CubeSat Modular Propulsion Systems Product Line Development Status and Mission Applications

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The CubeSat platform has greatly reduced the barrier to entry for space missions, resulting in significant market growth. Due to a lack of propulsive capabilities, CubeSat missions are confined to their dispersal orbits. Without propulsion the CubeSat platform cannot realize its total addressable market and the current market will stagnate. Propulsive capabilities enable the CubeSat platform to access the wider range of missions that will strengthen the value proposition of the platform and ensure continued growth in the market. The Aerojet CubeSat Modular Propulsion Systems Product Line satisfies the propulsive needs of the CubeSat community. The product line includes four products: MPS-110 cold gas system, MPS-120 hydrazine monopropellant system, MPS-130 AF-M315E monopropellant system, and MPS-160 solar electric power / solar electric propulsion (SEP[2]) system. Systems range in size from 0.5U to 2U with designs generally scalable up to 180 kg class space vehicles such as ESPA node satellites. The CubeSat platform and community have created an environment of rapid development and flight with streamlined processes, Aerojet has therefore incorporated new manufacturing and component technologies that streamline manufacturing and test processes in order to realize aggressive mission schedule and cost thresholds. The configurations, development status, and mission applications of each product are discussed as well as the enabling manufacturing and component technologies that are incorporated into their designs.

Introduction

THE relative simplicity, low development cost, and wide range of available low-cost launch options (as secondary payloads) enabled by the CubeSat platform have opened space access to new classes of users and missions for whom barriers-to-entry of traditional approaches are an order of magnitude or more too high. As the fastest growing Aerospace market segment, the rate of CubeSat launches has increased steadily over the past decade, reaching a current total of 146 nanosatellites as of 2012 tracing their origins to twenty different nations (Canada, Columbia, Denmark, Estonia, France, Germany, Hungary, India, Italy, Japan, Korea, The Netherlands, Norway, Poland, Romania, Spain, Switzerland, Turkey, USA, Vietnam, etc.). That even traditional space users have embraced the cost and schedule advantages realizable through the CubeSat model of using COTS parts with standard interfaces is exemplified in a number of NSF- and NASA-funded missions (CSSWE, Firefly, CINEMA; GeneSat-1, PharmaSat, etc.), and particularly, PhoneSat (NASA), where the total cost of components was less than $7,000.

Due to a lack of propulsive capabilities, CubeSat missions are confined to their dispersal orbits. Without propulsion the CubeSat platform cannot realize its total addressable market and the current market will stagnate. Propulsive capabilities enable the CubeSat platform to access the wider range of missions that will strengthen the value proposition of the platform and ensure continued growth in the market. Propulsive capabilities ranging from ~10m/s for small dispersal maneuvers to >200m/s for large apogee maneuvers are required. The Aerojet CubeSat Modular Propulsion Systems (MPS) Product Line satisfies the propulsive needs of the CubeSat community. The product line simplifies propulsion mission planning and integration so that any level of CubeSat builder can consider a propulsive mission.

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Product Line Overview

In 2011, Aerojet began development of a 1U modular propulsion system call the CubeSat High-impulse Adaptable Modular Propulsion System (CHAMPS) designated "MRS-142" to address the emerging need for CubeSat propulsion systems.[i,ii] Leveraging designs and components developed for the MRS-142 along with key new technologies enabled Aerojet to develop the CubeSat Modular Propulsion Systems product line shown in Figure 1. The systems leverage common parts and designs in order to reduce non-recurring engineering and to achieve economies of scale that will enable reduced cost and lead times as product line production rates increase.

The objective of the CubeSat Modular Propulsion Systems product line is to simplify mission planning, system selection, and satellite integration to the point that any level of CubeSat builder can consider a propulsive mission. This objective is accomplished through the following features:

- Catalog of standard systems with clear propulsive capabilities listed
- "U" based form factor that enables simple mechanical interfacing
- Elimination of requirement for fluidic connections typically required of the tightly integrated propulsion systems found on larger satellites
- Propulsion system control unit with a single power and data connection that simplifies electrical and software integration

Product Image	Product Number	Description	ΔV for 3U 4kg BOL	ΔV for 6U 10kg BOL
	MPS-110	• System Mass: Varies depending on selected size • Propellant: Inert gas • Propulsion: 1 to 4 cold gas thrusters	10 m/s	N/A
	MPS-120	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	209 m/s	81 m/s
	MPS-130	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: AF-M315E • Propulsion: Four TBD—1 N (BOL) rocket engines	340 m/s	130 m/s
	MPS-120XW	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	440 m/s	166 m/s
	MPS-120XL	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	539 m/s	200 m/s
Image Coming Soon	MPS-160	• System Mass: TBD • Propellant: Xenon • Propulsion: 80W Solar Electric Power/Solar Electric Propulsion System (SEP^2)	N/A	>2,000 m/s

Figure 1: CubeSat Modular Propulsion Systems Product Line

Enabling Technological Innovations

A. Miniaturized Rocket Engine Technology

Aerojet investments to commercialize technologies stemming from small form factor missile defense applications has enabled miniature rocket engines and valves capable of supporting CubeSat missions. The resulting MR-14X series of engines realizes a ~4× reduction in engine size as shown in Figure 2. Aerojet's efforts to adapt miniature rocket engine technology for AF-M315E propellants enables both hydrazine and AF-M315E solutions.

