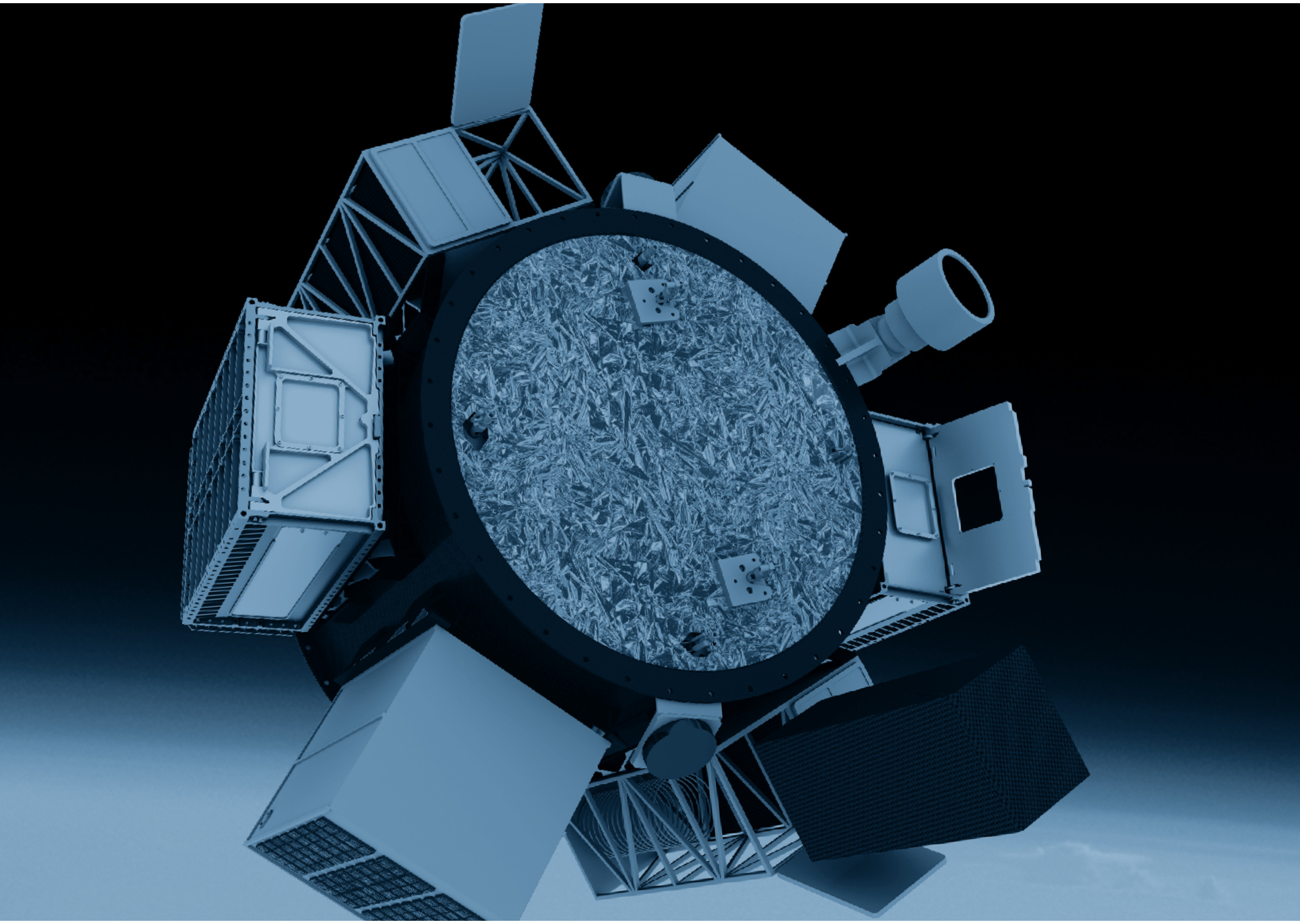

SPACE VEHICLES USER GUIDE

ORBITAL MANEUVERING VEHICLE
TUGS AND PLATFORMS

MOOG

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"Moog's OMV is one of the top game changers of this decade"
- David J. Buck, Lieutenant General, USAF (Ret.)

INTRODUCTION

This document is designed to provide information on the Family of Space Vehicles including the Orbital Maneuvering Vehicle (OMV) that Moog has to offer. This document will outline the differences between each Space Vehicle and showcase example missions to highlight the Space Vehicle functionality.

MOOG INTRODUCTION

Moog is a proven leader in components, subsystems, and systems for spacecraft of all sizes, from smallsats to GEO spacecraft. Moog has been successfully providing spacecraft controls, inspace propulsion, and major subsystems for science, military, and commercial operations for more than 60 years.

