Design, Development, and Testing for a Green Propulsion Dual Mode(GPDM) Technology Demonstration Mission

Nehemiah Williams, Ph.D.
Green Propulsion Technology Development
NASA Marshall Space Flight Center

May 9th, 2024

Outline

- Introduction
- Design & Development
  - Breakdown of GPDM Design
  - Compact Pressure Reduction System (CPRS)
  - Additively Manufactured Pressure Vessel
- Analysis
  - Thermal
  - Stress
  - Digital Image Correlation for Proof Test Validation
- Ground Based Test Campaign ‘Flat Sat’
- Lessons Learned from Lunar Flashlight
- Mission Operations Plan
- Summary
- Acknowledgements

Introduction

- NASA’s Strategic Plan (2022) outlines specific technology development activities which direct the Agency to “innovate and advance transformational space technologies”
- For the area of in-space transportation, an exemplary high-impact- space technology area is the use of low-toxicity or “green” rocket propellants which show favorable in-space storability, Isp performance, and ground handling capabilities vs. conventual hypergolic propellants
- The Advanced Spacecraft Energetic Non-Toxic (ASCENT Propellant) (formerly known as AF-315E) has 50% higher Isp density than hydrazine and has been demonstrated on missions including Green Propulsion Infusion Mission (GPIM, 2019) and Lunar Flashlight (2022)
- The Green Propulsion Dual Mode (GPDM) project seeks to exploit ionic liquid properties of ASCENT, using it as a dual-mode propellant for both chemical and electrospray propulsion using a common propellant tank/feed system on a 6U CubeSat during an in-flight demonstration targeting launch in late-2025
- GPDM is an MSFC-led, – SST/STMD funded activity in which NASA, university, and industry partners (funded by grants and the SBIR/STTR Programs) work together to develop flight components and will support specific mission operation activities

Design and Development: Breakdown of GPDM Design

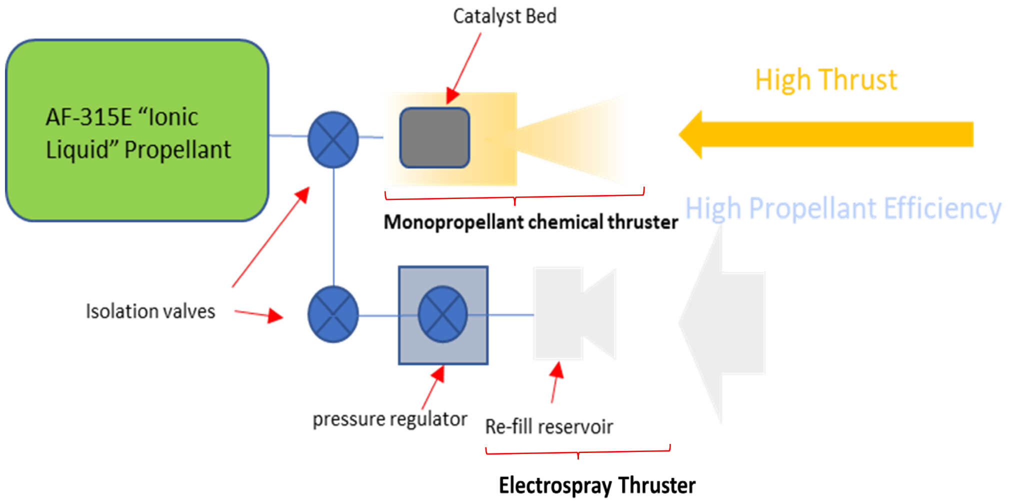
- To investigate the dual-mode capabilities of the ASCENT propellant, the GPDM system comprises of the common propellent tank, control valves, and a feed system which delivers propellant to both the chemical and electrospray thrusters

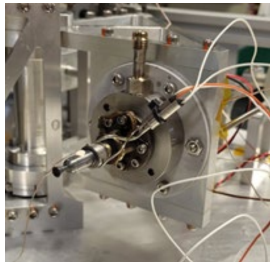
- The chemical thrusters use a pre-heated catalyst bed to create temperatures high enough for reaction with ASCENT to produce higher thrust

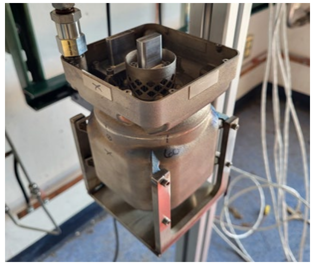
- The electrosprays ionize ASCENT using the electromagnetic field for high specific impulse, low thrust propulsion

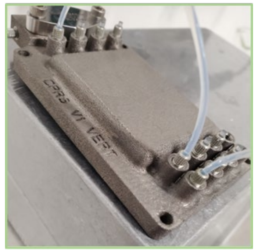
- In a blow-down configuration (pumpless), a pressure regulation mechanism is required to reduce pressure from the propellant tank to the electrosprays which require much lower inlet pressures

