are important considerations in the development of a remote servicing capability. In general, the spacecraft must be "robot-friendly", be safe to service, and be of rugged design. Spacecraft must also be constructed using modular techniques, and use standardized exchange procedures for replaceable ORUs. The modules must be easily accessible and have simple attachment/removal interfaces. User satellites would also require a grapple-type attachment point and a television target plate for manual OMV docking from which all ORU locations are accessible from the FTS.

The grapple fixture can be modified to add automatic oi-directional fluid couplings and electrical connectors. [Ref.33: p.34]

2. Electrical

User satellites would require the capability to maintain their own power during servicing and provide compatible fluid control and status monitoring via the electrical interface. Post-servicing equipment checkout should feature built-in test equipment and computer aided calibration to return the satellite back to operational status.

3. Operational

User satellite orientation is also assumed to be unconstrained during servicing. Spacecraft non-availability time would depend on the complexity of servicing required. It has been estimated that the servicing portion of the mission will require about 20 hours to complete. The figure includes a total of 15 hours for projected servicing activity (i.e., ORU changeout) and 5 hours of unproductive time to include a margin against unforeseen delays. The OMV provides attitude control to the user satellite for the duration of the servicing mission. [Ref.30: p.28]

VII. COMPARISON OF ESTIMATED OMV POLAR SATELLITE SERVICING COSTS WITH CURRENT SATELLITE REPLACEMENT COSTS

For the purposes of this study, only spacecraft construction and launch costs are considered in the analysis. The total cost of an OMV servicing mission would, therefore, require an additional premium to include ground services required to support the mission. ORUs, fuel and other logistic requirements that represent some fraction of the total satellite cost would also have to be factored in to the total servicing cost calculation. The space infrastructure required for OMV ground control (i.e., TDRSS) currently exists, and does not require modification to support the OMV servicer mission. Lastly, a space-based support platform is not considered to be available for OMV servicer use. All estimates are in FY 90 dollars.

A. OMV SERVICER

The first NASA OMV is currently in the final stages of development, with an initial launch date scheduled in 1994. The total estimated research, development and construction cost for the first OMV is $100 million. A second vehicle has also been specified for procurement by NASA at a follow-on cost of $65-$70 million. To incorporate the changes required for vehicle conversion from a battery to a solar powered configuration and extended duration service life (10 years or more) as stated in Chapter III, the follow-on OMV cost would rise to approximately $100 million. The cost to modify the OMV for the servicing role (i.e., bidirectional fluid transfer interfaces/couplings) and construction of the storage rack portion of the servicing front end kit is currently estimated to be $70 million. An additional $30 million (projected) would be required for modification and qualification of a space station configured FTS unit for OMV use. [Ref.4]

The launch cost for the OMV servicer, using the Titan IV ELV, currently is estimated at $105.5 million. The total cost for the OMV servicer and launch to a 100 NM polar orbit is estimated as follows:

Extended Duration, Solar Powered OMV	$ 100.0 Mil.
Servicing Front End Kit (Storage Rack and FTS)	$ 100.0 Mil.
Launch to 100 NM Polar Orbit Using Titan IV	$ 105.5 Mil.
OMV Servicer Estimated Total Cost	$ 305.5 Mil.

B. DMSP PROGRAM

Using the three year design life of the DMSP block 5D-2 satellites, the spacecraft and launch costs to maintain two satellites continuously on-orbit over a ten year period is approximately $480 ($80 per spacecraft launch times 2 spacecraft times 3 launches per 10 year period) million. The estimate assumes individual spacecraft launches using the Atlas E-H launch vehicle.

C. NOAA PROGRAM

The current NOAA satellites use a two year design life and are deployed to maintain two spacecraft continuously on-orbit. Over a ten year period, an estimated 10 spacecraft (2 satellites times 5 launches per 10 years) will be needed to maintain the constellation at a cost of approximately $640 (10 times $64 per mission) million. The figure assumes individual spacecraft launches using the Atlas E/F series expendable launch vehicle.

