Green Propulsion Dual Mode (GPDM) Path to Flight

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Abstract: A team led by the NASA Marshall Space Flight Center has been developing an integrated dual mode propulsion system operating on ASCENT propellant. The small spacecraft project leveraged a wide range of NASA Space Technology Mission Directorate funding opportunities to enable the mission. The Green Propulsion Dual Model project is manifested for launch in January 2026, demonstrating a single integrated propulsion system operating off a common ASCENT propellant tank for both a catalytic combustion thruster and a set of electrospray thrusters. The objective of the flight demonstration is to mitigate risks of future, larger scale, dual mode operational systems while achieving an overall system Technology Readiness Level of 7 or higher for specific applications.

I. Motivation and Background

Propulsion continues to be a driving subsystem for spacecraft performance and is especially challenging to smaller spacecraft. For large spacecraft maximizing propulsion performance, it is standard practice to fly spacecraft with both high-thrust chemical combustion systems and low-thrust electric propulsion systems. Single propellant dual mode systems (e.g. hydrazine) have been demonstrated with good performance for combustion thrusters and moderate performance electric propulsion systems. Dual disparate propulsion systems are routine with good performance for combustion thrusters (e.g. hydrazine) and high-performance electric propulsion systems (e.g. Xenon). Numerous studies have shown advantages of dual mode common propellant implementation [1], but few options have been demonstrated with potential for both high performance high-thrust and low-thrust systems. The advantages to performance are not limited to only the thruster performance, but also due to packaging advantages of a common propellant tank over two tanks of different propellants and mission flexibility with a single propellant reservoir serving either system as the operations require.

In September 2013, NASA's Game Changing Development (GCD) program competitively awarded three teams with contracts to develop Micro Electrospray Propulsion (MEP) systems from Technology Readiness Level-3 (TRL-3), experimental concept, to TRL-5, system validation in a relevant environment. The project was planned for 18 months of system development. One of the three awards was for the Scalable ion Electrospray Propulsion System (S-iEPS) development led by the Massachusetts Institute of Technology (MIT). [2] The MIT S-iEPS benefited from many years of component level development and experimentation. The S-iEPS is a microelectron mechanical system based on ionic liquid emission. An electrostatic field is used to extract and accelerate both

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positive and negative ions from a conductive salt that remains liquid over the operational temperature range. The concept is scalable in that the thrusters can produce flat panel arrays.

Near the conclusion of the NASA MEP project, in 2014, NASA funded a short test to determine performance of the S-iEPS using the Advanced Spacecraft Energetic Non-Toxic (ASCENT) propellant, and the performance exceeded expectations and demonstrated viability for ASCENT MEP. In parallel to the electrospray propulsion system, investments continued in ASCENT-based chemical combustion thruster development, including the first flight of combustion thrusters on NASA's Green Propellant Infusion Mission (GPIM) in 2019.

The overall timeline of GPDM investments is illustrated in figure 1. GPDM leveraged a wide range of Space Technology Mission Directorate (STMD) investment opportunities. Originally, MIT was developing the underlying MEP system through a Game Changing Development (GCD) award. GCD is the STMD program primarily focusing on rapid technology maturation from TRL 3 to TRL 6. NASA MSFC then funded Center Innovation Fund (CIF) augmentation to MIT on the Microelectrospray Project (MEP) as the first test of electrospray Propulsion using ASCENT. CIF projects are small internal NASA investments, typically for proof-of-concept development of novel technologies with significant potential. Based on the successful CIF, NASA continued to mature the concept of ASCENT dual-mode components leveraging multiple investments through NASA Small Business Innovative Research (SBIR) and Small business Technology Transfer (STTR) programs for technology development and delivery of the flight hardware elements. Experience and residual hardware from Lunar Flashlight [3] were leveraged, including the existing partnership with the Georgia Institute of Technology for control avionics and system integration. The project also continued research through NASA Space Technology Research Fellowships (NSTRF) to support maturing of the electrospray system for extended lifetime and performance optimization. Finally, the Small Spacecraft Technology (SST) Program funded the flight of the system, originally as the propulsion system with an integrator [4], and later for the full spacecraft.

