A Green Propulsion Dual Mode (GPDM)

In-Space Technology Demonstration on a 6U CubeSat

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ABSTRACT

Over the past decade there has been an increase in the launch and operations of small spacecraft. Small spacecraft (defined as having a total vehicle mass of < 180 kg) provide an opportunity for low-cost, high impact technology demonstrations on a small scale. They also create opportunities for government, industry, and academic to engage, transfer knowledge, and extend partnerships with non-traditional partners. NASA's Marshall Space Flight Center (MSFC) is leading a collaborative effort to demonstrate a dual-mode (chemical and electrospray) propulsion system using a common propellant system as a payload on a 6U CubeSat. The novel feature in the propulsion system is the interfacing of propulsion technologies requiring dramatically different operating conditions and support hardware. GPDM will use a low toxicity or "green" propellant known as Advanced Spacecraft Energetic Non-Toxic (ASCENT) to demonstrate using a chemical thruster for translation burns and electrospray propulsion for both attitude control and translational burns on the spacecraft. Specific mission activities could include demonstration of collision avoidance during frequent altitude adjustment maneuvers to validate thruster performance and managing extended duration thruster burns of at least 24 hours with limited vehicle contact times. This paper will summarize the ground testing, spacecraft development, mission objectives, and mission planning activities to achieve some of GPDM's technical objectives.

INTRODUCTION

The Green Propulsion Dual Mode (GPDM) mission is a Research and Technology (R&T) technology mission per NASA Procedural Requirement (NPR) 7120.8, funded out of the NASA Space Technology Mission Directorate (STMD)/Small Spacecraft Technology (SST) Program. The aim of the GPDM misison is to demonstrate the dual-mode (chemical and electrospray) propulsion capability of the low-toxicity or "green" monopropellant known as Advanced Spacecraft Energetic Non-Toxic (ASCENT) on a small spacecraft using a common propellant feed system.

As an NPR 7120.8 project, GPDM's low cost/high impact, high risk-acceptance posture focuses the effort on a small spacecraft platform, which leverages internal NASA workforce development (early career staffing), with university and industry partnerships to achieve specific mission and technology demonstration objectives. MSFC is leading the effort to develop an ASCENT based dual-mode propulsion system on a 6U CubeSat and subsequently characterize the chemical and electrospray propulsion systems by performing orbital maneuvers and incrementally more complex thruster firing operations. The GPDM Project is partnering with the NASA Space Communications and Navigation (SCaN) program office to use the Tracking and Data Relay Satellite System (TDRSS) constellation for contacts up to 37-minute averages for real-time mission operations troubleshooting during the checkout of the GPDM Propulsion System.

BACKGROUND

Developed over the past decade by the Air Force Research Laboratory (AFRL), ASCENT belongs to a family of ionic liquid monopropellants which are known for their lower toxicity, ease of longterm storage and ground handling, and higher volumetric storage capability vs. hydrazine [1]. Examples of ASCENT-based chemical propulsion systems which have demonstrated in-space translation activities include the NASA GSFC led Green Propulsion Infusion Mission (GPIM) which launched in 2019 [1] and the Lunar Flashlight Propulsion System (LFPS) which flew on the JPL-led Lunar Flashlight mission, launched in December 2022. Lunar Flashlight was a science mission on a 6U CubeSat platform which aimed to use laser spectroscopy to map water ice near permanently shadowed regions of the Moon [2]. The LFPS was a NASA MSFC led partnership with industry and university involvement to develop a pump-fed, ASCENT based prop system to perform Trajectory Correction Maneuvers (TCMs) and lunar orbit insertion burns [2].

Since ASCENT is an ionic liquid, it has been demonstrated as viable candidate for electrospray propulsion in addition to it's use as a chemical thruster monopropellant, lending to the possibility of use in a dual-mode propellant operating in a common feed system [3]. Benefits to the implementation of a dual-mode propulsion system include exploiting the benefits of higher thrust chemical propulsion with high propellant efficiency electrospray propulsion while limiting overal vehicle mass via the common propellant feed system.

