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Extending Rideshare: Mission Case Studies Using Propulsive ESPA

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ABSTRACT

Rideshare launches have become more available and frequent, but secondary payloads typically must accept a limited set of initial orbits based on constraints imposed by primary payloads. Subsequent operational orbits are then achieved through spacecraft maneuvers that can require substantial propulsion systems. A potential alternate architecture aggregates propulsion and delta-V in a propulsive rideshare adapter, for example an adapter based on an ESPA ring The LCROSS mission demonstrated the use of a propulsive ESPA to expand and enhance an existing lunar mission by utilizing the mass margin of the launch vehicles. Other propulsive ESPA architectures can provide Earth orbit flexibility and optimization. This paper summarizes multiple case studies that demonstrate the utility, value and flexibility of an Orbital Maneuvering Vehicle (OMV) as a mission enabling technology that augments standard launch services. Cases examined include:

- The deployment of multiple electro-optical/imaging CubeSats and Smallsats into a low altitude LEO constellation through exploitation of a secondary launch opportunity;
- A scenario to ferry a small spacecraft to Earth-Sun L1 and then operate as a hosted payload platform;
- A scenario to utilize NASA Commercial Resupply Missions (CRS) for CubeSat and smallsat deployment

Each of the scenarios demonstrates that a propulsive rideshare adapter can enable missions that are not currently considered due to the limiting nature of the current rideshare market.

INTRODUCTION

The increase in small satellite capability enables both science and commercial missions that were previously too complex for such a small form factor. However, launch vehicle options have not kept up with the decreasing size and budgets of these spacecraft. Multiple small launchers designed specifically to deliver small satellites are in development, with some tailored to launch a single small satellite. But this launch capacity has not yet arrived and economic viability is still to be proven. Meanwhile the number of small satellites requiring space access continues to increase and rideshare launches and hosted payload opportunities have gained popularity as a cost-effective way to reach orbit. In fact, the trend has increased so rapidly that secondary launches have boomed from under 40 secondary spacecraft launched in 2012 to over 110 in 2014[1].

The challenge for this growing number of secondary payloads, however, is twofold: (1) dependency on larger mission to release launch vehicle capacity for wider use, with (2) launch profiles that allow orbital injection of secondaries without undue added risk to the primary mission, be it real or perceived. To add flexibility while still utilizing the rideshare opportunities and excess capacity of both commercial and government launches, Moog has evaluated multiple mission scenarios that would benefit from adding a propulsive capability to the already common EELV Secondary Payload Adapter (ESPA) ring. Although this concept is not new to the secondary launch arena, Moog is taking advantage of many in-house components and capabilities, such as the ESPA ring, propulsion systems, and avionics to design an OMV that is tuned to each secondary launch or longer duration ESPA-based mission. Modularity is the key to reducing complexity and minimizing cost.

This capability is particularly relevant for small science missions that cannot accept compromise to orbital parameters in order to gain an inexpensive launch. The same is true for missions with destinations outside of earth orbit, looking to capitalize excess capacity. Alternative deployment options, such as using the Commercial Resupply (CRS) missions to the ISS have also been evaluated when a mid-inclination orbit is required. The OMV baseline configuration and multiple mission scenarios will be described in this paper to fully demonstrate the varied utility of this vehicle.

ORBITAL MANEUVERING VEHICLE

The OMV is part of a larger family of Moog spacecraft concepts that are based around the EELV Secondary Payload Adapter (ESPA) ring. This family ranges from secondary adapters, to individual spacecraft, to "tugs" that are used to transfer other spacecraft, and the capability to act as hosted payload platforms, as shown in Figure 1.

The OMV design has a flexible configuration that is tailored to each individual mission. The vehicle can act as an enabling technology to drop off individual spacecraft in specific orbits over a short period of time, or it can act as the core hub of a mission with all of the capabilities required for a longer duration mission.

