The iodine Satellite (iSat) Project Development towards Critical Design Review (CDR)

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Despite the prevalence of Small Satellites in recent years, the systems flown to date have very limited propulsion capability. SmallSats are typically secondary payloads and have significant constraints for volume, mass, and power in addition to limitations on the use of hazardous propellants or stored energy (i.e. high pressure vessels). These constraints limit the options for SmallSat maneuverability. NASA's Space Technology Mission Directorate approved the iodine Satellite flight project for a rapid demonstration of iodine Hall thruster technology in a 12U configuration under the Small Spacecraft Technology Program. The project formally began in FY15 as a partnership between NASA MSFC, NASA GRC, and Busek Co, Inc., with the Air Force supporting the propulsion technology maturation. The team is in final preparation of the Critical Design Review prior to initiating the fabrication and integration phase of the project. The iSat project is on schedule for a launch opportunity in November 2017.

I. Introduction

Sarting with support from the U.S. Air Force and NASA Small Business Innovative Research (SBIR) programs, investments continue for technology development required for iodine Hall thruster propulsion systems; first reduced to practice by Busek Co., Inc.[1,2] The results of testing indicate that iodine has comparable performance to that of the state-of-the-art (SOA) xenon. The iodine propellant has several advantages, with niches for low power volume constrained systems and at high power[3]. The iSat system exploits this advantages for a low power secondary payload demonstration. The iodine is stored as a solid, with a density more than twice that of xenon, and enables the high potential specific impulse densities or ΔV per unit volume. The propellant tank is launched unpressurized and only requires 1-2 psi during operation. This reduces the propellant tank mass, and lends itself to 3-D printing technology to maximize the packing efficiency of the tank. The system also leverages the sublimation of iodine in lieu of paying the full power cost of vaporization of the bulk propellant. These characteristics make the iodine propellant ideal for secondary spacecraft. Additionally, changing the propellant to iodine does not require a modification to the power processing unit (PPU) discharge supply resulting in cost savings and heritage leverage.

Despite the mission and system advantages, keys risks still exist in using an iodine-fed Hall thruster system. These risks have been identified and recommended for mitigation prior to use on higher class missions; those above the Class D mission that has high risk but is low cost with a short operational lifetime. Several of the risks are

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associated with the spacecraft interactions of the plume given the deposition potential with the iodine propellant. Additional risks at the time included the maturity of the feed system in a flight operational configuration and the maturity of an iodine compatible cathode. A flight operational feed system was one risk identified and funded for maturation through the NASA Marshall Space Flight Center (MSFC) Technology Investment Program (TIP). Following the TIP selection, a large number of collaborations have been working towards risk reduction beyond the feed system, including mission concept development, spacecraft design and strategic subsystem risk reduction. The Space Technology Mission Directory (STMD) is funding risk reduction activities culminating with a flight demonstration project of the iodine Hall system through the Small Spacecraft Technology Program (SSTP). The current scope of work progresses towards a mission critical design review (CDR) of the baseline iSat technology demonstration mission. The design evolution of the iSat spacecraft is illustrated in figure 1.