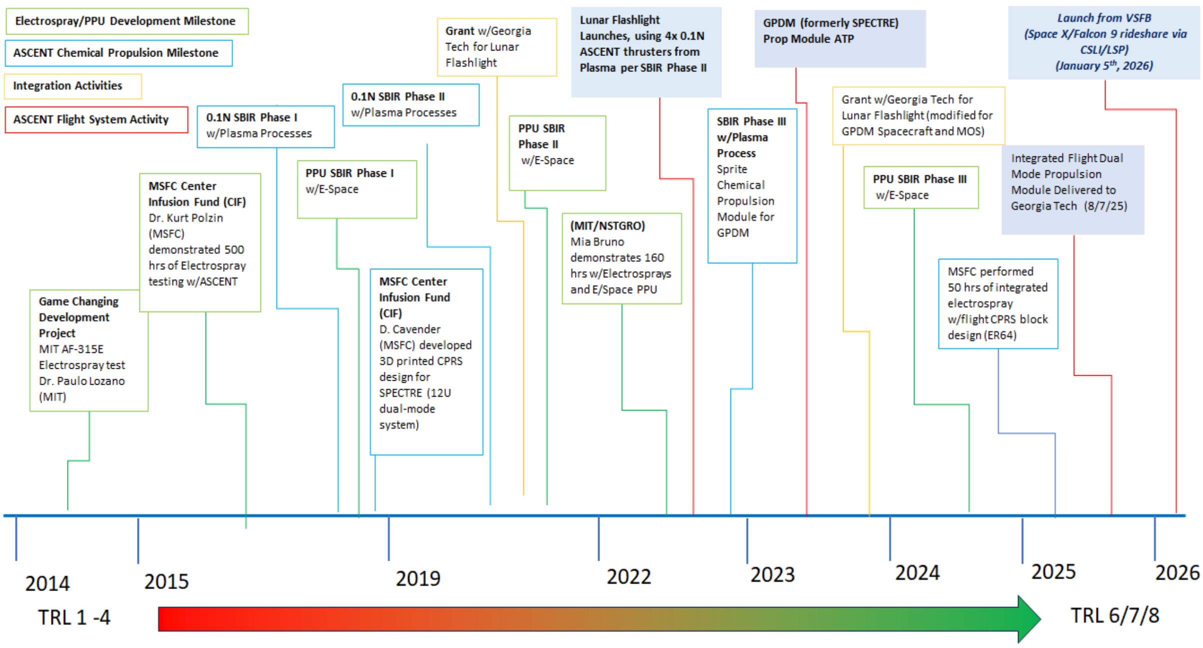

Figure 1: Timeline of Green Propulsion Dual Model elements.

II. Stakeholders and Team

While the official GPDM project is funded by the Small Spacecraft Technology program out of the STMD of NASA, there are several stakeholders in the success of the mission. The Air Force Research Laboratory (AFRL) and Unites States Space Force (USSF) have significant interest in the pervasive use of ASCENT propellant, but also dual mode operations. The flight mission is managed by the NASA Marshall Space Flight Center (MSFC) within the Science and Technology Office (ST) with technical work performed within the Engineering Directorate (ED), specifically the Propulsion System department (ER) for the design, development and testing of the propulsion system. Mission Operations are also supported by the MSFC mission operations department (HP), who developed the software for the GPDM Spacecraft to ground communication. The mission is also supported by industry and academic partners. The Massachusetts Institute of Technology led the development and delivery of the electrospray thrusters. The Georgia Institute of Technology led the spacecraft bus development and integration, in addition to supporting functional testing and mission operations. Plasma Processes' Rubicon Space Systems Division provided the Sprite chemical propulsion subsystem and provided hardware integration support. E-Space, Inc. led the design, development and flight unit delivery of the electrospray electric control boards and supporting hardware integration. The spacecraft structure was fabricated by the Georgia Technology Research Institute (GTRI). A grant with Georgia Tech included the procurement and integration of commercial off the shelf (COTS) spacecraft components including the antenna (High-Farr), radio transponder/receiver (Quasonix), attitude determination and control system (Blue Canyon) and avionics (Sierra Space).

III. Mission Definition and Objectives

The Green Propulsion Dual Mode mission, as currently defined, is to perform a flight validation of low-toxicity propellant in a dual operation configuration, consisting of both a high-thrust chemical mode and a low-thrust electrospray electric mode with a common propellant tank and feed system. The mission is a low-cost high-