D. LANDSAT PROGRAM

Using the five year design life of Landsats 6/7, the estimated cost to construct and launch the four spacecraft which would be required to maintain a two satellite constellation continuously on-orbit is $440 (4 times $110) million. The estimate assumes individual satellite launches using the Delta II launch vehicle.

A summary of the 10 year mission estimates are shown in Table 7.1.

E. OMV SATELLITE SERVICING

Assuming a worst case situation where the OMV servicer is required to descend from its base orbit (at 400 NM) to refuel with a resupply ELV (at 100 NM) and then proceed to rendezvous with a user satellite at a 450 NM altitude, approximately 6,000 lbs of bipropellant is required to perform a single servicing mission. [Ref. 4] This estimate is based on an OMV equipped with a 10,000 lb servicing kit (containing FTS, storage rack, spare ORUs and satellite fuel). Using

TABLE 7.1

POLAR SATELLITE AVERAGE MISSION COST SUMMARY (10 YEAR PERIOD)

PROGRAM	TOTAL COST	COST PER YEAR
DMSP	$ 480 MIL.	$ 48 MIL.
NOAA	$ 640 MIL.	$ 64 MIL.
LANDSAT	$ 440 MIL.	$ 44 MIL.
TOTAL	**$1,560 MIL.**	**$156 MIL.**

an Atlas J1 or Delta II ELV to boost the bipropellant to the OMV, an additional 100 - 500 lb of payload capacity (depending on ELV used) will be available for concurrent ORU or other supply delivery. Referring to Figure 3.3 in Chapter III, the OMV with a 10,500 lb payload is capable of altitude changes of approximately 750 NM, under conditions where small plane changes are performed (less than .5 degree). An OMV servicer based at 400 NM would first descend to 100 NM to retrieve the resupply module, then ascend to 450 NM to perform a servicing mission, and then return to a base orbit altitude of 400 NM for a total of 700 NM of transit distance. Since all of the polar satellite orbital planes under consideration are within .1 degree of each other (with a maximum altitude of 450 NM) the OMV servicer performance under these parameters will satisfy the mission requirement. [Ref. 4]

Deployment of a SBSP would greatly reduce the OMV fuel requirement to perform a servicing mission by providing a stable platform to store bipropellant for the vehicle and by eliminating the need for time consuming, costly and frequent transits to retrieve fuel at low altitude for each individual mission. OMV propellant could be stockpiled by using the large payload capacity of the Titan IV ELV to provide bulk transport. The ability to detach and temporarily store the servicer front end kit using a space platform would allow low cost OMV inspection missions to be performed. Additionally, the platform could provide a protected storage center for spare ORUs and other logistic needs. A SBSP would permit a wide range of resupply launch vehicles to be used, with payloads delivered into orbits which would optimize OMV propellant consumption for a given mission, while minimizing launch vehicle cost. The deployment of a SBSP for satellite servicing would greatly expand the feasible options (i.e., servicing satellites at higher altitudes and/or higher inclinations) available to a servicer-configured OMV.

For the purposes of the study, a $35 million Atlas or Delta series ELV is assumed to be required for each servicing mission to be performed. The yearly cost of the OMV servicer over the 10 year period is $30.55 million. Subsequently, the hardware cost for a single OMV mission on a yearly basis is $60.55 ($35 + $30.55) million. For the case where two OMV servicer missions per year are performed, the average cost per mission decreases to $50.3 ($35 + $30.55/2) million. Table 7.2 shows the average OMV servicer hardware cost per mission for several cases where an individual ELV (at $35 mil. per launch) is assumed to be required for each mission.

TABLE 7.2

OMV SERVICER COST PER YEAR (10 YEAR PERIOD)

NUMBER OF MISSIONS PER YEAR	OMV SERVICER AVERAGE COST PER MISSION (in millions)
1	$ 60.55
2	$ 50.30
3	$ 45.20
4	$ 42.60
5	$ 41.10

F. COMPARISON RESULTS

The cost figures, under the assumption that the OMV servicer requires an Atlas J1 or Delta II resupply prior to each servicing mission, compare favorably with those of satellite replacement. Satellite servicing refers to the replacement of essential on-board satellite consumables and propellant, while repair refers to defective ORU/solar array change-out.

