Design of a Cold Gas Propulsion System for the SunRISE Mission

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NASA's SunRISE Mission is a formation of six identical 6U CubeSats that will form the first low-frequency space-based radio telescope, studying the radio characteristics of the solar environment in order to yield insights into solar events that affect the safety of Astronauts and spacecraft, as well as systems on Earth. These spacecraft use cold-gas propulsion systems designed by the Space Systems Design Lab to perform delta-V and RCS maneuvers. Utilizing additive manufacturing processes for the main structure and tank, the SunRISE cold-gas propulsion system represents a continued demonstration of the Space Systems Design Lab's ability to design custom propulsion systems using flight-capable hardware. This report outlines the development of the SunRISE Propulsion System from its initial proposal through its design evolution, concluding in discussion of its future integration and test campaign, as well as the future flight units.

Nomenclature

AM	Additive Manufacturing
COTS	Commercial Off-The-Shelf
EIDP	End Item Data Package
FU-x	Flight Unit, Number x
GEVS	General Environmental Verification Standard
GTRI	Georgia Tech Research Institute
GLRG	Glenn Lightsey Research Group
GSE	Ground Support Equipment

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MEOP	Maximum Expected Operating Pressure
QA	Quality Assurance
SDL	Space Dynamics Lab
SLA	Stereolithography
SRPS	SunRISE Propulsion System
SSDL	Space System Design Lab
SLS	Space Launch System
SV	Sine Vibration
U	Unit, a standard CubeSat volume of 10 x 10 x 10 cm
USURF	Utah State University Research Foundation

I. Introduction

With the historically more expensive launch prices for science payloads, there has been a long-time desire to pack more science and engineering into a smaller, less massive, form factor. CubeSats represent an industry effort to standardize a small satellite form factor, with standard deployment and ride-share designs, in order to maximize research and technology development demonstrations. At Georgia Tech, SSDL is developing a series of 1-Unit (1U) CubeSats to establish heritage of a satellite bus that can serve as the foundation of testing new hardware and software technology. GT-1, shown in Figure 1, represents the first such Georgia Tech mission featuring a radio payload to communicate with HAM radio operators worldwide, as well as 23 solar cells and an attitude control system.

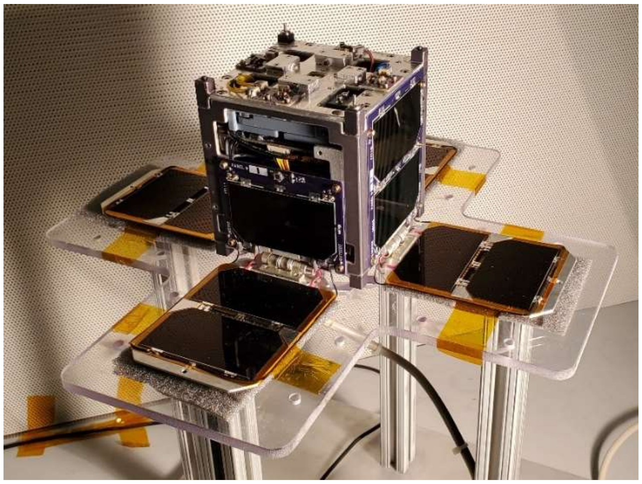

Fig. 1 Georgia Tech SSDL CubeSat, GT-1

CubeSat developers, while extremely creative in their use of space, are approaching a limit as to what degree of science can be done in as small a form factor without sufficient maneuverability in the form of propulsion. Propulsion systems on CubeSats allow for orbit adjustment and attitude maneuverability at larger magnitudes and greater time periods that would be possible through passive systems alone. Developing an efficient volumetric approach to propulsion systems on CubeSats and other small satellites is therefore of critical interest in the development of more advanced CubeSat missions.

This report outlines the design of a cold gas propulsion system for the SunRISE mission, whereby the Glenn Lightsey Research Group (GLRG) within the Space Systems Design Lab (SSDL) builds upon its experience with previous NASA CubeSat cold-gas propulsion systems to develop six propulsion systems for SunRISE's formation of six satellites.

A. SSDL Cold Gas System Heritage

SSDL has developed cold gas systems for multiple space missions. Cold-gas systems for CubeSats carry benefits of a relatively light mass, relatively simple mechanical and electrical interfaces, and most uniquely a highly customizable form factor. This customizability comes from SSDLs creative usage of additive manufacturing (AM) processes, allowing for more creativity on behalf of the propulsion system engineers. The flight heritage of cold-gas sytems within SSDL includes missions like Bevo-2, Biosentinel, Prox-1, Ascent, and now SunRISE, as documented in Table 1 [1]. These cold gas systems function based the energy of a pressurized propellant, releasing and expanding the vapor in order to produce thrust. This method, employed by SSDL's previous flight projects, has continued application in SunRISE.

Table 1. Georgia Tech SSDL Cold Gas Propulsion System and Flight Status [1]

Mission	**Mass**	**Status**
Bevo-2	0.380 kg	Flown
BioSentinel	1.265 kg	Tested and Integrated
Prox-1	6.000 kg	Tested
ASCENT	3.660 kg	Tested and Integrated
SunRISE	1.595	In production

Of note, the BioSentinel propulsion system developed by the Space Systems Design Lab in coordination with NASA Ames Research Center is responsible for performing momentum desaturation and momentum management maneuvers [2]. This mission represents a design standard for the Space Systems Design Lab, with the propulsion system undergoing a rigorous test campaign at Georgia Tech facilities as well as NASA's Glenn Research Center [3]. The results of the test campaign described by Lightsey, Stevenson and Sorgenfrei [3] establish an expected baseline of heritage total impulse and thrust performance for the SSDL's cold-gas propulsion systems when using the same configuration. BioSentinel is scheduled to launch as a secondary payload as part of the Artemis 1 mission of the Space Launch System (SLS). The SunRISE Propulsion System (SRPS), to be discussed in this report, builds upon the experience of the BioSentinel propulsion program to develop six flight-qualified cold gas propulsion systems.

II. SunRISE Mission

The Sun Radio Interferometer Space Experiment, SunRISE, is an array of six identical CubeSats that together create a space-based low radio frequency array. SunRISE is an Explorers Program mission managed by NASA's Jet Propulsion Laboratory (JPL) with the objective to simultaneously observe the solar environment, creating a 3D map that will determine where large particle emissions come from on the Sun and how they evolve as they expand outward.