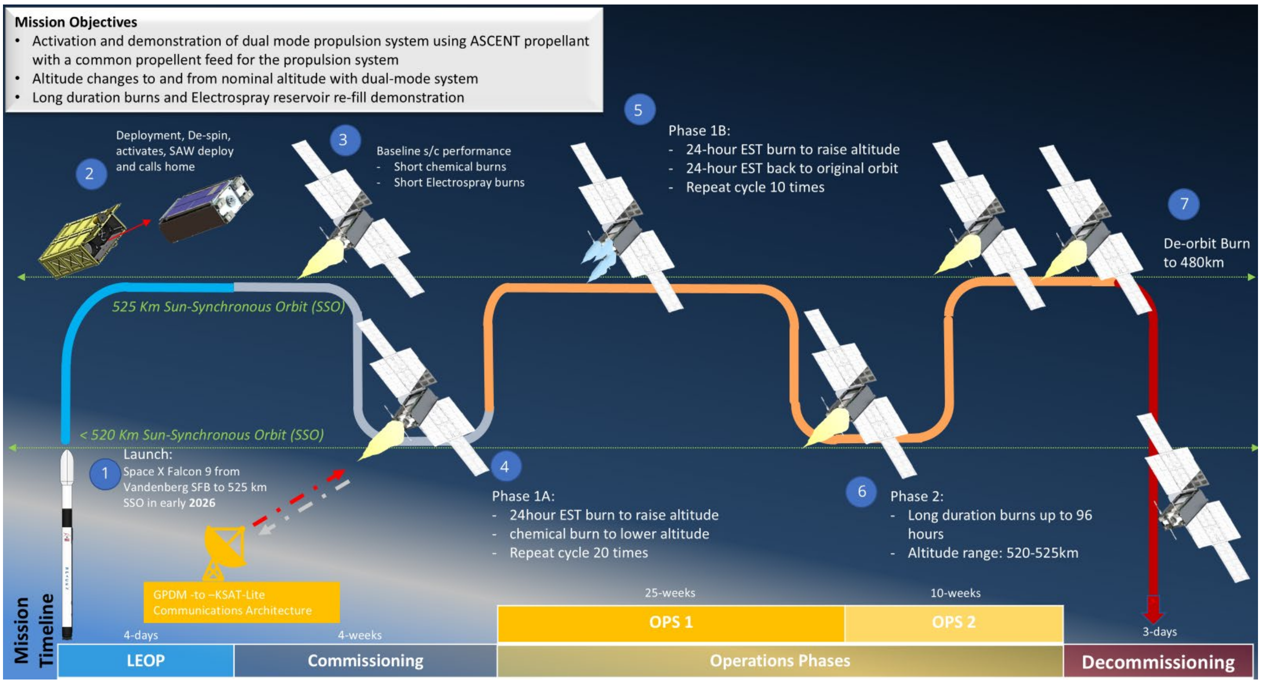

Figure 2: Concept of Operations for the GPDM Mission.

risk NASA Procedural Requirement (NPR) 7120.8 Research and Technology flight demonstration within a 6-U CubeSat. The total mission operational duration is 9-months, with the high-level Concept of Operations (ConOps) shown in figure 2. The minimum success criteria for the Level 1 requirements include one successful chemical propulsion maneuver and one successful electrospray maneuver during space operations. The mission must also demonstrate on-orbit filling of the electrospray thruster reservoir for minimum success. For full success, the spacecraft must demonstrate on-orbit filling of the electrospray reservoir, long-duration electrospray operations and then refilling of the reservoir. Full success also requires multiple chemical and electric mode maneuvers, performing orbit change and attitude control using the dual mode propulsion system.

The spacecraft is launched as a 6-U rideshare payload. The baseline operations will launch on a SpaceX Falcon 9 from Vandenberg Space Force Base into a 525km altitude Sun-Synchronous Orbit (SSO). After deployment from the CubeSat dispenser, the spacecraft will activate, gain attitude control, deploy its solar array and make communications contact with the operations center. After 4-weeks of health checkout and commissioning, the spacecraft will perform short chemical and electric mode maneuvers to characterize in-space performance. Following meeting the minimum success criteria of the mission, the spacecraft will perform multiple cycles of orbit raising and lowering using both electric and chemical modes over 25 weeks of operations. The spacecraft will then perform long duration maneuvers for 10 weeks, still staying within the 520km to 525km altitude range. Finally, the spacecraft will perform deorbit maneuvers dropping the altitude down below 480km orbit to allow drag to takeover and meet orbit lifetime debris mitigation requirements.

IV. Propulsion System Development and Testing

GPDM and precursor activities were focused on propulsion system development and testing of both the chemical and electrospray systems. The integrated GPDM propulsion system assembly is shown in figure 3, including the electrospray thruster assemblies and Power Processing Units (PPUs), the control avionics, the Sprite chemical propulsion module, and the Compact Pressure Reduction System (SPRS).

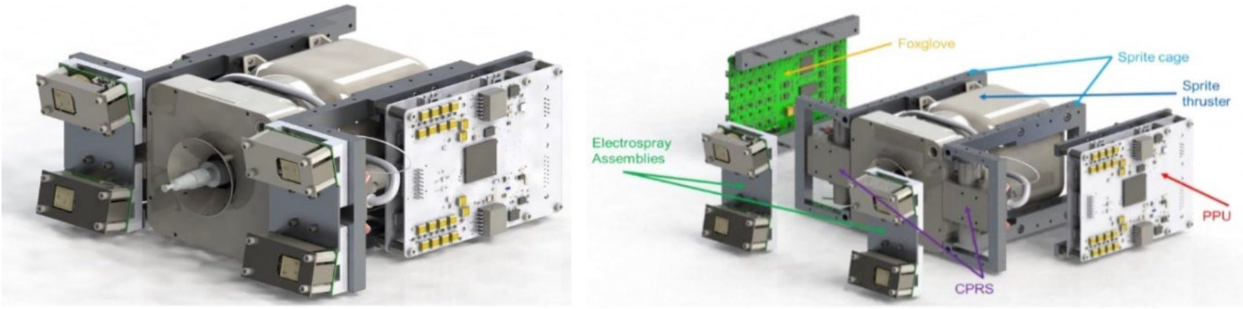

Figure 3: GPDM Propulsion System Assembly.