Using the case where a single OMV servicer mission (per year over a ten year period) is performed, repair of a non-mission capable NOAA TIROS-N satellite (total cost $64 mil.) yields a savings of approximately $3.5 million when compared to satellite replacement cost (i.e., construction and launch of a new satellite). Repair of a single non-mission capable Landsat spacecraft (total cost $110 mil.) results in savings of $49.5 million over satellite replacement cost. The projected savings margin would have to be adjusted by the added cost of OMV bipropellant, satellite fuel, ORUs and ground support costs. The small cost savings ($3.5 mil.) in the case of the NOAA spacecraft does not provide a large margin to absorb the added costs associated with an OMV servicing mission. However, in the case of the Landsat and DMSP satellites, a significantly greater margin ($49.5 mil. and $19.45 mil. respectively) is available to cover these other mission costs.

As the number of missions per year increases, a marked drop in the average cost per OMV servicing mission is observed. Table 7.3 shows the cost savings margin for the case where three OMV servicing missions per year (maintained through a 10 year period) is assumed.

The deployment of a long term SBSP (20 years or more), while increasing program costs initially, could result in significant long term net cost savings per mission by expanding the range of feasible mission options, and thereby generating a larger customer base. The cost of the SBSP could then be amortized over the 20 year period minimizing the cost increase per servicing mission. Potential customers

TABLE 7.3

OMV SERVICING MISSION COST VERSUS SATELLITE REPLACEMENT COST COMPARISON (3 SERVICING MISSIONS PER YEAR)

PROGRAM	REPLACEMENT COST	AVERAGE SERVICING COST	SAVINGS MARGIN
DMSP	$ 80 MIL.	$ 45.2 MIL.	$ 34.8 MIL.
NOAA	$ 64 MIL.	$ 45.2 MIL.	$ 18.8 MIL.
LANDSAT	$110 MIL	$ 45.2 MIL.	$ 64.8 MIL.

would then have the flexibility to utilize small, low cost boosters such as Pegasus or Scout to deliver servicing payloads. By increasing the number of servicing missions per year, the average costs of the OMV servicer, bipropellant, SBSP, and ground support would be reduced by spreading the cost over a greater number of users. Additionally, the use of a SBSP would provide the capability to economically service/repair larger and more expensive satellites which would not be possible if the OMV servicer is required to transit to low altitude for refueling prior to each mission or where multiple ELV resupply missions at higher altitudes would be needed.

VIII. CONCLUSION

Satellite servicing is a technologically evolving activity which has not yet attained the final stages of development. The on-orbit servicing operations thus far have depended entirely upon manned flights, severely limiting the number of potentially serviceable spacecraft to those in orbits accessible by the space shuttle. Remote servicing operations using robots will soon be developed to support construction of the long-term space station Freedom. International developments are also proceeding at a rapid pace, with the Federal Republic of Germany, Canada, and Japan playing key roles in the remote servicing technology area. Dependence on manned operations has allowed great flexibility in the servicing tasks attempted owing to the dexterity and ingenuity of humans, however, it has restricted the number of programs which can use this capability to those within the orbital performance envelope of the space shuttle. Additionally, the manned servicing operations require the use of expensive man-rated systems and extensive safety precautions to perform servicing tasks.

Spacecraft on-orbit servicing must consider such factors as: systems architecture; level of modularity of spacecraft and payload; degree of reliability; frequency of servicing needed during the lifetime of the spacecraft; level of commonality of systems or systems internal and external to the satellite. Inherent design decisions which are required to make satellite remote on-orbit servicing compatible with the OMV servicer will be more costly. NASA directed studies have shown that an estimated 8 percent per unit cost increase can be expected, with the spacecraft weight increasing between 5 to 10 percent resulting from modular design construction. [Ref. 22: p. 35]

Additionally, implementation of this concept depends on the achievement of a standardized spacecraft configuration to allow for removal and replacement of all ORUs and resupply of consumables, using telerobotic subsystems.