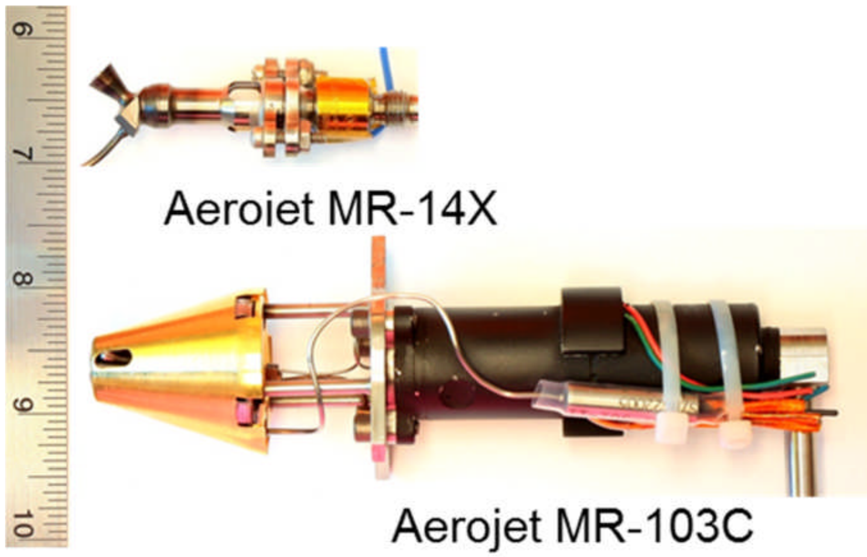

Figure 2: Aerojet Miniature Rocket Engine Compared with a Standard Rocket Engine

B. Additive Manufacturing Process Infusion

Subtractive manufacturing is a generic term used to describe a manufacturing process that removes material from a piece of stock in order to fabricate a part. Examples of subtractive manufacturing processes include: milling, turning, cutting, and drilling. In contrast, Additive manufacturing is a generic term used to describe a manufacturing process that deposits and bonds material together to fabricate a part. Additive manufacturing processes produce parts directly from a digital design. Additive manufactured parts typically require little or no tooling, significantly reducing the cost and lead time of designing, manufacturing, and maintaining tools. If fixtures or tooling are needed they can typically be fabricated during the build process, minimizing the need to create tools ahead of the build or maintain them after the build. The reduced requirement for tooling significantly reduces setup time and cost as well as inventory costs. Additive manufacturing processes typically consume only the material needed to make the part. Typically, most residual material used during the process is re-usable for fabrication of future batches of parts. Additive manufacturing eliminates the need for cutting fluids that are required in subtractive manufacturing processes. The combination of efficient use of material and elimination of support fluids results in significant reductions in material cost and waste. Overall, additive manufacturing process benefits can realize significant reductions in fabrication time and cost. These benefits enable opportunities for more design iterations than traditionally possible, enabling lower cost development programs with higher quality design outputs that are typically ready for direct transition to low volume production. These characteristics are of high importance to the typically long duration, high cost development programs and ultimately low volume production of spacecraft systems.

Current additive manufacturing machines are constrained to build envelopes of ~30 cm^3. The MPS-100 product line includes propulsion systems that fit the standard 1U CubeSat envelope of ~10 cm × 10 cm × 10 cm, making these systems ideal candidates for demonstration and infusion of additive manufacturing process technology. Aerojet has embraced the use of additive manufacturing methods and has begun infusion of new design philosophies and manufacturing processes to develop more affordable propulsion systems. The MPS-120 and MPS-130 liquid propulsion systems utilize a piston tank that includes a piston, propellant tank, and pressurant tank. Some components include internal flow passages that were identified as opportunities for improvements with additive manufacturing. Figure 3 shows how design for additive manufacturing enables improvements that reduce component count and eliminate potential leak paths in the system. Figure 4 demonstrates how additive manufacturing removes costly weld/inspection processes. These are just some examples of the benefits offered by additive manufacturing for propulsion systems. Aerojet is working to demonstrate that many types of additive manufacturing processes can be applied to the MPS-100 product line including: Electroforming (EL-Form®), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Laser Engineered Net Shaping (LENS™).

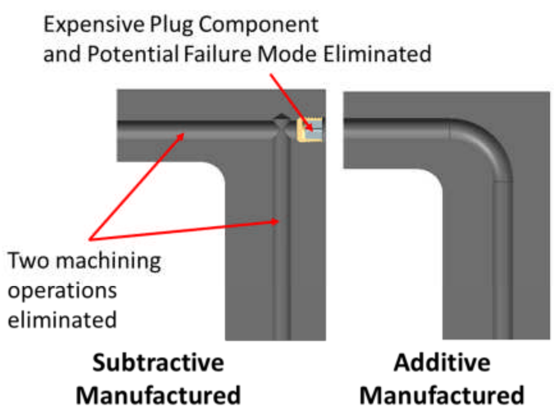

Figure 3: Internal Passages Enable Elimination of Components

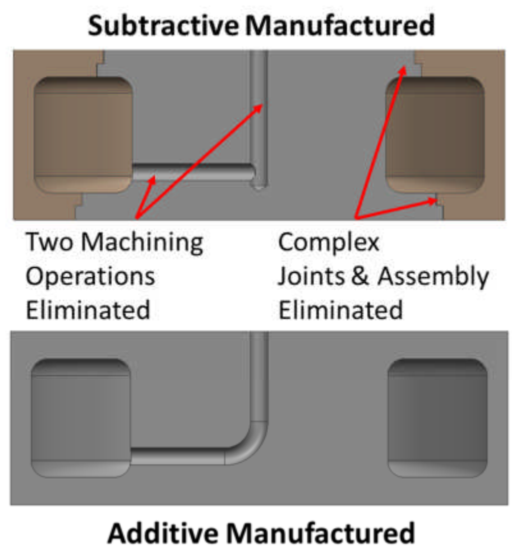

Figure 4: Internal Passages Enable Elimination of Processes

The EL-Form® process uses molten salt electrolytes, instead of the aqueous solutions of standard electroplating processes, to enable electrodeposition of compact metal layers onto a mandrel. EL-Form® enables refractory metals to be formed into dense, non-porous and crack-free layers. The EL-Form® process can create component structures on mandrels and/or dense coatings applied existing parts. The EL-Form® process was used to produce the Ir/Re chamber and nozzle for MR-143 engines in MPS-130 system. An operational demonstration of these components is planned for 2013.

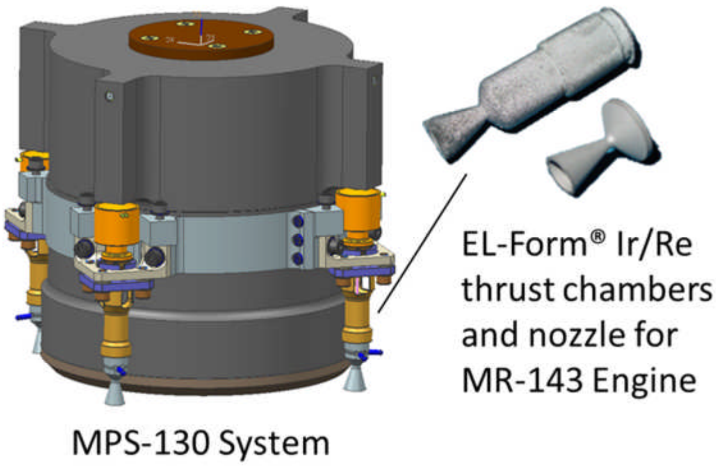

Figure 5: EL-Form® Components

The SLM and EBM processes deposit powder in layered fashion and apply laser (SLM) or electron beam (EBM) to sinter powder. Figure 6 are examples of Inconel and titanium components produced by SLM. Figure 7 presents as-printed propellant tank components manufactured by EBM. Operational demonstrations with these components is planned for 2013.