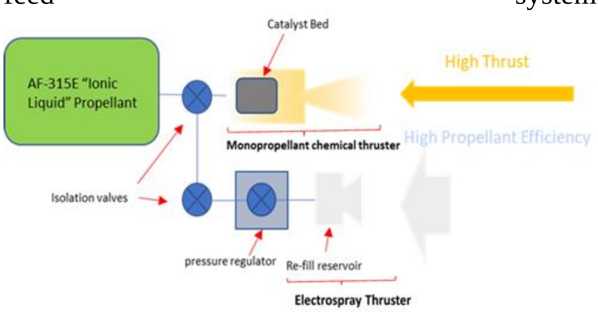


Figure 1: Conceptual diagram of a green dual-mode system.

Figure 1 shows a schematic of an idealized ASCENT blowdown dual-mode propulsion system which includes a common propellant tank, a chemical monopropellant thruster, electrospray thrusters and a compact pressure reduction mechanism which acts to reduce pressure from the propellant tank to the electrospray thruster reservoirs.

The primary objectives of the Green Propulsion Dual Mode (GPDM) Project, led by NASA MSFC's Science and Technology Office (STO) are:

(1) The development of a dual-mode ground test system ("GPDM FlatSat") in a relevant environment to test the concept before and during flight operations

(2) A flight-qualified dual-mode unit ("GPDM flight unit") as a payload on a 6U CubeSat, notionally targeting late 2025 for delivery as a secondary payload on a commercial launch vehicle to accomplish specific mission objectives during an on-orbit demonstration.

The GPDM Project's scope initially included only the development of a dual-mode propulsion system scaled for a small spacecraft; however, in 2023, the Small Spacecraft Technology (SST) Program directed the GPDM Project to lead a collaborative effort with university and industry partnerships to develop a 6U CubeSat bus with the GPDM Propulsion System as the payload within the full system.

While GPDM is funded by the STMD/SST and managed by NASA MSFC (out of the Science and Technology Office), it will leverage both industry and university partnerships in support of specific technology and mission operations activities. Specifically, GPDM is using NASA Small Business Innovation Research and Small Business Technology Transfer (SBIR/STTR) contracts with industry (Rubicon Space Systems) to develop chemical propulsion subsystem colloquially known as "Sprite" (including the 0.1 N ASCENT thruster, 3D printed tank, manifold, and propellant management device (PMD)). SBIR/STTR contracts are also being leveraged to develop the power & propulsion unit (PPU) for the electrospray propulsion system via an SBIR/STTR Phase II/E contract with E-Space, Inc.

The GPDM Project is also partnering with several universities (Massachusetts Institute of Technology) and Georgia Institute of Technology (Georgia Tech). MIT is developing the electrospray thrusters and their re-fill reservoirs to demonstrate long-life extensibility of electrospray propulsion, and which is funded through the NASA Space Technology Graduate Research Opportunity (NSTGRO) program. Georgia Tech is leveraging a university grant to both perform integration of the MSFC developed dual-mode propulsion system and is also leading (with MSFC oversight) the development of the GPDM spacecraft bus which will incorporate flight proven components into the full spacecraft. MSFC will oversee mission operations for GPDM though the ground operations will be performed and staffed by Georgia Tech at the GT Mission Operations Center (MOC).

Mission objectives for the GPDM flight demonstration include:

- Characterization of chemical and electrospray thruster performance including electrospray thruster re-fill capability
- Performing orbital maneuvers (e.g., going to and from the nominal 525 km Sun-Synchronous Orbit (SSO) orbit)
- Demonstrating electrospray long-life capability

To meet the various mission objectives, the GPDM team will use the Tracking and Data Relay Satellite System (TDRSS) in conjunction with the NASA SCaN office to allow the mission operations team (staffed by GT students and MSFC Mission Operations personnel) to monitor the GPDM spacecraft while it performs its planned thruster operations and system characterization. The GPDM spacecraft and propulsion system design, GPDM Flat Sat ground testing activities, and mission operation plans which will support the GPDM Project's overall goals and mission objectives are discussed in the subsequent sections.

GPDM SPACECRAFT DESIGN

GPDM developed as a spiritual successor to the Lunar Flashlight Propulsion System's (LFPS) technology developments and as an evolution of the Specter propulsion system. Design changes including moving from a fully NASA-developed chemical propulsion system to Rubicon Space System's developed Sprite propulsion module and a significantly updated Compact Pressure Reduction System (CPRS) compared to the proposed additively manufactured (AM) CPRS design as presented in [4]. The scope of GPDM also increased when GPDM increased from a 6U propulsion system to the entire 6U CubeSat.