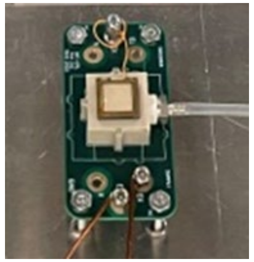
Dual-Mode Concept Idealization




Chemical Thruster

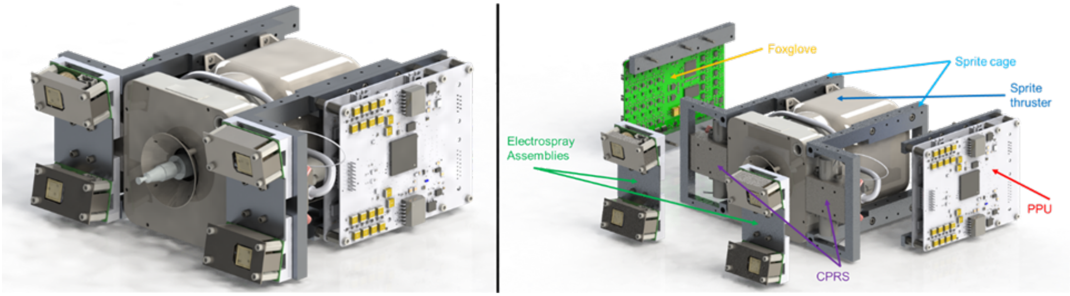

Propellant Tank


Pressure Regulation Prototype


Electrospray Thruster Prototype

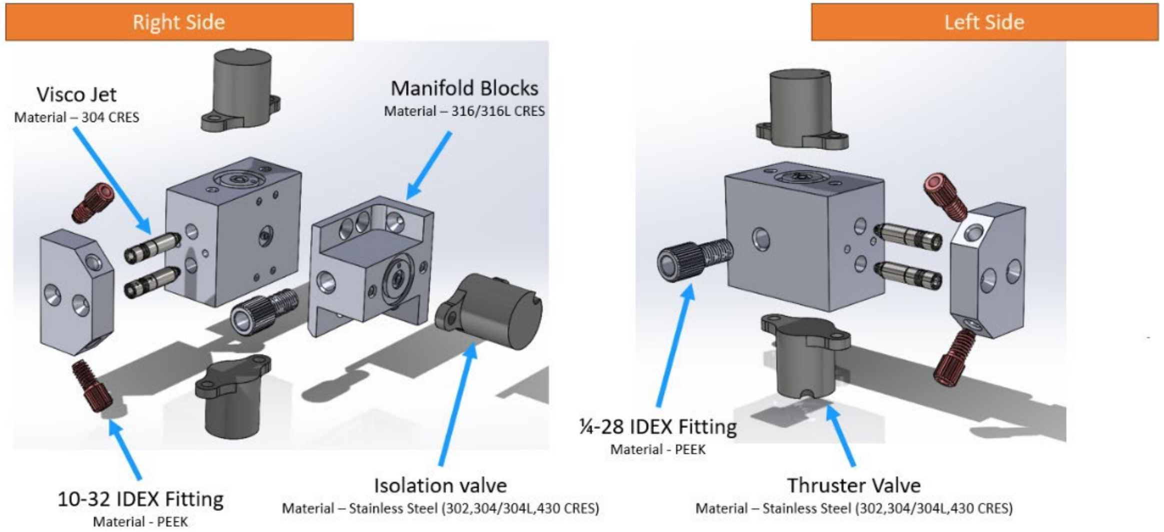
Design and Development: Breakdown of GPDM Design

- NASA Space Technology Mission Directorate (STMD) Technology Gap
  - Gap ID (1439) - 'modular, cost-effective, and novel form factors, mechanisms, and platforms for small spacecraft'
  - Gap ID (1430) - 'propulsion for small spacecraft including developing high delta-V and dual mode capabilities
- GPDM addresses technology gaps through two activities
  - A dual-mode ground test system 'FlatSat' for relevant environment testing of the GPDM concept
  - A flight-qualified dual-mode 'GPDM Flight Unit' built for a secondary payload launch opportunity in FY25

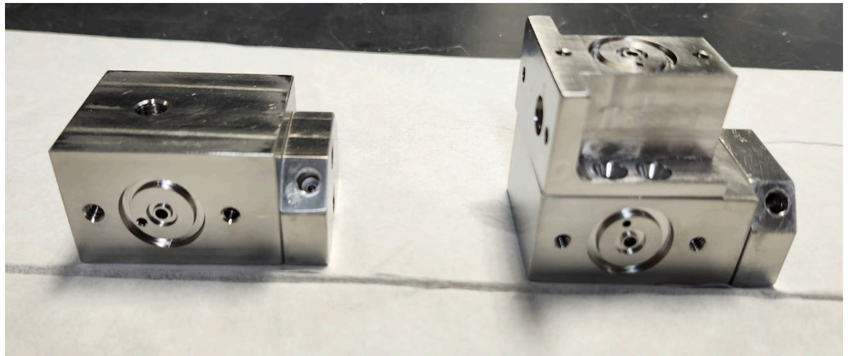


Design and Development: Compact Pressure Reduction System

- The MIT provided electrospray thrusters have several operational requirements that necessitated a specialized propellant feed system.
  - The porous PTFE propellant reservoirs on the electrospray system had a hard pressure limit of approximately 10 psia, which if exceeded may cause damage to the thruster.
  - The electrospray thrusters and reservoir must be electrically isolated from the rest of the system, driving the use for PEEK fittings and tubing downstream of CPRS.
- The Compact Pressure Reduction System (CPRS) was originally developed as an additively manufactured tortuous path device intended to provide the pressure drop necessary between the thrusters and the SPRITE tank.
- However, several issues with the manufacturing of the AM unit arose, due to its extremely small fluid passages, and a more traditional block manifold was designed in its place.
- In the block manifold version of CPRS that will be used on the spacecraft, Lee Co. Viscojets provide the flow restriction and pressure drop necessary to successfully fill the electrospray thrusters.
- Multiple reservoir fill tests have been completed with development versions of the feed system which have yielded flowrates and pressure drops in line with the requirements of the electrospray thrusters.