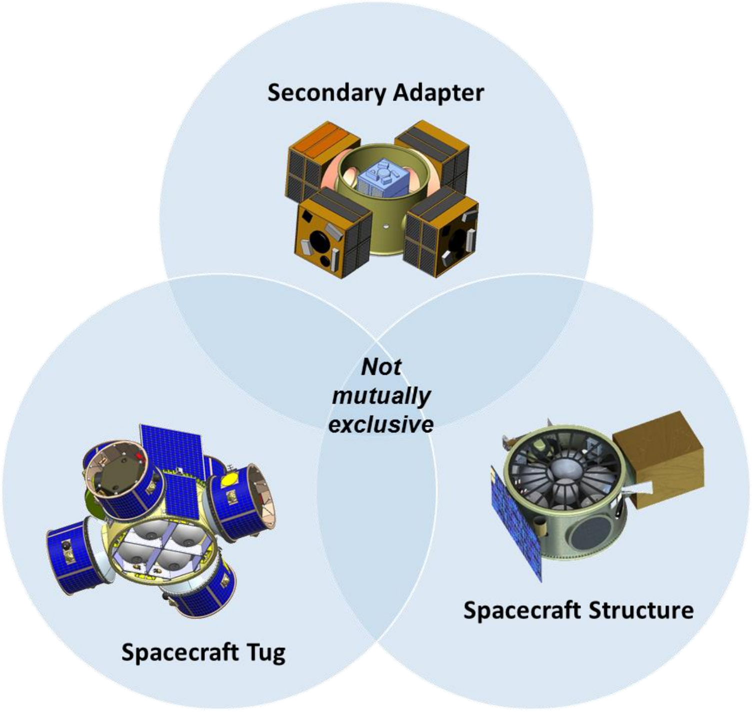

Figure 1: OMV Family of Capabilities

EELV Secondary Payload Adapter (ESPA) Form Factor and Heritage

The OMV typically utilizes the ESPA ring as the primary vehicle structure but alternative adapter design concepts have been evaluated for missions looking to utilize capacity on launches using vehicles other than EELVs. Using a standard structure that has on-orbit heritage and the ability to fly on multiple different launch vehicles opens up a large number of launch opportunities for OMV missions.

OMV Subsystems

The OMV presented in this paper is unique in that there is a high level of vertical integration enabled by Moog's breadth of in-house space technologies. A majority of the subsystem components, including avionics, propulsion and structures are built in-house and enable a rapid system optimization for each mission solution. A breakdown of the OMV components is shown in Figure 2.

Baseline Components

The OMV avionics are based on the Moog Broad Reach Integrated Avionics Unit (IAU). The modular nature of the IAU combines functionality for multiple subsystems into a single chassis. For the OMV, the following functionality has been evaluated for inclusion in a single IAU:

- Command and Data Handling boards
- Electrical Power System boards

- Valve Drive Control board
- Payload Interfacing board (if required)

The communication system for the OMV must be tailored to each mission. The factors used to evaluate the subsystem hardware include mission lifetime (eg. 1 week to 7+ years), orbital parameters (eg. LEO, GEO, L1, Lunar Orbit, etc.), data rate (spacecraft telemetry and, if required, payload data) and reliability (class of mission and overall risk posture).

The battery and solar array size of the OMV is mission specific and both fixed and deployed arrays have been evaluated and are compatible with a stowed launch configuration that is no larger than the volume of the ESPA ring.

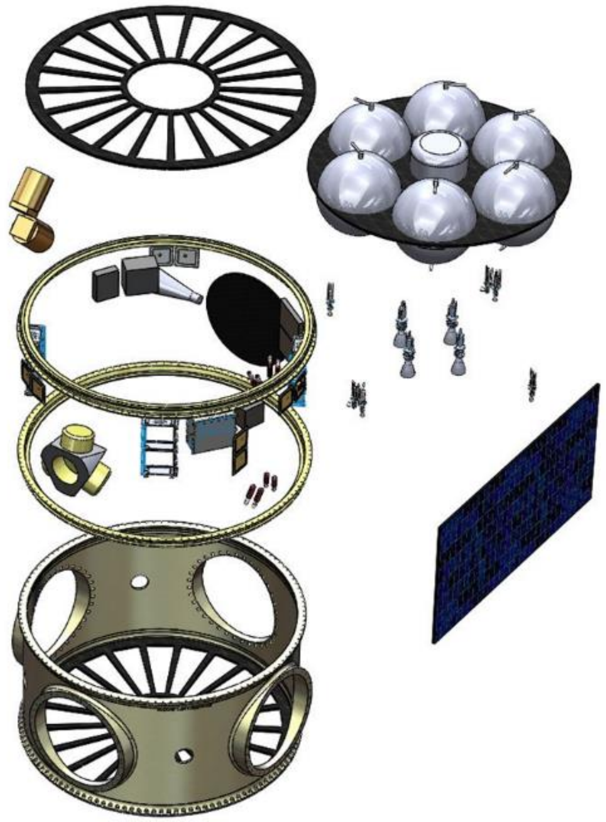

Figure 2: OMV Subsystems Components

The most variation in OMV components can be found in the GNC subsystem. For some short duration missions, an OMV may only require sun sensors and reaction control system (RCS) thrusters to control the vehicle and drop off individual spacecraft over a short period of time. However, longer duration missions may require the OMV to utilize a full suite of GNC components including a star tracker(s), reaction wheels, IMUs, sun sensors and a GPS receiver unit. The capabilities for GPS location ranging from LEO to GEO provides planning and mission operation advantages to even short duration missions.