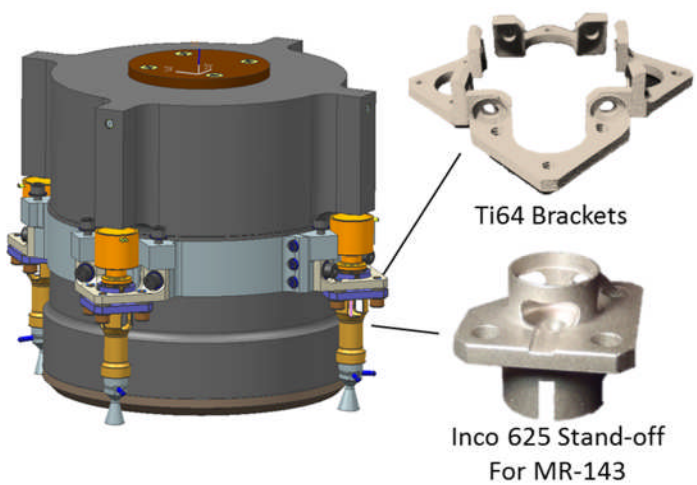

Figure 6: SLM Additive Manufactured Components

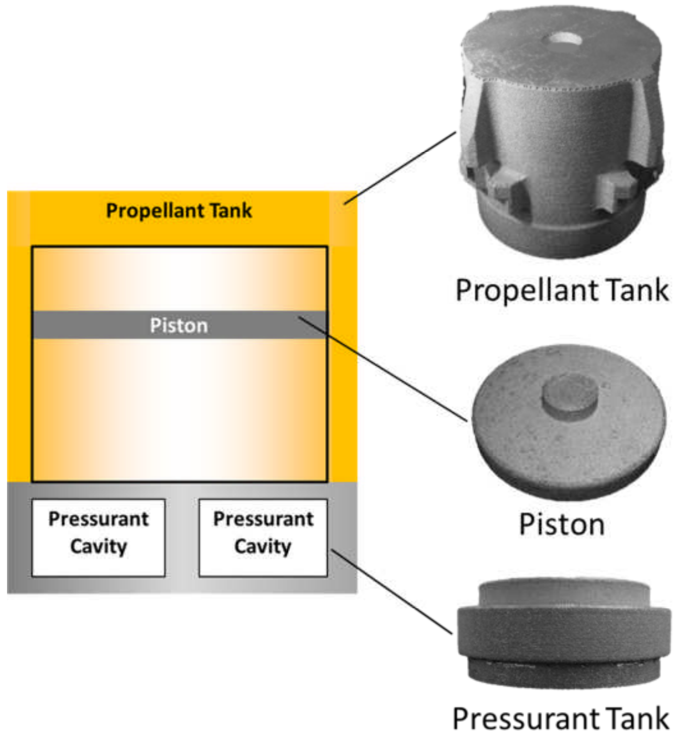

Figure 7: As-Printed EBM Additive Manufactured Piston Tank Components

Laser Engineered Net Shaping (LENS™) is a new manufacturing technology that simultaneously sprays and sinters powder, reducing or eliminating the need for powder removal required by SLM and EBM. Work is ongoing to demonstrate a LENS™ version of the common piston tank. An operational demonstration of the LENS™ tank is planned for 2013.

Demonstration of additive manufacturing production capabilities enables product line development, production, scaling, and tailoring at substantially lower cost and schedules than subtractive manufacturing processes alone. While the objective of the product line is to offer standardized parts, it is recognized that some customers will require non-standard sizes and geometries to fit within available space or to maximize use of available space. The use of additive manufacturing in the standard products enables Aerojet to offer non-standard configurations that do not necessarily require full re-qualification of the system. As an example, 1U and 2U variants of the MPS-120 will be standard, however it is possible to quickly develop and produce a 1.5U version if required by a customer.

C. Solar Electric Power/Solar Electric Propulsion (SEP^2) System Architecture

Several companies have offered electric propulsion systems for CubeSats capable of low ΔV and attitude control; however these systems have realized little mission utility. In order to truly benefit from electric propulsion, an apogee solar electric propulsion (SEP) system is desired that can provide significantly more ΔV than chemical systems. However, the cost and mass of electronics in typical apogee electric propulsion solutions are prohibitive on such a small scale. In order for an electric propulsion system to be effective on a platform as small and low cost as a CubeSat, a different approach is required compared with larger satellites.

For several years, Aerojet has been working on a technology called Direct Drive which operates electric thrusters directly from high voltage solar arrays in an attempt to boost efficiency, reduce components, and reduce waste heat. Previous Direct Drive development activities have focused on multi-kilowatt systems.[iii] However, the same technology applied to the CubeSat platform significantly reduces the mass and cost of power electronics to the point that primary electric propulsion on CubeSats becomes feasible. An integrated solar power system and direct drive solar electric propulsion control unit enabled Solar Electric Power and Solar Electric Propulsion (SEP^2) system enables electric propulsion apogee systems for CubeSats. Figure 8 is an example comparison of a traditional solar electric propulsion system with Aerojet's SEP^2 system concept.

