Test Results for the MPS-120 and MPS-130 CubeSat Propulsion Systems

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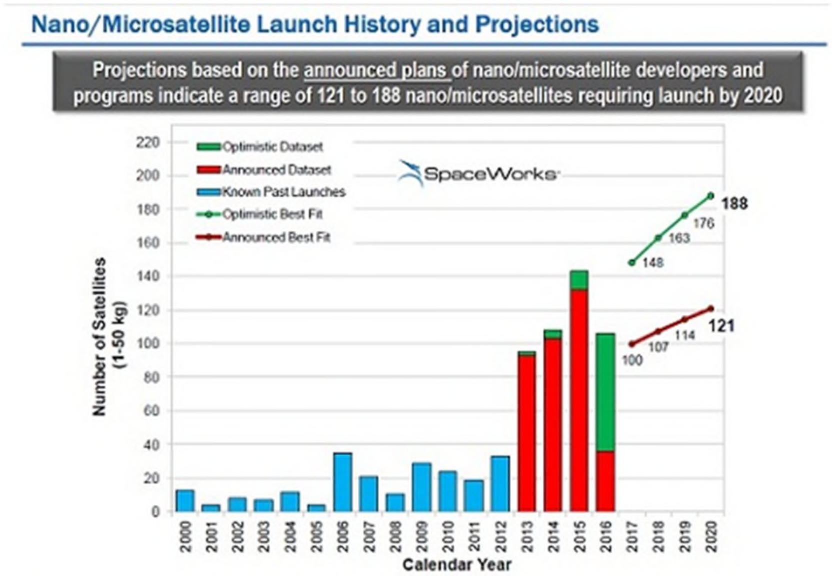
The CubeSat Market Will Stagnate Unless New Mission Applications Can be Accessed

- The CubeSat platform enabled low cost space missions resulting in significant market growth
- CubeSat missions are limited to dispersion orbits and this limitation will eventually cause market stagnation
- A wider range of missions must be enabled to strengthen the value proposition of the CubeSat platform and ensure continued growth in the market
- Propulsive capabilities exclusively enable CubeSats to access all mission areas of interest
- CubeSat modular propulsion systems product line simplifies propulsion planning and integration so that any level of CubeSat builder can consider a propulsive mission



Source: SpaceWorks Nano/Microsatellite Market Assessment, Feb 2013
http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_NanoMicrosat_Market_Feb2013.pdf

CubeSat Modular Propulsion Systems Product Line
Enables CubeSat Market Growth

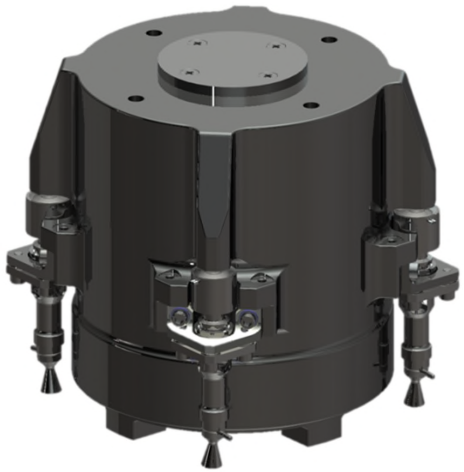
A Wide Range of CubeSat Propulsion Solutions are Required

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

The MPS-100 Product Line Provides CubeSat Mission Planners with a Wide Range of Solutions

MPS-120 Demonstration Program

- MPS-120 is a 1U, hydrazine propulsion system
- NASA MPS-120 Demonstration program started in February 2014
- Program Objectives
  - Demonstrate 3D printed isolation system
  - Demonstrate 3D printed piston tank
  - Demonstrate MPS-120 system level hotfire (with one MR-142 engine)



MPS-120

CubeSat
High-impulse
Adaptable
Modular
Propulsion
System

MPS-120 Test Results

- Isolation system demonstration testing conducted in June 2014
  - Machined aluminum isolation system test successfully conducted in March
  - 3D printed titanium isolation system test successfully conducted in June
  - Hermetic seal was verified prior to test
  - Isolation system operated at MEOP during testing to simulate flight condition
  - One of the two isolation devices failed to operate fully, but the root cause has been identified and minor design modification should resolve the issue
- Piston tank demonstration testing conducted in May 2014
  - 3D printed titanium tank was assembled
  - Water expulsing testing conducted
  - Entire pressure operating range was tested
  - Measured expulsion efficiency of >99% over 12 fill and drain cycles
- Future testing
  - One MR-142 engine was assembled and ready for hotfire
  - Anticipate system level hotfire testing in October 2014

MPS-120 Product Development is Proceeding with Positive Results

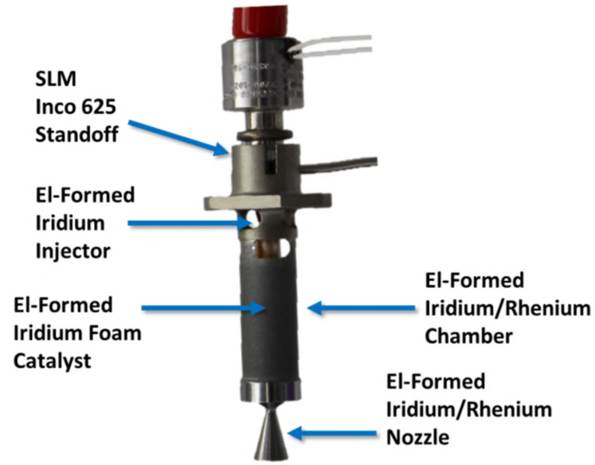
MPS-130 Demonstration Program

- MPS-130 is a 1U, AF-M315E green propulsion system
- MPS-130 uses same tank as MPS-120
- MPS-120 demonstration program will validate MPS-130 system design
- MR-143 1N, AF-M315E engine is unique to the MPS-130
- Aerojet Rocketdyne has been working with Plasma Processes, LLC on MR-143 engine materials development and demonstration on NASA SBIR Phase II program
- Program scope was to push the limits of El-form® materials

MPS-130

MPS-130 Test Results

- MR-143 hotfire test conducted February 2014
- Complete, flight weight MR-143 thruster assembled
  - EL-form® chamber, nozzle, injector, and catalyst
  - 3D printed stand-off
  - Brazed assembly
- MR-142 engine valve
  - Valve is not designed for long-term AF-M315E compatibility
  - Further testing is required to understand if the valve can be used for long missions, or if a design modification is required
- Hotfire testing was successful
  - Pre-heat demonstrated using flight-like swaged heater
  - Short duration hotfire achieved
  - Crack developed in thin-wall EL-form® tube, limiting test duration
  - All other El-form® parts performed as expected
- Plan forward
  - Machined injector will be used in future engines