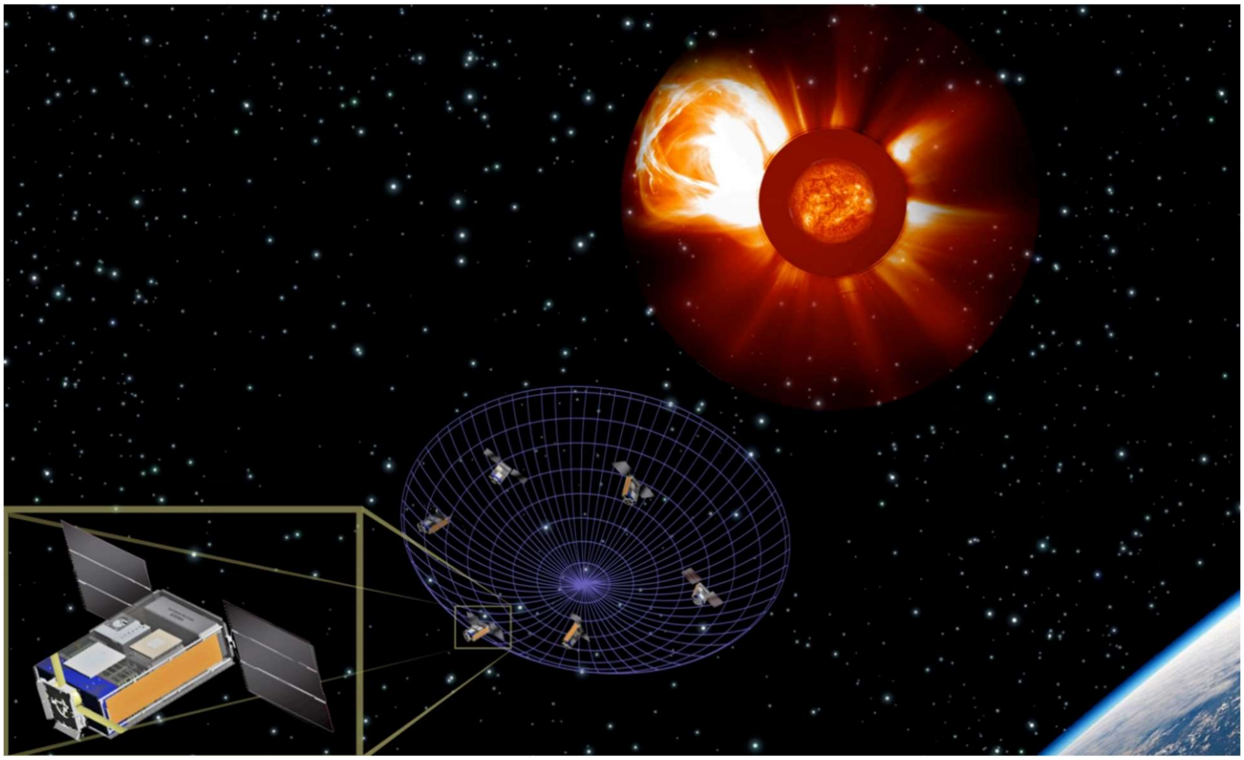

Fig. 2 SunRISE Mission Architecture, Artist's depiction [4]

The mission will also work to map the pattern of magnetic field lines from the Sun that extend into interplanetary space. SunRISE employs six identical CubeSats, each 6U in size with their own propulsion systems, flying in formation in a supersynchronous geosynchronous Earth orbit [4], as shown in Fig 2. The mission is led by Justin Kasper at the University of Michigan, Ann Arbor, who further details the mission architecture and science goals [5].

A. Propulsion Subsystem Role

As each spacecraft in the formation will fly around 10km from each other in precise formation, each spacecraft needs to control itself in position and attitude with respect to the formation. The SunRISE Propulsion System (SRPS) produces impulse required for translational delta-V maneuvers as well as reaction control system (RCS) momentum maneuvers, as needed by the spacecraft.

In context of the SunRISE spacecraft, the propulsion system unit of each spacecraft is located as shown in Figure 3 [4]. This position in the spacecraft stack introduces specific design constraints, from a volumetric perspective, and from a functional perspective. These challenges and their impacts on the final propulsion system design are discussed in further sections.

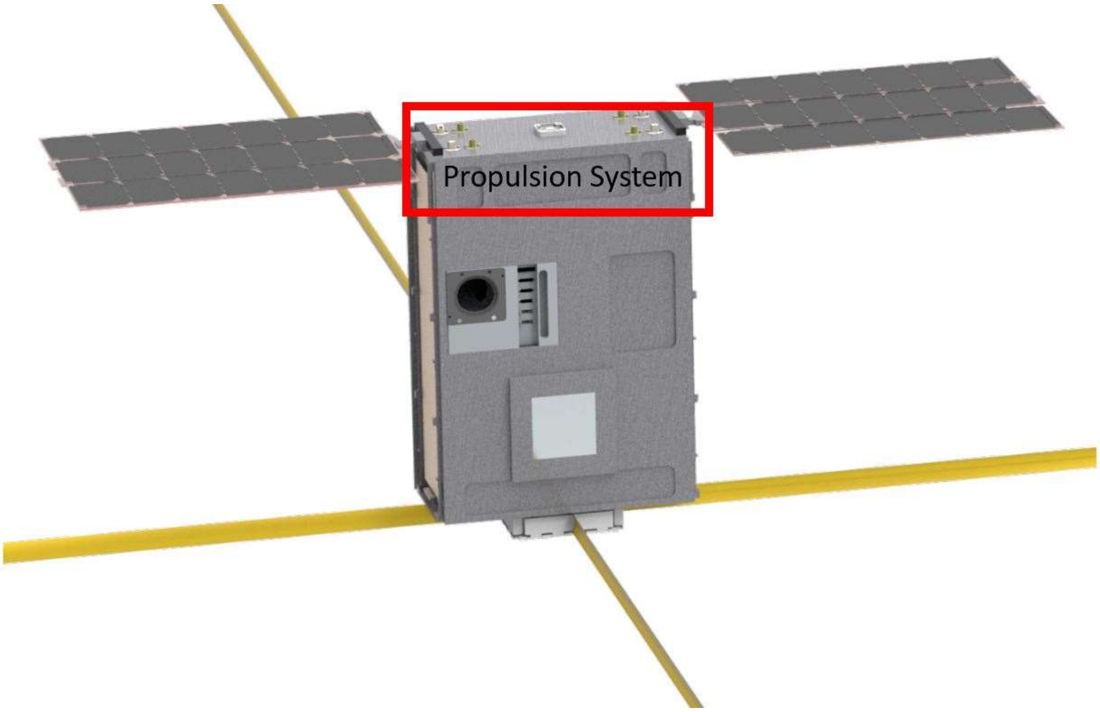

Fig. 3 SunRISE Spacecraft, with location of propulsion system [4]