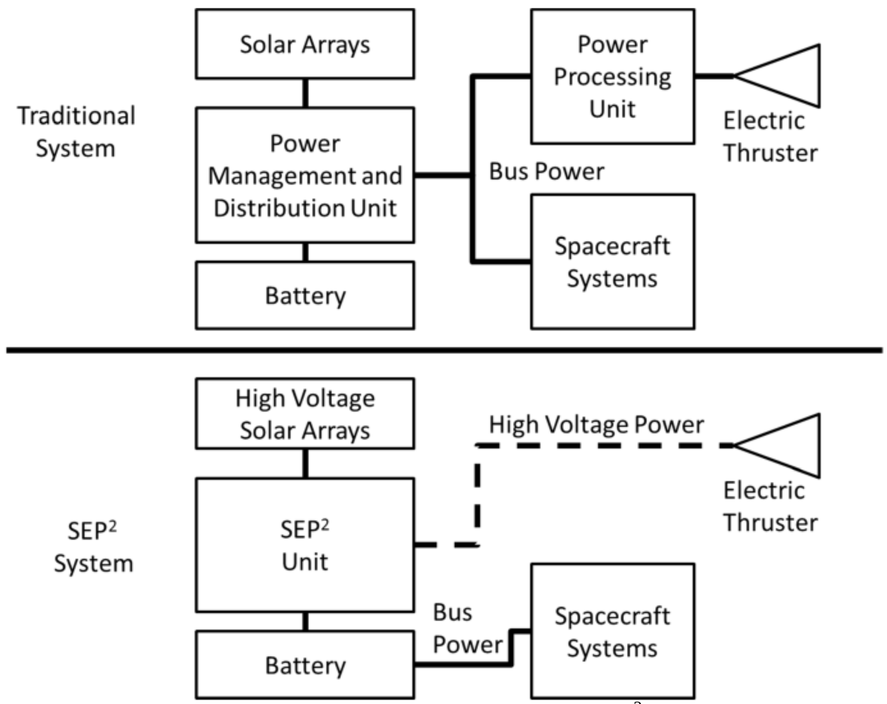

Figure 8: Comparison of Traditional and SEP^2 Systems

Modular Propulsion System Product Descriptions

D. MPS-120 Hydrazine Monopropellant Propulsion System

The MPS-120 maintains much of the original MRS-142 design with some significant changes to align with the overall product line approach. The system has been simplified with the new fluidic schematic shown in Figure 9. An additive manufactured titanium piston tank replaces the previous machined aluminum tank design of the MRS-142. While the aluminum tank is still an optional variant of the new MPS-120 product, the new baseline titanium version provides comparable ΔV and enables more commonality within the product line, reducing system costs. MPS-120 designs are complete and fabrication is currently under-way with MR-142 engines and additive manufactured titanium piston tank nearing completion and readiness for integrated testing.

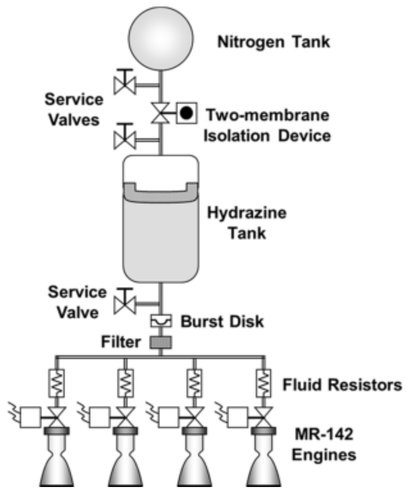

Figure 9: MPS-120 System Schematic

E. MPS-130 AF-M315E Monopropellant Propulsion System

The MPS-130 is a new product offering derived from the MPS-120. Figure 10 presents the fluid schematic for the MPS-130 which is almost identical to the MPS-120 except that a burst disk is not required for the AF-M315E green monopropellant and the system employs new MR-143 engines capable of operating on AF-M315E green monopropellant. The MR-143 engines are of similar size to the MR-142, but utilize rhenium chambers that survive the high combustion temperatures of AF-M315E propellant. At the time of this writing, the MPS-130 design and drawings are complete, and fabrication is currently under-way with MR-143 engine components produced and ready for engine assembly.

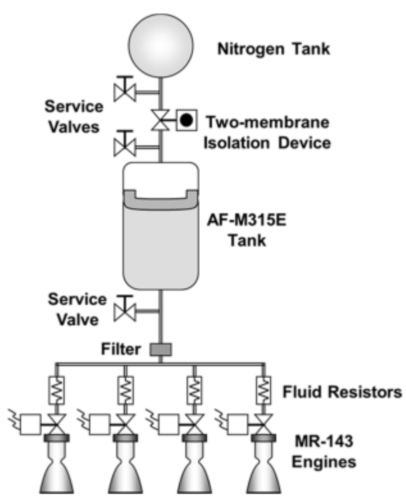

Figure 10: MPS-130 System Schematic

F. MPS-110 Cold Gas System

The MPS-110 Cold Gas system is being developed to provide a propulsive capability for missions on small platforms that need minimal ΔV to achieve their mission objectives. Applications would primarily be initial dispersion, minor orbit adjustments, or attitude control. The MPS-110 system derives valves, filter, and tank design from the MPS-120 system mentioned previously. Figure 11 is the fluidic schematic of the MPS-110. The system is capable of operating with a variety of pressurants such as GN2 or condensables enabling significant mission tailoring. MPS-110 pressurants have been selected and operational behaviors are well understood.

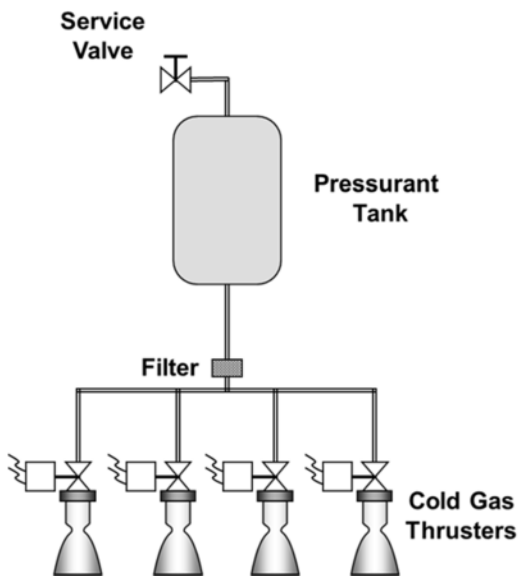

Figure 11: MPS-110 System Schematic

G. MPS-160 Electric Propulsion System

The MPS-160 is a concept system that differs significantly from the systems presented thus far in that it is a 2U system that includes both power and propulsion using the aforementioned SEP[2] system architecture. The MPS-160 concept development is aimed at developing such a system that would ultimately be capable of providing >2,000m/s to a 6U CubeSat from a 2U propulsion and power package. Figure 12 presents the MPS-160 system schematic. A Hall thruster is used to represent the apogee propulsion; however multiple types of electric thrusters are applicable. Hall thrusters, gridded ion thrusters, and other types of thrusters are in development at the power, voltage, and specific impulse levels required by the MPS-160 system enabling the system to support a wide range of missions.