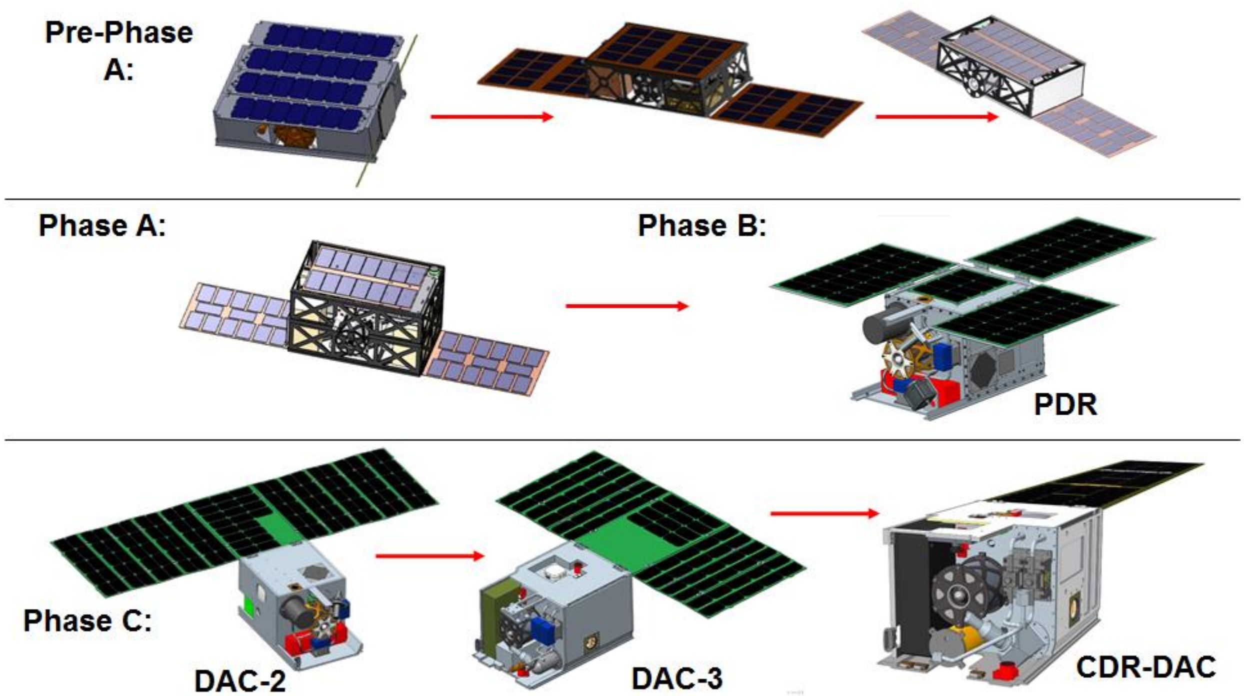

Figure 1. Concept design evolution of the iodine Hall demonstration system.

II. Mission Objectives and Requirements

The use of iodine as an alternative to xenon has been studied for more than a decade.[4,5] However, xenon has advantages as an inert noble gas. All condensable propellants raise concerns regarding deposition on the spacecraft, and iodine can be corrosive to materials. Additionally, the feed system has unique challenges with very low pressure flow control and/or parasitic power burden to keep the propellant and propellant lines heated. There appear to be two distinct niches for iodine, and both are becoming more prevalent; very small spacecraft and very high power electric propulsion systems. The iSat project will demonstrate small spacecraft maneuverability, but also mitigate concerns regarding iodine deposition regardless of spacecraft size.

A. Top Level Mission Objectives

It is important to note that iSat is not developing a propulsion system specifically for CubeSats. The project is leveraging the CubeSat form factor to reduce the cost of a high risk technology demonstration mission. The top-level objectives of the project are focused on validating the efficacy of iodine for future higher class missions while demonstrating high ΔV viability on a secondary small spacecraft (e.g. 50kg, 100kg, ESPA class, etc.). The mission will validate in-space performance of the iodine Hall system, demonstrate relatively high power and demonstrate high power density in a CubeSat form factor. Key metrics for the government also include the flight infusion of a Small Business Innovative Research (SBIR) product and the maturation of the iodine Hall technology through a

Commercialization Readiness Program (CRP). The mission is intended to increase the expectation of low risk implementation of iodine Hall technology for future commercial, NASA and DoD missions of interest.

B. Level 1 Requirements

There is only one Level 1 requirement for the iSat Project:

"The iodine satellite shall demonstrate on-orbit operation of a 200W iodine hall thruster based satellite system no larger than 12U in low Earth orbit."

In addition to the requirement, there are several success criteria for the mission. The success criteria have been modified since the Preliminary Design Review, following an Interim Design Review (IDR). To achieve full success, the mission must demonstrate a cumulative propulsion system operation of more than 100 cycles. The nominal maneuvers are currently five minutes in duration. The spacecraft must also discern the average thrust within 5% uncertainty and specific impulse within 10% for full success. The system will include instrumentation to assess the iodine environment, track solar array performance degradation and be capable of taking images. Last, the spacecraft must lower its orbit such that it will de-orbit within 90 days of end of mission. The de-orbit potential is largely driven by the rideshare opportunity starting orbit and the mission duration.