The OMV thermal management system will also be customized depending on the mission goals. An initial evaluation was completed for a typical long duration mission. Due to the propulsion system temperature requirements, a non-load bearing structure of in-house design (see Figure 5) was added to the top and bottom of the cylindrical ring structure to provide MLI tie down points. Additional closure panels may also be used to cover the ports if in-depth thermal analysis shows it is necessary.

Propulsion Subsystem Configurations

The OMV has been proposed for multiple mission scenarios and advanced design work has been completed for both monopropellant and bipropellant configurations including assessing new “green propellant” options. This OMV propulsion capability builds on early system design (see Figure 3) and the experience built by Moog delivering spacecraft propulsion systems such as those flying on the European Galileo program. The current OMV family provides a range of flexible options enabling several different missions with relatively modular propulsion system solutions.

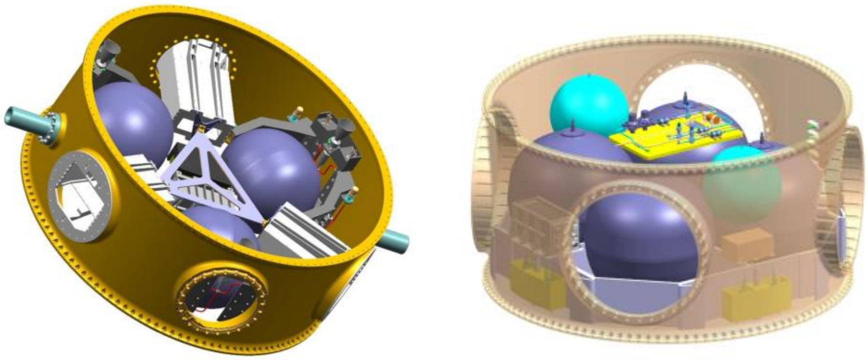

Figure 3: Early Propulsive ESPA Designs (ESPA SUM Free Flyer, left, ESPA Smart Carrier, right)

Monopropellant Options

The entry performance propulsion system option is based on a Hydrazine monopropellant system in blowdown mode (reference Figure 4). The selected propellant tanks utilize an elastomeric diaphragm to separate the pressurant from the liquid propellant. The baseline design includes six spherical propellant tanks and can be converted to four cylindrical tanks to increase propellant capacity or to a PMD type tanks for greater fill fractions. The overall height of the ESPA is easily variable to accommodate this tank growth.

Several 1 N or 5 N engines are used to provide Reaction Control System (RCS) maneuverability for stationkeeping and momentum management. Commonly, six such thrusters are baselined but alternative configurations have been employed to meet custom missions. All thruster options include identical valves so there are no mechanical or electrical configuration differences. A set of higher thrust engines are used to provide primary delta-V. Three different thrust classes can be used with minimal modification to the OMV. The baseline is four 116 N engines but the value can be modified based on mission requirements (see Figure 5). The power system is sized based on this "worse case" configuration to meet high power valve actuations in particular.

Higher performance can be achieved with the addition of a Pressurization System to increase the overall system performance and increase the maximum propellant capacity relative to a blowdown system. A common pressurization system is used across the different configurations with the ability to utilize several pressurant tank options.