Sprite Chemical Propulsion Module

Sprite serves as the core of the Dual Mode Propulsion System (DMPS). Sprite is a self-contained chemical propulsion system developed and delivered by Rubicon Space Systems, a subsidiary of Plasma Process, LLC. The Sprite system includes a titanium pressure vessel additively manufactured and integrated with a 100mN ASCENT catalytic combustion thruster as shown in figure 4. The Sprite is a blowdown system operating between 275 psi to 60 psi.

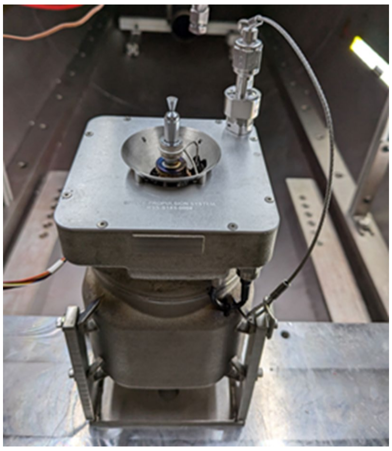

Figure 4: Sprite Chemical Propulsion Module

Electrospray Thrusters and Power Processing Units

The DPMS includes four (4) ASCENT electrospray thrusters as a variant of the ion Electric Propulsion System developed and delivered by the MIT Space Propulsion Laboratory under an STTR, shown in figure 5 left. The electrospray system includes an emitter array aligned with an extractor electrode to accelerate ions from the ASCENT propellant. The ASCENT propellant is fed into the propellant reservoirs with a porous membrane that vents the water content and volatiles within the propellant prior to extraction. The electrospray thrusters have a maximum inlet pressure of 10 psi, which requires a pressure reduction from the main propellant tank. The electrospray system is powered by Power Processing Units (PPUs) developed and delivered by Espace Inc. shown in figure 5 right.

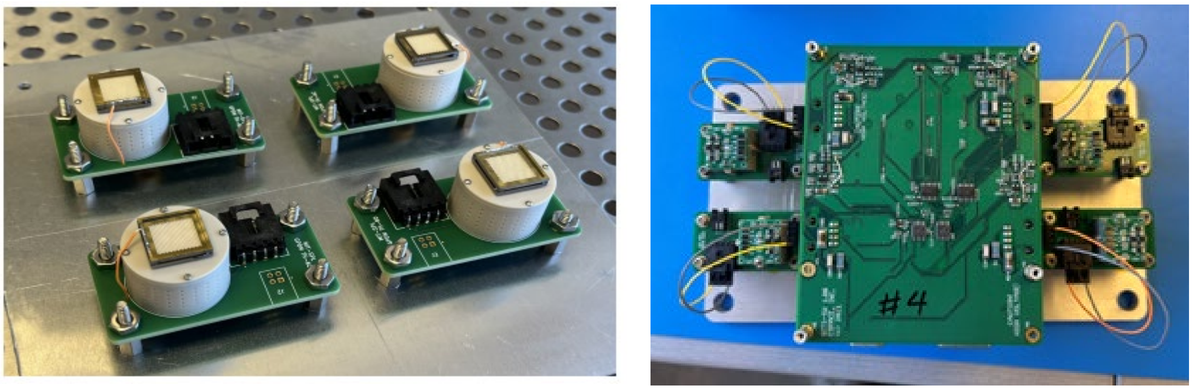

Figure 5: Electrospray Thruster Assemblies (left) and Power Processing Units (right).

Compact Pressure Reduction System

To provide the low pressure to the electrospray system from the high pressure common propellant tank, a compact pressure reduction system (CPRS) was required. Earlier investments include additively manufactured versions to optimize for volume. However, the additively manufactured version was prone to foreign object debris (FOD) and brazing challenges. When the scope of the MSFC project grew to include the entire spacecraft, the team was able to optimize the total vehicle layout and allowed the CPRS to use proven components with machined parts. At the cost of higher volume, COTS viscojet flow restrictors were installed upstream of each thruster valve. The thruster valves were heritage from the Lunar Flashlight propulsion system. The interfaces to the electrospray thrusters used COTS fittings for polymer tubing compatible with metal ports. The completed flight CPRS is shown in figure 6.

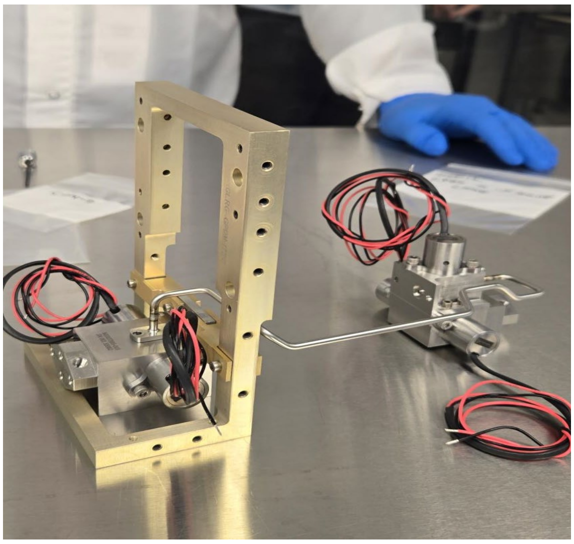

Figure 6: Compact Pressure Reduction System.