C. Future Mission Potential

Detailed studies of iodine enabled missions have been completed.[3] The mission studies indicate the enabling nature of iodine for volume constrained systems. Specially, MicroSats (10-100kg) can perform significant orbit transfers including GTO-to-GEO or deploy into a full constellation from a single launch. Finally, spacecraft of ESPA or ESPA Grande[6] class can perform more than 10 km/s of ΔV and perform orbit transfers from GTO to the Moon, Mars, Venus and Asteroids. The technology enables missions of opportunity starting from GTO for future Human Exploration and Science Mission needs. Even with potential extended operations times, the resulting architectures can represent greater than 5x reduction in total mission life cycle costs due to the reduction in launch costs over conventional space transportation architectures.

III. iSat Mission Concept Overview and Development Status

The present effort of the project team is the maturation of the overall mission concept, focusing on key risk reduction activities for the mission. The focus of FY16 has been finding a viable cathode solution, system level propulsion testing and overall bus design maturity towards the critical design review.

D. Concept of Operations

The mission concept of operations (CONOPS) is partially dependent on the orbit to which the iSat vehicle is deployed. Previously, all mission CONOPS were based on deployment into a sun-synchronous 600km circular orbit.

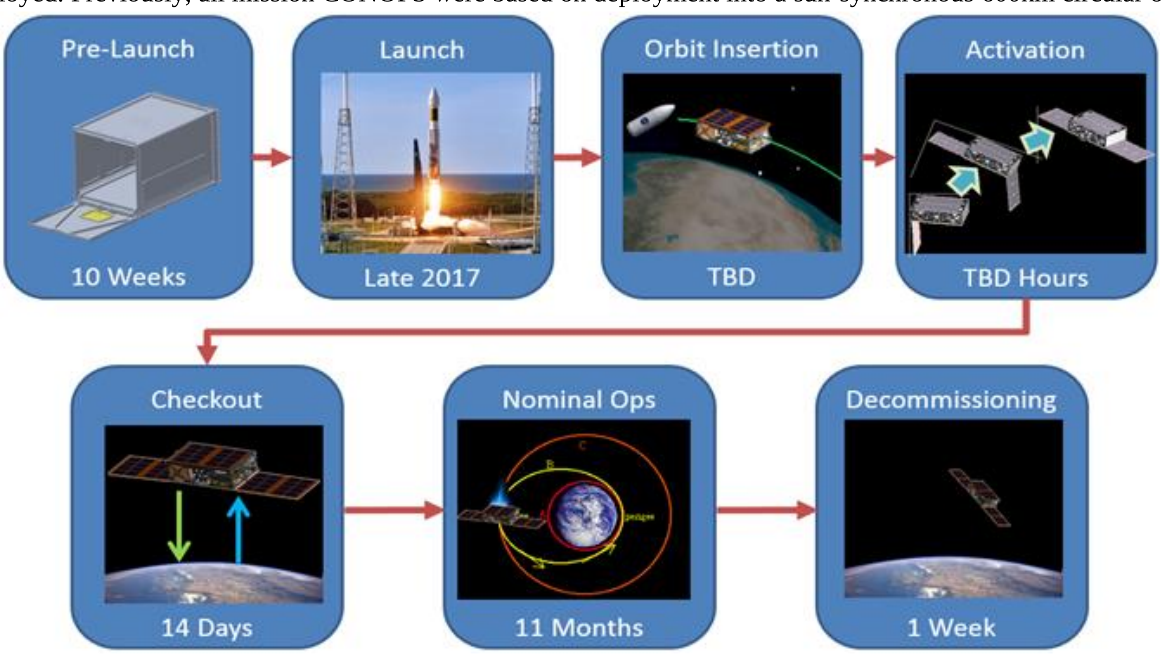

Figure 2. Basic mission Concept of Operations.