SPACE VEHICLES GENERAL INTRODUCTION

Moog's Space Vehicles family leverages Moog's extensive experience in spacecraft avionics, flight software, propulsion, and structures to address many challenging mission types. Example programs include AFRL's ANGELS and EAGLE programs (Avionics and Software), EAGLE and NASA's LCROSS (ESPA structure), and the Galileo Position System (Propulsion). Other key programs such as OneWeb share the same supplied subsystem components that make up the Space Vehicles family. Space Vehicle platforms can be tailored for different mission requirements including the level of integration with the end customer's payload/mission.

OMV FAMILY

The OMV family can be divided into two primary categories, **Tugs** and **Platforms**.

Tugs are vehicles which are intended primarily to deploy payload satellites into a specific target orbits. A typical tug mission involves a tug delivering 1 or more satellites into a first orbit, then completing phasing or altitude change maneuvers to deliver additional satellites to different orbits.

Platforms are meant to operate primarily as a generic bus to host a payload. There is overlap, however, in that tug platforms can host payloads internally in addition to delivering separate payloads into orbit and thereby function as both a platform and a tug for different payloads.

Commonality is maintained between product lines wherever possible, and in most cases the subsystems of the various tugs and platforms have many years of flight heritage behind them and are not novel in and of themselves even as they are packaged in novel configurations. These novel configurations offer flexibility to tackle challenging missions of nearly any flight profile or mission type.

Pro Tip: Use a tug to deploy a payload satellite into orbit.

Use a platform when you have a payload subsystem designed and built but cannot design an entire satellite to go around it. The use of platform enables the outsourcing of the satellite design, in effect.

TUGS

Tug vehicles provide power, thermal control and propulsion capabilities to payloads as it carries them into specific orbits. A typical tug mission targets multiple orbits for different payloads using on-board high-thrust chemical propulsion and is complete in days or weeks. Special 'loiter' variants of tug vehicles can extend deployment times to months or years after launch using non-propulsive attitude control and long-lasting, dual-redundant avionics and power systems.

These **loiter** variants are especially useful in scenarios which require constellation replenishment, with new vehicles delivered rapidly into new orbital slots within days of being called up, versus waiting months for a new launch.

Table 1 below contains high level specifications for the OMV line of vehicles. This line supports payloads from CubeSat size up to 5000+ kg, with power and data throughputs to scale.

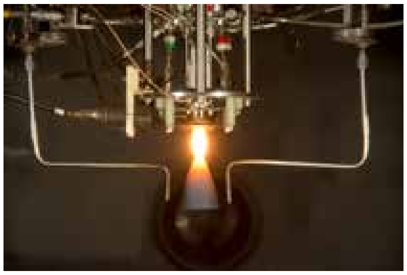
Pro Tip: For missions or deployment sequences over a year in length, consider a loiter variant of the OMV family. The primary mission-time constraint for OMV's is usually propellant from propulsive attitude control and not radiation or reliability. Tug variants use propulsion-only attitude control so all control requires propellant. Platforms all use Reaction Wheels so no limitations there.

TABLE 1

Vehicle	Wet Mass	Payload	Propulsion	Can Host Payload
SL-OMV	92 kg	125 kg, Up to 8x 6U CubeSats and/or top mounted payload	6x 1N ACS / ΔV thrusters; green monopropellant	Yes
COMET	800 kg	1,500 kg	4x 22N ΔV thrusters; 6x 5N ACS thrusters; hydrazine	Yes
ASTRO	1,400 kg	500 kg to GEO or GTO	Dual-mode hydrazine / NTO	Yes

OMV FAMILY

A major advantage of the use of an OMV is that it allows for custom orbit targeting from rideshare launches. Rideshare launches have the problem for payload developers in that they generally go to the target orbit of the primary payload, and all secondary payloads have to live with that. The use of an OMV means that a secondary payload can target an orbit independent from the primary payload using the same launch vehicle. There are limits to this, however – while large altitude changes can be easily accomplished by an OMV, major inclination changes (greater than a -degree) are typically not available due to the tremendous (kilometers per second) change in delta-v required to alter inclination.