Exploded view of the CRPS CAD, detailing the installation of the viscojets and overall system assembly.



Photograph of the CPRS manifold blocks prior to installation for integrated thruster testing.

Design and Development: Additively Manufactured Pressure Vessel/Manifold

- GPDM includes a self-contained chemical propulsion module known as "Sprite" designed and developed by the Rubicon Space Systems Division of Plasma Processes, Inc.
- The Sprite subsystem includes a 3D printed, additively manufactured Ti propellant tank, PMD structures and manifold which house the chemical propulsion functionality for GPDM
- Sprite includes a 0.1 N flight qualified ASCENT thruster, micro-thruster valve, service valve, an internal controller and thermal shielding
- GPDM's propulsion system will operate in a blow-down configuration with a max BOL pressure of 275 psi and the CPRS regulating pressure to the electrospray thrusters
- After initial development and subsequent manufacturing of the Sprite units, MSFC developed stress/fatigue analysis models of Sprite as well as implemented proof and burst testing of several Sprite EDUs
- Sprite was tested up to over 2700 psia; subsequent CT scans showed no sign of fatigue or strain during post-test inspection activities

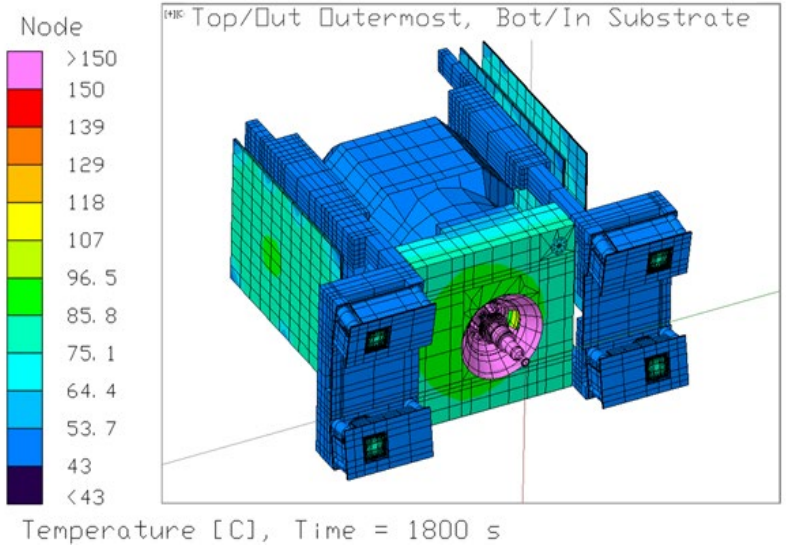
Used with permission from Rubicon Space Systems

Analysis & Test

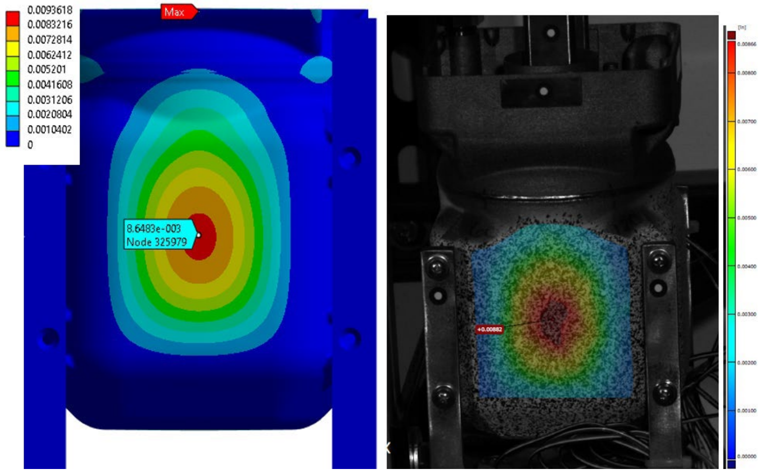
- Design, Analysis, and Test Products are being developed for the GPDM flight demonstration
  - Thermal – Solar & Thruster to bus interaction
  - Structural/Fracture - Additive manufactured pressure vessel
  - Vibe/Shock - Launch Vehicle Loads
  - Mission Design – Dual Mode, Low Earth Orbit atmosphere interactions

- For optimal solar power availability, GPDM will use an dawn/dusk SSO orbit; this drives the expected thermal environment requirements for GPDM

- Additionally, using 3D printed tanks/manifold drive the focus of analysis on structural/fracture control



Thermal analysis for GPDM under ASCENT thruster long-duration firing conditions (temp rang truncated to 150 degC)