Ultimately, the sun-synchronous orbit may be the final orbit selected, however, an opportunity to a lower inclination orbit has been identified and is the leading candidate for manifest. This new orbit for consideration has an inclination of 52 degrees with an apogee of 659km and perigee of 550km or lower. The system is still designed for deployment from the Planetary Systems Corporation (PSC) 12U deployer. The perigee, or starting orbit in general, is set to such that even with a total mission failure, the selected orbit will meet the natural orbit decay requirement of less than 25 years.

The iSat CONOPS is split into seven phases as shown in figure 2: Pre-Launch, Launch, Orbital Insertion, Activation, Checkout, Nominal Ops, and Decommission. MSFC will deliver iSat to the launch integrator installed in the deployer powered off in a ready to deploy configuration, launch integration services are still to be negotiated. During this phase any final software updates and battery charging will be completed prior to launch. Launch and Orbital Insertion are designed to GEVS standards. Upon deployment, iSat will automatically activate through separation switches. After a predetermined delay, iSat will deploy the solar panel, begin sun tracking, and make contact with NEN ground stations, potentially including White Sands, Fairbanks, and Wallops. Checkout is scheduled to last two weeks. After check-out, the spacecraft will transition to nominal ops, a more automated mode with regularly scheduled thruster operations. The iSat spacecraft will lower its perigee altitude from starting perigee to 225km to achieve a less than 90day deorbit. Upon achieving this altitude iSat will be decommissioned to include consuming any remaining propellant and disabling the electrical power system.

B. Technical Performance Metrics

To track the progress of the project towards successfully meeting all mission objectives, the project is using the standard application of technical performance metrics (TPMs). For iSat the TPMS are based on fitting in the 12U package and meeting the mission success criteria. The TPM status and progress from PDR through the Interim Design Review (IDR) is shown in Table 1. Consistent with figure 1, a design cycle following PDR resolved the technical performance limitations heading into the design and analysis cycle (DAC) 3. During DAC-3, the solar array was reduced due to configuration and packaging constraints associated with the solar panel winglet thickness and hinge design margins. The reduction in power resulted in operational limitations for demonstrating significant ΔV and accumulated thrust time due to the time required between maneuvers for battery recharging. The project is working to complete operations with the fiscal year and the reduced power generation decreased the maneuver cadence from several to only 1 maneuver per day. With only one maneuver per day, there was insufficient time to demonstrate the 80hrs of cumulated time on the propulsion system. With cycles more stressing, the success criteria was revised as noted above.

Table 1. Technical Performance Metrics from PDR to Start of DAC-3.

TPM	Metric	Status at PDR	Status at start of DAC-3	Status at IDR	Comments
X/Y/Z Margin	Planetary Sys. Envelope	GREEN	GREEN	GREEN	Fits within envelope
Total ΔV	As determined by sim	GREEN	GREEN	RED	Currently 85.2 m/s
Max Duration of Single 200W Burn	Max Duration Burn at 200W assuming one burn an orbit	RED	GREEN	GREEN	Below 70% state of charge, but only one cycle
Max Duration of Single 100W Burn	Max Duration Burn at 100W assuming one burn an orbit	RED	GREEN	GREEN	Below 70% state of charge, but only one cycle
Thruster Operation Duration	Total Cumulative run time of thruster during mission	GREEN	GREEN	RED	41.3 hours – 80hrs is full success
Data Bandwidth	Available bits vs. Requested bits per day	GREEN	GREEN	GREEN	
Battery SOC	Battery SOC for smallest repeatable interval of each mission phase	RED	GREEN	YELLOW	68.2% State of Charge (31.8% Depth of Discharge) for standard maneuvers.
Mass Margin	Total S/C mass vs. allocation	YELLOW	GREEN	YELLOW	1.8kg of margin in addition to 1kg of ballast and 0.5kg of propellant beyond required.
Available Payload Data	Available bits for the payload vs. requested bits for the payload per day	GREEN	GREEN	GREEN	S-BD solution more than meets the requirements for the data from the diagnostic sensors.
Available Payload Power per Power Budget	Required power on a per obit basis vs. allocated power	RED	GREEN	GREEN	The diagnostic sensors do not require much power.