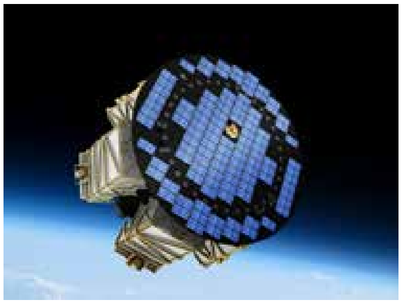


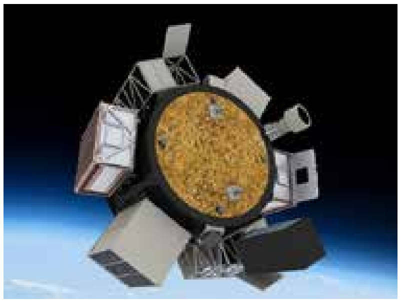
PROPULSION HOT FIRE TEST

SL-OMV

The small launch orbital maneuvering vehicle (SL-OMV) is optimized for use with small launch vehicles such as Virgin Orbit's LauncherOne. The SL-OMV family comes in several flavors, each intended for specific mission profiles or orbital regimes, though they generally retain compatibility with all the small launch vehicles such as Rocket Lab's Electron or Virgin Orbit's LauncherOne.

A typical mission for a SL-OMV vehicle is a rapid inter-orbit phasing of a batch of constellation 6U payloads. Normal deployment sequences last about a week in time, though as previously mentioned, 'Loiter' variants of the SL-OMV platform can extend this sequence over several months or even years in order to replenish depleted constellations or to reach new orbital targets of opportunity.





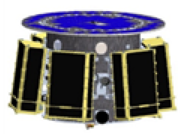
SL-OMV

All SL-OMV vehicles are intended to occupy a single standard ESPA port and can support clusters of cannisterized payloads (such as CubeSats), top-mounted microsatellite payloads that separate via motorized lightbands, hosted payloads, or some combination of the above. Table 2 contains a listing of the SL-OMV family members and their specifications. As shown, the SL-OMV family support a range of orbits from LEO all the way out to cis-lunar space, and they can be configured with **green chemical propellant** or highly efficient (but low-thrust) electric propulsion.

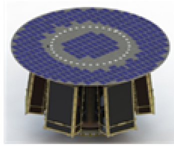
While small launch vehicles are a prime user of the SL-OMV, it is just as compatible with Falcon 9 and other larger launch vehicles. The SL-OMV is well suited to deployment of several CubeSats to different orbits from a single ESPA port on a Vulcan flight as it is on an Electron.

Pro Tip: Green Chemical Propellants allow for standard launch site processing without any specialized facilities or costly SCAPE suits. LMP-103S has similar performance to Hydrazine without the additional hazards.

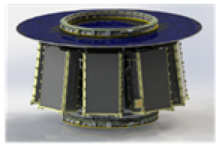
OMV FAMILY



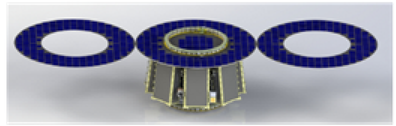
Mk I - 6x6U



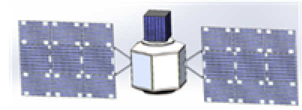
Mk I - 8x6U



Mk I DUAL LAUNCH



Mk II



Mk IV

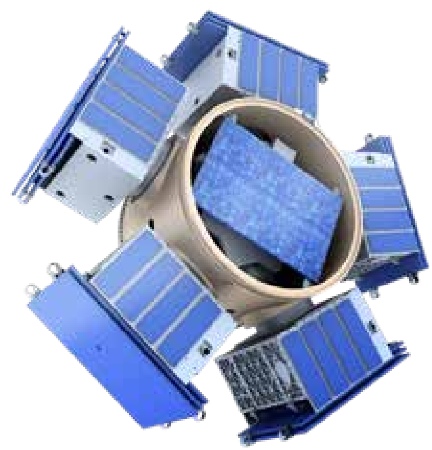
TABLE 2

	LEO		High LEO / MEO	GEO / Lunar
Parameter	**Mk I**	**Mk II**	**Mk III**	**Mk IV**
Mission Type	Small sat constellation deployment, dual or single launch	Enhanced Mk I for longer life, hosted payloads, on-orbit 'sentinel'	High energy upper stage for high LEO and MEO missions	High delta-V upper stage for GEO and Lunar missions
Life	< 1 year	3 - 5 years	< 1 year	1 - 3 years
Launch Mass	150 - 225 kg	150 - 300 kg	Varies; < 500 kg	Varies; < 500 kg
Payload	6x6U or 12x3U 8x6U / 12U option	8 locations on perimeter or one large payload on top	50 - 100 kg payload on top	Varies; 50 - 200 kg payload on top
Propulsion	Green monoprop	Electric propulsion	Green monoprop	Electric propulsion
Power	Fixed array	Deployable array	Deployable array	High density deployable arrays
Avionics	Single string	Single string	Single string	Single string

COMET

COMET is a similar vehicle to the SL-OMV and has fixed solar arrays and a larger propulsion system than the SL-OMV for phasing maneuvers, RAAN adjustments or even payload delivery beyond Earth orbit such as Lagrange points. Comet supports up to 1,500 kg of port-mounted payloads, with a typical format being ESPA ports. The COMET platform itself is roughly the size and shape of an ESPA Grande ring, with payloads mounted to the side. COMET is a good choice for missions which require significant post-launch maneuverability due to the larger propulsion system that it carries.