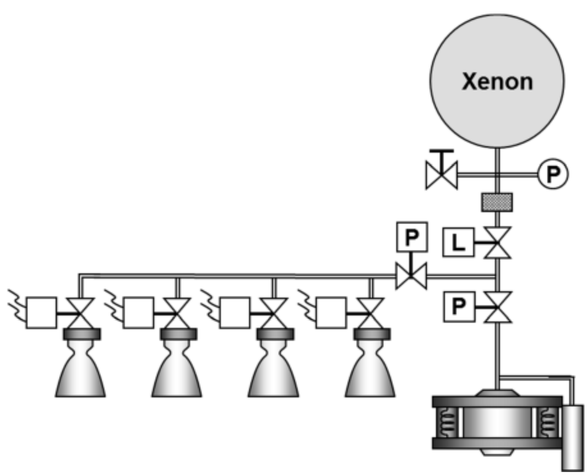

Figure 12: MPS-160 System Schematic

Mission Applications

H. Missions Requiring Dispersal

Every satellite begins its mission life with a deployment event from the launch vehicle upper stage, and to prevent re-contact after a number of orbits if the upper stage is not actively de-orbited, propulsive maneuvers are typically employed by the satellite to assure that collision does not occur with the upper stage. Alternatively, some satellite missions may desire to conduct propulsive maneuvers to "scatter" away from the larger upper stage, which can easily be tracked by amateur radio operators and launch trackers. Secondary payloads to date typically reserve any minimal ΔV capability found with cold gas systems for utmost critical mission events like attitude control or end-of-life de-orbit requirements. High-impulse propulsion systems, such as the MPS-120 CHAMPS, can provide secondary payloads with the tactical advantages that larger satellites have enjoyed for decades. Figure 13 shows the dispersal capabilities of Aerojet's CubeSat Modular Propulsion Systems product line to impart 5 m/sec of ΔV to the maximum satellite mass that is achievable. This amount of ΔV is considered the minimum needed to achieve safe and tactical deployment, and also matches the typical 5 m/sec achieved from a CubeSat P-POD jettison event. Two observations can be made from this figure: the MPS-110 cold gas system is adequate in providing enough ΔV for most 3U CubeSats and some 6U CubeSats for dispersal applications, and the MPS-120 and MPS-130 can be integrated on satellites much larger than CubeSats to gain tactical dispersal capability for low cost compared to custom propulsion system solutions. This is very compelling for missions for smallsats in the range of 50-300 kg that are designed for simple mission capability and low-cost and where modularity is emphasized or required. Similarly, the MPS-120 and MPS-130 can be used as a modular addition to a deployable ESPA node to create a dedicated stage to capable of delivering multiple CubeSats to a desired orbit and/or phasing.

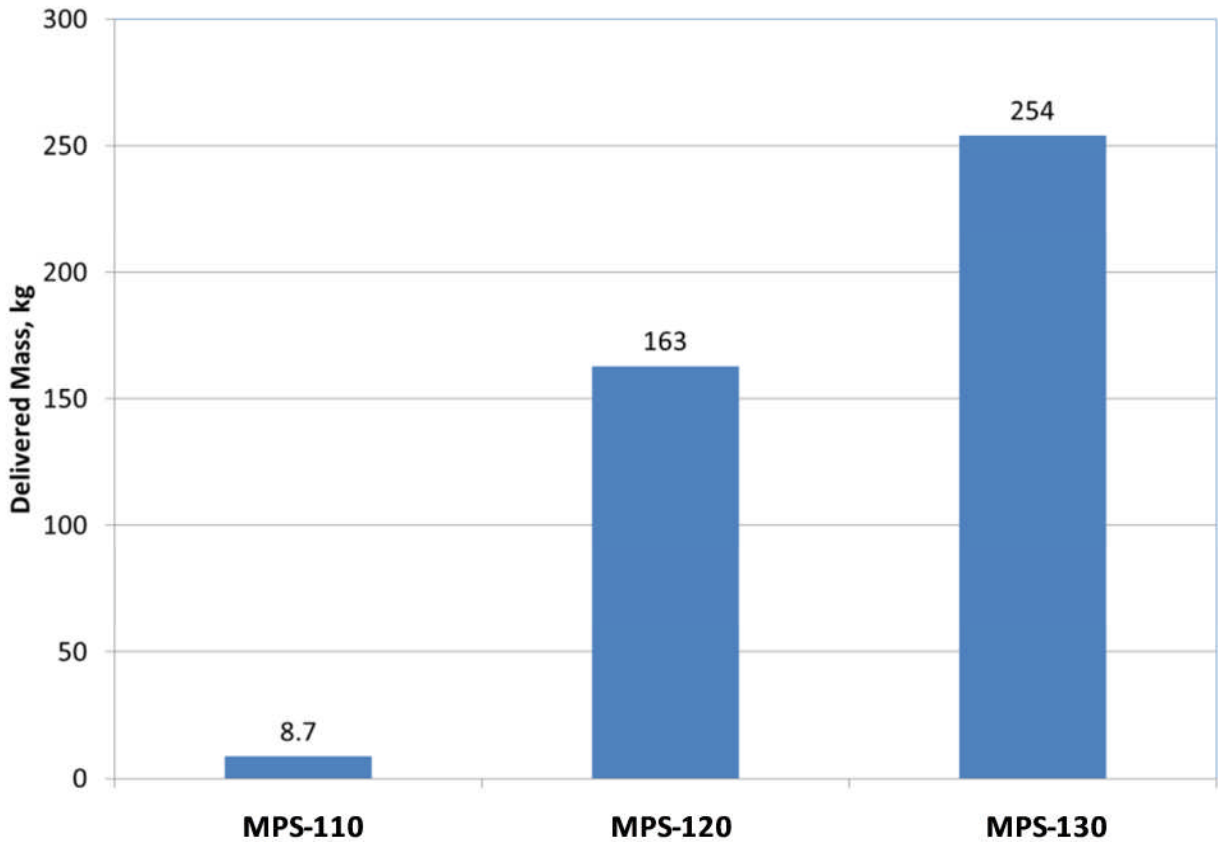

Figure 13: MPS Product Line Mass Dispersal Capability at 5 m/sec ΔV.