The CPRS can be operated in two different modes, vapor pressure mode or direct transfer mode. The vapor transfer method is an extremely low-pressure propellant transfer, albeit slow. Leveraging the properties of ASCENT and the porous reservoirs, the vacuum environment allows a path for the water to vent. Gas bubbles form, and the bubbles move to the reservoirs while also transferring propellant. Through cycling valve operation, high precision propellant loading is practical. Direct transfer is a higher-pressure propellant transfer performed by opening both thruster and propellant isolation valves. The flow restrictor provides a safe pressure to load the reservoirs in a blow down mode.

Component Testing, Avionics and System Integration

For propulsion system integration, a custom controller was designed, called the Foxglove, developed and delivered by Georgia Tech. The power and telemetry layout of the propulsion system is shown in figure 7 and is an evolution of the controller flown on Lunar Flashlight.

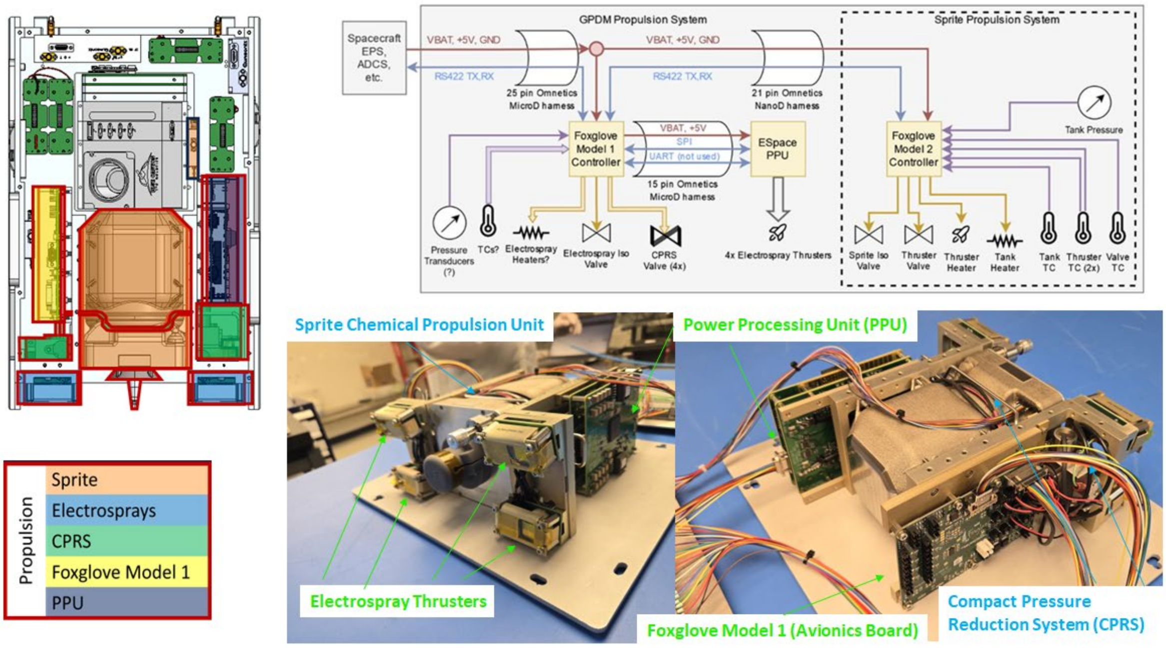

Figure 7: GPDM Propulsion Module Power and Telemetry Layout.

For a rapid low-cost flight demonstration, the project performed significant testing of the propulsion system components due to their low maturity. The project was not simply integration of proven elements. The project included the combustion thruster feed system development with thruster characterization and large test matrices for sensitivity to pressure and temperature. The CPRS was tested repeatedly for electrospray filling demonstrations. Performance testing of all components to the GPDM durations and cycles completed. The electrospray reservoir completed testing with CPRS integration and design changes were implemented. Next, testing included combined chemical thruster testing with electrospray reservoir filling. Finally, the propulsion testing included the combined chemical and electrospray full system operations. Chemical mode and electric mode development testing is illustrated in figure 8.