COMET is intended for missions under 1 year in duration, though as with SL-OMV, it can be upgraded to an HPP for missions lasting **3 to 5 years**. A typical COMET mission would deliver 1500 kg of payload to a sun-synchronous orbit above 700 km.



COMET

Pro Tip: Launching multiple vehicles with a single, long-lasting OMV allows them to be deployed 'on demand' without having to wait for the lead time of launching individual satellites on subsequent launches.

OMV FAMILY

ASTRO and ASTRO+

ASTRO and ASTRO+ are tug vehicles designed with high-impulse, deep-space deployments in mind. These vehicles are intended to travel to GTO, GEO or deep space with up to 829 kg of high-thrust **hypergolic propulsion**. The ASTRO+ variant can also be used to host payloads, in addition to deploying them. All Moog tugs and platforms use radiation tolerant avionics and this feature is especially useful for the kinds of deep space missions that ASTRO and ASTRO+ can empower.

Both ASTRO variants boast full 6 DoF control using reaction wheels, for non-propulsive attitude control. The body of the ASTRO vehicle is a 3-port ESPA ring that is 54" tall and 62" in diameter, while ASTRO Plus supports up to 6 payload ports on a 67" tall ESPA ring-style body.

Pro Tip: Hypergolic propulsion systems have decades of flight heritage and are reliable, restartable and ready to take your payload into deep space quickly. Hypergolic systems typically complete maneuvers in the span of minutes rather than the days or weeks of electric propulsion.

ASTRO+

ASTRO

PLATFORMS

Moog platforms are primarily intended to serve as generic buses for hosted platforms. While there is some overlap with the OMV line, these platforms are intended for missions which will be delivered to their orbits rather than as to serve as the means to reach an orbit. These bus platforms are highly configurable internally and can support payloads ranging radios to telescopes and everything in between.

These platforms build on decades of Moog component heritage, offering nearly unprecedented mission assurance for small satellites. These platforms can support payloads from 200 kg to 1500 kg in mass, in a variety of target orbits and with power needs up to 1 kW (orbit-averaged).

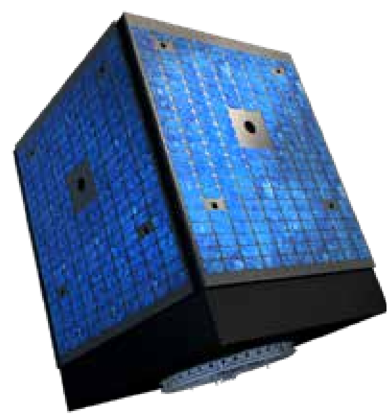
TABLE 3

	Vehicle Mass	Payload	Power	On-Orbit Life
ASTEROID	< 150 kg	200 kg	25-100 W OAP	1-3 years in LEO (< 625 km)
METEORITE	< 140 kg	200 kg	100-500 W OAP	5+ year in LEO; 3+ years in High LEO (1,000-1,200 km)
METEOR	< 1,000 kg	1,500 kg	1 kW OAP	3-5 years in LEO / GEO

ASTEROID

ASTEROID is a repackaged version of the SL-OMV line dedicated to hosting payloads rather than delivering them to separate orbits. The Pioneer Bus is suitable for ESPA Grande class missions. An ASTEROID is designed for telescopes up to Ø36” and 54” length.

ASTEROID is intended to service science missions and small constellations, and without the addition of propulsion are limited in altitude to comply with orbital debris requirements with a 25 year passive de-orbiting phase. Attitude control is non-propulsive, with reaction wheels and torque rods for use in LEO.



ASTEROID

PLATFORMS

METEORITE

METEORITE is a repackaging of the COMET into a dedicated hosted payload configuration. METEORITE offers additional payload power compared to ASTEROID (up to 500 W OAP), with an option for a tracking solar array, as well as accommodating larger payloads of the ESPA or ESPA Grande class. METEORITE has a non-propulsive attitude control system with torque rods and reaction wheels which enable long on-orbit life.

The use of the optional tracking solar array allows for a decoupling of the satellite's attitude from power generation. Often, the attitude of the satellite dictates the amount of power it can receive, which in turn dictates where the payload points as well as the power available to it. The use of a tracking array greatly reduces this conflict and allows for more agile and responsive payload use.