I. Missions Requiring Low Flight

Another significant area of interest in the CubeSat community is using low-cost imaging-capable CubeSats to fly at low altitudes to augment the resolution capability of COTS-based imaging systems. This can be employed to support responsive disaster monitoring, localized weather monitoring, and other situations where data from a particular area of interest becomes valuable for a temporary period. To make this concept compelling, significant ΔV is required to counteract drag and extend the lifetime of the satellite to the point where enough data is mined over the life of the satellite to be regarded as worth the cost of an otherwise expendable satellite. This evaluation should also factor in the responsive capability of the CubeSat form factor; a 6-12U imaging CubeSat that is small enough to be integrated with dedicated small satellite launch vehicles or tactical small satellite air-launched platforms could trump the logistical cost of maintaining a constellation of higher-value imaging satellites over longer mission lifecycles which do not necessarily guarantee fast image-capture over a new area of interest. Packageable within a 20 cm x 20 cm x 30 cm volume, these types of CubeSats could be pre-integrated with smaller, dedicated, on-demand launch vehicles sized to deliver spacecraft weighing less than 50 kg to LEO, to be used when other space-based assets are either not accessible or too expensive to utilize. This on-demand capability lends immediate tracking resources to organizations responsible for monitoring disasters like tornados, oil spills, forest fires, etc.

To assure frequent image updates over an area of interest, a low-altitude, repeating ground track orbit can be utilized to provide up to two revisits per day per satellite. Figure 14 below shows such an orbit at 262 km circular, which can provide up to 1.7 m resolution with a COTS type optical system that provides a 9 cm aperture and 1.25 m focal length. Revisit sites over areas of interest for repeating ground track orbits can be easily selected by calculating the required orbital injection site and inclination of the launch vehicle, with the satellite propulsion system conducting the final orbit "cleanup" burns. Image acquisition over multiple areas of interest can potentially be achieved with this system, as Figure 14 demonstrates, to support short and long-term change detection for global map data, crop management, climate monitoring, etc.

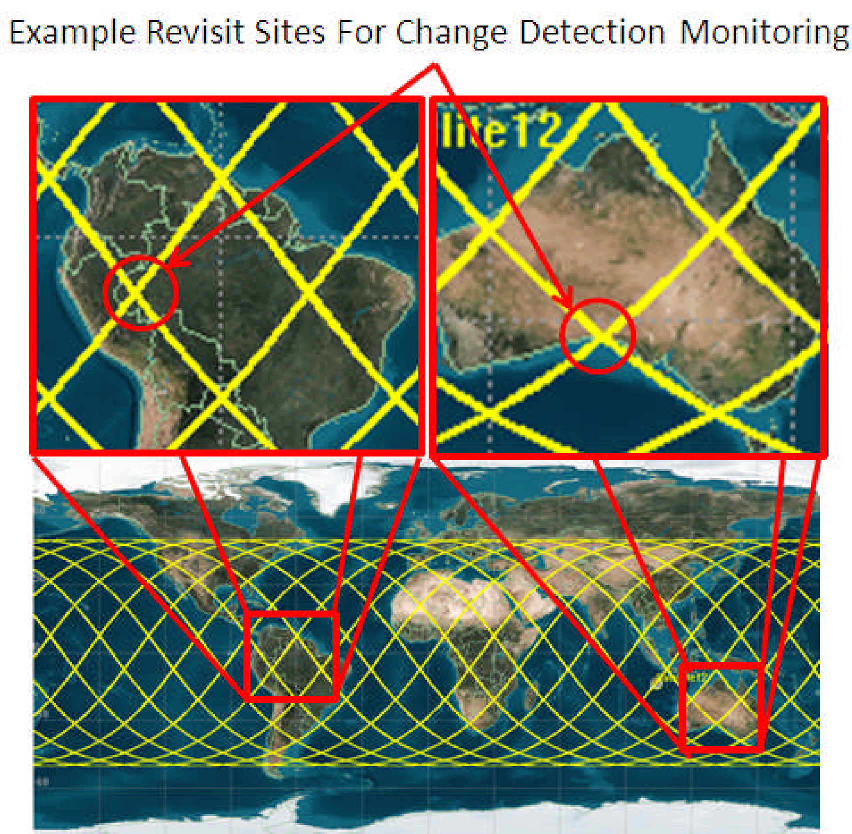

Figure 14: Low Altitude Repeating Ground Track Orbit Enables High Revisit Rate per Satellite.

At the altitude of the repeating ground track orbit in Figure 14, the CubeSat Modular Propulsion Systems product line can extend life of 6U CubeSats (baselined weighing 10 kg) with varying ballistic coefficients to the values shown in Table 1 below. This life augmentation capability provides the end user with frequent and persistent data to support many operational situations that required dedicated imaging assets over longer time periods.

Table 1: CHAMPS Lifetime Extension at 262 km Circular Orbit.

Lifetime (days) for 6U (10kg S/C) at 262 km			
	MPS-110	MPS-120	MPS-130
	Ballistic Coefficient = 50 kg/m^2		
Solar Max	4.5	43.0	66.0
Solar Nom	11.1	183.4	286.9
Solar Min	27.5	402.0	626.9
	Ballistic Coefficient = 50 kg/m^2		
Solar Max	19.0	169.3	259.9
Solar Nom	44.0	776.0	1215.9
Solar Min	109.4	1712.5	2675.1

Several COTS imaging systems have been identified[ivv] that can be retrofitted for structural and thermal stability as well as some optical aberrations to provide this resolution capability, while taking up less than 2U of payload space on a CubeSat. Such an optical system that employs a Maksutov-Cassegrain telescope mirror system is shown below in Figure 15 for visual comparison to the overall CubeSat form factor.

