Benefits of a Reusable Upper Stage Orbital Maneuvering Vehicle

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This article describes 1) the Orbital Maneuvering Vehicle (OMV) and 2) the benefits of that system over alternative methods of delivering payloads into low-Earth orbits. Alternative methods considered were using Space Shuttle Orbital Manuevering Systems (OMS) kits, Orbiter direct insertion and integral propulsion systems. The heart of the OMV system is a remotely controlled, free-flying propulsive, upper-stage vehicle designed to provide a maneuvering capability for various spacecraft for a variety of missions. The benefit of using the OMV over either OMS kits or Orbiter direct insertion is the same as for any multiple-staging, increased performance. Performance can be improved in terms of more payload to orbit, higher orbital altitude, increased plane change capability or a combination of these. When compared with integral propulsion, the resuable OMV has a similar overall cost for placing payloads into orbit. The higher cost for launching the OMV is roughly balanced by the savings from the multiple use. However, it is significantly less costly to use the OMV than integral propulsion when the OMV is left on orbit between missions. In addition, the OMV provides increased flexibility for retrieval and servicing of satellites, found not provided with integral propulsion systems.

Introduction

THE Space Transportation System (STS) Space Shuttle provides a low-cost alternative method for satellite delivery as well as new opportunities for satellite retrieval and servicing. The cost reduction occurs because the Shuttle is reused numerous times instead of being discarded each time as in the case of an expendable launch vehicle. To extend this capability, the Orbital Maneuvering Vehicle (OMV) has been proposed.

The Orbital Maneuvering Vehicle is a reusable space system designed to enhance the capability of the Space Transportation System and to provide telepresence and support for satellites in low-Earth orbit.It is an outgrowth of the Teleoperator Retrieval System (TRS), a program initially designed to save Skylab by boosting it to a higher orbit. The TRS program was cancelled when solar activity higher than expected caused the Skylab to re-enter the Earth's atmosphere before the Space Shuttle was ready. The OMV system consists of a vehicle, associated ground and airborne support equipment, and a control station.

The development of the OMV system began with the establishment of an OMV demand mission model. The model is a subset of the STS Mission Model[1] containing only potential OMV satellite support missions. Types of OMV missions identified were: subsatellite operations, satellite delivery, buildup, inspection, retrieval, servicing, orbit adjustment and debris collection. The diversity of the spacecraft support provided by the OMV is illustrated in Fig. 1. Using the mission model, requirements for the Orbital Maneuvering Vehicle were established. Alternative methods of satisfying those requirements were developed and evaluated through trade studies. The results of those studies then defined the OMV.

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OMV Vehicle

The primarily element of the Orbital Maneuvering Vehicle System is the OMV spacecraft in the center of Fig. 1. It is mainly a propulsion system having other hardware required to support the missions. A major consideration in the design is the need to make the OMV as short and light as practical, thereby reducing OMV launch costs.[2] As a result the OMV is a disk-shaped, lightweight structure approximately 1m long and with a diameter barely fitting inside the Orbiter payload bay. It weighs about 40 kN (9 klbs) fully loaded, with approximately 2/3 of the weight due to the propellant. An important issue in the OMV design is the determination of the propellant. Vehicles have been proposed based on monopropellant, bipropellant, and cryogenic propellant propulsion systems. The primary advantages of the biprop system are performance and propellant availability (Orbiter RCS excess). The advantages of the monoprop system are propellant handling, contamination, simplicity, and system cost. Although major consideration is currently focused on bipropellant versions, the OMV spacecraft shown in Fig. 1 and used in this analysis is based on the Mark II monopropellant propulsion system and other existing flight-qualified hardware.[3] The study conclusions are valid for either propellant type; however, some of the costs change slightly for a biprop system.

The Mark II propulsion system, an element of the Multi-Mission Modular Spacecraft, is a four-tank hydrazine, 5-to-1 blowdown system with a total impulse of 5.4 MNs (1.2 Mlb·s).[4] It has four 445-N (100-lb) orbit adjust engines and twelve 22-N (5-lb) Reaction Control System (RCS) thrusters. Twelve additional RCS thrusters have been added to the OMV, providing full translational and rotational motion with backup.