Historical evidence has shown that many LEO spacecraft performing important missions such as weather data collection, radar imaging and other scientific research have experienced serious mission degradation and in some cases total mission loss due to the failure of an on-board subsystem component prior to the designed satellite lifetime. These failures have often resulted in the loss of vital data and revenue to the user, in addition to the cost of spacecraft replacement. In the past, for most satellites, maintainability has been associated with the timely application of telemetry reconfiguration and use of redundant satellite subsystems as necessary over the life cycle of the spacecraft [Ref. 12: p. 1]. Spacecraft whose mission performance could be enhanced or expanded by on-orbit maneuvers (i.e., weather reconnaissance and earth resource satellites) are constrained by the reduced spacecraft lifetime resulting from such maneuvers.

Advances in the areas of microelectronic processors, robotic systems, and artificial intelligence have opened the way for the addition of on-orbit satellite support services, which are not limited to astronaut EVA repair operations. The servicer configured orbital maneuvering vehicle has the potential to greatly expand the scope of servicing operations to orbital inclinations and altitudes far beyond the reach of the current space shuttle. Modification of the OMV fluid systems (bipropellant and monopropellant) to enable bidirectional propellant and pressurant transfer requires only plumbing and valve additions. A simple, direct fluid transfer system utilizing the existing RGDM equipped with automatic fluid couplings and engagement devices uses existing hardware. Modifications for OMV conversion to solar power, long life protection and the addition of the servicer front end kit boost the cost of the OMV servicer to $305.5 million. The space infrastructure required to support OMV servicing operations currently exists (i.e., TDRSS). Ground control of the FTS, operating in a supervised autonomous mode, is compatible with the OMV S-band communication and data relay rates and the TDRSS link time delay. Operating in this mode, ORU exchange task instructions are programmed into the FTS onboard computer and executed automatically with intervention from the ground control site as a backup/override option.

Two OMV servicing options have been discussed. The first option, which was the primary case examined in the study, utilizes an OMV equipped with a servicer front end kit, operating at a base altitude between 300 NM to 400 NM. The OMV servicer in this case is located in a sun-synchronous orbit (inclination 98 to 99 degrees) and performs servicing/repair missions on the DMSP, NOAA and Landsat series spacecraft. The study assumes the spacecraft are compatible for OMV servicing operations for the purposes comparing spacecraft replacement costs with OMV servicing estimated costs. In this comparison, OMV servicing costs compared favorably with satellite replacement costs. Assuming that an individual Delta II or Atlas J1 (at $35 mil. per launch) was required for each servicing mission, and that the OMV servicer would be used for a single servicing mission per year (over the projected 10 year vehicle lifetime), estimated cost savings of $3.5, $19.45 and $49.5 million would result when compared to the single satellite replacement cost (i.e., satellite construction and launch expense) for the NOAA, DMSP, and Landsat spacecraft respectively. These cost saving estimates do not include the added costs of OMV bipropellant, satellite fuel, ground support or any ORUs that might be required for a particular mission. Subsequently, the cost saving margin would have to be reduced by the combined cost resulting from these factors; however, in the case of the DMSP and Landsat programs still should provide a significant savings margin over spacecraft replacement. Application of an OMV servicing concept to future platforms such as the large and expensive Earth Observing System (EOS) would result in even larger cost savings margins when compared to platform replacement at the planned five year interval.

In addition, as the satellite user community increases, a concentrated effort to standardize interfaces, subsystems and ORUs for spacecraft bus systems and payloads would permit expansion of OMV services to a larger number of satellites and thus further reduce the cost per servicing mission. The main disadvantages associated with the OMV servicer in considering this first option is the requirement to provide a large amount of OMV bipropellant using a large and relatively expensive booster prior to each servicing mission. Further, without the capability to detach the large servicer front end to a stable platform, the OMV cannot be used economically for other missions such as debris collection and satellite servicing missions at higher altitudes and/or other orbital inclinations.