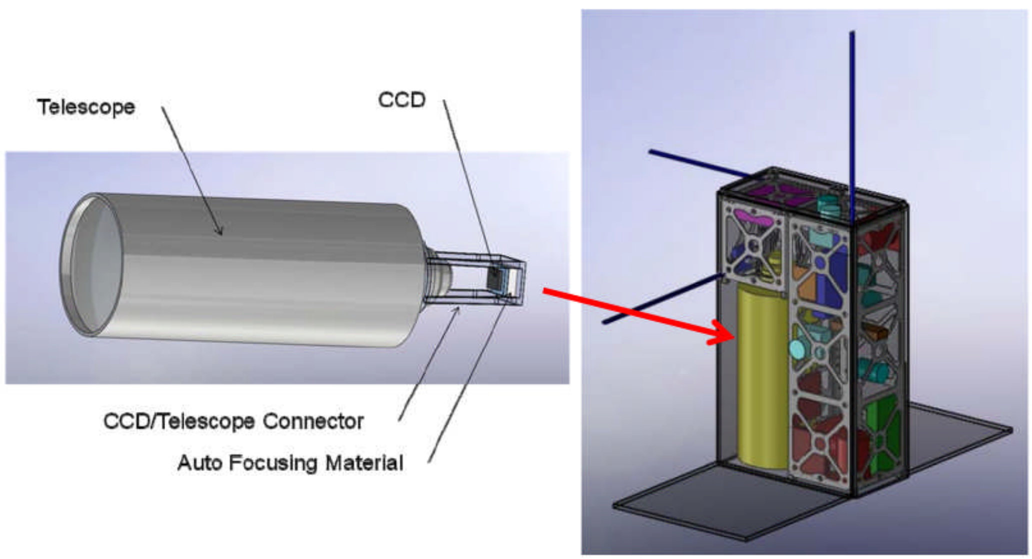

Figure 15: COTS imaging optics can package within CubeSat volumes.

Tasking, Processing, Exploitation, and Dissemination (TPED) has historically been problematic for these types of CubeSat missions due to difficulty of communicating with available ground stations to guarantee that high-value imaging data is collected and delivered to the end user with acceptable latency. However, recent CubeSat missions have employed deployable high gain antennas to communicate with ground assets with low RF power. Specifically, the AENEAS mission launched a 3U CubeSat that deployed a 0.5m parabolic antenna for communication on WiFi frequencies to ground assets that boasted a gain of 18dB[vi]. Other entities are currently developing 2m deployable antennas for S-band communication that occupy only 1U. Advancements in deployables technology continue to mature the possibility of achieving a link from LEO to a dedicated or mobile ground station using burst transmission mode, as well as the possibility of achieving a link to a higher altitude satellite communication network (i.e. TDRSS, etc.) to support high rate data transfer.

J. Constellation Deployment Missions

Another capability that can enable tactical satellite missions is the ability perform relatively fast phasing maneuvers to quickly deploy a constellation, or "scatter" it. This always comes at a cost impact in the form of propellant consumption, and thus less ΔV remaining for additional necessary maneuvers. Figure 16 below describes the phasing capability for MPS products for a variety of constellations at an orbital altitude of 500km.

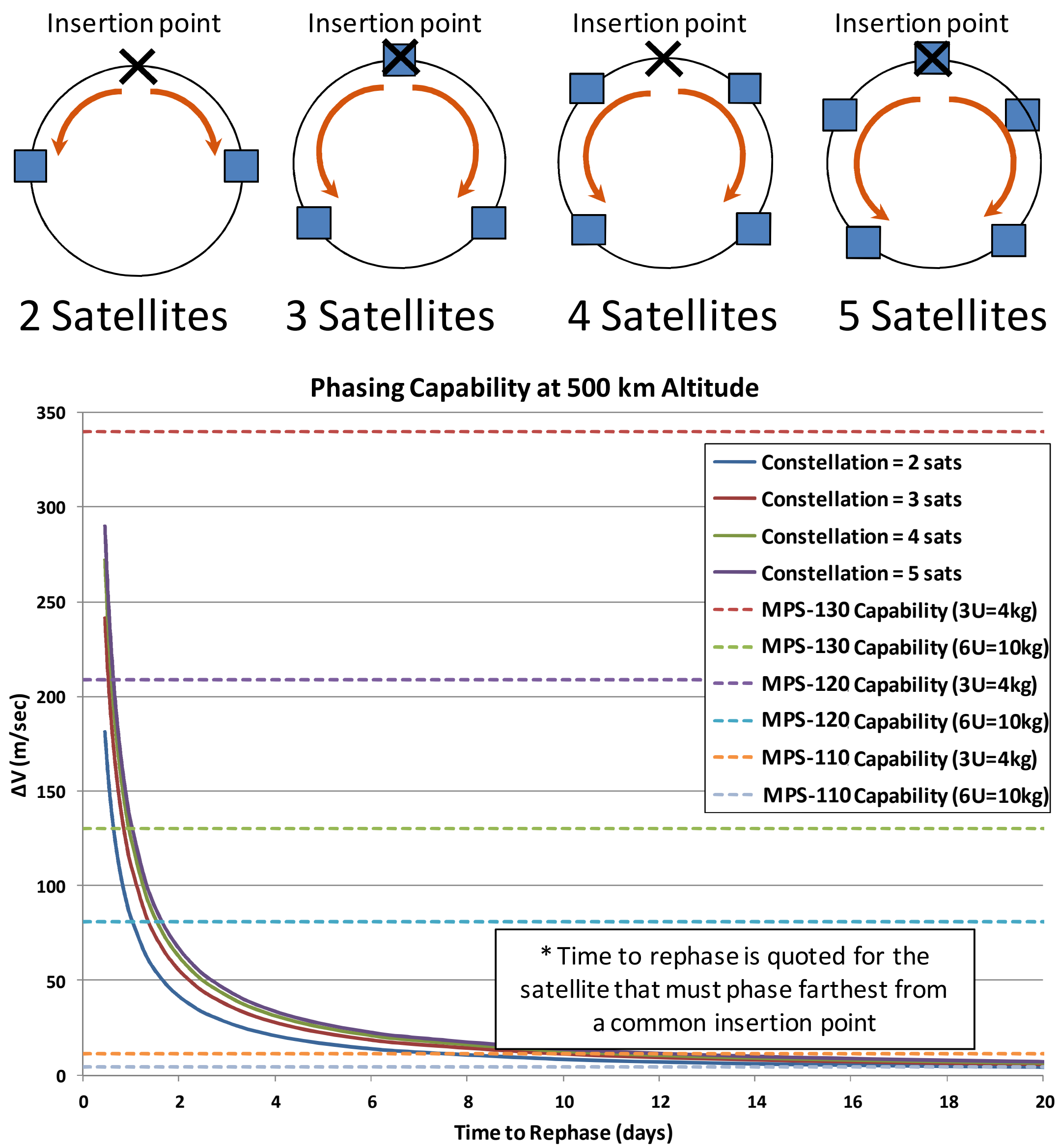

Figure 16: Product Line Phase/Rephase Capability at 500km Altitude.