III. Propulsion System Design

A. Proposed System and Requirements

The proposed propulsion system utilizes R-236fa, a commercial refrigerant that is non-toxic, non-flammable, and low pressure, to provide high volumetric impulse [6]. This proposed system utilizes a standard two tank approach, by which a main tank holds a saturated liquid-vapor mixture, and a secondary plenum contains the propellent in only a vapor state, as shown in Figure 4. This propellant, at the maximum system operating temperature of 50 C, has a saturation pressure of 84.73 psi [7]. This represents the maximum expected operating pressure (MEOP) of the system, though all analysis and design are completed with a factor of safety of 2.5.

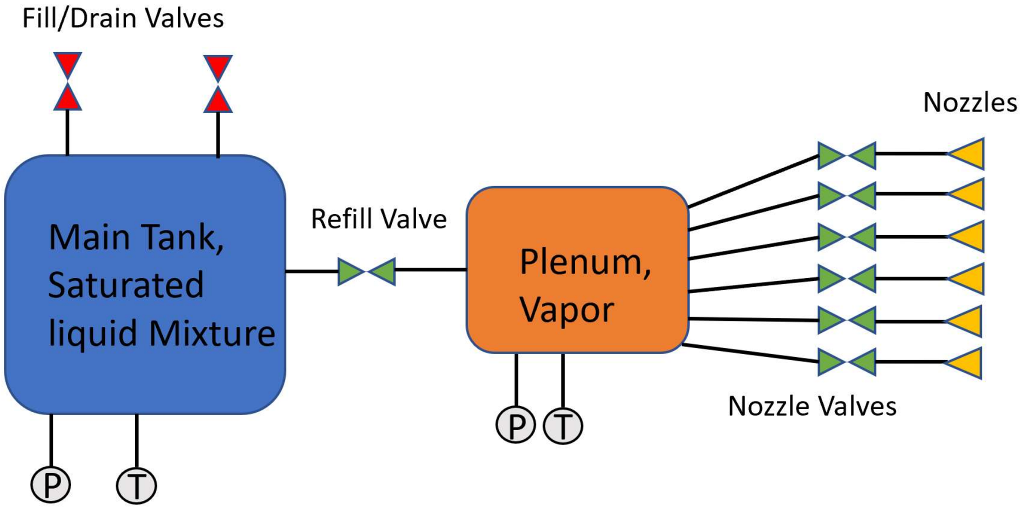

Fig. 4 Architecture of SunRISE Cold-Gas Propulsion System

Cold-gas systems, like those with system architecture shown by Figure 4, generate thrust through the expansion of a pressurized propellant. Such systems utilize neither heating nor reactions to extract more work from the propellant in the way that monopropellant and bipropellant propulsions systems do. As Stevenson [6] describes, this allows for a small spacecraft to control attitude and delta-V in a relatively simple process, when compared to more complex combustion or electric propulsion methods.

In the proposal for the SunRISE propulsion system, Figure 5 shows the originally designed system with seven nozzles, in a form factor that built upon the experience of BioSentinel. This proposed system utilized the heritage nozzle and fluid hardware from BioSentinel, resulting in a system with flight-qualified testing at the component level that met the system-level design requirements outlined in the request for proposal for the system.

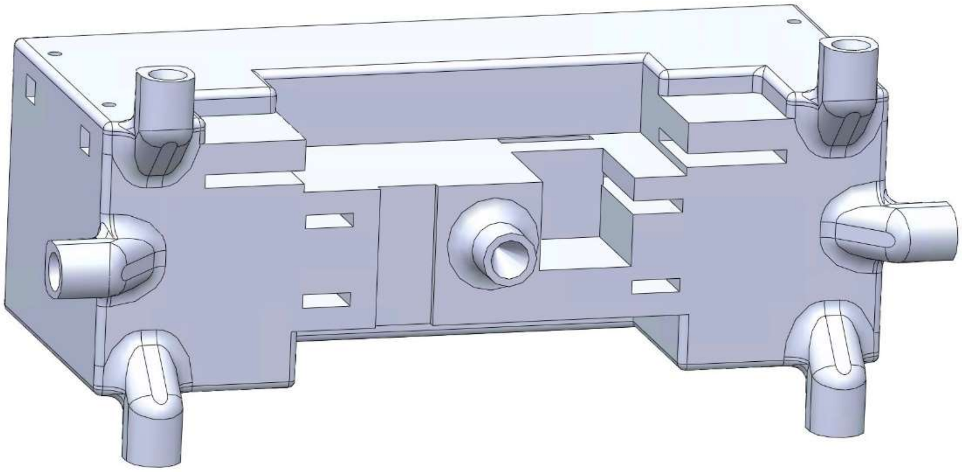

Fig. 5 Initially Proposed Design for the SRPS

A sample of these system-level requirements are shown in Table 2, noting that requirements 005 and 006 play into the strength of the custom 3D printed structure, allowing for a highly volumetrically efficient design. The requirements of 017 and 018 represent standard lifetime environmental system requirements that are met through the proposed design heritage in its similarity to BioSentinel and previous SSDL flight missions.

Table 2. Sample of SRPS System-level Requirements

Requirement	**Description**	**Notes**
SUNR-REQ-005	Dry Mass	The propulsion subsystem dry mass shall be less than 1.15 kg.
SUNR-REQ-006	Total Impulse	The total impulse capability of the propulsion system shall be greater than 240 N-s
SUNR-REQ-017	Random Vibration	The propulsion system shall be random vibration qualified to NASA GEVS qualification and acceptance levels.
SUNR-REQ-018	Thermal Performance	The propulsion system shall be TVAC/thermal cycle qualified from -30 °C to +50 °C.