The bus portion of the spacecraft (in other words, everything other than the propulsion module payload) relies mostly upon COTS components or evolutions of custom components with flight heritage. The major COTS components include the XACT-50 attitude control system by Blue Canyon Technologies, the 112W SADA solar array by MMA Design, the antenna suite by Haigh-Farr, the RDMS receiver and TIMTER transmitter by Quasonix, and the Q7 flight computer by Xiphos.

The electrical power system (EPS) is designed and built by GT. It includes of 15 18650 Li-Ion distributed across the spacecraft in 3 packages. The EPS is largely based on the system used on Lunar Flashlight, with minor updates, namely cell balancing between battery packs, an in-house hardware-based watchdog circuit, and voltage regulated outputs.

The Communication system consists of a Quasonix transmitter and receiver and will be communicating in the S-band frequency range. Each radio will include a Quasonix omni-directional antenna. It will be integrated and tested by Georgia Tech and will communicate with the Tracking and Data Relay Satellite System (TDRSS) in single access protocol.

The ADCS is the BCT XACT-50 integrated unit. It is comprised of 3 reaction wheels, allowing for 3-axis control. The XACT-50 is also equipped with 3 sun sensors, a star tracker, and an Inertial Measurement Unit (IMU). The XACT-50 has been used on 19 university sponsored Cube Sats that have launched since 2019, including Lunar Flashlight [2].

GPDM PROPULSION SYSTEM DESIGN

GPDM's payload is its propulsion system, referred to as the GPDM Propulsion System (GPDMPS). It comprises of three major mechanical systems, the Sprite propulsion module, the ion Electrospray Propulsion System (iEPS), and the Compact Pressure Reduction System, and two electrical boards, the Foxglove controller, and the Power Processing Unit. GPDMPS was designed to be spacecraft agnostic. The GPDMPS is shown below in Figure 2.

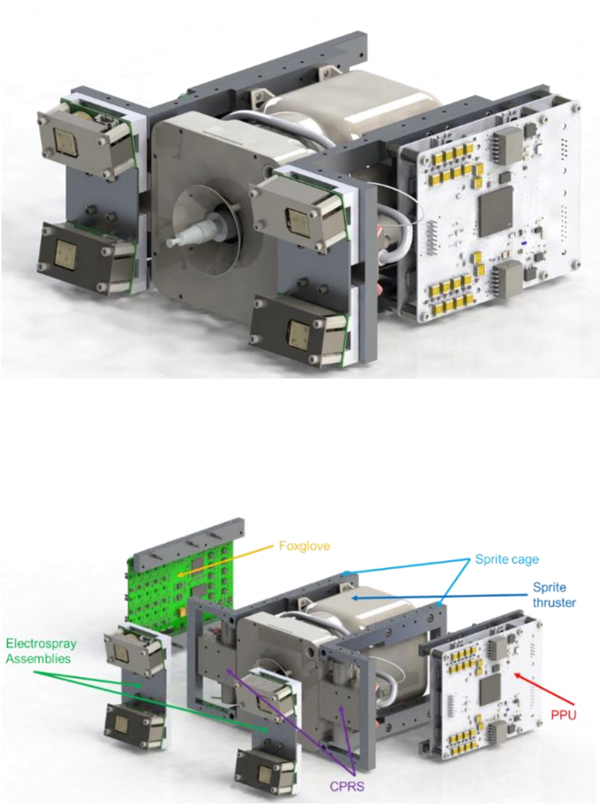


Figure 2. GPDM Propulsion System.

Sprite serves as the “core” of GPDMPS. Sprite is a self-contained chemical propulsion system provided by Rubicon Space Systems (a subsidiary of Plasma Processes LLC). Sprite is an additively manufactured, titanium pressure vessel with a single integrated 0.1 N (100 mN) ASCENT thruster. These thrusters’ design was qualified for Lunar Flashlight. Sprite is a blowdown system operating from 275 psi to 60 psi.

GPDMPS contains 4 ASCENT electrospray thrusters in the ion Electrospray Propulsion System (iEPS) provided by MIT SPL under an STTR agreement. The electrospray thrusters consist of an emitter array aligned with extractor electrode that can extract ions directly from the ASCENT propellant. The emitter is passively fed propellant via a reservoir that rids ASCENT of its water content and other volatiles. The Power Processing Unit (PPU) was designed by Espace and supplies the electrospray thrusters their required high voltage power.