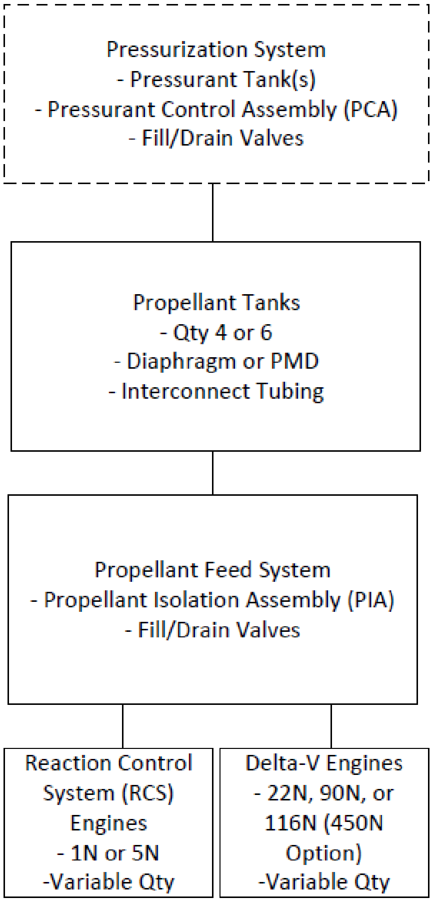

Figure 4: OMV Propulsion System Block Diagram

Green Monopropellant Option

The same configuration and most of the options for the Hydrazine system can be employed to allow the use of a Green Monopropellant. Green Monopropellants are intended to replace traditional Hydrazine with a reduced toxicity propellant to minimize both propellant loading costs and environmental impacts. Green Monopropellants offer higher performance and density than Hydrazine increasing the relative "Density-Isp" meaning more capability in the same size system or the possibility to maintain the same capability in a smaller system. Here Hydrazine is

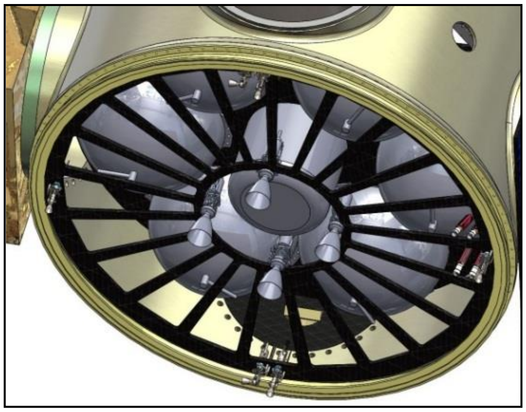

Figure 5: Baseline OMV Propulsion Configuration

replaced with High Performance Green Propellant (HPGP) called LMP-103S manufactured by ECAPS[*]. Moog is able to employ HPGP with minimal modifications from typical Hydrazine systems. Alternate thrust chamber and nozzle assemblies are required but all other propulsion elements selected for the Hydrazine design are compatible with LMP-103S and have been flight proven on the PRISMA mission. Moog provided many of the components for PRISMA in addition to providing thruster valves to ECAPS. Moog worked closely with ECAPS on this program including providing the conventional Hydrazine propulsion system that was also part of the mission experiment.

ECAPS provides a wide-range of thrust classes analogous to the Hydrazine thrusters including the same RCS engine thrust range and similar Impulse Bit (I-Bit) performance so Guidance, Navigation, and Control (GNC) software can remain virtually the same. The one exception is the four 116 N engines would be replaced by two 220 N engines requiring a minor modification to the mechanical support and GNC software and hardware configuration. Depending on the required thruster authority these same engines could be orificed to match the thrust level of the baseline Hydrazine thrusters so there is no software change between propellant configurations. HPGP provides a higher engine specific impulse and the propellant is a greater density than Hydrazine yielding a Density-Isp approximately 30% greater than the baseline. This effectively creates a more capable propulsion system in the same form factor as Hydrazine with the same component masses and nearly identical power requirements. This has the benefit of trading different mission options with effectively no change in the propulsion system or OMV other than propellant mass.

Bipropellant Option

The OMV propulsion system is flexible enough to be used in a bipropellant manner to increase the overall specific impulse and propellant density. An initial trade between Monomethylhydrazine (MMH) and Nitrogen Tetroxide (NTO) bipropellant versus a Hydrazine and NTO “dual mode” system showed advantages for a dual mode system for specific mission applications especially with a modular systems approach. The six tank configuration could be maintained the same with two being filled with NTO and four with Hydrazine. The exact same RCS engines and layout would be used so the GNC and Power systems for the OMV can remain the same between monopropellant and dual mode (in addition to thermal, communication, and other subsystems not varying between propellant types). One of the advantages to a dual mode system is the ability to use Hydrazine RCS thrusters. The Delta-V engines would operate in the higher efficiency bipropellant mode where the majority of the propellant is consumed.