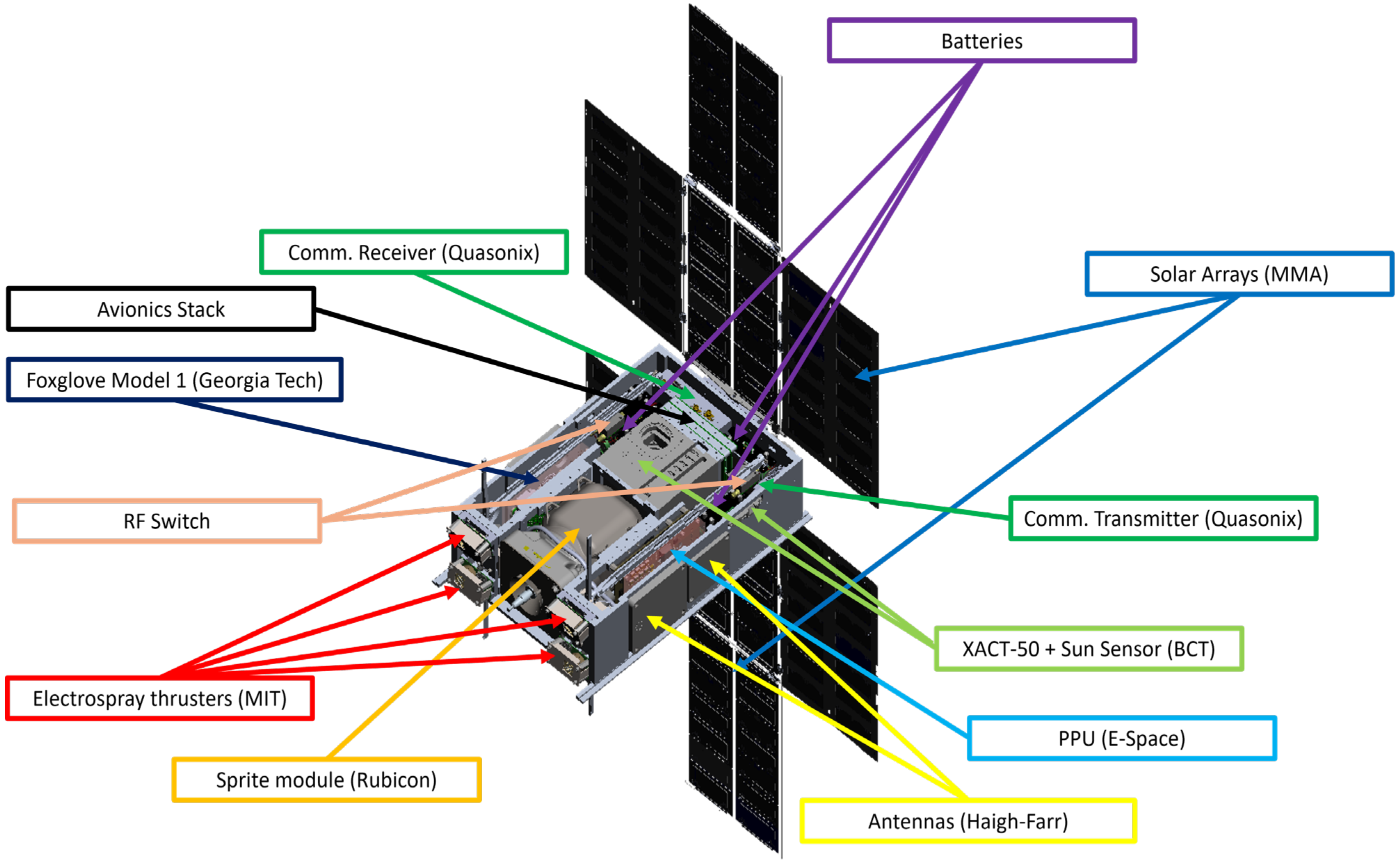


GPDM stress model using validation with ARAMIS proof test data

Statement A: Approved for public release; distribution is unlimited.