MPS-130 Product Development is Proceeding with Positive Results

Conclusions

- MPS-120 development is proceeding
  - Isolation system design and operation was verified
  - Piston tank design and operation was verified
  - MR-142 engine is assembled
  - Flight weight, system level hotfire testing planned for October

- MPS-130 development is proceeding
  - Isolation system design and operation was verified
  - Piston tank design and operation was verified
  - Flight weight MR-143 engine level testing conducted
  - Hotfire test demonstrated EL-form® material capabilities
  - Looking for opportunities to conduct system level hotfire demonstration

Aerojet Rocketdyne is Maturing
Additively Manufactured, Modular Propulsion Systems
for CubeSats

Aerojet Rocketdyne

CubeSat Modular Propulsion System Key Technologies

MPS-100 Product Line Key Technological Innovations

- IR&D investments to commercialize missile defense technologies and develop new AF-M315E green propellant technologies have enabled miniaturized rocket engines capable of supporting CubeSat missions
- Additive Manufacturing of key components and primary structures enables packaging of propulsion system components into CubeSat volumes as well as lower cost fabrication and more opportunities for validation testing
- Integrated Solar Electric Power and Solar Electric Propulsion System (SEP^2) based on experience with Direct Drive enables SEP for CubeSats

The MPS-100 Product Line Implements Technological Innovations that Enable Performance and Cost Advantages

Miniature Rocket Propulsion System Technology

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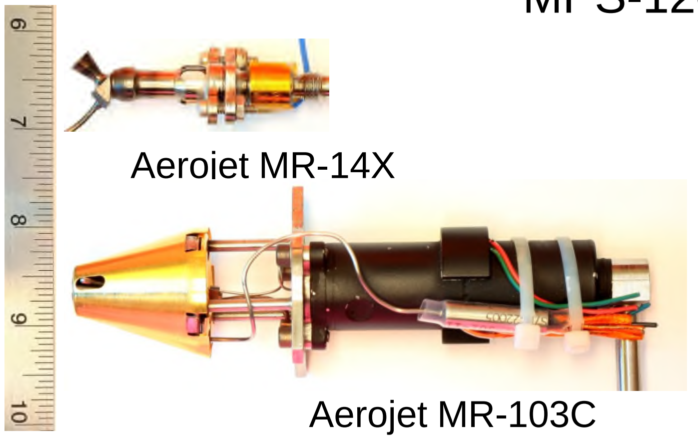
- IR&D investments to commercialize missile defense technologies has enabled miniature rocket engines capable of supporting CubeSat missions
- IR&D investments have established system designs
- NASA and DoD program funding is increasing TRL of each system

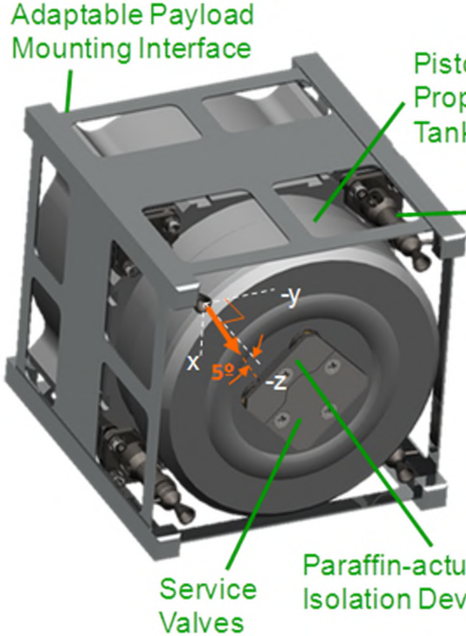


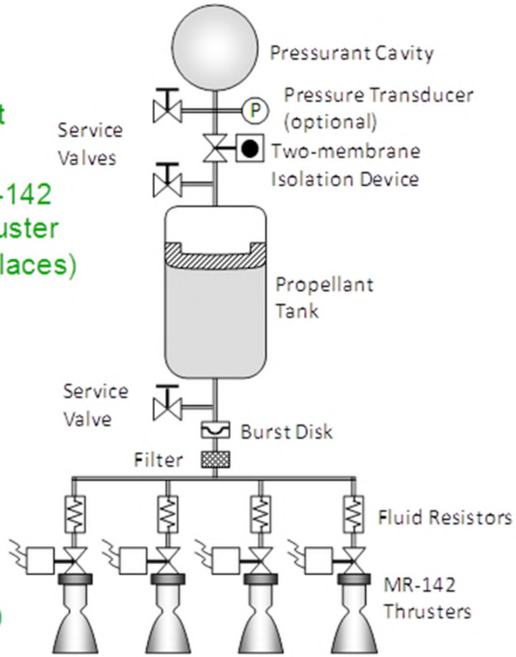
Aerojet MR-14X

Aerojet MR-103C

0.2lbf Engines

MPS-120





Recent Commercialization of Missile Defense Technologies and Aerojet IR&D Investments Enables CubeSat Modular Propulsion Systems

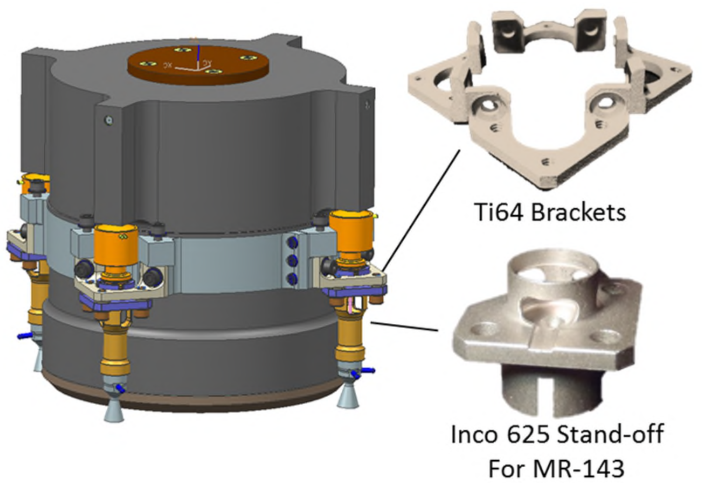
Infusion of Additive Manufacturing

- Aerojet Rocketdyne is developing technologies to significantly reduce cost and lead time for propulsion systems: Additive manufacturing was identified as a potential solution
  - Limitation: Most machines limited to $30 cm^3$ build area
  - CubeSat product line identified as ideal test case due to size and complexity
- Candidate manufacturing processes were identified
  - Electroforming (EL-forming) for thin-walled components
  - Selective Laser Melting (SLM) for fine detail components
  - Electron Beam Melting (EBM) for metallic structural components
  - Laser Engineered Net Shaping (LENS™) for metallic and ceramic components
- Aerojet Rocketdyne established additive manufacturing demonstration programs for CubeSat Modular Propulsion Systems
- Additive Manufacturing has enabled highly efficient system integration of necessary components to support high-impulse propulsion systems in 1U form factor