The Pressurization System would remain nearly identical and the Propellant Feed System is basically duplicated for the second propellant. Swapping between monopropellant and bipropellant does not cause large system level impacts limiting non-recurring engineering costs between system designs. The Delta-V engines can be comprised of several 22 N platinum/rhodium (Pt/Rh) engines that provide 310 seconds or more specific impulse with almost no change to structural configuration relative to the monopropellant system. It is possible for a 450 N single apogee-class engine to be used but that does require different packaging and a taller ESPA. This increases the specific impulse to 324 seconds or more. Between the higher specific impulse and greater propellant density the density-impulse is 55% to 62% greater than Hydrazine (depending on thruster configuration). Once again this

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[*] ECAPS is a Swedish company focused on green propulsion based products and is part of the larger Swedish Space Corporation (SSC).

creates a more capable propulsion system in nearly the same form factor as the baseline Hydrazine. Using the same RCS engines and similar power requirements the remainder of the OMV remains virtually unchanged.

Another option leverages Moog design concepts for launch vehicle upper stage applications. Here the overall diameter for a launch vehicle upper stage application is reduced to match the standard ESPA inner diameter (see Figure 6). This configuration would be different than the modular propulsion system "building blocks" in the OMV family design but have minimal impact on the rest of the OMV as it is the same dual mode system with the same RCS thrusters and similar power system requirements. There could be design synergies within upper stage and OMV propulsion system once again reducing the non-recurring engineering costs of the finalized design.

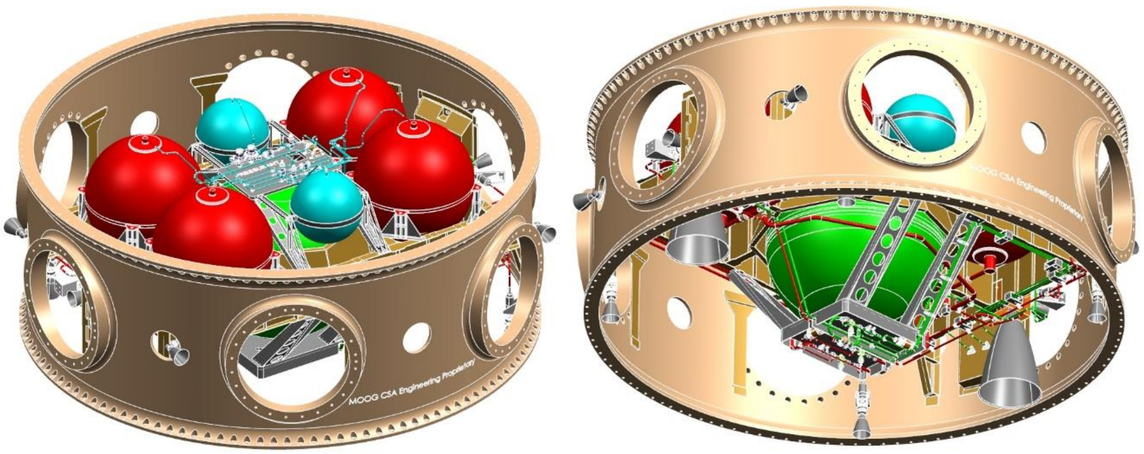

Figure 6: Common Upper Stage/OMV Propulsion System Design

Drop Tank Option

The OMV design can also be utilized in a "drop tank" configuration. Here two OMV units are launched in a stacked configuration but the lower OMV is basically the propulsion system components only (see Figure 7). The power and avionics are all from the upper OMV. The propulsion system between the two is identical so the Integrated Avionics Unit (IAU) controls the lower OMV drop tank through an umbilical. Upon depletion of the drop tank propellant, the stage separates, and the upper OMV continues with the mission. The propulsion building block design means different combinations of propellant types can be mixed and matched with the drop stage to allow for Delta-V optimization within mass constraints. This "Nth Stage" application increases mission options and flexibility.

Figure 7: OMV Drop Tank Concept

Range of OMV Capabilities

To summarize the typical performance of an OMV, a graph is shown below in **Figure 8**. This graph allows mission designers to perform an early evaluation of the typical capability for a specific payload mass and propulsion system, but does not take into account the many nuances of the OMV subsystems including the flexibility of the ESPA itself. For instance, a standard 300 kg is used for the spacecraft mass in this example, based on the use of a 24 inch ESPA mounting port. Other port sizes and configurations are available including 15 inch mounting ports or custom pad mounts. The overall height and load carrying capability of the ESPA are easily variable based on spacecraft and mission requirements.