C. Propulsion Subsystem

The propulsion system is the core of the iSat spacecraft. The propulsion system provides most of the spacecraft requirement drivers, including power, thermal management, and attitude control. The iSat project had an engineering model (EM) thruster and feed system on hand for all early test and evaluation. For risk reduction, iSat successfully completed an 80 hour development test using the EM thruster and MSFC feed system operating with iodine through the thruster and xenon for the cathode. The thruster exceeded expectations while concerns were discovered with titanium components within the feed system.

1) Thruster

The thruster is a derivative of the Busek Co., Inc. BHT-200 xenon-fed flight thruster. The BHT-200 is the first American Hall effect thruster flown in space, launched in 2006 as part of the TacSat-2 project. The BHT-200 was first tested with iodine under an Air Force SBIR and presented in 2011.[7] The performance results indicate the thruster performs at similar efficiencies or slightly higher efficiencies as with xenon propellant, but with slightly higher thrust-to-power and reduced plume divergence. Busek has since received continued investment for iodine thruster testing and development including an iodine 600W system development and higher power iodine testing.[8] For the iSAT project, Busek has delivered a BHT-200 engineering model thruster with a design optimized for iodine operation and compatibility, BHT-200-I. The BHT-200-I thruster was delivered in June of 2014 and is shown in figure 3.

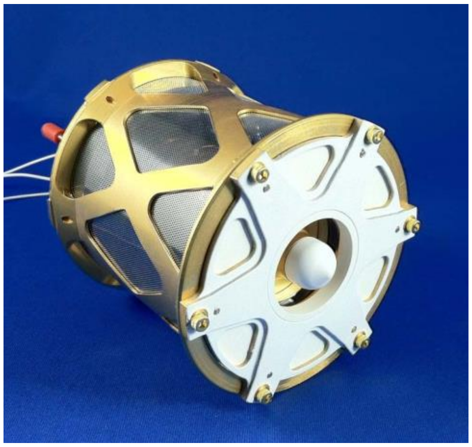

Figure 3. BHT-200-I EM Unit for iSAT.

2) Cathode

The cathode remains an key area of risk in the iSat system. For larger systems, the lifetime capability of an iodine cathode is the primary area of concern. For the very small vehicles, propellant throughputs may be less than a few kilograms. At 12U, the vehicle can perform more than 1km/s of ΔV with less than 1.5kg of propellant and less than 450 hours of operation. For iSat specifically, the risk is first to demonstrate reliable and repeatable ignition, and then system level efficiency. It is relatively impractical for the iSat vehicle to generate excess power to accommodate cathode heating for several minutes prior to each thrust maneuver. Requiring 10s of watts of power for a multi-kilowatt system may be acceptable for a larger vehicle, but not for a CubeSat-sized spacecraft and thruster. Busek and NASA GRC have been investigating iodine cathode options for long life capabilities. Additionally, NASA and Busek have been investigating the C12A7 electride cathode as a heaterless option.[9] Colorado State University has demonstrated 50 hours of operation on a single insert, including testing on iodine, and their results did not show any signs of cathode degradation. The iSat project purchased multiple cathodes from CSU for additional testing with iodine. Specifically, NASA Glenn has modified one cathode with diagnostics for ignition characterization testing. In addition to the C12A7 electride cathode, NASA Glenn is evaluating alternative options for an iodine cathode for both the iSat project and future iodine-based missions that will require significantly longer lifetime. Busek has also shown promising results with a Barium Oxide cathode operating on iodine and has become the baseline cathode for iSat. Busek demonstrated more than 100 cycles and over 50 hours of operation with a laboratory model BaO cathode. The component level cathode testing on iodine is shown if figure 4. Integrated testing of the BaO cathode with the EM thruster and MSFC feed system is on-going through July to close critical iSat propulsion risks prior to the propulsion subsystem CDR.

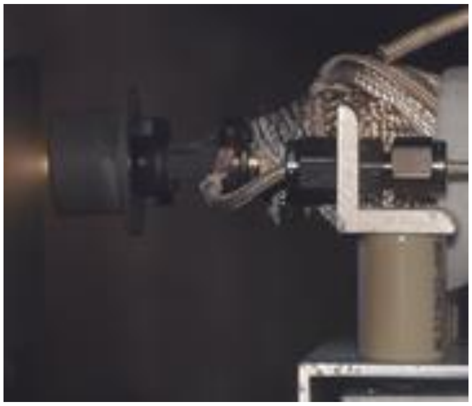

Figure 4. Successful laboratory BaO Iodine cathode component testing.