Through the design process, with input from the System Dynamics Lab (SDL) and NASA's Jet Propulsion Lab (JPL), the final flight unit propulsion system configuration shown in Figure 6 has several notable changes. The most notable changes in design, the nozzle placement and alignment, the mounting interfaces, and the asymmetric fill port placement, will be discussed in the following section. These changes, as well as the addition of cutouts and a more complicated volume envelope than the proposed design, represent an iterative design process including critical feedback from the spacecraft design and integration team and evolving design constraints from other spacecraft systems.

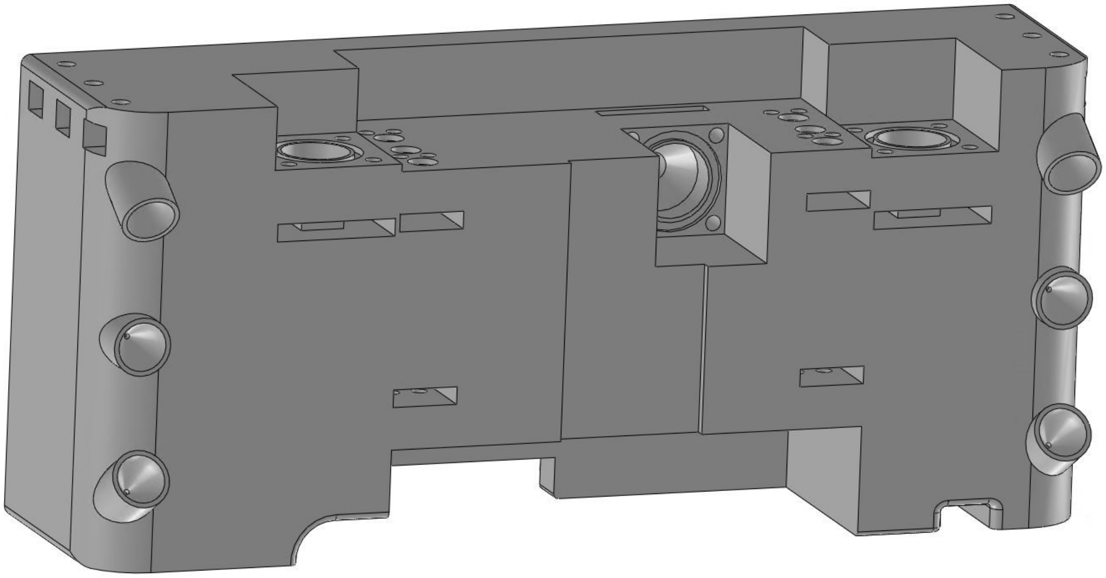

Fig. 6 Final Design Flight Configuration of the SunRISE Propulsion System

B. Tank Design

As noted previously, there are several notable volume constraints driving the design of the SRPS structure, and therefore restricting the internal volume of the tanks and fluid pathways. The largest changes to be accounted for involve pathways in the structure allowing passage for external, non-propulsion system connections through the spacecraft and the placement of axial and canted system nozzles, as shown in figure 7. This figure includes arrows highlighting passages through the length of the propulsion system and across the face, allowing for wire routing across the surface. These custom passages within the proposed volume envelope introduce volumetric constraints on the internal tank, ultimately driving the system performance and ability to meet the requirements previously outlined in Table 2. The nozzle placement was selected to minimize internal line length of the fluid passages from the plenum to the nozzles, while also maximizing the internal volume disruptions from internally protruding features from the nozzles. Ultimately, a decision was made to reduce the number of nozzles from 7 to 6, and adding pairs of canted nozzles to allow the angular control authority needed for the SRPS to perform its role in the momentum desaturation maneuvers and RCS capability of the spacecraft. These design changes were made with feedback from the spacecraft design and integration team.

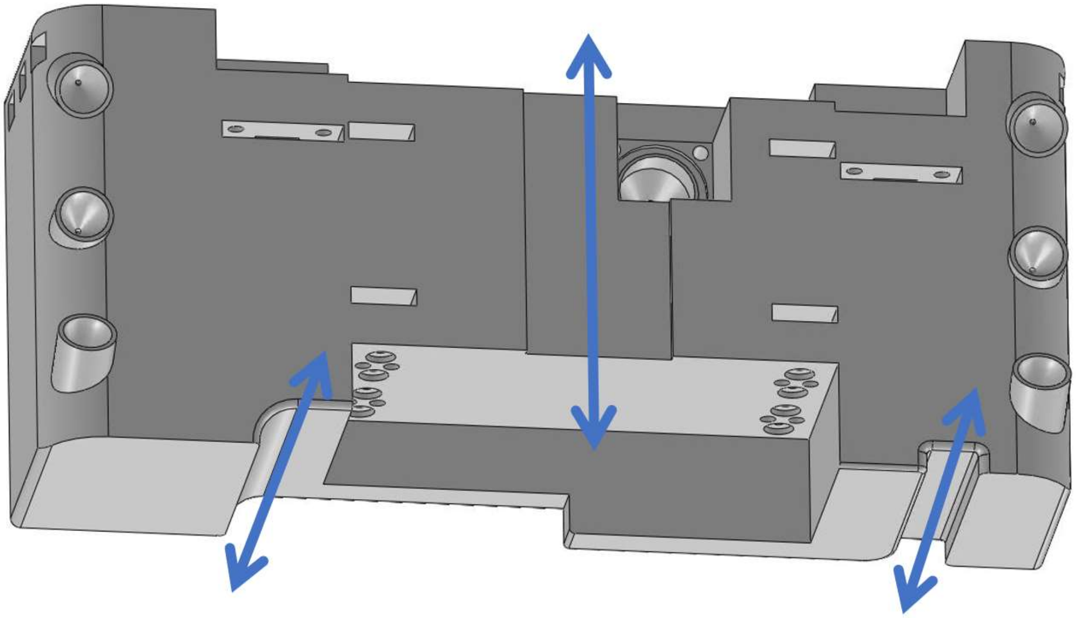

Fig. 7 Channels for routing Spacecraft connections

The impact of the external volume constraints is shown in Figure 8, highlighting the effects that the external design has on the internal volume, something that may be less obvious when making system-level design changes. Minimum distance must be kept on internal faces to satisfy previously discussed pressure level requirements at the maximum operating temperature. The complexity of the internal plenum and tank structure arises due to a balance of pressurization requirements and functional fluid flow passage requirements. Performance of the system is driven in part by the line lengths of the piping leading from the plenum to the nozzles. In an ideal world, the internal plenum and tank could be created such that they emulate organic structural elements, allowing the plenum to evacuate through the valves directly to the nozzles. Using the flight-qualified COTS components that the SRPS does, the internal tank and plenum must meet certain interface conditions imposed by the manifold and interface components, while also allowing for proper integration of the pressure and temperature sensors. The results design compromise made here is to minimize line lengths while also maximizing tank size, resulting in the internal passages shown by figure 8.