The OMV attaches directly to the sides and the keel of the Orbiter in the payload bay. It carries a television camera and a radar for rendezvous and docking. The communication link uses the Tracking and Data Relay Satellite System (TDRSS). An inertial reference unit with horizon scanners and a sun sensor for reference updates is used for attitude knowledge and pointing control. Thermal control is based on a cold-biased, passive system consisting of paints, radiative panels, multilayer insulation, and heaters. Electrical power is provided by a combination of primary and secondary batteries, with a solar array for long-term orbit storage of the

OMV. The subsystems are sized such that the OMV can provide transportation and suport to an attached satellite servicer. The OMV itself is designed to be serviceable on orbit.

The OMV Mission Model identified payload delivery, servicing and retrieval to altitudes up to about 1100 km (600 NM). The payload delivery capability for this OMV is shown in Fig. 2. This performance incorporates a 5% fuel penalty for RCS and a penalty for return to the Orbiter via a 185 km (100 NM) phasing orbit. Each of the potential OMV missions in the STS Mission Model can be satisfied with 50% of the Mark II capability.

OMV vs OMS

Although there are presently no plans for building the Shuttle Orbital Maneuvering Systems (OMS) ΔV kits, it is informative to compare those kits against the OMV as a delivery or retrieval alternative. The OMV is about one half as long and weighs about half as much as a single OMS kit. Thus, the OMV launch cost is less than the launch cost of the OMS kit.[2]

OMV performance vs the OMS kits is shown in Fig. 3. This figure gives the performance capability for the OMV and the Shuttle for launches from Vandenberg AFB. This capability is based on the Shuttle design goal performance for a sun-synchronous orbit (98° inclination).[5] The OMV curves assume the Orbiter delivers the OMV and the payload into a 278 km (150 NM) circular orbit. The curves represent limits in performance capability. The curve with no plane change is for the case where the OMV is delivered directly into the plane of the delivery. The other curve shows the performance of the OMV with a two-degree plane change and return to the Orbiter. This amount of plane change covers the inclination variation in the normal sun-synchronous orbits. Other curves show performance for the Shuttle, the Shuttle with a single OMS kit, and the Shuttle with two OMS kits.

Payloads with weights and desired altitudes which lie in the region bound by the Shuttle limit curves can be satisfied by the Shuttle with OMS kits. The region of capability for the OMV outside the OMS kits represents additional payload requirements which could be satisfied. The performance improvement is a result of using a 4 Mg (9 klb) upper stage OMV instead of a 90 Mg (200 klb) Orbiter to deliver satellites. This improvement in payload capability also increases the possibility of multiple payload manifesting. Payloads can then share the ride and launch costs, resulting in a cost decrease for each payload and a potential revenue increase for NASA.

Using the OMV instead of the Orbiter integral OMS engines reduces the frequency of OMS engine refurbishment. This results in an additional cost saving to the STS.

OMV vs Direct Insertion

Direct insertion with the Shuttle is another method for achieving higher orbits for payloads. In this method, the Orbiter reaches altitudes above the nominal through the process of altering the ascent trajectory. The main engines are run longer, raising the Orbiter to a higher altitude orbit which eliminates the need for the first of the two integral OMS engine burns. To do this, the emergency return-to-launch-site profile and external-tank impact location are changed. This results in an approximately 185 km (100 NM) increase in altitude capability. Shuttle delivery capability from the Kennedy Space Center, Eastern Launch Site (ELS), using direct insertion is shown in Fig. 4, along with the performance of the OMV. Payloads falling in the area between the OMV and Shuttle performance curves can be delivered only by the OMV. It is obvious from this figure that the OMV can deliver payloads under various conditions which cannot be satisfied by the Shuttle using direct insertion.

Even in the region where direct insertion can accommodate the payload requirements, the OMV still offers advantages over direct insertion. Using the OMV, the Shuttle has the opportunity to provide service to multiple payloads, reducing the cost to the individual payloads. The additional performance of the OMV over direct insertion can also be used for orbit maneuvering, i.e., making plane changes. The Orbiters capability to make a plane change is limited to less than two deg. The OMV is capable of making a plane change of almost eight deg, delivering a small payload and making the same eight-deg plane change to return to the Orbiter.