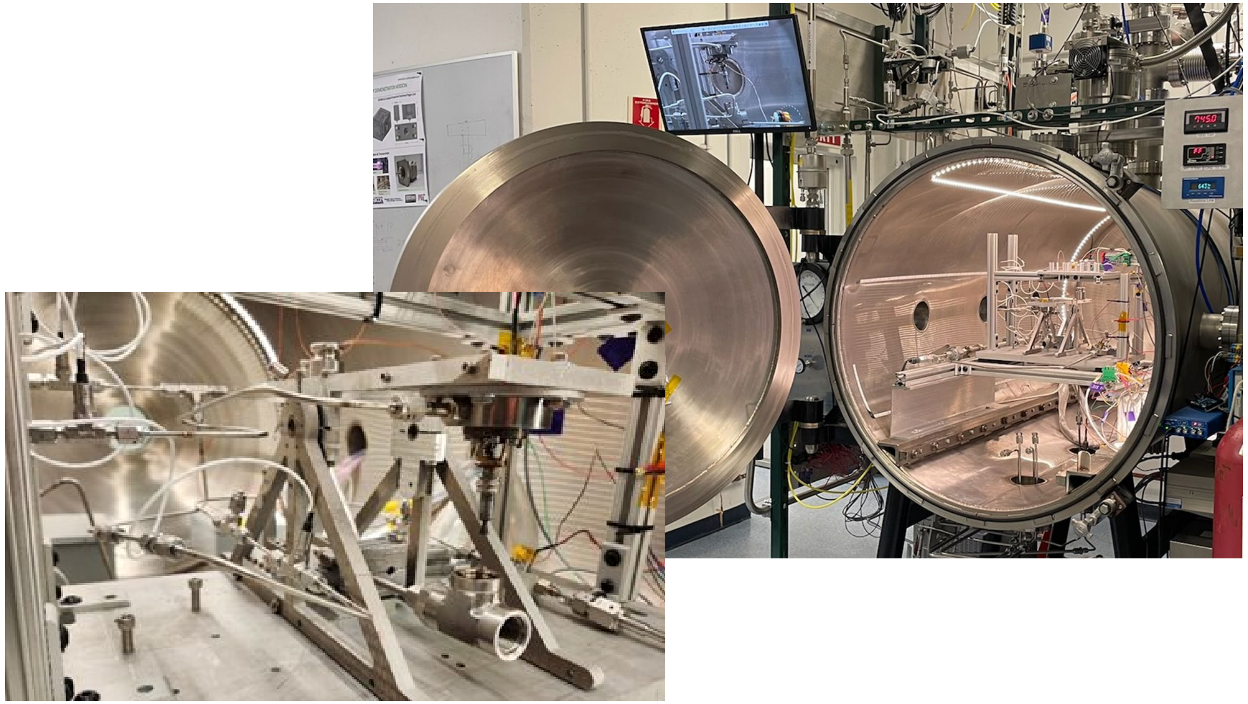
Design and Development: Breakdown of GPDM Design

- GPDM's propulsion module is a payload which will provide translation capability to the 6U CubeSat
- The GPDM spacecraft bus (developed by Georgia Tech with NASA MSFC oversight) will provide power, ground communications, and control capability to help execute specific mission objectives to test the dual-mode propulsion system
- GPDM spacecraft bus comprises of spaceflight proven commercial-off-the shelf (COTS) components including the flight controller, antennae, solar arrays, batteries, and transmitter/receiver
- GPDM's modular propulsion system is able to be integrated into a generic 6U CubeSat configuration, agnostic to a specific vehicle design/configuration