There are numerous options available to optimize the performance for a specific mission and Moog suggests that a mission designer identify the option of using an OMV early in the system trades to allow all of the configuration options to be identified and traded based on cost, complexity and performance parameters. Moog Advanced Missions and Science staff in Golden, Colorado work at this stage of a mission to allow for mission designers to quickly find optimal solutions and develop mission proposals.

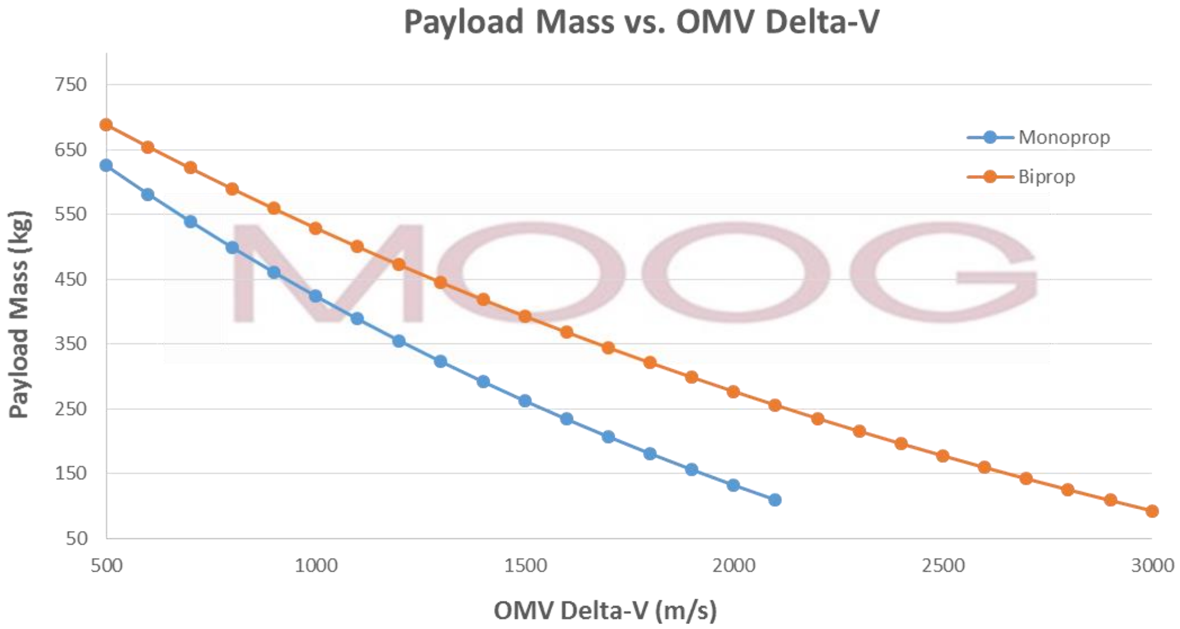

Figure 8: Typical OMV Performance Curve

Subsystem Flexibility

As mentioned above and within the individual descriptions of the OMV subsystems, all areas are evaluated based on the mission requirements and goals. Capability can be expanded by:

- Increased solar array area using deployable panels
- Increased payload carrying capability by utilizing a taller ESPA ring, multiple ESPA rings, or designing custom port adapters to facilitate mounting more than one spacecraft per port
- Increased propulsion capability via larger propellant tanks and/or use of a bipropellant system
- Additional IAU to reduce the hardware costs between the platform and payload interface units

Conversely, for a system that is only using the OMV for a short duration, it could be most cost-effective to control the OMV via a spacecraft that will eventually deploy. This would require use of the avionics and communication system of the spacecraft. Trades between complexity and cost savings would be critical in this scenario.

OMV MISSION SCENARIOS

For this paper, three distinct OMV concept of operations (CONOPS) were examined to show as example missions which can be enabled through this technology.

LEO CubeSat and Smallsat Deployment from a Secondary Launch Opportunity

The popularity and capability of CubeSats and microsats has far exceeded the ability of launch vehicles to place them in a desired orbit for a reasonable cost. The OMV can help to create a balance between using the excess capacity on existing launch vehicles and placing microsats into an optimal operational orbit.