Additive Manufacturing Enables Significant Improvements in Propulsion System Affordability, Responsiveness, and Size

Selective Laser Melting (SLM) and Electron Beam Melting (EBM)

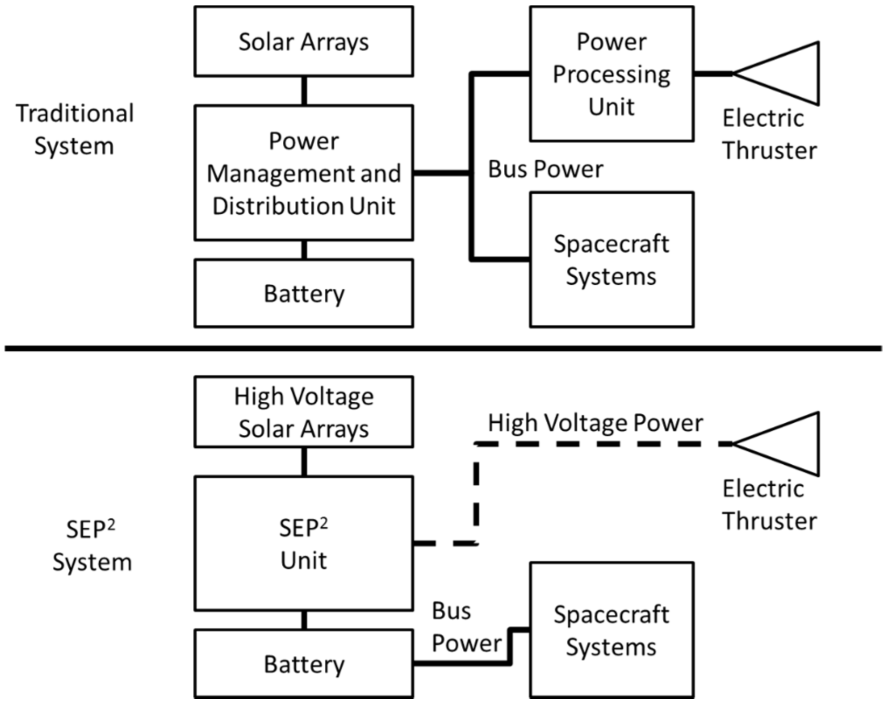
- SLM and EBM deposit powder in layered fashion and apply laser (SLM) or electron beam (EBM) to sinter powder
- Inconel (SLM) and titanium (SLM and EBM) components produced
- Process for inspection and flight qualification is established



SLM & EBM Successfully Applied to MPS-100 Product Line

SEP^2 System Architecture

- Low ΔV EP for CubeSats has been offered by several companies ; however these systems have realized little mission utility.
- An apogee solar electric propulsion (SEP) system is desired that can provide significantly more ΔV than chemical systems
- Cost and mass of electronics in typical apogee electric propulsion solutions are prohibitive
- Integrated Solar Electric Power and Solar Electric Propulsion (SEP^2) system enables low cost and mass electric propulsion for CubeSats



SEP^2 Architecture Enables Apogee Electric Propulsion for CubeSats

CubeSat Modular Propulsion System Capabilities

CubeSat Modular Propulsion System Capabilities

Mission Maneuver	MPS-110	MPS-120	MPS-130
Initial deployment /scatter ~5m/s)	~8kg	~160kg	~250kg
Constellation deployment & re-phasing (1/2 day, 500km maneuver)	6°	113°	180°
Drag make-up for low flight (90 day mission; min. altitude)	>289km	>200km	>190km
Orbital maneuvering (3U, 3.3kg mass SV) - altitude gained from LEO, km - altitude gained from GEO, km	13m/s 23 360	260m/s 480 8170	418m/s 800 14400
Satellite inspection/prox-ops		Capable	Capable
GEO operations		Capable	Capable
Formation flying		Capable	Capable

Near-Term CubeSat Modular Propulsion Systems Enable Significant Maneuvering Capabilities

Constellation Deployment/Re-Phase Capabilities

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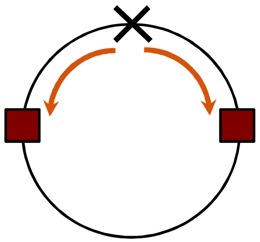

2 Satellites

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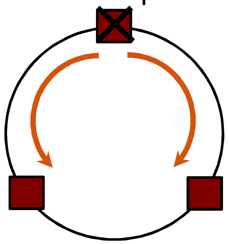

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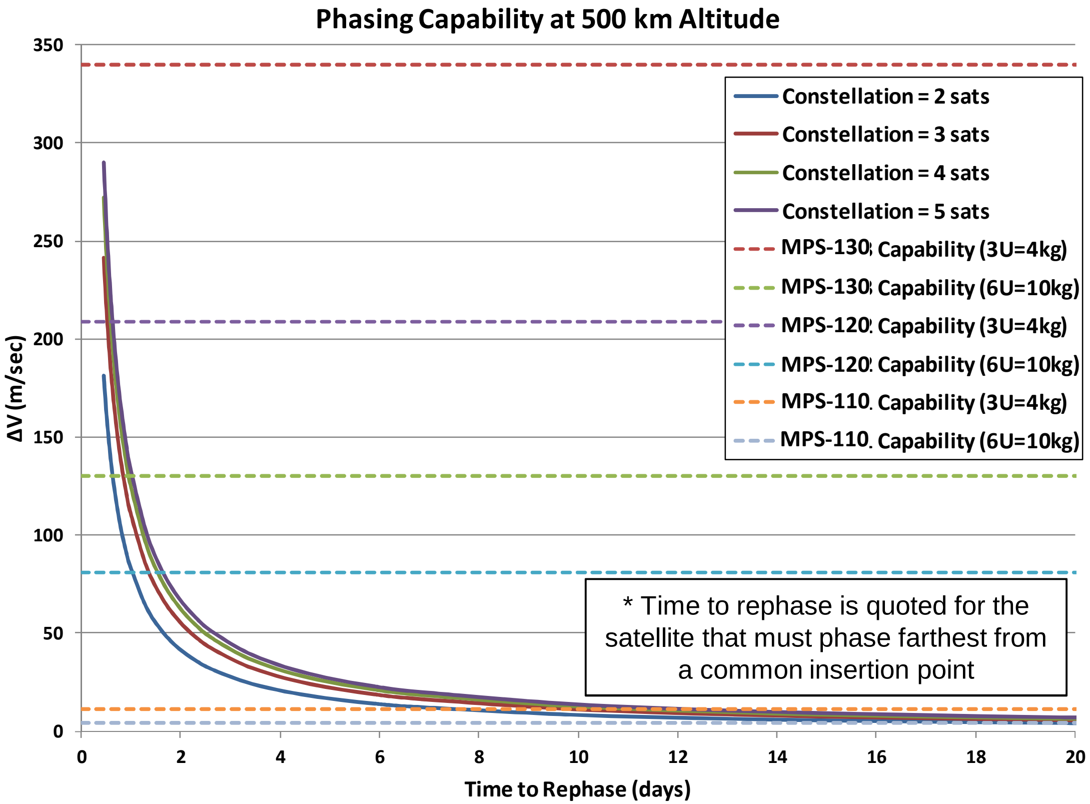