The electrospray thrusters have a maximum inlet pressure of <10 psi. With the Sprite module operating at pressures up to 275 psi, there is a need for a system to step down the tank pressure to a pressure acceptable for the electrospray thrusters. The Compact Pressure Reduction System (CPRS) serves this purpose and as the manifold to distribute the propellant from one outlet line to four electrospray thrusters. CPRS is managed, designed, and tested by MSFC with collaboration with GT.

The Foxglove controller was designed by GT and commercially manufactured. It is a slightly modified version of the Foxglove controller used on the Lunar Flashlight Propulsion System. The Foxglove controller serves as the flight controller for the GPDM spacecraft, commanding the GPDMPS components.

Compact Pressure Reduction System

The CPRS underwent a significant number of design changes from Specter to GPDM. The initial development was conducted by MIT in support of their iEPS. An AM version of the CPRS was proposed as part of the design development for the Specter propulsion system. An AM design was proposed to meet volume constraints. Furthermore, the design was developed to take advantage of COTS micro solenoid valves and leverage the ability of AM designs to allow for longer channel lengths in a more compact volume. Typically, the rough surface finish of the AM channels is a detriment to fluid flow, in this case however, it added to the desired pressure drops. In turn, this allowed for larger cross-sectional areas compared to capillary tubes from the MIT design. As shown in Figure 3, a unit was designed, printed, and tested in support of the Specter Flat Sat testing in 2021.

Testing for the AM design resulted in successful demonstration of dual-mode operations. However, limitations with the AM CPRS design were identified. The brazed valves to the CPRS made removing a valve and qualifying the joint challenging. In addition, concerns with removing powder from the complicated channels resulted in re-evaluating the AM design. Further, the change of the GPDM mission from purely a propulsion system to the entire spacecraft, allowed for additional volume for a larger CPRS as needed. Concerns about the controllability of the passive AM CPRS along with foreign object debris (FOD) concerns from an AM CPRS resulted in the desire to redesign the CPRS.

Figure 3. Top: Specter AM Brazed CPRS Design. Bottom: AM Fitting-joint CPRS Design.

The redesign of the CPRS ultimately incorporated more robust, proven components with the additional volume available and was able to deliver propellant reliably to the electrospray thrusters. Instead of being a single module, CPRS evolved into a pair of traditionally machined blocks that allowed the thruster valves to be close coupled to the electrospray thrusters. This limited the line length between the electrospray thrusters which mitigated risk by decreasing the length of polymer tubing required for electrical isolation.

Instead of using tortuous AM pathways for pressure reduction, COTS viscojet flow restrictions were installed upstream of each thruster valve. The COTS micro-solenoid valves were replaced with Lunar Flashlight Propulsion System Heritage Solenoid Valves due to their excellent performance on that spacecraft. The interfaces to the electrospray thrusters were redesigned as part of the CPRS development, to use COTS fittings designed to work with polymer tubing, but compatible with metal ports. The flight version of CPRS can be operated in two modes: vapor pressure and direct transfer. Both methods of transfer have been tested at MSFC using the COTS viscojet as the flow restriction. The completed CPRS design is shown in Figure 4.