This first OMV scenario outlines the least complex of the scenarios described in this paper. The intention is to demonstrate that a basic OMV could provide a number of large propulsive maneuvers to optimize the placement of microsats and

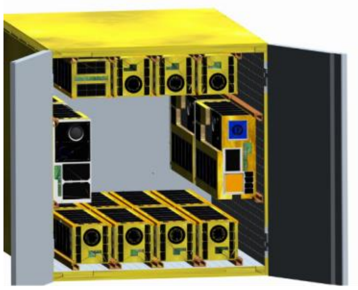

Figure 9: FANTM-RiDE Adapter
Image Credit: TriSept Corporation

utilize the excess capacity on a pre-existing launch. The example mission is summarized in Table 1, which outlines the payloads as:

- Two FANTM-RiDE Adapters to deploy 16 CubeSats each
- Two 50 kg microsats

The starting orbit is assumed to be 750 km and the subsequent deployment altitudes are 600 km and 450 km for the microsats and Cubesats, respectively.

With multiple CubeSat constellations in the design phase, and others already launched, such as PlanetLabs, this capability allows a small sat constellation to reach the optimal orbit and start generating data (and hence revenue) almost immediately after launch.

Table 1: Scenario 1 OMV Mass Summary

OMV Mass Summary		
Subsystem	**Mass**	
Spacecraft Bus	366	kg
Payload – CubeSats	360	kg
Payload – Microsats	100	kg
Sub-Total	826	kg
Hydrazine Propellant	306	kg
Total	1132	kg

To summarize the example case, the following delta-V table shows the required OMV maneuvers.

Table 2: Delta-V Summary

Deployments & Maneuvers	OMV Delta-V	OMV Fuel Required
Decrease altitude to 600 x 600 km	79.9 m/s	34.7 kg
Complete 180 deg phase change	150 m/s	58.8 kg
Drop altitude to 450 x 450 km and Deploy 8 CubeSats	82.6 m/s	29.0 kg
Complete 90 deg phase change and Deploy 8 CubeSats	43.7 m/s	14.4 kg
Complete 90 deg phase change and Deploy 8 CubeSats	43.7 m/s	13.5 kg
Complete 90 deg phase change and Deploy 8 CubeSats	43.7 m/s	12.7 kg
TOTAL	**443.6 m/s**	**163.1 kg**

As a comparison, on-board CubeSat propulsion options are limited at this time and often require a large percent of the mass and volume to accommodate existing systems[2]. However, the OMV can simplify the implementation of requirements by using a single system to place multiple satellites.

Hosted Payload Platform and Ferry to Earth/Sun L1

Many recent missions have brought to our attention the usefulness of the Earth-Sun Lagrange points for science and space weather missions. These orbits offer consistent viewing of the sun and/or stars for long durations without the temperature gradients associated with eclipses. Most recently, in February of 2015, the DSCOVR mission launched and will eventually reside in an orbit around the L1 point[3]. The James Webb Space Telescope (JWST) will also launch to a Lagrange point orbit at L2[4]. And previous missions, some of which are still operational today, include SOHO and ACE.

Although many of the large, high priority science missions have bought their own launch vehicle in order to minimize the propulsion requirements of the spacecraft, reaching a Lagrange point orbit is feasible from an initial launch into a Geo Transfer Orbit (GTO). Due to the large number of commercial GEO spacecraft launched each year (upwards of 25 spacecraft), there are many opportunities for secondary payloads to take advantage of in the future[5]. Using an OMV to launch into GTO for transfer to a Lagrange point orbit has several benefits:

- The vehicle can be launched below a primary spacecraft destined for GTO without any changes to the primary's launch vehicle interface.
- Utilizing an ESPA ring as the primary vehicle structure of a Lagrange point mission allows additional secondary payloads to be launched on one or more ESPA ports and deployed in GTO with minimal upgrades to the OMV, such as a deployment sequencer electronics box.
- An OMV can provide the propulsive capability required for transfer from GTO to a Lagrange point orbit and act as the spacecraft bus upon arrival at the chosen Lagrange point orbit.

To understand the delta-V requirements for an OMV mission to the Earth/Sun L1 point, the SOHO mission orbit insertion was used as an example case[6]. Table 3 shows the resulting maneuvers and total propellant required.