3) Power Processing Unit

While the thruster is usually emphasized for technology development and mission benefits, the power processing unit (PPU) usually represents the highest cost and schedule risk item at the system level. Even more so than the thruster, the BHT-200 PPU has benefitted from significant investments through both the NASA and AF SBIR programs. A key programmatic advantage for iodine Hall

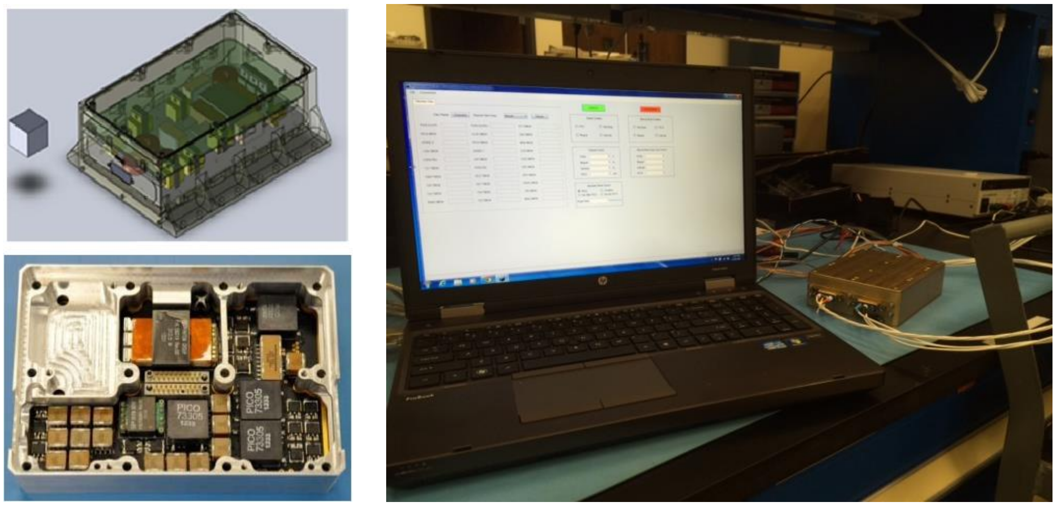

Figure 5. Current Compact PPU design with a 1” cube for scale (top-left), low-mass 200W PPU (bottom-left) and bench-top testing for control software development and early integration testing (right).

thrusters is that the thruster requires almost exactly the same voltage and current as when the same thruster is operated on xenon, permitting the direct use of PPUs that have already been designed and qualified for conventional xenon Hall thrusters.

The PPU for the iSat project is a derivative of the Compact PPU first developed under an Air Force effort to advance a low mass PPU based on the BPU-600 Flight Model PPU, but with power electronics for a 200W capability. The compact PPU effort reduces the mass and volume of the PPU by almost 80% and 90% respectively. Following the AF investment, NASA Glenn continued to invest under the SBIR program in a simplified PPU iteration. Finally, a third iteration on the compact PPU is ongoing to deliver an EM PPU for a 600W iodine system, designed for higher grade EEE parts, but populated with commercial grade parts. The iSat project will leverage the three compact PPU efforts to manufacture a protoflight 200W PPU. The PPU will use an RS422 interface, accept an input voltage range from 24-36V and leverages FPGA based control of all outputs and telemetry. Previous iterations of the compact PPU are shown in figure 5. The 600W PPU held a technical design review earlier this summer and the iSat PPU design is nearing completion with layout and mechanical design complete. Because the iSat PPU is designed with higher grade EEE parts than typical CubeSat electronics, the project has gratefully leveraged parts from NASA GRC, GSFC, MSFC and JPL to help with minimum lot buys and long lead procurements.