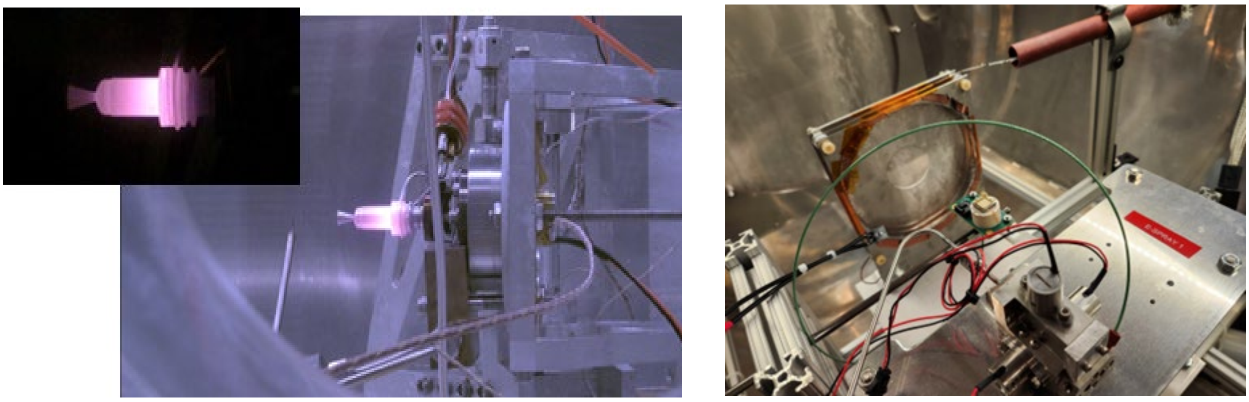

Figure 8: Chemical mode (left) and electric mode (right) testing during GPDM development.

V. Spacecraft Integration

Outside of the propulsion system, the spacecraft is intentionally primarily commercially off-the-shelf components and flight heritage subsystems. The attitude control system is the XACT-50 provided by Blue Canyon Technologies. The spacecraft uses 112W solar array by MMA Design, the antenna is provided by Haigh-Farr, the communication receiver and transmitter are from Quasonix and the flight computer is the Q7 by Xiphos. The spacecraft bus, components with power and telemetry layout are shown in figure 9. The final flight system fits within a standard 6-U rideshare deployer.

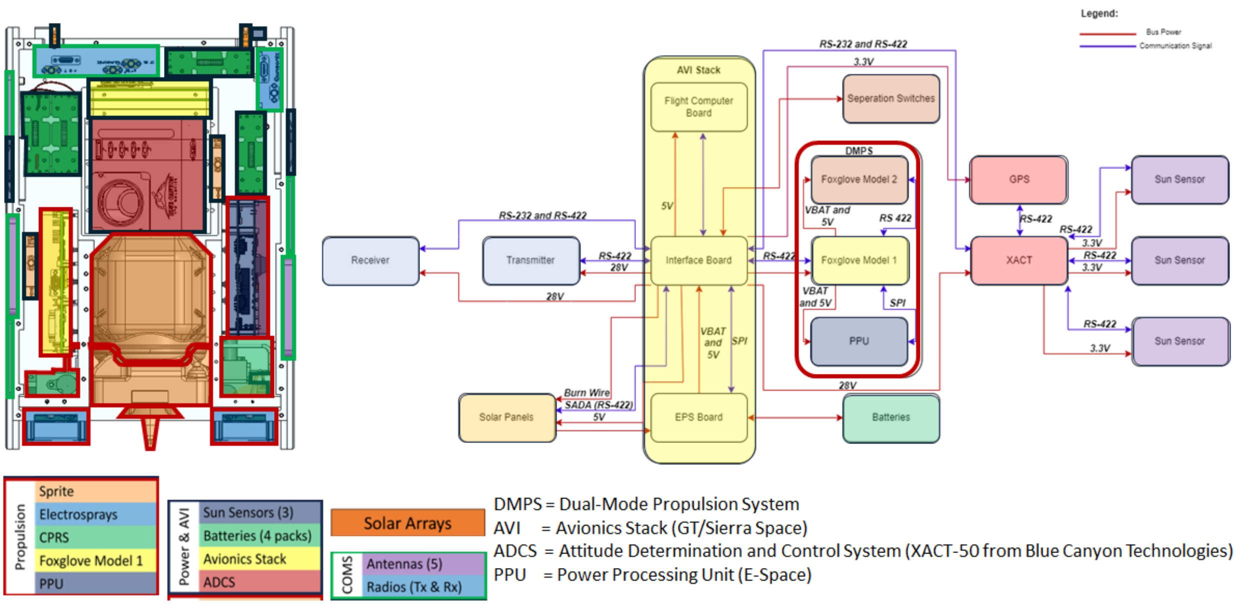

Figure 9: GPDM Spacecraft Power and Telemetry Layout.

VI. Project Lessons Learned and Applied

Several new lessons learned were identify during GPDM development, but lessons learned were also applied from the Lunar Flashlight follow-on project. Additional additively manufactured parts honing and cleaning practices were applied. GPDM also applied additional inspections for obstructions, multiple filters were included and testing validated cleanliness and FOD mitigation. However, future builds highly recommend the general elimination of additively manufacturing components and source propellant tanks when using thrusters and feed system passages of this scale. The concern has been likely eliminated through the use of 500mN thrusters or larger, or even derating larger thrusters with larger throats.