Table 3: Delta-V Summary

Deployments & Maneuvers	OMV Delta-V	OMV Fuel Required	Duration after Launch
Perigee Raising Maneuver 1	250	91.75 kg	1-2 weeks
Perigee Raising Maneuver 2	250	82.3 kg	
L1 Transfer Orbit Injection Maneuver	250	73.9 kg	
Trajectory Correction Maneuver	10	2.8 kg	as required
L1 Halo Orbit Insertion	50	13.8 kg	3 months
Station keeping (15m/s per year)	75	20.1 kg	5 years
TOTAL	**885 m/s**	**284.6 kg**	
Margin	**8.5% on delta-V (Total capability = 987 m/s)**		

The overall mission mass budget is shown in Table 4 and includes the additional GNC components required for this scenario, including redundant star trackers, IMUs and wheels assuming an operational class of mission

Extrapolating this scenario further, an OMV-based science mission could also use a drop-off in GTO as a stepping stone for interplanetary missions.

Table 4: Scenario 2 OMV Mass Summary

OMV Mass Summary		
Subsystem	**Mass**	
Spacecraft Bus	405	kg
Payload	180	kg
Sub-Total	585	kg
Hydrazine Propellant	306	kg
Total	891	kg

Utilizing NASA Commercial Resupply Missions (CRS) for Smallsat Constellation Deployment

With a growing number of earth observation missions taking advantage of smaller satellites, the opportunity to use the excess capacity of the CRS missions is a feasible launch option for a mission requiring a mid-inclination orbit. Additionally, the OMV can place the spacecraft in orbits of slightly different inclination, rather than waiting for the satellites to precess using differential drag and/or orbital maneuvers with an individual satellite's propulsion system.

The precedence for launching from the upper stage of a SpaceX Dragon CRS launch comes from multiple missions. First, the ORBCOMM[†] Generation 2 (OG2) prototype spacecraft was launched in 2012. and then in February 2014 the NASA ELANA program launched 5 CubeSats as auxiliary payloads on the SpaceX-3 Cargo Resupply (CRS) mission to the ISS[7,8].

[†] The OG2 constellation is built by ORBCOMM Inc.

An OMV with minimal power and GNC capabilities will suffice for this mission due to the small number of maneuvers over a short period of time. The mass summary for this configuration is shown in Table 5 based on the propellant estimates shown below and utilization of four 51L propellant tanks.

The initial working CONOPS for this OMV scenario requires inclination and altitude changes to minimize the maneuvers required by the individual spacecraft:

- Launch the OMV and 8 microsats attached to the upper stage of the launch vehicle (not the Dragon Capsule).
- After the Dragon capsule is released from the upper stage of the rocket, the OMV will be released into the 300 x 300 km parking orbit.
- The OMV will complete a 2 degree inclination change to move away from the ISS orbit (51.6 degree inclination).
- The OMV will perform a second maneuver to increase the altitude to the desired 650 x 650 km orbit.
- The microsats will be released periodically – 2 per orbit with a difference of 0.1 degrees of inclination between each orbit.

Table 5: Scenario 3 OMV Mass Summary

OMV Mass Summary		
Subsystem	**Mass**	
Spacecraft Bus	354	kg
Payload	136.8	kg
Sub-Total	490.8	kg
Hydrazine Propellant	204	kg
Total	694.8	kg

Table 6: Delta-V Summary

Deployments & Maneuvers	**OMV Delta-V**	**OMV Fuel Required**
2 degree inclination change in 300 x 300 km orbit	269.7 m/s	76.8 kg
Altitude Change to 650 x 650 km	194.8 m/s	50.1 kg
3 x Inclination Change Burns to move 0.1 degrees	42 m/s	10.3 kg
De-orbit Burn to 300 x 300 km	194.8 m/s	44.2 kg
TOTAL	**696.5 m/s**	**181.3 kg**
Margin	**13% on delta-V (Total capability = 800 m/s)**	

CONCLUSIONS

The need for rideshare launch opportunities is growing, and Moog sees within that growth a class of missions and constellations that require a more precise, timely or unique orbital placement than a passive secondary adapter can provide. Utilizing an OMV can enable these missions to launch as a rideshare and realize cost savings over the purchase of an entire launch vehicle without sacrificing orbital-dependent mission requirements such as lifetime, instrument resolution, or ground station coverage.

Considerations for the use of an OMV must include evaluation of the delta-V requirements, deployment timeline, excess launch capacity available, OMV lifetime, and, most importantly, the additional cost of an OMV compared to the value of optimal orbital placement. These trades will be a key factor in the launch and deployment of future distributed small satellite systems which are being traded against conventional architectures based around a few large spacecraft. A propulsive adapter, such as the OMV, can be the enabling factor that allows small satellites to step outside the constraints of conventional LV and satellite architectures in the future.

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