4) Feed System

The iodine feed system is one of the main drivers in the iSat system development since it contains much of the propulsion system risk. Preliminary feed system efforts have been published separately[10] and are only briefly summarized here. Unlike xenon, iodine is a solid under ambient conditions. The entire propellant management system operates at very low pressure, much less than 1 atmosphere. This has significant advantages at the spacecraft and mission level, but presents challenges for the feed system. Additionally, iodine is highly reactive with iron and expected to be reactive with a range of typical flight feed system materials.

The feed system is designed similarly to the Advanced Xenon Feed System.[11] The integrated setup as delivered from MSFC to GRC is shown in figure 6. The core of the flow control is a pair of parallel flow paths with VACCO proportional flow control valves (PFCVs). The PFVCs, blue in figure 6, have been modified from the xenon qualification valve to reduce the pressure drop, add internal heaters and temperature

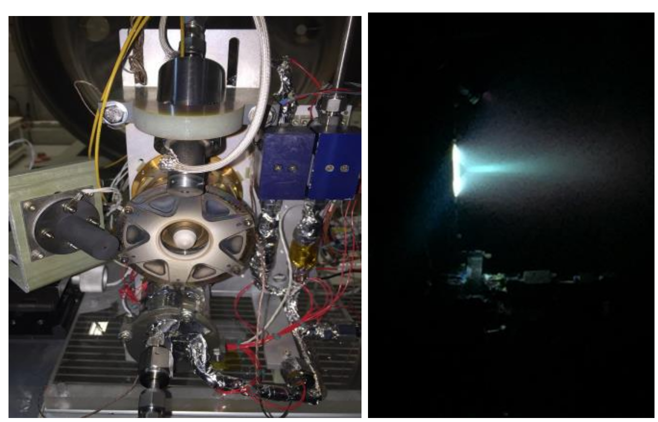

Figure 6. Integrated testing setup (left) and preliminary development testing (right) of the feed system.

sensors, and material changes for iodine compatibility. The first generation iodine valves also encountered challenges during the long duration integrated testing and a 2nd generation valve is under development for the qualification model and flight model propulsion systems. NASA MSFC has been leading a larger effort for the feed system design of iodine based propulsion systems regardless of the thruster.

Traditional systems rely on high pressures to ensure adequate mass flow to the cathode and thruster, and are largely unaffected by gas buildup and small pressure drops along the lines. The iodine in the propellant feed system starts as a solid in the propellant reservoir and operates at very lower pressure. This approach is very sensitive to all pressure drops which can overwhelm the tank pressure and prevent adequate flow or cause flow reversal. Designing a low pressure sublimation-driven propellant feed system requires careful consideration of the line pressure and design sensitivity to several factors, including temperature, physical line dimensions, filter choice, and tube material. For the feed system design, both modeling and experiment characterization has been completed and continues. The MSFC team has characterized individual components for model validation and has been leveraging the Generalized Fluid System Simulation Program (GFSSP)[12] combined with a sublimation model for system characterization and sensitivity analyses. The modeling effort includes the sensitivity to all components, tube lengths, material, diameter, bend radius, etc. One area of study has been the ability to provide a flow pulse to ignite and then sustain the cathode. Starting with a very low pressure (<1 psi) in the propellant source, as the cathode builds up in pressure, flow reversal is possible and would extinguish the cathode. MSFC completed the preliminary testing of the feed system with both xenon and iodine and shipped the system to NASA GRC in June for formal development testing and characterization through July.

5) Materials Testing

In addition to direct propulsion testing, NASA MSFC is performing material testing to inform the spacecraft and propulsion system design. Much of the material testing has already been completed, but additional testing continues for longer durations and higher temperatures. The materials effort was initiated due to the fact that most iodine compatibility data relates to medical use of iodine dissolved in alcohol at room temperature. Only limited data exists of applicable corrosion rates and compatibility. For iSat, and augmented by the NASA Engineering and Safety Center (NESC), material testing has and will be performed on a wide range of metals, polymers, composites, glass, circuit boards and conformal coatings. The intent is to assess all potential materials for spacecraft components, coatings, feed system wetted surfaces, etc. that may be exposed to iodine either as a gas or during thruster operation.