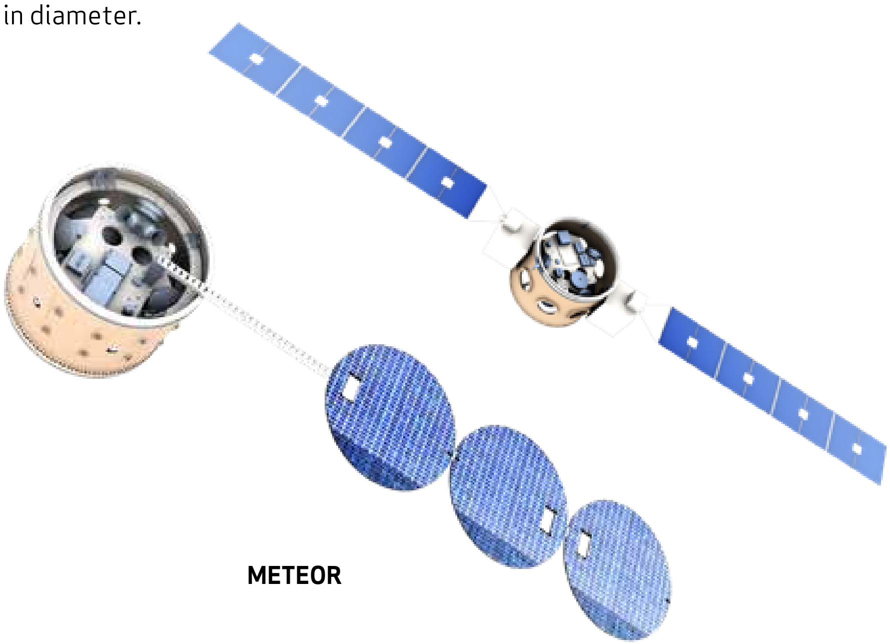
METEORITE

METEOR

The METEOR satellite bus is an enhanced variant of the COMET with a 3 to 5 year lifetime. This lifetime is inclusive of **GEO** orbits, which are typically a harsher environment than LEO. METEOR can optionally support high bandwidth communications in frequencies up to Ka-Band. METEOR also offers flexible payload mounting arrangements for deployed payloads, including 4, 5 and 6 circular ESPA ports, 4-point attachment fitting affixed to an ESPA port, or even top-mounted payloads on 4-point attachment fittings.

The platform supports up to 1500 kg of port-mounted payloads in total and is 42" tall and 62" in diameter.

Pro Tip: GEO and cis-Lunar orbits are above the Earth's Van Allen Belts and therefore experience more radiation than LEO orbits which are under the belts. GTO orbits actually transit the belts, which are radiation hazards themselves. For this reason, satellites typically only operate in GTO briefly as they rise to geostationary altitude, where they then perform maneuvers to circularize the orbit at GEO.



METEOR

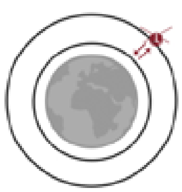
OMV DESIGN REFERENCE MISSIONS

Some key Design Reference Missions (DRMs) are presented in this section with a brief discussion on mission objectives, and the OMVs that can bring mission success. All the information in the coming sections comes from an auxiliary mission design and **OMV matchmaking excel program** that uses 1st order 2-body impulsive orbital approximations to complete the matchmaking process and to determine key mission requirements. The program allows for numerous custom inputs that can match the needs of the customer and the aforementioned mission.

Pro Tip: OMVs can support multiple mission types including several types within the same mission. Moog has developed a proprietary mission planning tool that can be used for preliminary sizing. Contact Moog for access to this tool or more complicated mission planning.

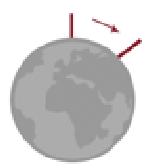
WHY OMV

The OMV is designed to launch on NSSL-class launch vehicles (Atlas V, Delta IV, Falcon 9) while supporting up to 1500 kg of secondary payloads with a variety of standard separation systems. The OMV can be used to disperse small satellite constellations, act as a Hosted Payload platform, or deliver a single spacecraft to it's ideal orbit. The OMV is a modular platform and has its own avionics, power, propusion, and communications systems that are configurable for short durations up through multiyear missions in a wide range of orbits and transfer capabilities.



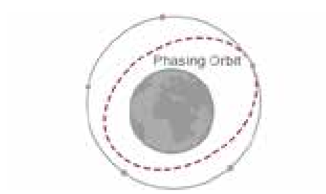
CHANGE ALTITUDE

Increase or Decrease Altitude multiple times if needed. Ideal for Commercial Rideshare Brokers and Multi-Mission Manifest offices.



CHANGE INCLINATION

Increase or Decrease Inclination several degrees either separately or in conjunction with altitude changes (e.g. SSO). Ideal for Commercial Rideshare Brokers and Multi-Mission Manifest offices.