A second OMV servicing option involves the deployment of a modular SBSP to provide a thermally controlled storage facility for OMV servicer needs such as fuel, replenishment consumables (e.g., cryogenics) and ORUs. The SBSP includes the required subsystems such as electrical power and distribution, thermal control, data processing, communication, guidance and attitude control that are present in other spacecraft. Using this option, the concept takes advantage of large and cost efficient (on a per pound to orbit basis) boosters such as the Titan IV to provide bulk quantities of OMV bipropellant, satellite fluid consumables and other servicing mission needs. Under the assumptions of this scenario, the servicing concept can use low cost boosters, such as Pegasus and Scout, to launch required ORUs or other servicing payloads. The launch is coordinated to minimize OMV transit distance and propellant consumption. The use of a SBSP would significantly expand the OMV servicer operational envelope, thus providing a greater range of servicing mission options available. Additionally, the OMV front end servicing kit could be detached when not actually required, allowing the OMV to pursue other missions such as debris collection or satellite inspection much more economically. The primary disadvantage of a SBSP deployment is the additional cost that would be added for a given servicing mission. This would be partially offset by the reduced OMV propellant consumption for a given mission and the fact that a dedicated OMV servicer bipropellant resupply mission would not be required prior to each servicing mission. The added cost per mission of a SBSP servicing concept could be initially reduced through government subsidy, encouraging the development of an on-orbit OMV servicer capability, with commercial services expansion as a primary goal. Ultimately, the wide range of servicing and other mission options available would attract an increasing number of users and reduce the cost per mission.

The potential to extend satellite service life and reduce overall life-cycle cost are strong reasons to pursue the on-orbit OMV servicer support concept, particularly in the case where large and expensive spacecraft constellations are located. Additionally, implementation of the concept permits the incorporation of on-orbit preplanned product improvement (P^3I) upgrades, preventive maintenance actions, recalibration, reboost and spacecraft inspection [Ref. 2: p. 1]. The OMV servicer also provides the flexibility for rapid ground response to on-orbit emergency situations which could minimize the loss of vital data from spacecraft and permit resumption of services with minimal program disruption. Unmanned servicing operations using the servicer configured OMV and expendable launch vehicle combination offers one effective approach to perform satellite servicing and other missions beyond the reach of the space shuttle.

APPENDIX

LIST OF ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
Ag-Zn	Silver Zinc
BOL	Beginning of Life
DARPA	Defense Advanced Research Projects Agency
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DOF	Degrees of Freedom
ELV	Expendable Launch Vehicle
EOL	End-of-Life
EOS	Earth Observing System
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ETR	Eastern Test Range
EVA	Extra Vehicular Activity
FT	Feet
FTS	Flight Telerobotic Servicer
Ga-As	Gallium Arsenide
GCC	Ground Control Console
GEO	Geosynchronous Earth Orbit
GN & C	Guidance, Navigation and Control
GPS	Global Positioning System
HR	Hour
IMU	Inertial Measurement Unit
IOC	Initial Operating Capability
IRS	Indian Remote Sensing Satellite
Kbps	Kilobits per second
KSC	Kennedy Space Center
KW	Kilowatt
LB	Pound
LEO	Low Earth Orbit
MMS	Multi-mission Modular Spacecraft
MOS	Marine Observation Satellite
N_2	Nitrogen
N_2H_4	Hydrazine

NASA	National Aeronautics and Space Administration
Ni-Cd	Nickel Cadmium
$Ni\text{-}H_2$	Nickel Hydrogen
NM	Nautical Mile
NOAA	National Oceanic and Atmospheric Administration
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replacement Unit
OSC	Orbital Science Corporation
OTV	Orbital Transfer Vehicle
P^3I	Preplanned Product Improvement
PLF	Payload Launch Fairing
PM	Propulsion Module
RCS	Reaction Control System
RGDM	Remote Grapple Docking Mechanism
RMS	Remote Manipulator System
SBSP	Space Based Support Platform
SRV	Short Range Vehicle
STS	Space Transportation System
TDRSS	Tracking and Data Relay Satellite System
TIROS	Television Infra-red Observation Satellite
TM	Thermatic Mapper
TPDM	Three Point Docking Mechanism
USAF	United States Air Force
UST	Universal Servicing Tool
W	Watts
WTR	Western Test Range

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