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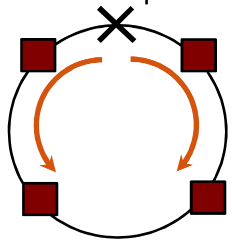

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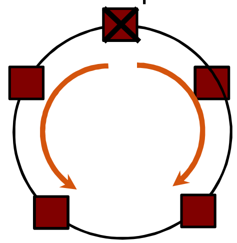
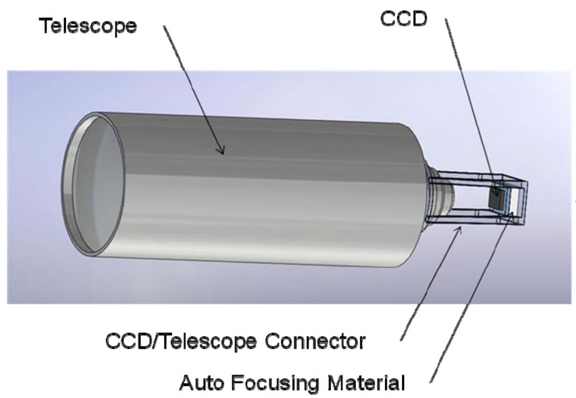


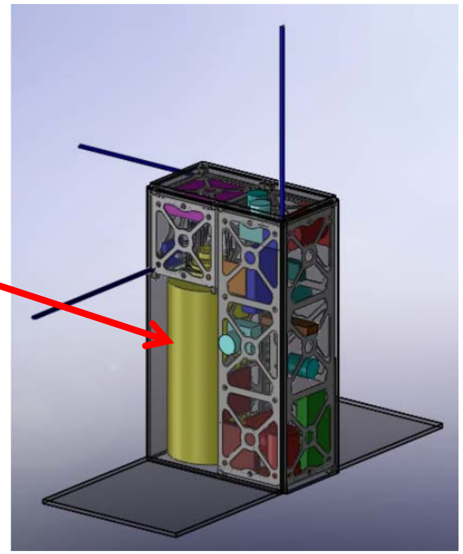
5 Satellites

Near-Term CubeSat Modular Propulsion Systems Enable CubeSat Constellation Deployment and Re-Phase Maneuvering

Conceptual Low Flying Imaging Satellite

- Resolution capability of 1.29 arc-sec with a Maksutov-Cassegrain two-mirror COTS optical system exist today:
  - Reference either Naval Postgraduate School TINYSCOPE CubeSat or design study by University of Washington students below:
  - http://www.agi.com/downloads/partners/edu/UW_PDR_2009_paper.pdf
  - Optical system can fit within a 2U volume and weighs 1.68 kg with upgrade options to carbon fiber construction for lighter weight and less distortion due to thermal effects
  - Optical system compacts a 1.25 m focal length into ~20 cm with 9cm aperture diameter
- A CCD of at least 10 megapixels would be sufficient to capture images



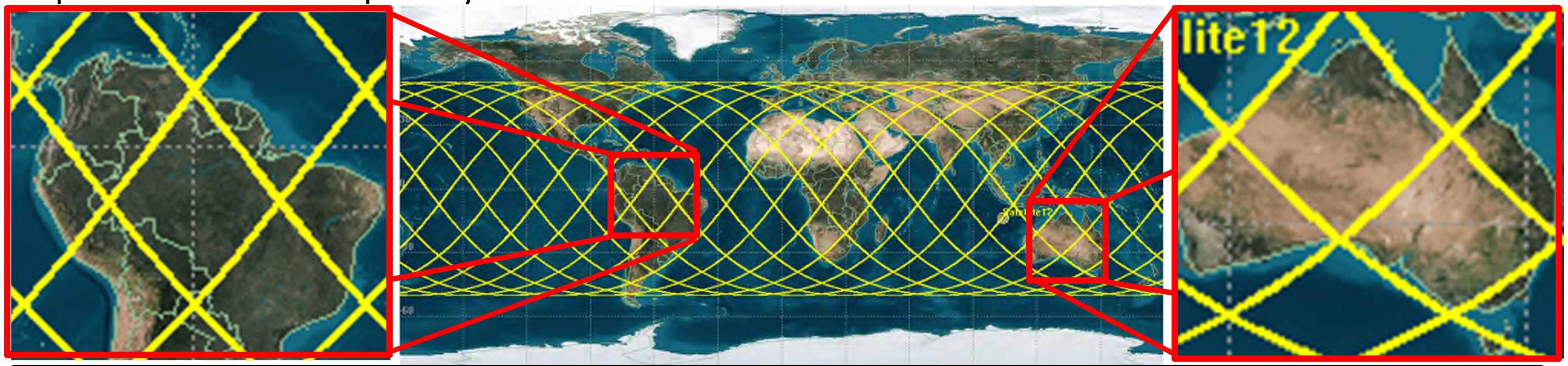


COTS Imaging Systems Can Fit In CubeSat Volumes

Low Flight Capabilities: Conceptual CubeSat Imager Mission

- Repeating ground track orbits can be used to support short and long-term change detection for global map data, crop management, climate monitoring, etc.
- Circular orbit at 262 km and 50° inclination (shown below) provides 1.7 m resolution capability with repeating ground tracks even after one months of operation
- Propulsion enables up to 9 months of mission life compared to less than a few days without propulsion
- 16 unique tracks, with 1 revisit per day; intersection points provide two revisits per day