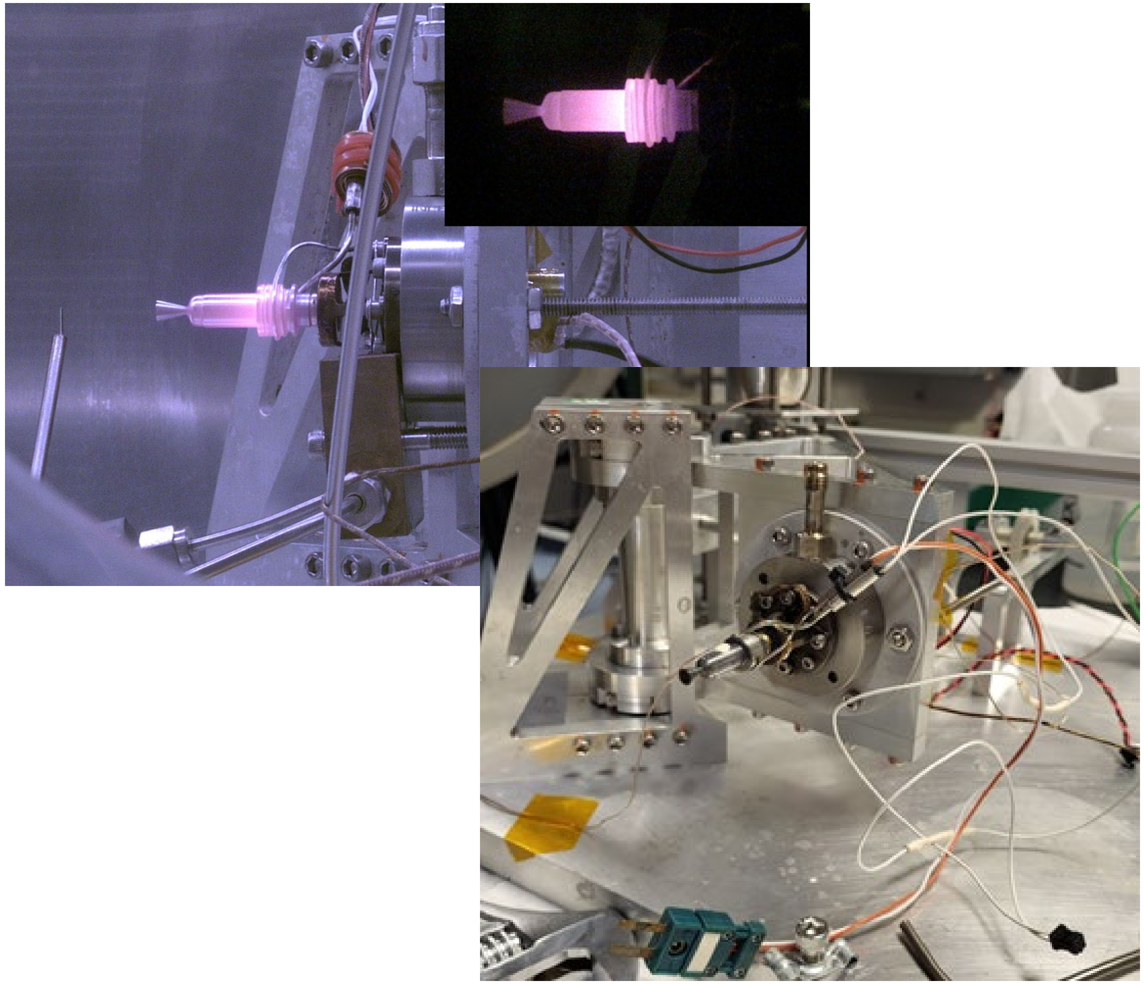
Ground Based 'Flat Sat' Testing

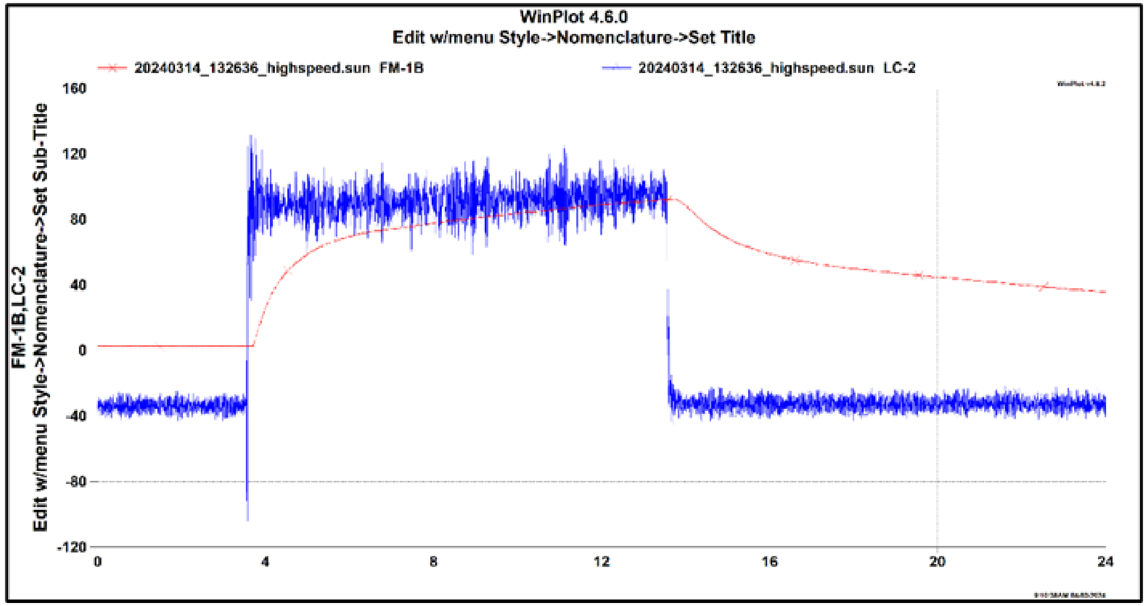
- The Green Propulsion Laboratory at NASA MSFC is undergoing ground-based test campaigns concurrent with the flight unit development
- Each test campaign will focus on incorporating flight-like hardware, software, and procedures in a systematic method
- The culmination of the 'Flat Sat' test method is a test sequence for the dual-mode propulsion module which operates in a flight-like condition
- Initial testing has confirmed flight-like operations of the 0.1N chemical thruster during a campaign of hot-fire tests which simulate beginning-of-life (BOL) and end-of-life (EOL) inlet pressure performance
- Future work is planned for Summer 2024 which will include the fully operational CPRS and electrospray thrusters



Campaign	Description	Status
1A	Chemical feed system builds and limited thruster testing	Complete
1B	CPRS and electrospray filling demonstration	Bench Level
2A	Performance data in LF typical profiles	Completed
2B	Performance data in GPDM typical profiles	Completed
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