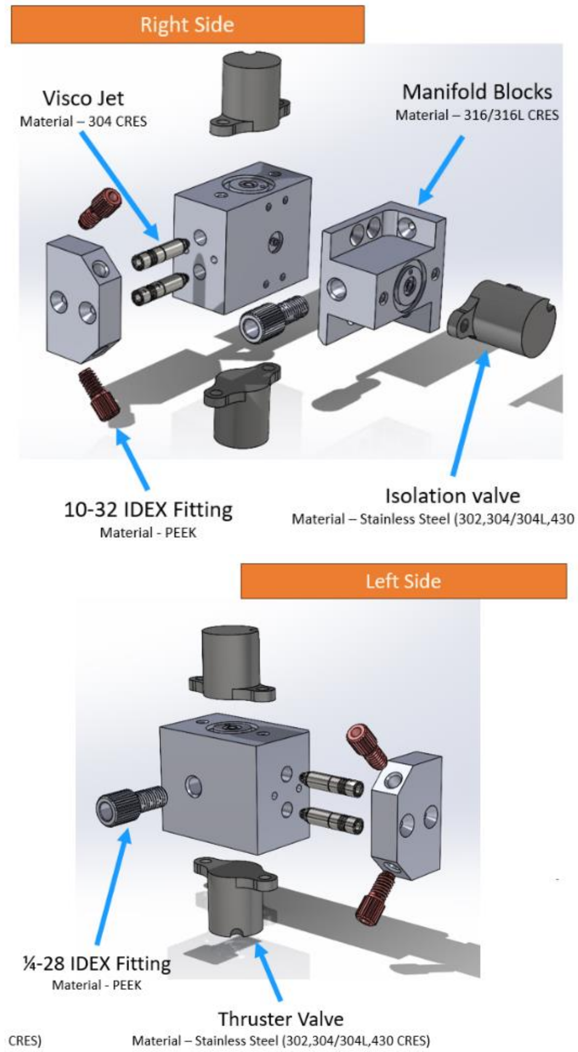


Figure 4. Detailed breakdown of updated CPRS design.

The vapor pressure method relies on the properties of ASCENT itself and the porous teflon reservoir of the electrospray thrusters. Since gasses can move freely out of the reservoirs, the vacuum environment allows the water in ASCENT to vaporize and escape. In practice, this means that propellant lines not isolated from the thruster reservoirs will form gas bubbles over time, and those bubbles will travel the length of the propellant line to the reservoir, pushing liquid ASCENT along for the ride. Although this method is slow, it results in an extremely low-pressure transfer of an exact fluid quantity.

Figure 5. Vapor transfer testing using clear polymer tubing for visualization.

The direct transfer method is simply opening both the thruster and propellant isolation valves and allowing ASCENT to flow directly into the reservoir. The COTS viscojet device provides a significant pressure drop whose exact value is dependent on the pressure of the Sprite tank, since it is a blow-down system. Testing is ongoing at MSFC to determine the flowrates and pressure drops of the CPRS system as a function of Sprite pressure. The transfer initially will be completed in a series of pulses at the higher Sprite pressures and can be completed in a single transfer of the total volume at lower Sprite pressures. This transfer method has the benefit of the being fast but is a higher-pressure transfer that must be monitored for the safety of the electrospray thrusters.

The original viscojet devices provided by The Lee Company (Lee Co) contain a brazing alloy that is not materially compatible with ASCENT for prolonged durations. Additional brazing materials (including silver and gold alloys) were provided by Lee Co to MSFC for accelerated compatibility testing, but unfortunately, all displayed some degree of incompatibility. As of June 2024, Lee Co has designed a drop-in replacement, braze-less viscojet utilizing laser drilling of the component with materials that are known to be compatible. After production of the engineering units, MSFC will characterize the new design the same way as before.

Additively Manufactured Pressure Vessel

The Sprite pressure vessel represents one of the first additively manufactured pressure vessels to be incorporated on a spacecraft. Typical pressure vessel standards still apply to prevent loss of craft or mission; however, most of these standards are not formulated with additive manufacturing in mind and the unique qualities of the final product. This presented a challenge to follow both NASA-STD-6030 (for additive manufacturing) as well as ANSI/AIAA S-080 for metallic pressure vessels [5, 6]. A tailored approach to both standards due to the size of the tank and its contents allowed for successful completion of the design.

Preliminary analysis of the pressure vessel has shown significant margins on static (pressurized) strength as well as inertial loading due to launch loads. These static margins were verified through pressurized testing where the MEOP of the tank was exceeded by more than a factor of 5. A burst test of a qualification unit was attempted, but the maximum facility pressure (limited by the calibrated pressure gauge on hand) of approx. 2750 psi was reached before the vessel yielded or showed signs of deformation detectable to the naked eye. The analytical strain measurements were experimentally verified as well with a Digital Image Correlation software suite showing good agreement between the predicted and actual deformations.

However, for spaceflight the pressure vessel must also be accepted by range safety. One of the challenges with additive manufacturing is that the part is challenging to inspect, and minimal fatigue and fracture properties are available which are required for compliance to S-080 and NASA-STD-6030. Work across Marshall developed fatigue and fracture properties of the material from printed specimens, which allowed for point certification of this specific tank set. While the NASA standards for additive manufacturing require substantial sample sets to certify both the machine and process for general usage, this was tailored to the specific flight hardware by developing test samples obtained from the build plate utilized for the flight hardware. Existing tensile test data compared well with tensile tests performed and Marshall while fracture specimens and fatigue specimens were fabricated and tested successfully to develop properties to be used in the analysis.