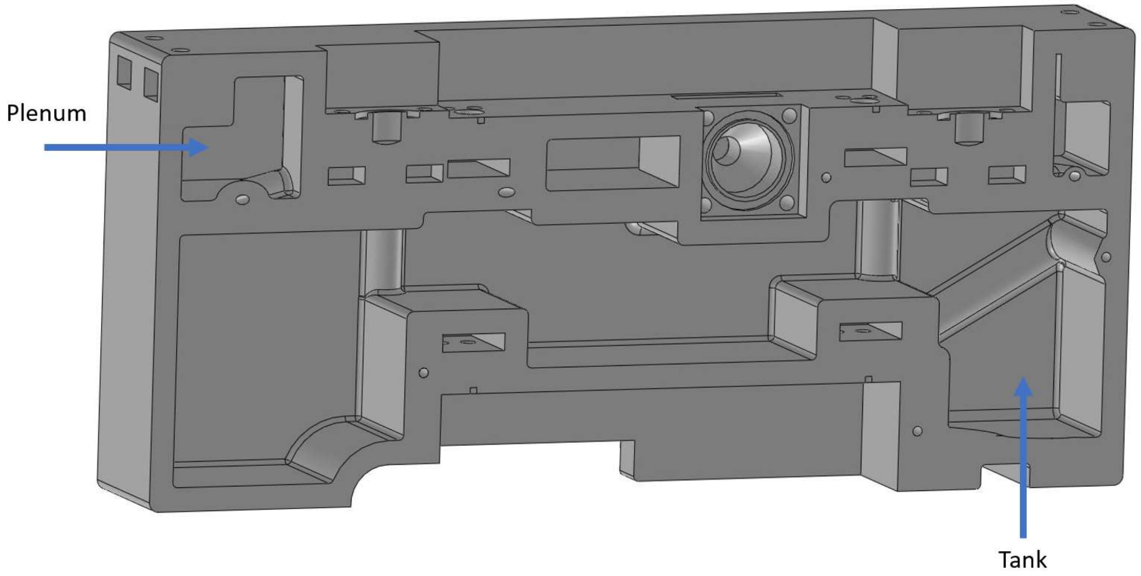

Fig. 8 Layout of Tank and Plenum Internal to the Printed Structure

A more effective view of the tank may come in the form of the solid structure "negative", that is the space occupied by the propellant volumes in either saturated mixture or vapor-only form. This view is shown by Figure 9, with particular emphasis on the fluid pathways, tubing that connects tank and plenum, as well as carrying propellant from the plenum to the nozzles. This highlights the quintessential strength of AM processes in the design of cold-gas systems, the ability to creatively route internal piping through volumes that would be difficult or impossible to traditionally machine without significantly more points of leak and failure. Together, figures 8 and 9 can give indication as to how the internal design must shift when accounting for external system-level volume allocations and design changes.

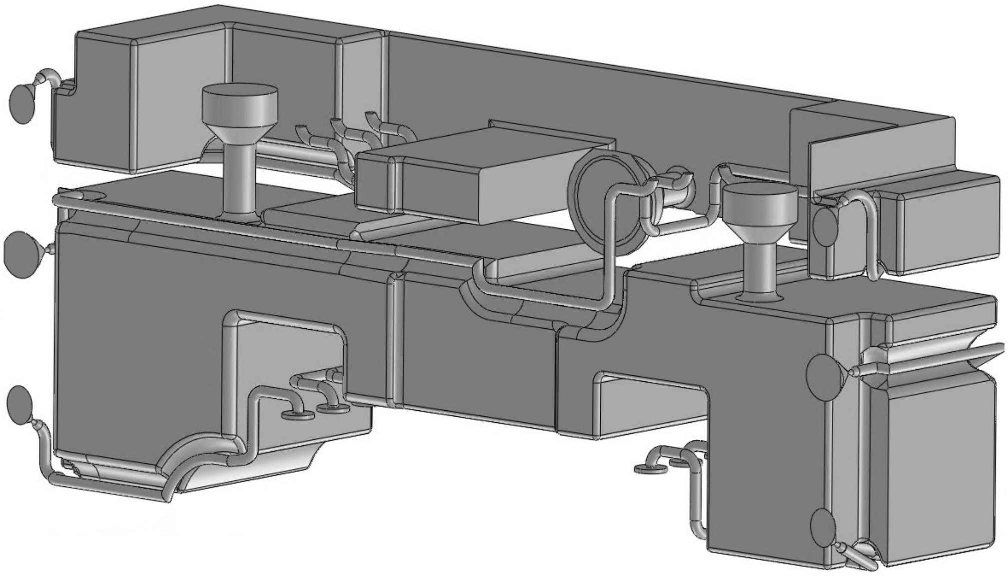

Fig. 9 Fluid routing channels between plenum chamber and nozzles

Another important consideration through this design process was the mechanical mounting of the propulsion system to the spacecraft. With input from SDL on the available spacecraft mounting surfaces, the propulsion system physical characteristics, and the location of the system within the spacecraft (again, as shown in figure 3), it was determined through analysis that the structure needed additional mounting surfaces, increasing the contact area at the mounting interface and providing a more stable mount. These mounting locations are highlighted in figure 10, but it must be added that the mounting interface includes a non-trivial amount of space allocated for mounting backplates that further complicates the design space for internal tank volume and fluid pipe routing, as shown in figure 9.