Direct insertion also requires considerable planning and analysis to develop trajectories and timelines other than "nominal." This effort adds to STS costs, and, more importantly, deviates from NASA's goal of achieving "routine"

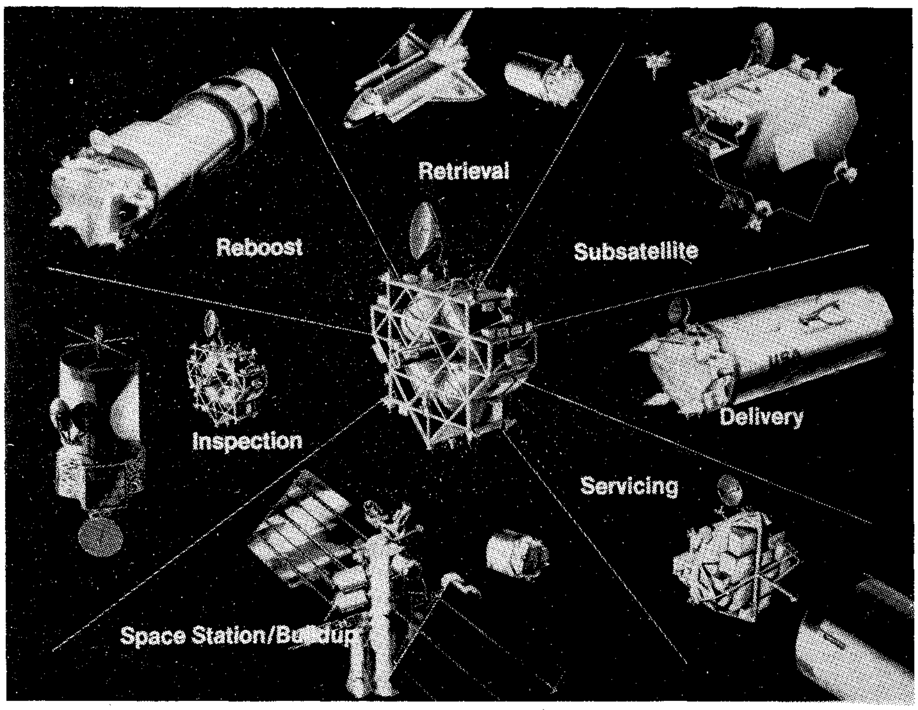

Fig. 1 OMV operational missions.

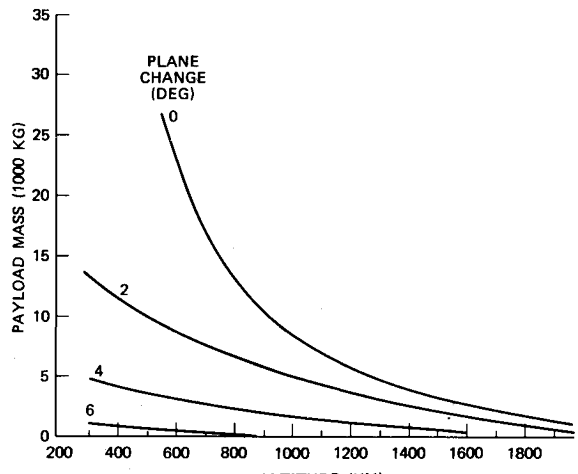

Fig. 2 OMV satellite delivery capability.

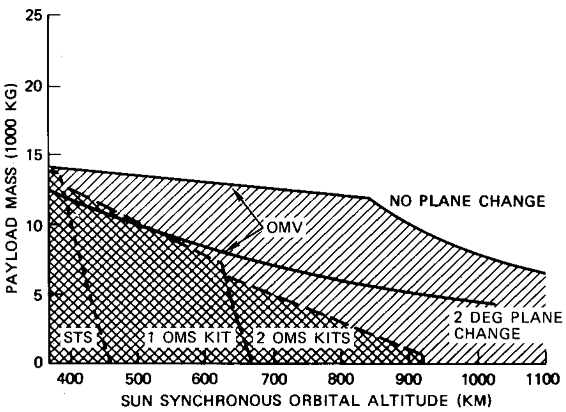

Fig. 3 Shuttle performance enhancement at Western Launch Site.