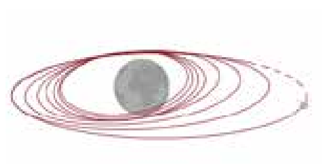


IN-PLANE PHASING

Rapidly deploy a constellation around an orbit (e.g. "String of Pearls") in a week or less. Ideal for constellations and limited propulsion capability payloads.

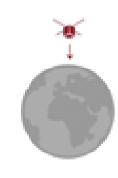
MULTI-PLANE DEPLOYMENT

Deploy an entire constellation on a single launch. Multiple OMVs are used to each deploy up to 3 individual planes. Ideal for constellations of CubeSats or Small Satellites.



LIQUID INSERTION STAGE

"Smart Upper Stage" or Tug that can be used to extend the range of a launch vehicle including GTO to GEO (or Beyond) transfer capabilities.



ON-ORBIT LOITER, HOSTED PAYLOAD

Remain on-orbit for an extended duration including immediate call up missions, technology demonstration missions (up to 1 year) when OMV completes its primary tug mission.

OMV DESIGN REFERENCE MISSIONS

DRM #1: SINGLE PLANE CONSTELLATION POPULATION

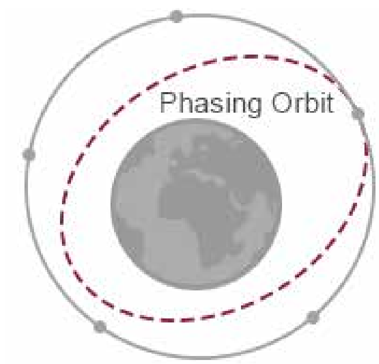
Populate a single plane constellation utilizing a single launch

- Conduct phasing and/or corrective maneuvers to delivery multiple spacecraft to the same orbital plane
- Common on orbit maneuvers expected for mission completion
  - Change orbital altitude and shape
  - Change orbital inclination
  - Phasing for satellite spacing on orbit

DRM #1.1: SINGLE PLANE CONSTELLATION OF 6U CUBESATS

Example mission parameters:

- Qty. 6x 6U CubeSats and associated dispensers (approx. 100 kg payload mass)
- Single plane target with payloads equally spaced in plane
  - Target plane is a 500 km near circular (0.02 eccentricity) orbit at 55 degrees
- Launch plane is a mid-inclination LEO launch
  - Launch plane is a 200 km near circular (0.02 eccentricity) orbit at 53 degrees



With mission parameters defined, it is determined to require approximately 428 m/s of ΔV to transfer from the launch plane to the target plane. The inclination change maneuver accounts for 60% of that required ΔV showing how fuel expensive inclination changes are. Once in the target plane more ΔV will be required to deliver the payloads to their respective spots on the orbit. This payload delivery and separation phase is highly customizable as there is a trade between time spent running the deployment sequence and ΔV required to do so. The relationship can be seen in *Figure 1* which simply shows the shorter the deployment sequence the more ΔV required.

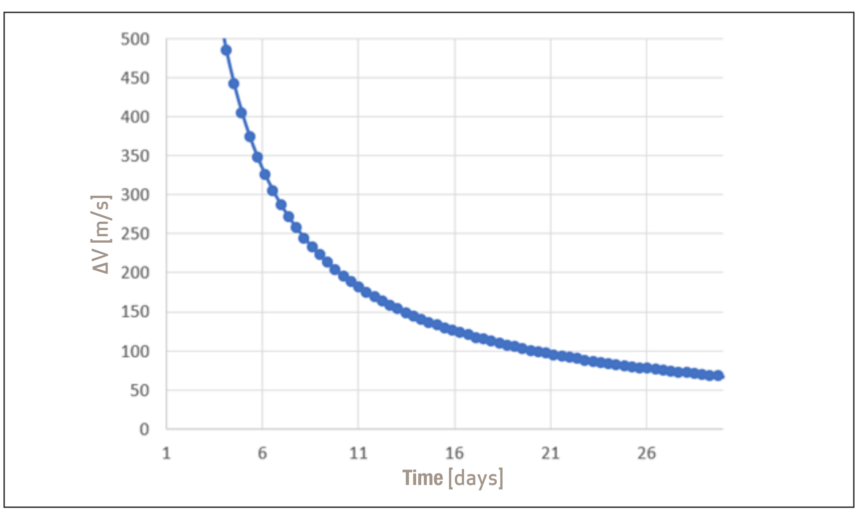


Figure 1

OMV DESIGN REFERENCE MISSIONS

Choosing a position around the 3-week mark requires approx. 96.2 m/s of additional ΔV making the mission total requirement 524 m/s. With the payload mass known, the required performance (ΔV) known, and the payload type, an OMV can be fit to these mission requirements. The table below shows the three OMVs that are most capable of accomplishing this mission. For these requirements the SL-OMV – Tug would likely work best.