Ground Based ‘Flat Sat’ Testing



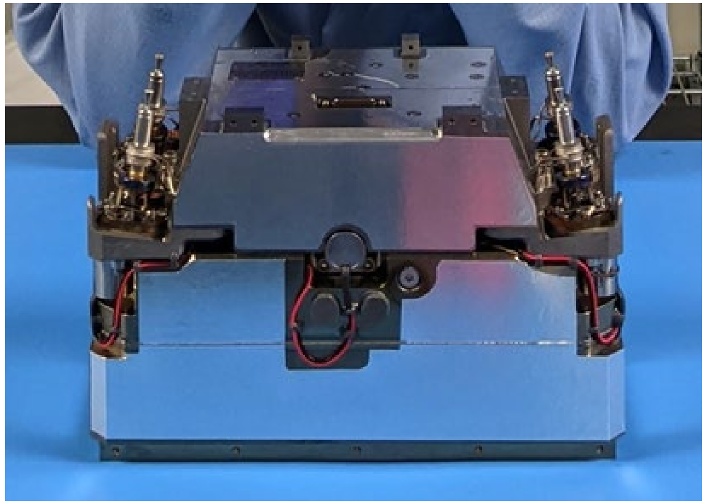


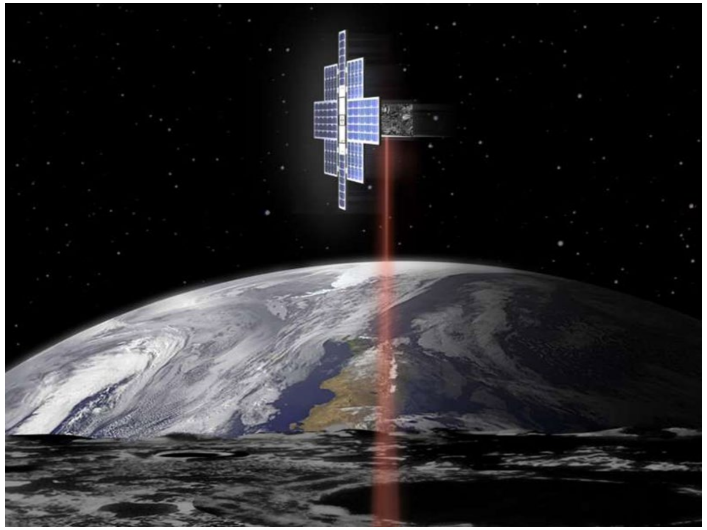
Chemical Thruster Test Progress Summary

- The latest 0.1N chemical thruster test runs show performance results consistent with the GPDM mission needs
- The 1A test case suggest consistent performance across several test runs for steady state conditions at the BOL inlet pressure (275 psi)/120 mN of thrust
- Work continues to perform the full sweep of inlet pressure conditions
- Future work will include adding the fully functioning CPRS and electrospray thrusters to the thrust stand and complete integrated dual-mode testing, having tested each component individually

Lessons Learned From Lunar Flashlight: Why We Flew

- LF was a 6U (small luggage case sized) satellite supporting an STMD funded, JPL led science mission to use a laser for lunar spectroscopy
- STMD/PI wanted to use this s/c to detect water in the form of ice on permanently shadowed regions of the moon
- In addition to science, LF was a technology demonstration platform which created an opportunity for intra agency partnerships (including JPL and MSFC), industry & small business and university partnerships (GT)
- In terms of propulsion- this created the opportunity to demonstrate a using green propulsion (using ASCENT) technology infusion to industry -> new pumps, thrusters, valves and in incursion into 3D printing using additive manufacturing
- This was a Class D mission (high risk, high reward) – initially slated to fly as a secondary payload on SLS during Artemis I with Orion