As a note, all additively manufactured parts of Sprite were built before Marshall was able to implement manufacturing control plans. Instead, MSFC has developed a Part Production Record that contain departures from NASA-STD-6030 and rational for their acceptance supported by qualification and specimen test data. As such, MSFC qualification efforts for Sprite are GPDM specific, and not a blanket Sprite Flight Qualification.

GPDM FLATSAT GROUND TESTING

The GPDM FlatSat hardware and integrated system developed at NASA MSFC serves as the ground complementary hardware for the flight mission configuration. It provides comprehensive testing capabilities aimed at refining the dual-mode propulsion system for the GPDM mission. Designed to emulate flight-like conditions, the GPDM FlatSat comprises a as much flight and flight-like hardware as possible to meet the intent of the 'test as you fly, fly as you test' philosophy. This approach ensures that key aspects of the dual-mode propulsion system are demonstrated successful before flight. The modular nature of the FlatSat allows for iterative improvements as new hardware is available or as the mission configuration changes. The FlatSat hardware is tested in vacuum conditions at the NASA Marshall Space Flight Center Green Propulsion Laboratory. Through a series of campaigns, the FlatSat hardware enables the evaluation of chemical and electrospray performance data, flight controllers and firmware, and prepares engineers for the flight operations following launch.

Each of the campaigns focuses on specific areas of the GPDM propulsion system design and operation. Along with the hardware, the spacecraft software, firmware, and procedures for operating the system were developed. The original sequence of testing, as planned, would have completed the campaigns in sequential order. However, development doesn't always follow a linear path, and each of the campaigns builds on others during the execution of the FlatSat development. Table 1 summarizes the campaigns performed. Each of the campaigns are described below. Table 1. GPDM FlatSat Campaign Descriptions

Table 1

Campaign	Description	Status
1A	Chemical feed system builds and limited thruster testing	Complete
1B	CPRS and electrospray filling demonstration	Complete
2A	Performance data in LF typical profiles	Complete
2B	Performance data in GPDM typical profiles	Complete
3	Performance data in GPDM expected profiles (durations and pulse rates)	Partial
4	Electrospray reservoir, CPRS integration/modifications	Upcoming
5	Combined chemical thruster testing and electrospray reservoir filling	Upcoming
6	Combined chemical and electrospray thruster operations	Upcoming

Campaign 1A: This campaign focuses on chemical thruster feed system development and integration. Previous lessons from the LF mission and the team's testing of the hardware form a significant part of the current efforts. Developing the feed system and supporting structure for the GPDM FlatSat testing during this part of the testing was iterative. Accurate flow measurement at the 100 mN thrust range (approximately 45 mg/sec) ASCENT flow rates is challenging, both for steady-state and pulsing flows. The original system used a propellant supply tank internal to the FlatSat system that resided in the altitude chamber. However, to shorten the propellant lines and improve operations and fidelity of specific impulse measurements, the propellant supply was moved outside of the altitude chamber. Hot fire testing of the 100 mN ASCENT chemical thruster proved the hardware and feed system's ability to provide propellant accurately to the FlatSat test article.

Campaign 1B: This campaign focuses on the electrospray reservoir filling hardware and CPRS developments. The GPDM mission requirement to fill and refill each of the electrosprays introduces complexities in pressure reduction and flowrate control to protect the electrospray thrusters from over-pressurization.

Campaign 2A and 2B: These campaigns return focus to the chemical thruster operations. Modifications to the test stand hardware/feed systems and potentially different operating environments necessitated a basis for comparison to previous data. Campaign 2A replicated operational profiles from LF, while Campaign 2B focused on GPDM anticipated sequences.

Campaign 3: This campaign is like campaign 2B but expands into inlet pressure variation mapping. Previous propulsion systems developed at MSFC use pump-driven pressurization schemes that provide a constant thruster inlet pressure regardless of the propellant tank supply pressure. However, GPDM’s requirements and mission goals didn’t require the pump capabilities; therefore, the 100 mN thruster will operate in blowdown mode. This campaign focuses on thruster performance at lower inlet pressures, ranging from 75 psia to 275 psia, to support mission design and thermal models.

Campaign 4: Begins integrating chemical and electrospray reservoir hardware. The CPRS design continued to evolve during the early phases of the FlatSat development. As the design matured, parts were added to the FlatSat system or tested on the bench to verify operation. Because the development hardware isn’t flight-like, the system is controlled with lab data and control systems.