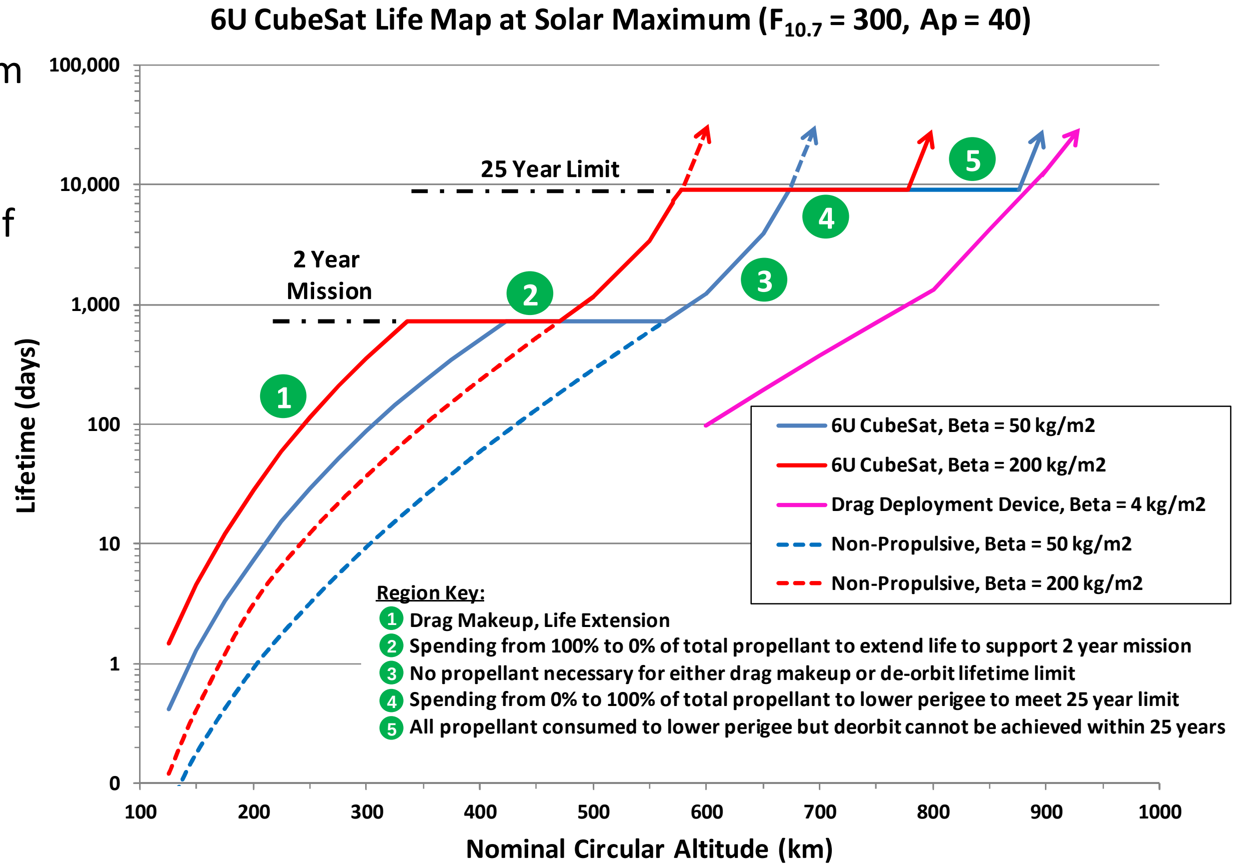
Lifetime (days) for 6U (10kg S/C) at 262 km			
	MPS-110	MPS-120	MPS-130
	Ballistic Coefficient = 50 kg/m^2		
Solar Max	4.5	43.0	66.0
Solar Nom	11.1	183.4	286.9
Solar Min	27.5	402.0	626.9
	Ballistic Coefficient = 200 kg/m^2		
Solar Max	19.0	169.3	259.9
Solar Nom	44.0	776.0	1215.9
Solar Min	109.4	1712.5	2675.1



CubeSat Propulsion Enables Repeating Ground Track Orbits At Low Altitudes Providing a Niche for CubeSat Imagers

Orbital Maneuvering Capabilities: Collision Avoidance

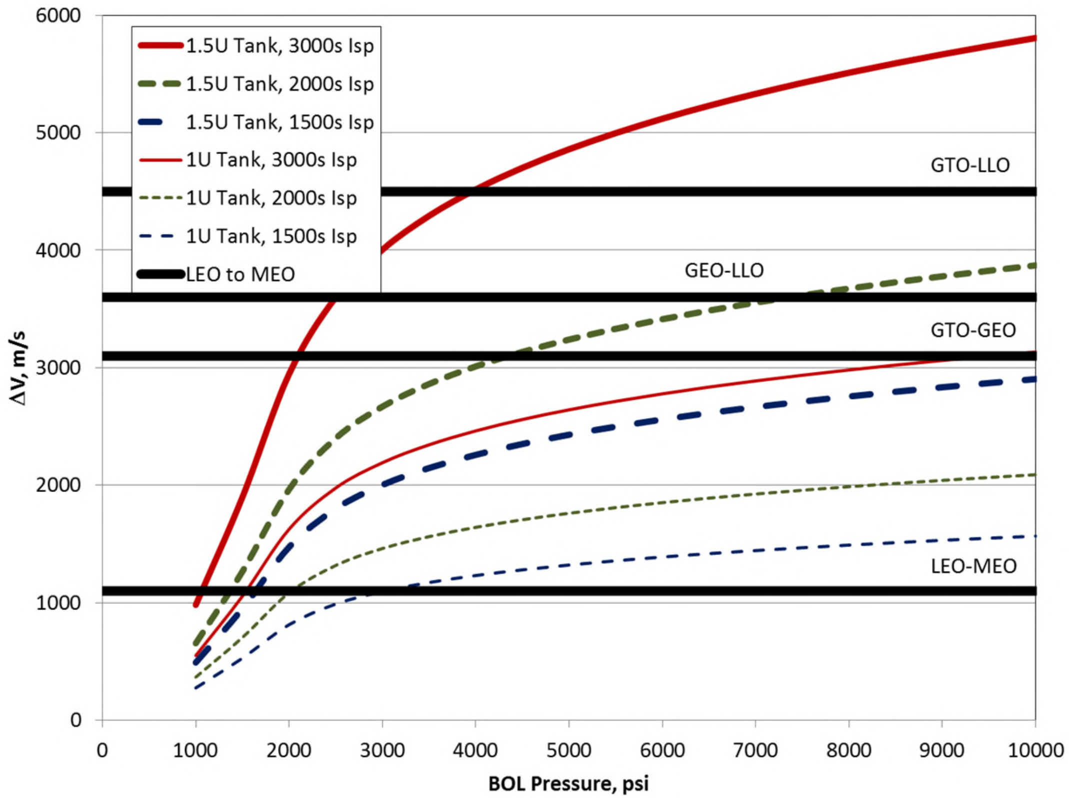
- Recent collision of Ecuador Pegasus CubeSat underscores need for propulsion capability to avoid debris stigma
- High-impulse propulsion system enables collision avoidance maneuvers and deorbit capability to mitigate growth of space debris due to collisions
- This also allows mission planners to design missions at higher altitudes without worrying about 25 year rule
- Will drive CubeSat component providers to manufacture components with increasing longevity to meet increasing mission lifetimes enabled by life-extending propulsion



High-Impulse Propulsion Capability Mitigates Growth of Space Debris and Enables Longer Lifetime Missions

Orbital Maneuvering Capabilities: Low Thrust Missions

- ΔV is a function of BOL Storage pressure
- 1.5U tank, 3000s Isp offers significant mission capabilities at low pressures
- MPS-160 enables GTO rideshare CubeSats to access GEO and the Moon
- Further detailed study is needed to ensure reasonable trip times and payload masses can be achieved.