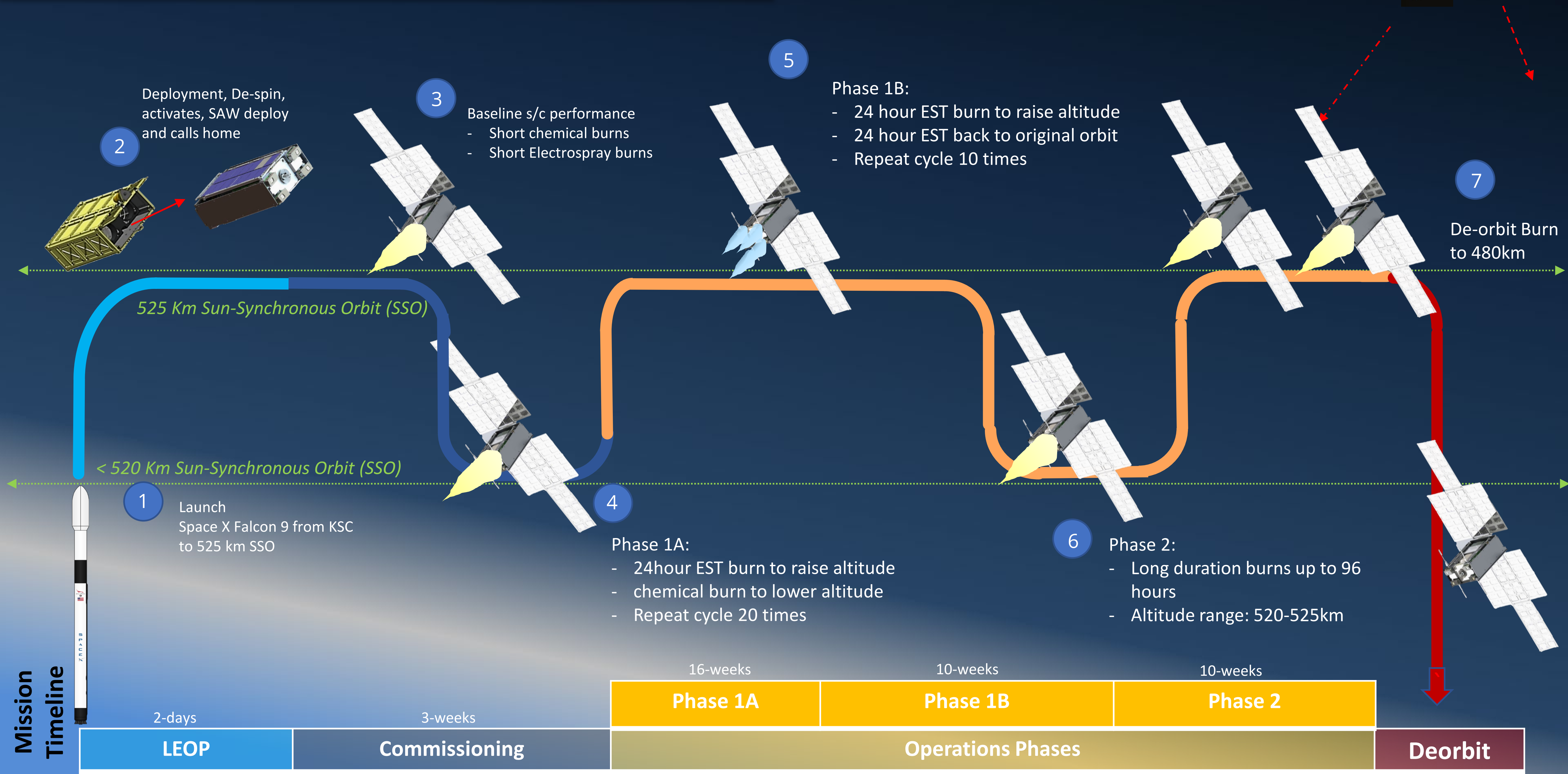




Lessons Learned From Lunar Flashlight: What We Learned

- ***The Anomaly:*** after fueling at MSFC and after launch, initial attempts to de-spin the vheicle (per telemetry) revealed thruster performance degradations initially in Th1. This behavior eventually was shown in the other thrusters, providing inconsistent thrust through the mission – later a joint team fault tree analysis and deductive reasoning pointed to mass flow limits due to FOD in the AM manifold
- ***How to face rapidly changing constraints:*** As with many small Projects, Lunar Flashlight's Propulsion System faced a myriad of challenges from initial development through the flight anomalies
- ***How to face schedule constraints:*** Changing launch vehicles later in the life cycle, changing project leadership, challenges with vendor pushed the project into an accelerated schedule – 14 months from ATP to delivery of HW which forced the project to take on risks – including inconsistencies in documentation specifically related to filtration, contamination control and cleanliness standards for the 3D printed manifold
- ***For GPDM*** – the lessons point to focus on higher contamination & control standards, implementation of extrude-honing and CT scans of 3D printed internal passages (most machining/cleaning), use of filtration as barriers of FOD protection and ground hot-fire testing of propulsion system EDUs in flight-like configurations

- Activation and demonstration of dual mode propulsion system using ASCENT propellant with a common propellent feed for the propulsion system
- Altitude changes to and from nominal altitude with dual-mode system
- Long duration burns and Electrospray reservoir re-fill demonstration



Mission Ops Plan

- GPDM will use the Mission Operations Control (MOC) located at Georgia Tech
  - Support from Science Operations Center (SOC) at MSFC for propulsion analysis
  - MOC will communicate with/command to the spacecraft through the Tracking and Data Relay Satellite System (TDRSS)
- Console Operations will be two continuous hours M-F for most mission phases
  - Additional 30-minute console operations will be supported during commission phases for 5-hour and 10-hour EST burns after each 90-minute period of autonomous spacecraft operations to build confidence actual performance matches expected performance
  - Additional 30-minute console operations will be supported the first 5 times the spacecraft autonomously performs a 24-hour EST burn after each 4-hour period of autonomous spacecraft operations to build confidence actual performance matches expected performance
  - Console Operations will be Sun-Sat for the 10 weeks of 96-hour autonomous EST burns
- Two week burn trajectory planning is required for coordination with the NASA's Conjunction Assessment Risk Analysis (CARA) Office
  - Most satellite missions use a stable orbit. However, by mission design, GPDM is performing altitude change maneuvers on ~ 45% of its on-orbit mission days
  - That increases conjunction probabilities requiring additional planning, analysis, and coordination to ensure the safety of the GPDM Spacecraft and other spacecraft in the same section of Lower Earth orbit (LEO)
- Mission Operations oversight/guidance provided by the Payload and Mission Operations Division at NASA MSFC leveraging decades of mission operations experience.

Summary

- Green Propulsion Dual Mode (GPDM) will demonstrate using ASCENT propellant as a chemical and electrospray propulsion using a common feed system

- The Green Propulsion team is working with university and industry partners to develop specific components for a 6U CubeSat based on technology investments from Lunar Flashlight, university research

- GPDM Project is working with the CubeSat launch initiative for a flight assignment in the Fall 2025 timeframe

References

- [1] 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.
- [2] M. Kilcoin, D. Cavender, N. Daniel, and A. Lentz, "Sprite, a Modular Template of In-Space Propulsion," in *37th Annual Small Satellite Conference*, Logan, UT, 2023.
- [3] A. R. Bruno, M. R. Schroeder, and P. C. Lozano, "Characterization of Electrospray Thrusters with HAN-Based Monopropellants for multimode Propulsion Applications," in *AIAA SciTech,* San Diego, CA, 2022.
- [4] A. R. Bruno and P. C. Lozano, "Design and Testing of a Propellant Management System for Bimodal Chemical-Electrospray Propulsion," in *IEEE Aerospace Conference*, Virtual, 2021.
- [5] 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.