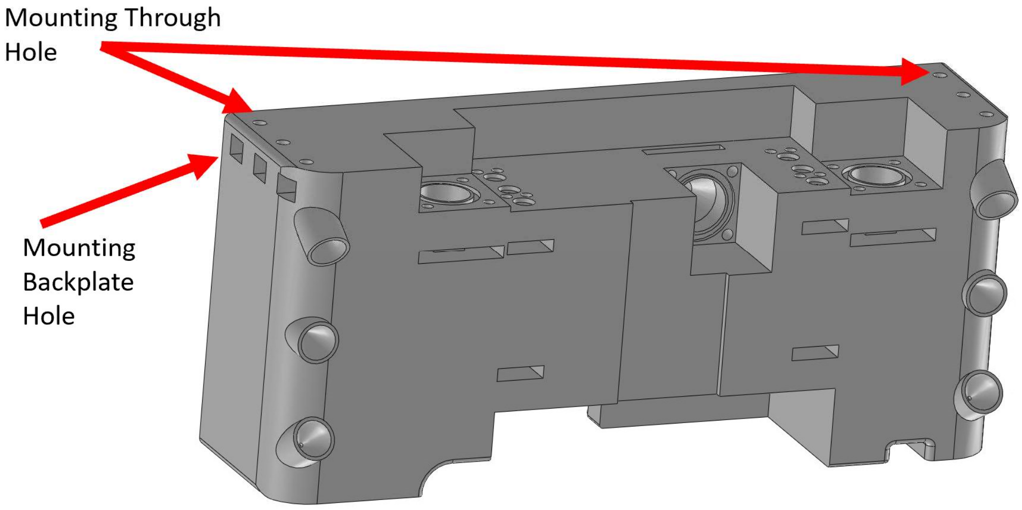

Fig. 10 Mounting Interface of SRPS to Spacecraft

C. Valve Manifold Design

In seeking to preserve as much flight-tested component heritage as possible, the SRPS utilizes previously developed valve manifold designs, as shown in figure 11, including flight-qualified valves (yellow) and filters (blue). Notably, these microfluidic components represent the largest flow restriction in the system, given the valves rated flow resistance [8]. These fluid components are mounted to custom, traditionally machined interface blocks using COTS compression fittings (orange). The valve manifold itself is then coupled with the SRPS's custom flight controller board, allowing connection of the valves directly to the board. The complete set of valve manifolds is split into two halves on the system, as shown in figure 12, accommodating the allocated volume of the propulsion system in a similar form factor and functional design as SSDL's previous cold-gas systems.

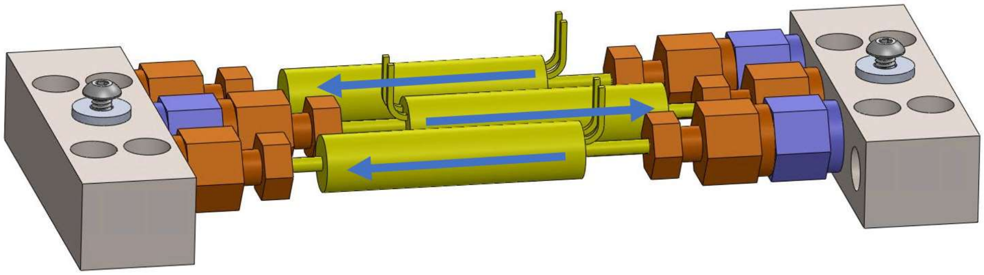

Fig. 11 Valve Manifold Assembly

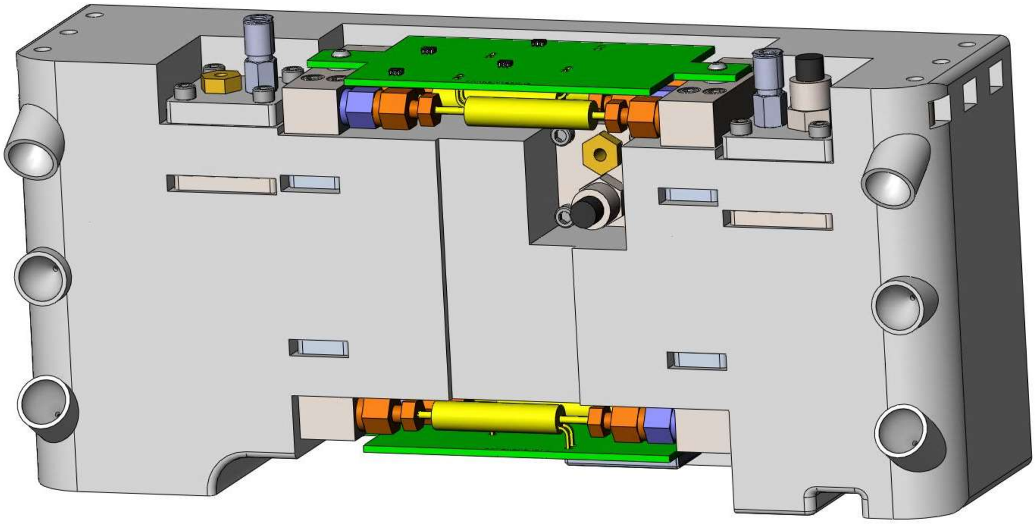

Fig. 12 Model of Integrated SRPS

IV. Manufacturing

A. Traditional Machining

The SRPS utilizes custom designed traditionally machined components in several places, including the mounting attachment blocks as well as the fill and valve manifold blocks. Figure 13 shows an example of one such machined block, with the assembled commercial off-the-shelf (COTS) fill valve. The custom mounting blocks were designed by the SSDL and machined by the Georgia Tech Research Institute (GTRI) machine shop. A distinct definition and exploration of traditional (subtractive) machining methods, and their applications within SSDL flight projects is explored by Huggins and Lightsey. [9] The apparent use-case for traditional machining methods in the SRPS involves locations on the system where there will be fluid interfaces or structural mounting. The benefit of using these traditionally machined mounting plates and mounting blocks is two-fold: a simpler interface at the fluid boundary in the space environment through a robust heritage seal design, and ease of installation. At the interface of the fluid boundary, a compressed o-ring static seal against the machined block is used prevent propellant leak over the storage and mission lifetime. This is easier to do with traditionally machined components, as there is greater control over tolerances and surface finishes when compared to the layered 3D printed manufacturing process that will be subsequently discussed. The other benefit, ease of installation, is more straightforward. When dealing with small COTS components on a CubeSat scale propulsion system, it’s easier to install things securely to a traditionally machined plate than it is to install them on the printed structure itself. This also allows for separate metal mounting plates and backplates, as threads that meet torque specifications and seal requirements can’t be printed in the plastic structure, and previous tests of helical insert installation into the printed material have been less than promising [6].