MPS-160 Potentially Enables GTO Rideshare CubeSats to Access GEO and the Moon

Summary

- A wide range of high-impulse propulsion solutions are required to enable the CubeSat platform access to newer, challenging, game-changing missions:
  - Imaging, Constellation Deployment
  - TPED
  - Collision Avoidance
  - High-altitude Deorbit Capability

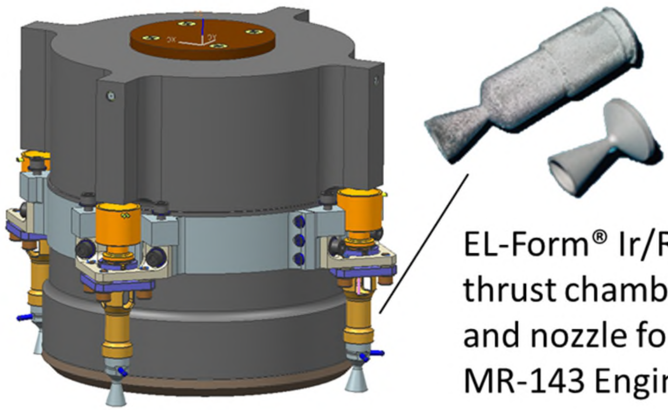
- Additive manufacturing design philosophy has been applied to Modular Propulsion Systems for CubeSats product line to enable low-cost, volume-optimized systems

Aerojet Has Established Additive Manufacturing Capabilities for Modular Propulsion Systems

Backup Slides

Electroforming (EL-Form®)

- EL-Form® enables refractory metals to be formed into dense, non-porous and crack-free layers
- Molten salt electrolytes enable electrodeposition of compact metal layers onto a mandrel
- Can create component structures on mandrels and/or dense coatings applied to existing parts
- EL-Form® Ir/Re chamber and nozzle produced for MR-143 engines in MPS-130 system



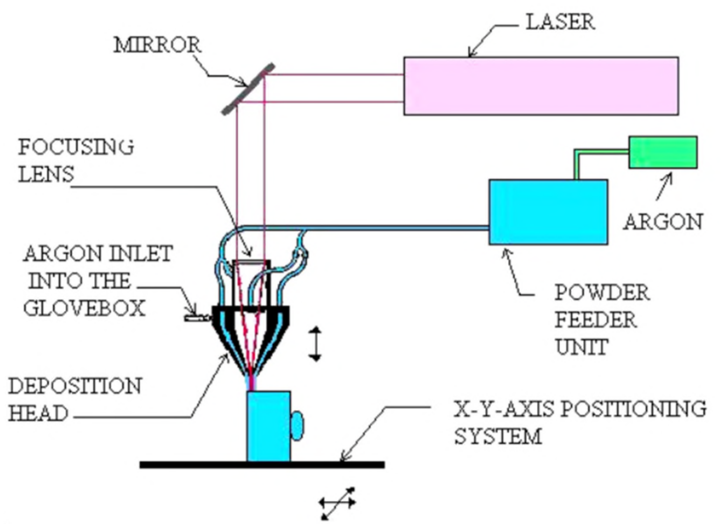
EL-Form® Ir/Re thrust chambers and nozzle for MR-143 Engine

MPS-130 System

EL-Form® Successfully Applied to MPS-100 Product Line

Laser Engineered Net Shaping (LENS™)

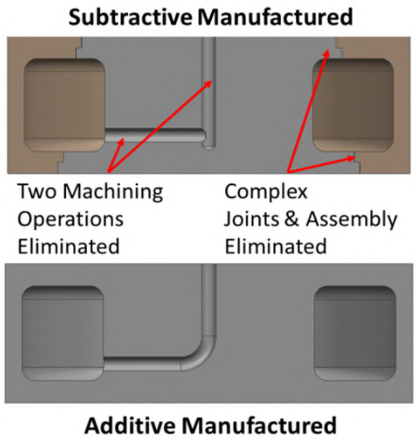
- LENS™ simultaneously sprays and sinters powder, reducing need for powder removal
- Objective is to develop alternative to EBM for titanium parts with small passageways
  - LENS™ does not produce entrained sintered powder so cleaning process is significantly simpler
- LENS ™ enables components printed from multiple materials
- Demonstration focused on printing MPS-130 tank (similar to MPS-120)

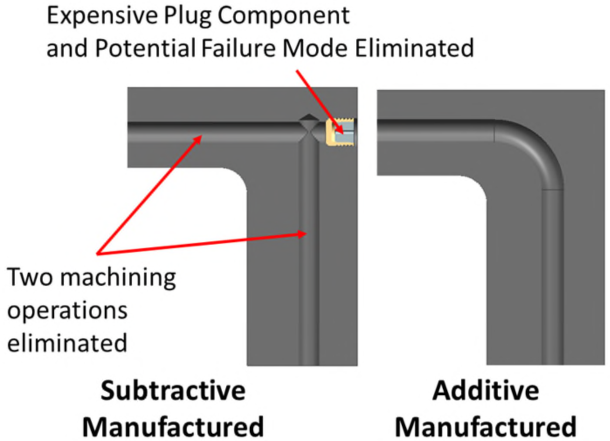


LENS™ Development and Evaluation is Ongoing

Additive Manufacturing Enables Significant Improvements in Affordability, Responsiveness, and Size

- Additive Manufacturing
  - Adds material layer by layer to fabricate parts from CAD data
  - Current machine limit of ~30cm^3 build envelopes insufficient for large systems, but supports full CubeSat Propulsion System
  - Significantly reduces manufacturing cost and lead time
    - Little/no tooling or setup, and option for embedded tooling
    - Consumes only material required by the part, eliminates cutting tools and fluids
  - Enables embedded features that greatly improves spatial utilization, manufacturing, and test capabilities
  - Enables standard offerings to be customized and qualified quickly and affordably