K. Low Thrust Missions

The MPS-160 provides low thrust apogee propulsion for a wide range of missions. A small pressurant tank stores the xenon propellant at supercritical conditions and the ΔV capability is a function of tank size and storage pressure. Figure 17 plots the MPS-160 notional ΔV capabilities as a function of beginning-of-life storage pressure, tank size, and thruster specific impulse. A propellant storage temperature of 70°C was used to bound a worst-case estimate. ΔV requirements for various missions of interest are overlaid in the figure to show mission capability thresholds. It can be seen from the graph that the 1.5U, 3000s Isp case provides significant capabilities at a relatively low storage pressures. Further study is needed to ensure reasonable trip times and payload masses, however this preliminary assessment demonstrates that the MPS-160 could enable rideshare CubeSats to access missions to GEO and the Moon.

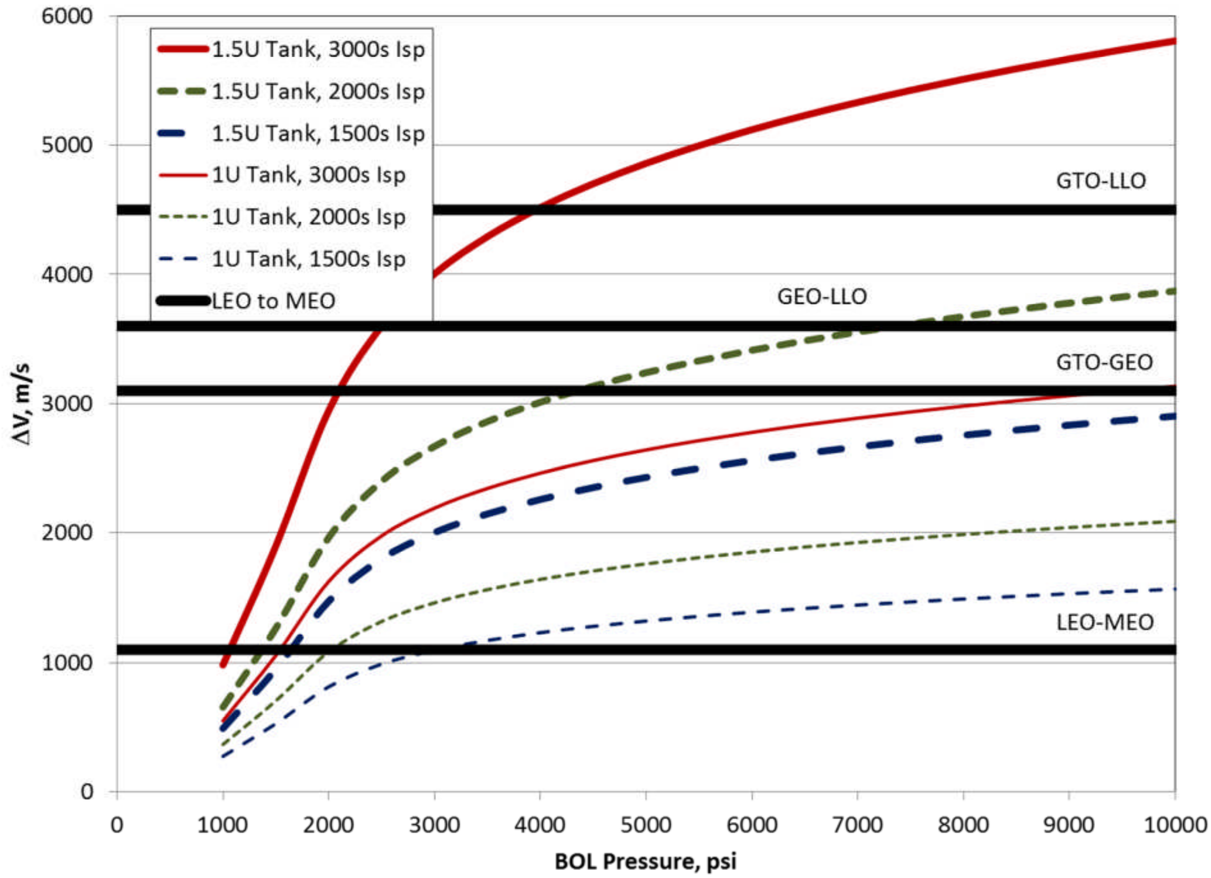

Figure 17: MPS-160 Notional ΔV Capabilities as a Function of Xenon Storage Pressure

Conclusion

As with traditional space applications, propulsion options providing means cost-effective of dispersal, constellation deployment, orbit management, and angular momentum dissipation will greatly augment the range of missions CubeSats can perform. In so doing, these expanded mission capabilities will strengthen the value proposition of the platform and further stimulate current market growth trends. The large reduction in launch costs potentially offered by CubeSats makes propulsion even more pivotal for their future, however, in that the full advantage of substantially increased multi-manifesting (stemming directly from the small CubeSat form factor) can only be realized if co-launched CubeSats possess a practical means of post-deployment orbit differentiation. To meet this growing need, Aerojet is developing the CubeSat Modular Propulsion Systems product line to simplify mission planning, system selection, and satellite integration to the point that any level of CubeSat builder can carry out a successful propulsive mission. Four products are in development with MPS-110 Cold Gas and MPS-120 Hydrazine Monopropellant systems on track to be flight-ready by 2014, to be followed by the MPS-130 and MPS-160 advanced (AF-M315E) monopropellant and solar electric propulsion[2] systems by 2015 and 2016, respectively.

References

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