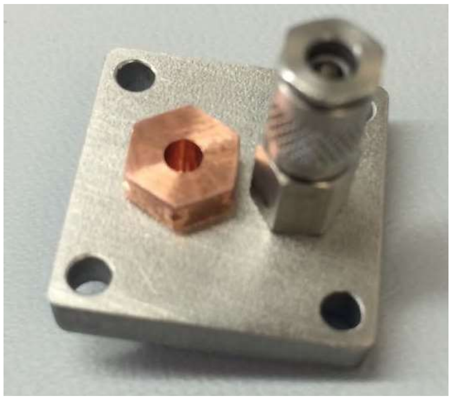

Fig. 13 Example of a Traditionally Machined Fill Manifold Block

B. Additive Manufacturing

The SRPS utilizes a method of additive manufacturing known as stereolithography (SLA), by which a laser is used to cure a liquid resin plastic in the form of a layered structure, working from the bottom-layer up. This layered polymer allows for more volumetrically constrained and custom pieces that can be printed rapidly. Figure 14 highlights some SSDL designed AM structures, including the Bevo-2 propulsion system and BioSentinel Propulsion System.

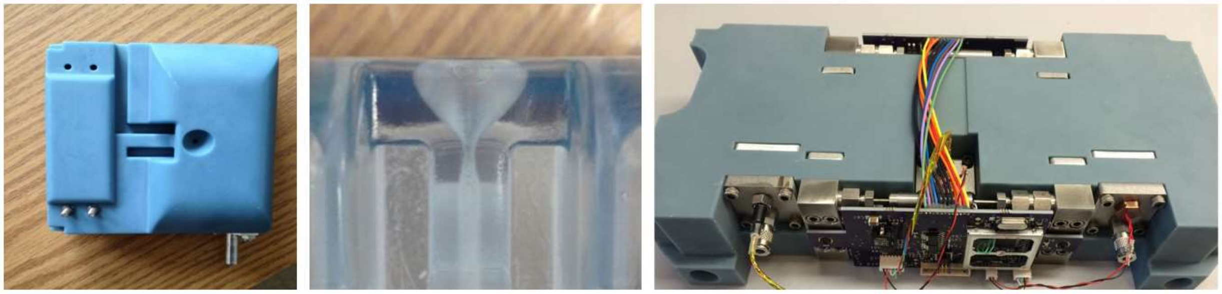

Fig. 14 Previous SSDL Additively Manufactured Structures (left to right): Bevo-2 [10], Bevo-2 Nozzle Highlight [10], BioSentinel [2]

The chosen SLA process does come with drawbacks, notably the addition of support structure both internal and external to the designed part during the printing process. It must be noted that for the SRPS, I worked with our AM printer, Interpro Additive Manufacturing Group, to orient the structure during print such that there was no internal support structure. This required some design iteration with the manufacturing team, involving the addition of material on the internal tank faces and in some locations around corners and piping routes, but resulted in a final printed structure design that has no internal printing-supports that could become dislodged and impair the system performance.

A distinct advantage of the SLA printing process chosen here is the level of control that a propulsion system designer has over the internal structure, minimizing the number of fluid interfaces for the system. The SRPS has a total number of 17 pressure seals: one on each of the two fill manifolds, one on the plenum sensor manifold, and 14 across the valve manifolds (6 on one, and 8 on the other).

V. Integration and Testing

A. SunRISE Propulsion System Integration

At the time of writing, all SRPS custom and COTS components have been received and cleaned, but integration has not yet begun. The integration plan and procedure for the SRPS project is modeled on those developed for

BioSentinel, which were jointly developed by SSDL and NASA Ames Research Center. The developed procedures enumerate each required component, document, and tool, as well as the safety and handling information for all materials and tools. Each sub-assembly procedure follows the required integration steps, noting specific quality assurance (QA) check-offs. The developed integration procedure allows for full confidence in the quality of the assembled unit, including the safety and cleanliness of the assembly environment, which will be the SSDL class 100,000 clean room and class 10,000 clean benches.

B. Environmental and Performance Testing Campaign

As noted, at the time of writing the SRPS has not yet undergone qualification testing. Here I will discuss the planned test campaign, from a description of the test goals to details of the tests chosen to evaluate the quality, safety, and performance of the system. SSDL has worked with SDL to establish a set of testing goals, listed in Table 3. These involve both functional and performance tests, that will inform the spacecraft team of the final specifications of the delivered flight systems.

Table 3. Description of SRPS Testing Goals

Test Identification Number	**Test Description**
Prop-GT01	Leak Rate Testing in vacuum, at -30C and +50C
Prop-GT02	Impulse Bit Testing in vacuum, at -30C and +50C, for each nozzle
Prop-GT03	Thrust Testing in vacuum, at -30C and +50C
Prop-GT04	Plenum Refill Characterization in vacuum

An initial pressure test post-integration will be done before any subsequent tests. This test will be a proof test, that is a test to 1.5 times MEOP. Procedure development for this test is still underway at the time of writing but will involve regulated Nitrogen pressurizing the system in quantized steps at room-temperature. The proof pressure will be held for a chosen period of time before stepping the pressure back down to ambient pressure. A visual inspection will be completed, and a functional test will be performed.

Using GTRI vibration table facilities, the SRPS flight unit will undergo a standard sine vibration (SV) sweep followed by a random vibration test to NASA GEVS levels along all system axes. Custom ground support equipment

(GSE) is being developed to allow the SRPS to integrate with the GRTI vibration table while maintaining access for functional testing at each step. The functional testing at each step serves as a checkpoint for system functionality over the testing campaign. It is currently planned that all vibration tests will occur with a filled system, meaning that safety precautions will need to be taken during the test to ensure that any escaped propellant, while non-toxic, occurs in a well-ventilated area. An oxygen monitoring device will be used to alert test conductors of any reduced relative air oxygen content.