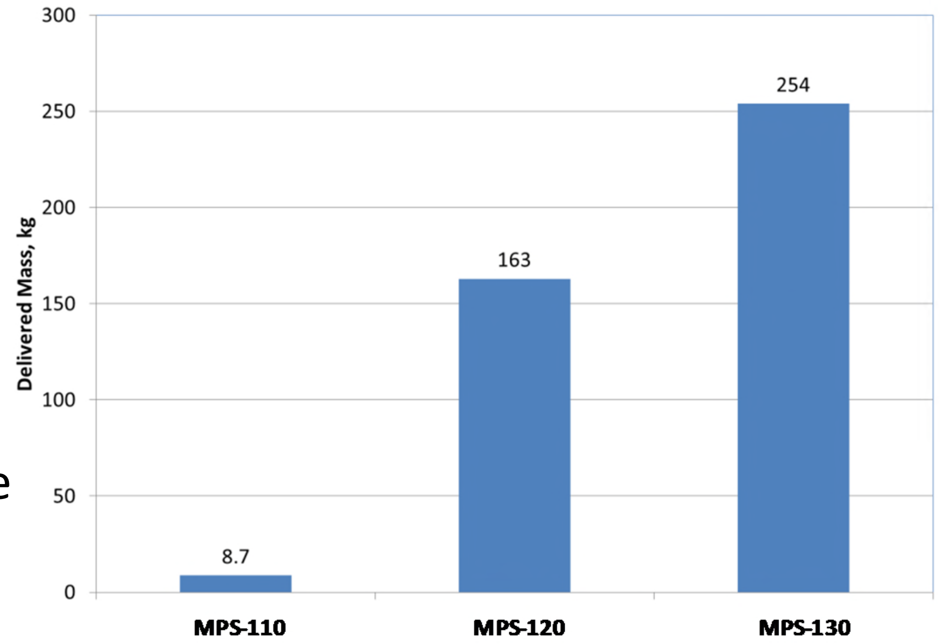




Aerojet has developed and applied additive manufacturing design philosophy to MPS-100 Product Line

Deploying Multiple Secondary Payloads

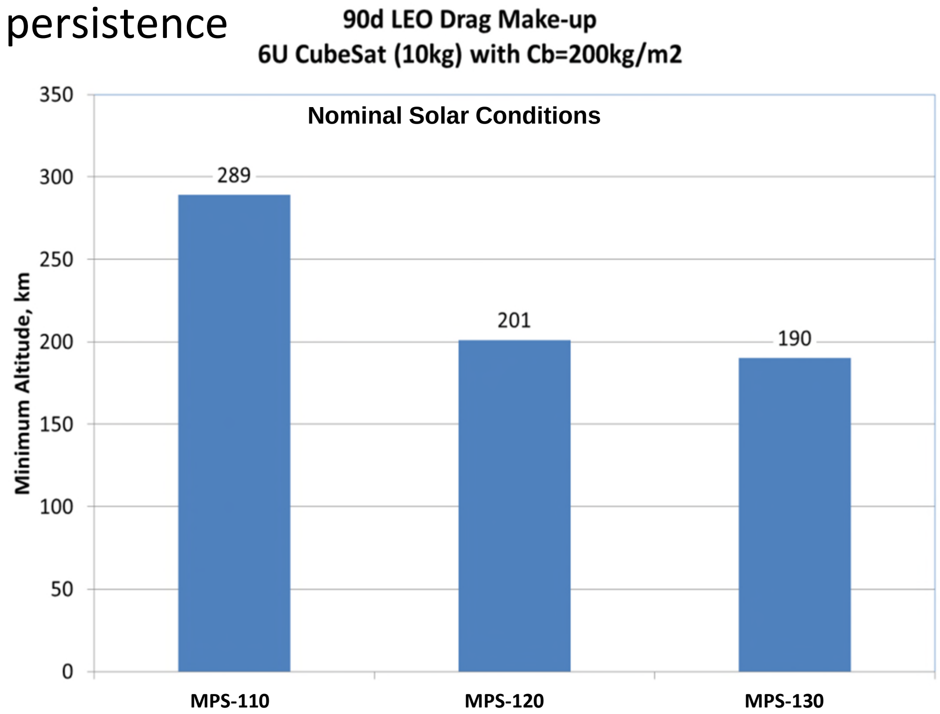
- CubeSat customers have a need to deploy multiple CubeSats from a single launch vehicle
- ~5m/s propulsion is required per CubeSat to enable satellites to escape the launch vehicle's orbit in order to prevent collisions due to coalescence
- Modular Propulsion Systems can be used as
  - A dedicated propulsion system to deliver single CubeSat/SmallSat
  - A stage to deliver multiple CubeSats



Near-Term CubeSat Modular Propulsion Systems Enable Deployment of Multiple Secondary Payloads

Counteracting Drag for LEO Missions

- CubeSat customers have expressed a desire for persistent LEO imaging and communications
- Propulsion is required to deploy and counteract drag in order to enable low flight and significant persistence



Near-Term CubeSat Modular Propulsion Systems Enable Persistent LEO Imaging and Communications Missions

LEO Imaging, Operational Responsiveness

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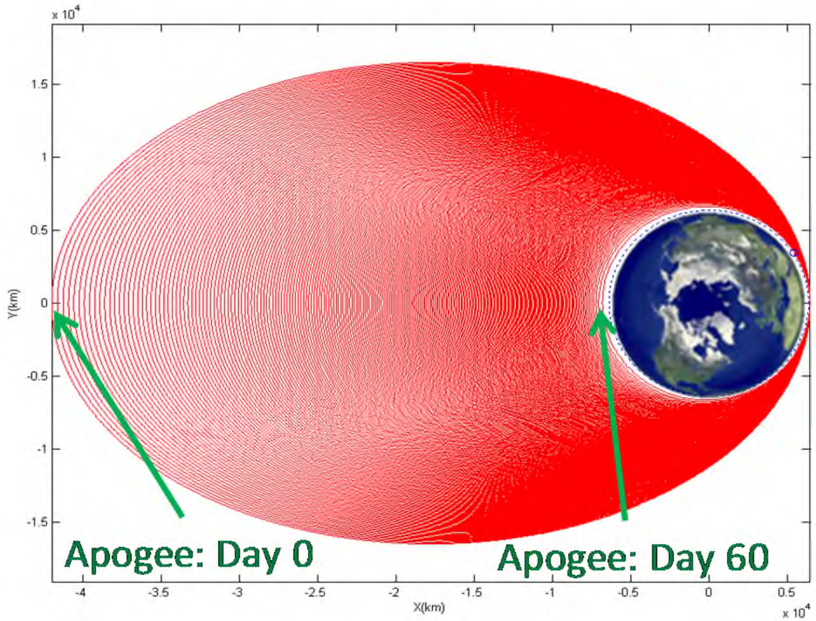
- 3U and larger CubeSats will eventually be capable of being launched by dedicated nanosatellite and microsatellite launch providers

- Allows imaging satellite to select optimal orbit for specific area of interest
- This on-demand capability lends immediate tracking resources to organizations responsible for monitoring disaster situations like tornados, oil spills, forest fires, etc.
- Useful for situations where other space-based assets are either not accessible or too expensive to utilize in comparison to a CubeSat over the course of the expected disaster resolution timeline.