The GPDM Project was also intentionally used as an opportunity to train and provide hands on development and testing with early career employees and/or those flight hardware lead engineering roles for the first time. The lack of previous flight hardware development, testing and quality assurance emphasized the need for strong mentoring, schedule margin and a balance between traditional NASA MSFC flight system rigor with the agility and flexibility with small business and university engineering activities.

VII. GPDM Forward Work and Green Propulsion Investment Strategy

There are remaining tasks before GPDM launch and operations are complete. Also, GPDM is only one project towards advancing domestic application of ASCENT propellant.

Near Term GPDM Activities

The propulsion system integration is complete. The spacecraft final integration is underway at Georgia Tech. The bus avionics integration and checkout is next followed by the attitude control system checkouts. Afterwards, the team will complete final system testing and then thermal vacuum testing. After TVAC, the solar array will be mated with the spacecraft, followed by vibration testing, post-environmental testing, day-in-the-life testing, and then the spacecraft will be shipped back to NASA MSFC. MSFC will then perform pressure system leak testing, EMI testing, spin balance and then hold until the launch date is confirmed. Once within two months of launch, the spacecraft will complete propellant loading, integration with the dispenser, and then shipped for launch.

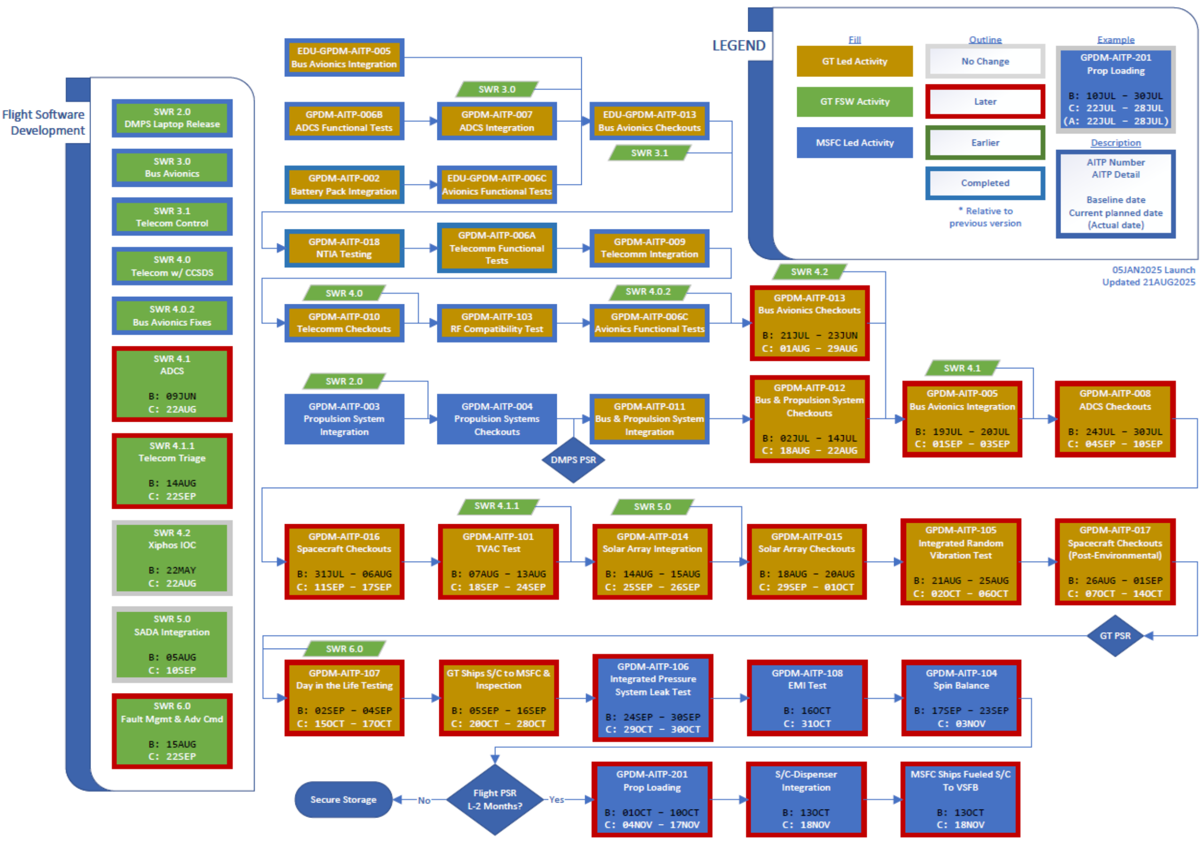

Figure 10: GPDM Final Assembly, Integration and Test (AI&T) Flow.