Leak rate testing will be completed at the operational "cold" and "hot" cases, from -30C to +50C. The test will involve a complete fill of the system using the flight propellant and will take place in the SSDL Vacuum Chamber. The chamber is rated to micro-torr pressures and will contain the SRPS over a period of 72 hours in each operational temperature test case. Leak rate is computed over the course of this test based on a measured mass of the system, using a scale with milligram precision. The thermal vacuum chamber that will be used for testing is shown in figure 15. This leak rate test, completed at operational temperature extremes, meets the testing goal GT01 outlined in Table 3.

Fig. 15 SSDL Thermal Vacuum Chamber

Most relevant to the remaining testing goals (GT02, 03, and 04) outlined in Table 3, a series of performance tests will occur. These tests will use a specially fabricated thruster test stand that utilizes a torsional spring and known system dynamics with measured linear variable differential transformer (LVDT) deflections to predict system impulse [6]. From system impulse measurements, the system thrust will be computed. Over the duration of the tests hundreds of impulse firings will occur for each nozzle, at various temperatures in the operating range, giving a cohesive understanding of the system performance in impulse, thrust, and refill timing over the expected flight temperature profile.

VI. Future and Continuing Work

At time of writing, the SRPS is approaching the beginning of integration. To date, all design work of the first flight unit (FU-1) has been completed. A cleaning and subsequent bakeout of all flight unit 1 components have been completed by SDL, and all components are ready for assembly.

The future work for the SRPS team involves the assembly process of sensor subassemblies, which will then be shipped to SDL for inspection and bake-out. The sensor assemblies will be shipped back to GT, and the SRPS FU-1 assembly will begin. Post-assembly, the SRPS FU-1 will go through the test campaign of proof, leak, vibration, and performance testing. Following testing, an end-item data package (EIDP) will be delivered along with FU-1 to SDL for further acceptance testing and integration with the spacecraft.

As SSDL is producing six identical systems, the same assembly process and test campaign will be completed for each subsequent flight unit. I have completed all procurements of COTS components for all future FUs, with the only outstanding components for future FUs being the custom machined blocks and AM structure. These final components will be ordered once FU-1 has completed integration and testing. The future SRPS FUs will then be precision cleaned and assembled, much like FU-1, followed by identical integration and test campaigns. After delivery of all SRPS flight hardware to SDL, the Georgia Tech SSDL will continue in supporting the project as needed.

VII.Conclusions

The SRPS is a continuation of previous SSDL propulsion designs, based most closely on BioSentinel, in order to make use of the heritage hardware and testing of the program. As such, there aren’t major functional design changes either mechanically, electronically, or operationally; this preserves the previous flight projects experience, without re-inventing the system architecture and mechanisms. There are, however, some changes that occurred by necessity of designing for a new spacecraft and mission, with new requirements and design parameters. Working with the Space

Dynamics Lab and NASA's Jet Propulsion Laboratory, a cold-gas R-236fa propulsion system was developed by the Georgia Tech Space Systems Design Lab for the SunRISE Mission. This system utilizes traditionally manufactured mounting blocks and manifold hardware allowing for integration with heritage COTS components, and additive manufacturing stereolithography to print the main structure incorporating all fluid passages and channels into the internal structure allowing for volumetrically-efficient usage of propellant. At the end of this project, there will be 6 identical propulsion systems, with an optional flight-spare unit. This project has had many challenges, not the least of which has involved global supply chain disruption and personal challenges for all individuals involved due to the COVID-19 pandemic. Design challenges have been overcome through hard work and cooperation with the GT SSDL SunRISE propulsion team, the Space Dynamics Lab, and NASA's Jet Propulsion Laboratory. As this report is written and submitted, the SRPS FU-1 is approaching integration with delivery in Fall of 2021, with the subsequent SunRISE FUs beginning integration soon after.

VIII. Acknowledgments

I would like to thank Dr. Glenn Lightsey for his advisement and support on this project and throughout the years at the SSDL from my undergraduate days to now. Additional thanks to SDL SunRISE team for all the feedback, and for helping me learn and grow through this project. Final thanks to my fellow SSDL grad students for your support during this journey. Special thanks to Sam Hart for being an invaluable sounding board, and to Nathan Daniel for being an invaluable partner on this project!

References

[1] D. Andrews, and E. G. Lightsey, "Design of a Green Monopropellant Propulsion System for the Lunar Flashlight Mission," Tech. rep., Dec. 2019.

[2] T. Stevenson, E. G. Lightsey, "Design and Characterization of a 3d-Pritned Attitude Control Thruster for an Interplanetary 6U CubeSat", 2016 AIAA/USU Conference on Small Satellites, SSC16-V-5, 2016.

[3] E. G. Lightsey, T. Stevenson, and M. Sorgenfrei, "Development and Testing of a 3-D-Printed Cold Gas Thruster for an Interplanetary CubeSat," Proceedings of the IEEE, Vol. 106, No. 3, Feb. 2018, pp. 379–390. doi:10.1109/JPROC.2018.2799898.

[4] L. Kanayama. "SunRISE becomes new NASA mission to Study Giant Solar Particle Storms". 2020

[5] J. Kasper, J. Lazio, A. Romero-Wolf, J. Lux and T. Neilsen, "The Sun Radio Interferometer Space Experiment (SunRISE) Mission," 2021 IEEE Aerospace Conference (50100), 2021, pp. 1-11, doi: 10.1109/AERO50100.2021.9438184.

[6] T. Stevenson. “Development of Multi-Functional Structures for Small Satellites”. PhD thesis, Georgia Institute of Technology, December 2018.

[7] DuPont. “Hfc-236fa clean agent. properties, uses, storage, and handling”, 2012

[8] The Lee Co. “How to calculate flow resistance for gases”, May 2019

[9] G. Huggins, and E. G. Lightsey, “Development of a Cubesat-Scale Green Monopropellant Propulsion System for NASA’s Lunar Flashlight Mission,” Tech, rep., Masters Report, July 2019.

[10] S. Arestie, E. G. Lightsey, and B. Hudson. “Development of a modular, cold gas propulsion system for small satellite applications”. Journal of Small Satellites, 1(2):63–74, 2012.