Campaign 5: This campaign is the first opportunity to test loading electrospray reservoirs using the GPDM flight-like controllers and software. The timing for loading operations and fluid flow characteristics are the primary data from this campaign.

Campaign 6: A full demonstration of chemical and electrospray operations. The previous campaigns demonstrate all the features of the system separately, but this test sequence will be the first demonstration combined into one sequence. Reaching this test campaign requires extensive verification that the facility, personnel, and FlatSat are ready for operations. Once the electrosprays are wetted with propellant, the altitude chamber will not be repressurized until the completion of testing.

Results: Data reduction and video analysis of the test campaigns continue. Preliminary reviews show excellent performance to meet the GPDM needs. Data matching the LF performance agrees at the tested conditions. Figure 6 shows a single 10-second steady-state pulse at 275 inlet pressure. At this condition, the expected thrust is approximately 120 mN.

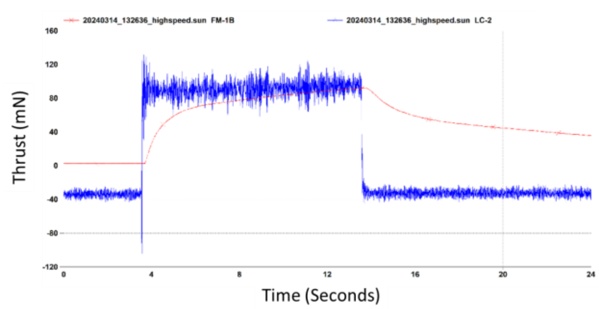


Figure 6. 10 second Single Pulse of the ASCENT 100 mN Chemical Thruster

Additional data reduction in on-going with the electrospray reservoir loading. Preliminary data shows consistent ability to load and re-load the electrospray thrusters.

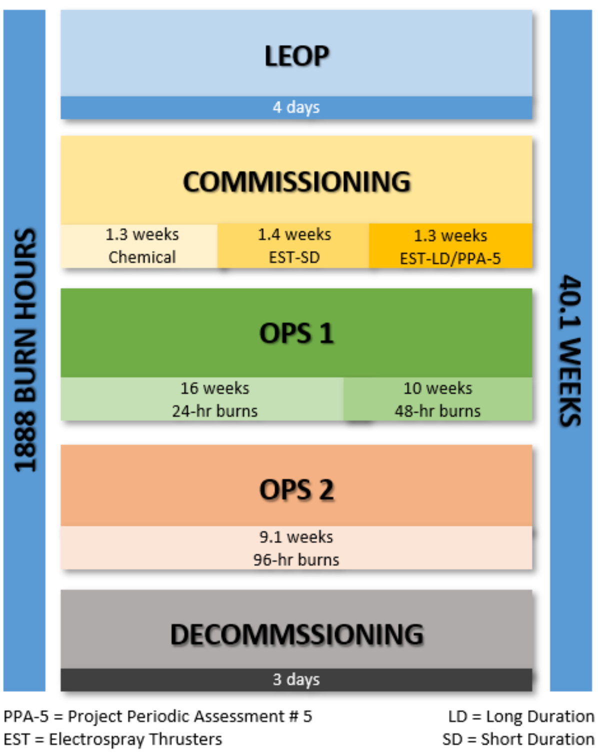
GPDM MISSION OPERATIONS PLAN

Mission Operations is conducted by investing in the collaboration between Georgia Tech University and NASA’s Marshall Space Flight Center (MSFC). Efforts are aimed at driving innovation, fostering knowledge exchange, and cultivating a skilled workforce to propel humanity's exploration of space forward. Georgia Tech's expertise in engineering, computer science, and robotics complements NASA's mission objectives, fostering innovative solutions for space missions.

MSFC expertise in mission operation contributes to Georgia Tech's execution to mission planning and operations. They assist in analyzing data, simulating mission scenarios, and developing software for mission control systems. This partnership ensures efficient and effective execution of the GPDM mission.

The Mission Operations Center (MOC) for the GPDM satellite is situated at the Georgia Institute of Technology (GT), with propulsion experts stationed at NASA/MSFC in Huntsville, AL. The mission comprises four phases (Launch and Early Operations (LEOP), Commissioning, Operations and Decommissioning) of increasing complexity building on each successful burn duration until mission duration is complete or fuel reserves required for decommissioning are reached.