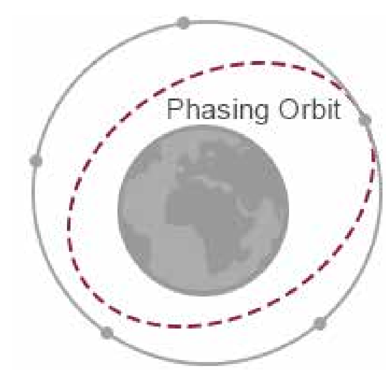
TABLE 4				
	Operating Orbits(s)	Payload Types(s)	Payload mass [kg]	delta V [m/s]
Mission Requirements	**L LEO**	**CubeSat**	**100**	**523.91**
SL-OMV - Tug	L LEO, H LEO	CubeSat, Other	123.1	476.31
SL-OMV - Hex	L LEO	CubeSat, Other	86.2	436.47
SL-OMV - Baseline	L LEO	CubeSat, Other	86.2	400.81

DRM #1.2: SINGLE PLANE CONSTELLATION OF ESPA CLASS SATELLITES

Example mission parameters:

- Qty. 5x ESPA class and associated dispensers (approx. 1300 kg payload mass)
- Single plane target with payloads equally spaced in plane
  - Target plane is a 500 km near circular (0.02 eccentricity) orbit at 53 degrees RAAN shifted from target plane by 20 degrees
- Launch plane is a mid-inclination LEO launch
  - Launch plane is a 200 km near circular (0.02 eccentricity) orbit at 53 degrees

Similar to the CubeSat mission requirements here the mission is in LEO and requires no inclination change, but rather a shifted RAAN angle from that of the launch orbit. RAAN changes can easily become complex and require a lot of ΔV to perform. However, if you utilize Earth's oblateness and time, the ΔV requirements can be greatly reduced. This process requires transferring the OMV to an intermittent orbit, and the shape of this orbit determines the required dwell time to rotate RAAN as well as the required ΔV to transfer to and from the orbit. *Figure 2* shows the relationship between intermittent orbit perigee altitude, eccentricity, and the required ΔV.



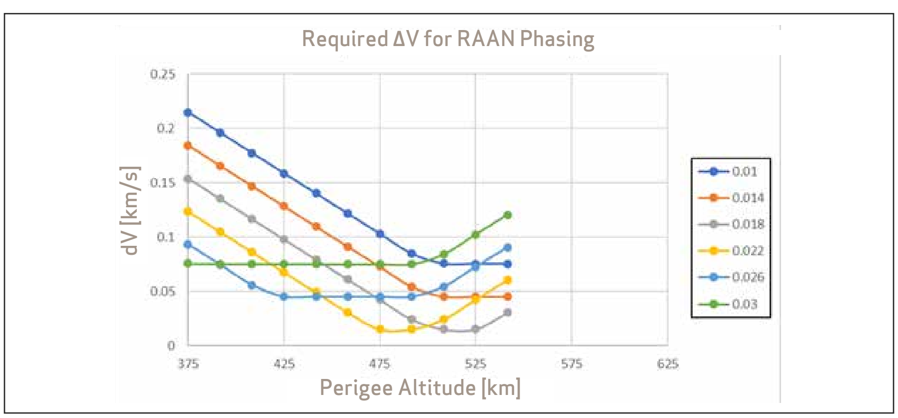


Figure 2

OMV DESIGN REFERENCE MISSIONS

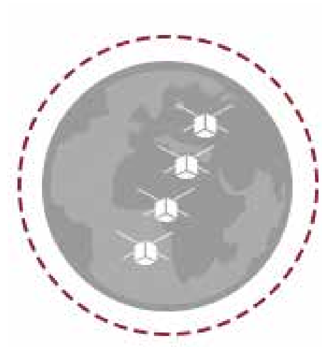
If the mission can accommodate a 1 month dwell time while waiting for RAAN alignment, then the mission will require 511 m/s of ΔV to reach the target orbit. Taking 3 weeks to conduct the payload separation in the target orbit bring the total mission ΔV requirement to 591 m/s. The ΔV can be further adjusted as necessary by balancing the payload phasing parameters as well as the J2 rotation parameters. It can be seen in Table 5 that the COMET OMV fits these mission requirements quite well and can even supply more ΔV than the mission requires with the current parameters. Thus, if desired the timeline could be accelerated as there is some ΔV to spare.