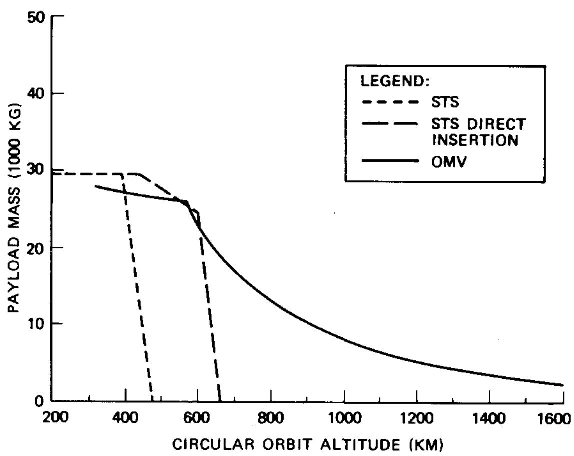

Fig. 4 Shuttle performance enhancement at Eastern Launch Site.

Shuttle operations. Using the OMV, the Orbiter will rarely need to go to a nonstandard orbit.

OMV vs Integral Propulsion

It is obvious that the current and projected future performance capability of the Space Shuttle cannot satisfy the delivery requirements for all foreseeable payloads. This causes the payloads to require some additional means for achieving their final destinations. A capability is also needed for retrieval and servicing of satellites at altitudes beyond the Shuttle's limited capability.

This comparison considers two methods for achieving higher altitude orbits. Both use the STS Shuttle for reaching low-Earth orbit. Once delivered to this orbit, the payload would then move to a higher orbit, boosted either by an OMV or by an integral propulsion system (IPS). The IPS is a permanent part of the spacecraft. In contrast, the OMV is attached to the satellite only during delivery, retrieval or other orbital maneuvering.

The main advantage of an IPS over an OMV is that the integral propulsion system is continually available to the satellite. Thus it could be used for unscheduled evasive maneuvers, or drag makeup. Payloads with this requirement will need an integral propulsion system. However, those which do not require this capability, may be designed to use the OMV or an IPS. There are several reasons for choosing the OMV.

The OMV is more flexible than an IPS. It has the capacity to accommodate unforeseen changes, even after the payload has reached its operational altitude. For example, if it becomes necessary to retrieve a satellite, the OMV could rendezvous and dock with the satellite and return it to the Orbiter or a space station. To allow for this and other contingencies, an integral propulsion system would have to be oversized. The OMV can also be used for inspection or remote on-orbit servicing. That compares favorably with using an IPS to return the satellite to the Orbiter and then reboosting the satellite after inspection or servicing. The OMV can also be used for space structure assembly and subsatellite operations.

Another advantage of using the OMV over the integral propulsion system is that after the OMV maneuvers with a satellite, it and the satellite separate. Thus, the OMV does not contribute to the attitude control problem of the satellite. This detachment significantly reduces the major contributor to the fuel slosh problem because the amount of attitude control propellant is substantially less than the amount required for orbit modification maneuvers. The separation also decreases the possibility of satellite contamination by the propellant.

In an economic comparison, the cost can be broken into two parts: the cost of the Shuttle ride to low-Earth orbit and the cost of the transfer from that orbit to a higher one where the payload operates. The Shuttle ride cost is based on Shuttle launch costs and the part of the Shuttle capability used, either payload bay volume (vehicle length) or weight to orbit.[2] The cost of the second part of the delivery is the cost of purchasing a ride on the OMV, or alternatively the cost of an IPS. The cost of incorporating an IPS can be further broken into three distinct parts: nonrecurring cost, integration cost, and recurring cost.

The nonrecurring cost is the design, development, test, and evaluation (DDT&E) cost. This could be as little as zero in the rare case when an existing off-the-shelf propulsion system satisfies the requirements. The other extreme is one where the propulsion system requires a totally new design. For a new IPS of the size required for the OMV Mission Model delivery type mission, that cost can be as high as $25M. Even though several components, tanks, valves, engines, etc. may be off-the-shelf items, the propulsion system still must be designed and qualified as a whole. This includes thermal, vacuum, vibration, and system performance testing.