Operationally Responsive CubeSat Assets Will Provide Sufficient Imaging Capability at Low Cost

Tasking, Processing, Exploitation, and Dissemination

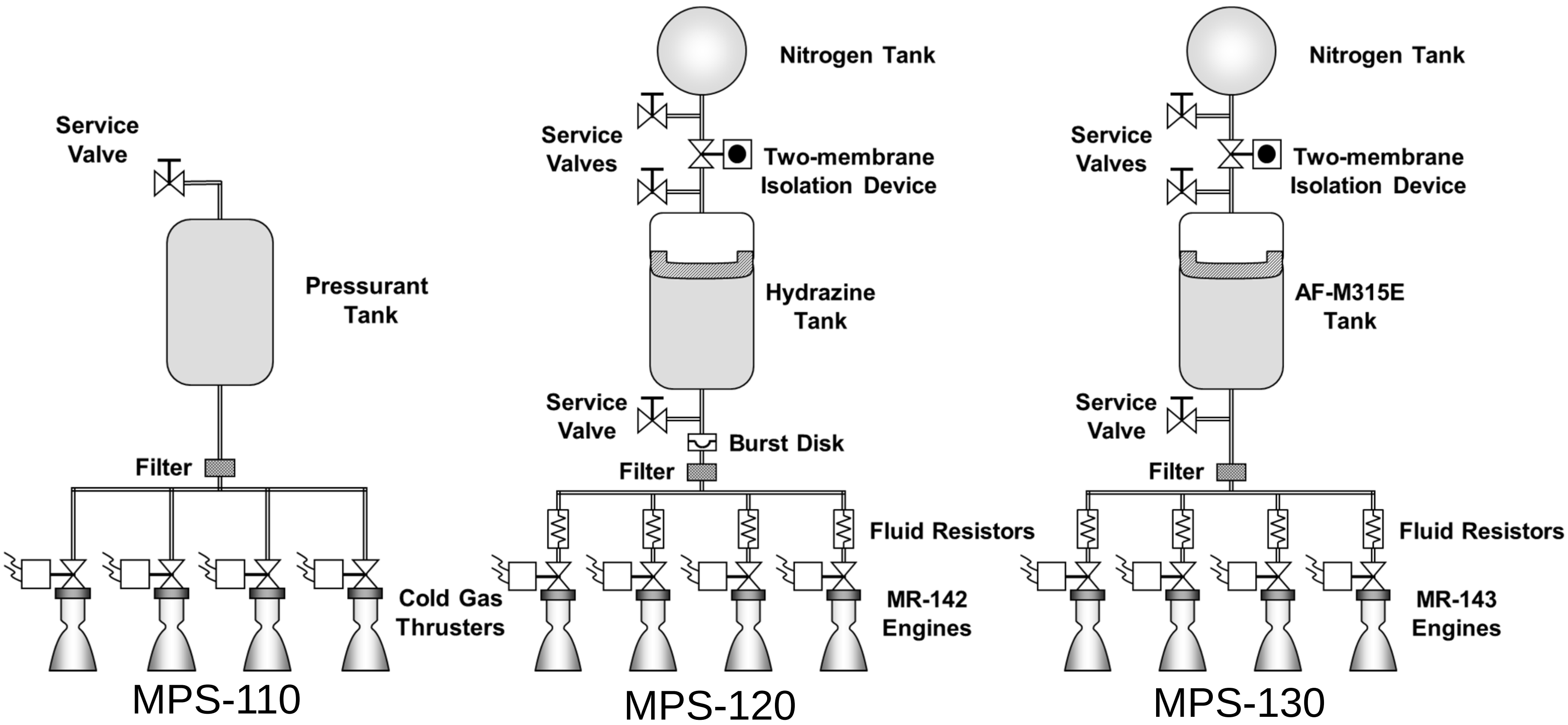
- CubeSats have historically been challenged with high data rate missions due to:
  - Difficulty of establishing reliable and repeatable communication links with ground stations
  - Limited power capability to support burst mode transmission when a ground station becomes available
- Recent successes with high gain deployable antennas offer the potential to communicate from higher apogee altitudes, where ground stations are more frequently within a given swath angle
- With the launch of NRO-36, the Aft Bulkhead Carrier (ABC) has been proven as a potential rideshare location for GTO dispersal
- Higher apogee orbits can be obtained with CubeSats by deploying in GTO and lowering perigee
- "Lock" in orbit at desired apogee altitude by utilizing apogee burn to raise perigee out of high-drag regime
- Depending on desired orbit, more efficient use of propulsion than orbit-raising burns from typical CubeSat LEO dispersal orbits



High-Impulse Propulsion Capability Provides Access to Any Apogee Altitude Orbit

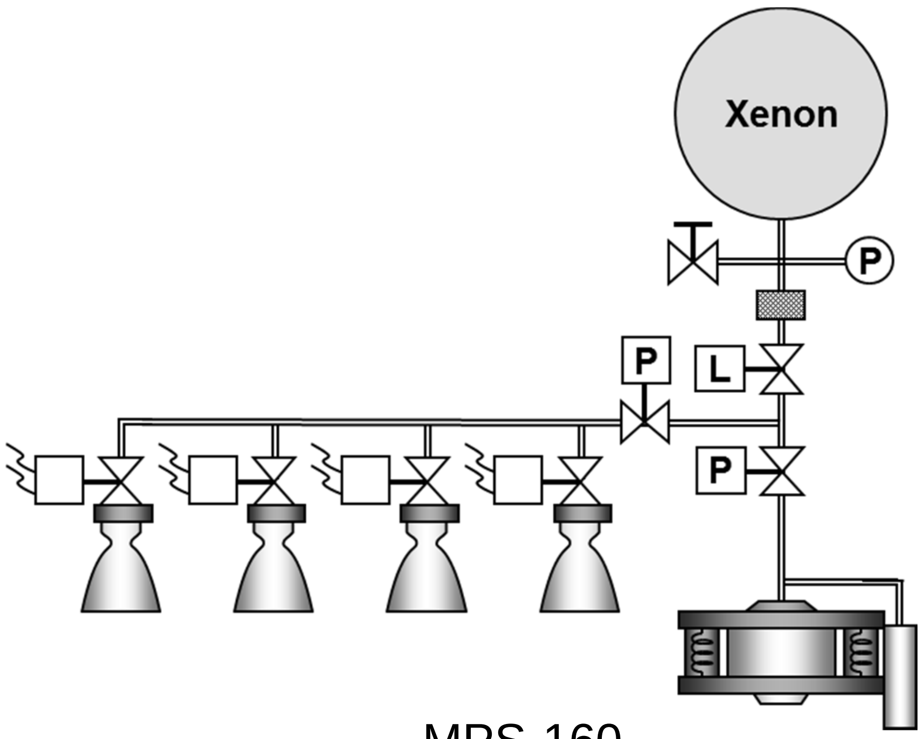
Fluidic System Schematics

- MPS-110, -120, and -130 use common: filter, service valves, and propellant tank approach
- MPS-120 and -130 use a common isolation system
- Additive manufactured piston tank/structure scalable from 1U to 2U in length for "XL"
- All systems are compliant with AF-SPCMAN 97-10



Fluidic System Schematics

- MPS-160 implements SEP[2] architecture
- MSP-160 supports multiple low power electric thrusters currently in development enabling support for a wide range of missions and technology demonstrations



MPS-160