TABLE 5

	Operating Orbits(s)	Payload Types(s)	Payload mass [kg}	delta V [m/s]
Mission Requirements	L LEO	ESPA	1300	591.05
COMET	L LEO, H LEO, GEO+	ESPA, Hosted, Other	1500	707.97
METEOR	L LEO, H LEO, GEO+	ESPA, Hosted, Other	1500	926.78
M-OMV	L LEO	ESPA, Hosted, Other	1000	510.05

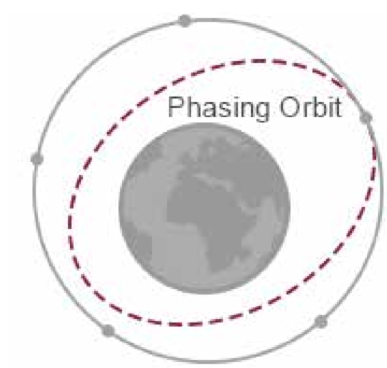
DRM #2: MULTI-PLANE CONSTELLATION POPULATION

Populate a multi-plane constellation utilizing a single launch



- Conduct phasing and/or corrective maneuvers to delivery multiple spacecraft to orbits in different orbital planes
- Common on orbit maneuvers expected for mission completion
  - Change orbital altitude and shape
  - RAAN phasing utilizing J2 rotational effects
  - Phasing for satellite spacing on orbit

DRM 1.2 can be further investigated by adding another target plane. Thus, splitting the payloads between two target planes that are separated by a RAAN shift of 30 degrees. To recap these parameters, using Moog's OMV sizing tool, are as follows;



- Qty. 5x ESPA class and associated dispensers (approx. 1300 kg payload mass)
- Two target planes with payloads equally spaced in plane (3 on first, 2 on second)
  - 1st target plane is a 500 km near circular (0.02 eccentricity) orbit at 53 degrees RAAN shifted from launch plane by 20 degrees
  - 2nd target plane is a 500 km near circular (0.02 eccentricity) orbit at 53 degrees RAAN shifted from 1st target plane by 30 degrees
- Launch plane is a mid-inclination LEO launch
  - Launch plane is a 200km near circular (0.02 eccentricity) orbit at 53 degrees

OMV DESIGN REFERENCE MISSIONS

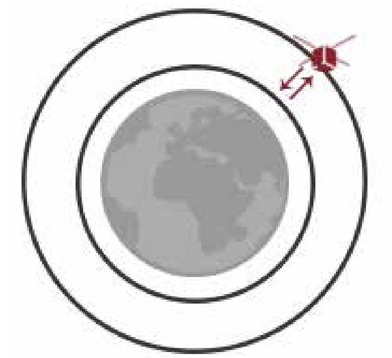
From here the process is very similar to that of DRM 1.2. It is a balance between time spent on orbit and ΔV requirements. If the mission allows for 1 month dwell times for each J2 rotation and 3 weeks for the payload phasing maneuvers, the total mission ΔV requirement is 934 m/s. In this case the METEOR OMV would perform better than the COMET as it has a larger ΔV performance value.

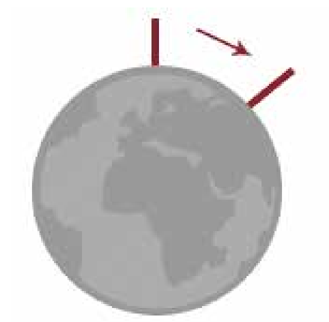
DRM #3: SINGLE PLANE CONSTELLATION POPULATION WITH LOITER

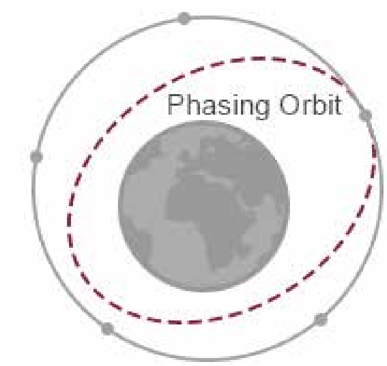
Populate constellation with long dwell times between deliveries

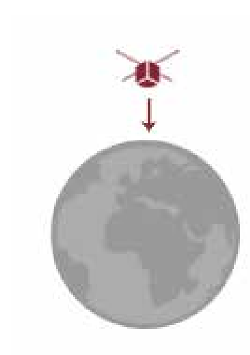
- Conduct phasing and/or corrective maneuvers to delivery multiple spacecraft to target orbital plane(s)
- Conduct long dwells or hosted payload operation
- Common on orbit maneuvers expected for mission completion
  - Change orbital altitude and shape
  - Change orbital inclination
  - On-orbit loiter or hosted payload operation
  - Phasing for satellite spacing on orbit

This model is calculated exactly like that of DRM 1.1. The only difference being some of the OMVs include built in redundancies that allow for longer on orbit times. If this is a desired trait from the mission standpoint, then a loiter specific OMV should be selected. A Moog representative can further aid in this discussion as some models are directly intended for loiter applications.









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