The cost of integrating the propulsion system into the spacecraft is highly variable, difficult to establish, and quite dependent on the degree of integration. Propulsion system integration varies from the case where the spacecraft is designed and built around the propulsion system, with the structure actually incorporating the tanks, to the case where the propulsion system is simply strapped on the rest of the payload. Integration of the IPS into the satellite impacts the following subsystems: structure, thermal, power, control, telemetry, and command. If the spacecraft requires a propulsion system for attitude control, then an increase in the size of that system may have a small effect on the integration

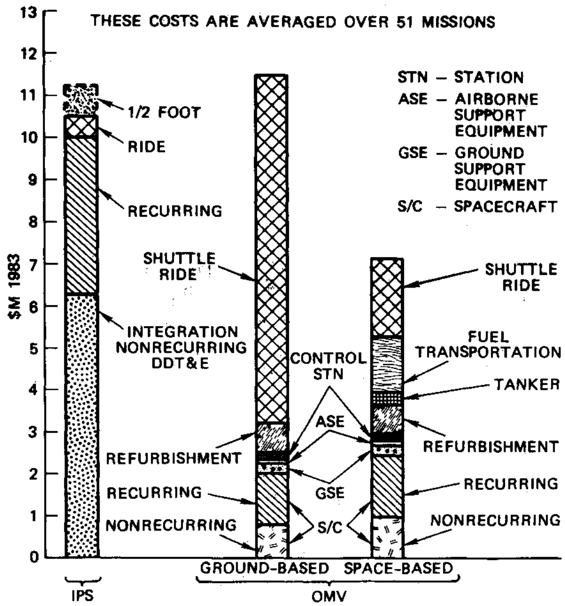

Fig. 5 Payload delivery cost comparison.

cost. The average nonrecurring and integration cost for payloads in the OMV Mission Model is estimated to be about $6M (see Fig. 5).

The recurring cost is based primarily on the size (weight) of the propulsion system. There is a slight reduction in that cost if several propulsion systems are purchased together for multiple satellites. The average IPS recurring cost for satellites in the OMV Mission Model is estimated to be almost $4M.

The total cost for the IPS is the sum of the nonrecurring, recurring, and integration costs. It averages around $10M per payload for the satellites in the OMV Mission Model.

The cost of this Orbital Maneuvering Vehicle is estimated to be $150M for two spacecraft (one at each launch site), including refurbishment, ground support equipment (GSE), airborne support equipment (ASE), and a ground control station. When this cost is shared among the 51 payloads in the OMV Mission Model, the average OMV cost per payload is about $3M. Thus the difference between using the OMV and purchasing an IPS is about $7M per payload in favor of the OMV.

The IPS launch cost is based on how much weight or length the propulsion system adds to the payload.[2] Determining how much the inclusion of an IPS would change the payload length requires detailed designs for each payload. Theoretically, the propulsion system could be integrated into the satellite without increasing the payload length. However, for spacecraft achieving minimum length, any volume increase to incorporate the propulsion system will cause some increase in the overall length. For this conservative analysis, no increase in payload length due to IPS was assumed. The additional weight to the payload by the IPS is primarily the weight of the fuel. There is also a small additional weight increase due to the weight of the tanks, additional structure, and the engines.

When the OMV is ground based (launched each time with a payload), the STS launch cost for the OMV is dependent on the weight or length of the OMV/payload combination. For the average payload in the OMV Mission Model, the cost for the Shuttle ride for a ground-based OMV is more than $8M greater than the cost for the ride for the required IPS.

Adding the Shuttle ride and transfer costs, the average cost of delivering a payload using a ground-based Orbital Maneuvering Vehicle is similar to the cost for using an integral propulsion system as shown in Fig. 5. The difference of only $1M lies within the uncertainty of the rough order of magnitude costs in this analysis. If the integration of a propulsion system adds 15 cm (6 in.), about the length of a small thruster, to the payload length, then the payload delivery costs using an OMV and an IPS are approximately equal.

Basing the OMV on orbit greatly reduces the OMV launch costs, although there is an additional cost for an in-bay tanker. The average savings on a payload delivery for space basing the OMV is above $4M. Therefore, the average payload delivery cost using an orbit-based OMV is about $3M less than the cost for using the IPS.

Costs in this analysis are average costs for the OMV Mission Model. They are representative only of the model as a whole. Each payload must consider each alternative and select the method which best suits its requirements.

Conclusions

The Orbital Maneuvering Vehicle is an attractive method for delivering payloads to orbits above the Orbiter standard orbit.

The OMV is much more flexible than the alternative methods of payload delivery. It provides a capability for payload retrieval and servicing as well as space structure assembly, inspection, reboost, and subsatellite operations, both planned and on a contingency basis.

The cost of using the Orbital Maneuvering Vehicle to deliver payloads is similar to using integral propulsion if the OMV is ground based. However, if the OMV is left on orbit and resupplied, the cost of using the OMV is significantly less than the cost of using integral propulsion.

Acknowledgment

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