Table 2: GPDM Mission Operations Phases



The first phase of the mission is **Launch and Early Operations (LEOP) Phase**. During the launch, the GT team will be on-console to monitor the satellite's deployment from the launch at 520km – approximately 1 hour after liftoff. At the pre-determined timing sequence from deployment, the spacecraft will initiate automated bootup, perform detumbling processes to stabilize itself, and establishing communication with the MOC. Once ground communications are established, the Mission Ops team will assess the spacecraft's health, ensuring all systems are operating nominally.

Following the LEOP phase, is the **Commissioning Phase**, focusing on activation of the chemical and electrospray thrusters. The team will prepare the propulsion system for operations and perform short thruster firings to determine the initial heath of the chemical thrusters. Once the team has a baselined performance of the chemical propulsion system the remaining commissioning phase will focus on the four electrospray thrusters. The commissioning of the electrospray thrusters begins with loading each electrospray thruster's reservoir with propellent. After loading the propellent and allowing time for vapor off-gassing, each of the thrusters are fired individually while monitoring reaction wheel states. At the completion of electrospray commission, there will be a cumulative of 16 hours of operation.

At the completion of commissioning, the vehicle propulsion system and the vehicles response to propulsive inputs will be known. A Periodic Project Assessment (PPA) or Mission Readiness Review (MRR) will be conducted to review the vehicle status, including propulsion system performance, to assess the readiness to move into Flight Operations.

Following commissioning of the spacecraft and approval from the PPA to proceed, the team will focus on the **Operational Phase** of the mission. The electrospray and chemical thrusters will be used in a combined fashion to prove the capabilities of dual-mode systems to meet a variety of mission parameters.

Operations begin with short, dual-mode operations where the electrospray thrusters will operate for 24-hours to raise the spacecraft's altitude in an outward spiral. After which, a chemical thruster operation will return the spacecraft to its original altitude with a two-burn Hohmann transfer (or similar burn profile). Then, the electrospray thrusters can be refilled during the two-day spacecraft and data analysis period before the next operation. Over the mission duration, this process will be repeated 20 times to reach approximately 480 hours of electrospray operations for this phase, bringing the cumulative total to 496 hours.

After the dual-mode, short duration operations, the spacecraft will enter electrospray only operations. During this period, the electrospray thrusters will operate for 24-hours to raise the spacecraft's altitude in an outward spiral. Then, the electrospray thrusters will operate for 24-hours to return the spacecraft to its original altitude. This 48-hour burn cycle will be completed 9 times for 432 hours of electrospray operations for this phase, bringing the cumulative total to 928 hours.

After the electrospray only operations, the spacecraft will enter dual-mode, long duration operations. The altitude raise will be like the dual-mode short duration phase, but electrospray thrusters will operate continuously for 96 hours followed by a chemical thruster two burn Hohmann transfer (or similar burn profile) to return to the original altitude. This will be repeated 10 times for 960 hours of electrospray operations, bringing the cumulative total to 1888 hours.

At the Project Manager's discretion with recommendations from the Propulsion Expert, the flight operations phases (Dual-mode Short Duration, Electrospray Only, and Dual-mode Long Duration) can be interchanged freely. Modifying the number of each type of operation will affect the electrospray hours. At the end of the operations phase, 35% of the propellant is reserved for the decommissioning phase.

In the **Decommissioning Phase,** the spacecraft will use the remaining propellant to fire the chemical thruster to achieve the required 480km altitude for passive reentry. Before final sign off from the MOC, as a final action, they will command the spacecraft to purge any remaining propellant and pressurant to ensure the propellant tank pressurized volume is inert prior to spacecraft reentry.

SUMMARY AND FUTURE WORK

This paper summarizes an STMD/SST supported, NASA MSFC-led, university and industry collaboration effort to design, develop, ground test, and fly an ASCENT-based green dual-mode propulsion system within a 6U CubeSat envelope. It is hoped that this activity will stimulate interest in green dual-mode propulsion technology especially applied to small spacecraft and science missions, while buying down risk for future potential investors. Currently, the GPDM Project is moving towards its implementation life cycle phase, having completed several design review milestones and significant portions of its Flat Sat ground testing activities. Subsequent plans include commencing integration of the GPDM spacecraft/propulsion system flight unit, subsequent ASCENT propellant loading, and delivery for flight integration with a future launch provider as a secondary payload in the Fall 2025 timeframe.

ACKNOWLEDGEMENTS

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