Green Propellant Technology Development Plans after GPDM

The GPDM mission is a single project within a larger overall strategy for green propulsion technology development leveraging the ASCENT propulsion system. There is a strong desire to move away from toxic hypergolic propellants overall. However, there are significant technology development challenges remaining to scale up ASCENT propulsion system and meet the throughput and duty cycle requirements of propulsively challenging missions. NASA does not develop electrospray systems internally, so we will continue to rely on industry partners to provide higher power electrospray systems. Also, NASA is planning near-term procurements for high throughput ASCENT thrusters qualified at the 5N and 22N thrust class. A significant technology advancement is likely required before the development of significantly high thrust class ASCENT systems, due to catalyst and thermal challenges associated with thruster operations.

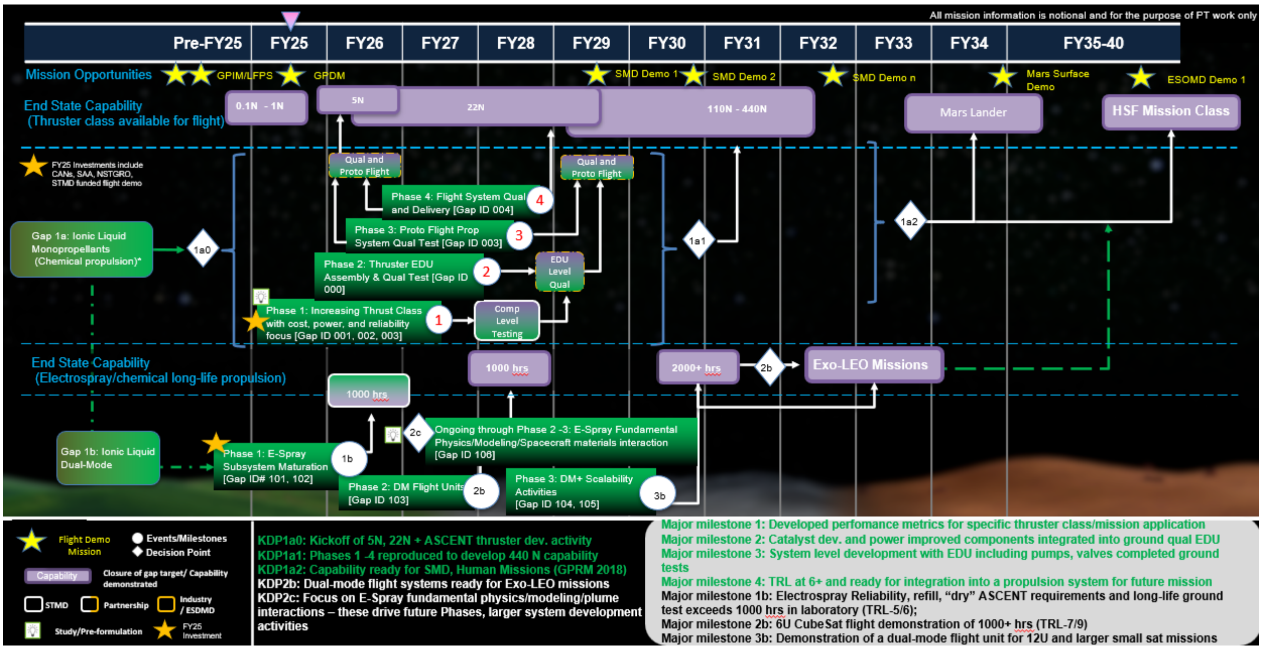

Figure 10: NASA's Green Propulsion Notional Development Roadmap.

VIII. Summary

In summary, NASA and its partners are near completion of the Green Propellant Dual Mode flight system delivery, with launch manifested in January 2026. A large number of NASA's Space Technology Mission Directorate investment opportunities were leveraged to transition the mission from an early-stage proof-of-concept demonstration to flight validation. The mission benefited from a direct follow-on from the Lunar Flashlight mission and completes another step towards U.S. non-toxic propulsion applications. The mission will demonstrate integrated system ASCENT propellant dual mode operation and retire risks for future operational infusion.

References:

[1] J. L. Rovey, C. T. Lyne, A. J. Mundahl, N. Rasmont, M. S. Glascock, M. J. Wainwright, S. T. Berg, "Review of Multiple Space Propulsion," *Progress in Aerospace Sciences* 118, April 2020.

[2] D. Krejci, F. Mier-Hicks, C. Fucetola, P. Lozano, A. Hsu Schouten and F. Martel, "Design and characterization of a scalable ion electrospray propulsion system," IEPC-2015-149 34th International Electric Propulsion Conference, Kobe, Japan, 2015.

[3] C. Smith, N. Creek, C. Burnside, J. Baker, P. Adell, F. Picha, M. Kowalkowski, and E. G. Lightsey, "The Journey of the Lunar Flashlight Propulsion System from Launch through End of Mission," in 37th Annual Small Satellite Conference, Logan, UT, 2023.

[4] B. J. Colón, M.J. Glaser, E.G. Lightsey, A. R. Bruno, D.P. Cavender, and P. Lozano, "Spectre: Design of a Dual-Mode Green Monopropellant Propulsion System," in AAS-094, 2022.