Material testing is performed using both active flow testing and static iodine bath testing to simulate the environment and perform a worst case saturated exposure respectively. The hot flow testing is planned to be repeated at multiple temperatures with a maximum temperature of our facility rated to 1100°C. The analyses will assess physical and chemical alteration in addition to optical and emissivity property alteration. One of the challenges of material testing is that samples must be kept at vacuum or purged to prevent corrosion due to oxygen and water exposure after the test and during post-test analyses. Images from preliminary one-week exposure tests are shown in figure 7.

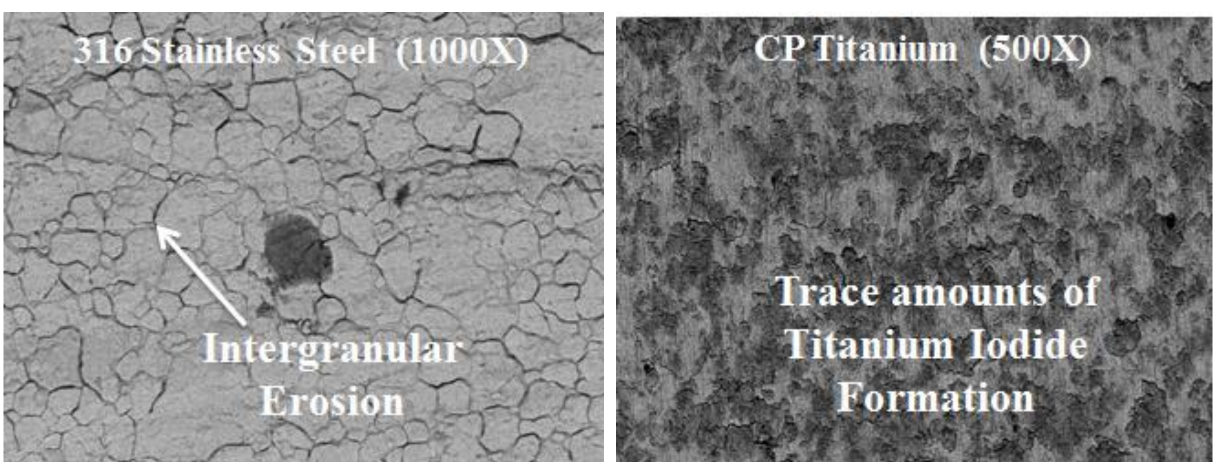

Figure 7. Preliminary results from one-week iodine exposure testing.

D. Electrical Power Subsystem

The power system for the iSat spacecraft is well in excess of the capabilities of the typical CubeSat. In this work, power generation is achieved using a relatively conservative approach of custom, passively deployed solar panels. The solar panels are based on the SolAero Tech 29.5% efficiency Third Generation Triple Junction (ZTJ) cells to provide approximately 60W of power. The panels are strung to provide sufficient power margin for the mission requirements. The solar arrays will provide a minimum of 20VDC that will be boosted to 34V to recharge the battery. The project initially planned on in-house custom solutions, but is now leveraging two Andrews Space Cortex 130 boards for power management and distribution. This allows for easy integration with the chosen Cortex 160 flight computer. The two Cortex 130 boards include the capability to provide 8 regulated DC voltage buses. The design requires five buses of the possible eight: 28V, 12V, 10V, 5V and 3.3V to meet the needs of the various spacecraft components. In addition to the regulated DC channels from the Cortex 130s, the PPU is supplied unregulated 28V power directly from the battery through a custom switch. The Cortex 130s also provide circuitry for peak power tracking and health monitoring.

Figure 8. Battery design.

The battery was identified as a risk item in the original iodine Hall technology demonstration proposal. A heritage lithium polymer was the original proposed battery, but it failed during in-house testing. Iron Phosphate batteries have also been considered and tested extensively when bus temperatures were higher than the current design. The final battery selected is an industry-provided battery comprised of 32 Panasonic Lithium Cobalt Oxide NCR18650 cells. This type of battery cell has flight heritage on multiple spacecraft. For iSat, the cell choice is driven by the high energy density, the capability to provide a high current (>10A), the ability to recharge quickly, and lack of memory. Complete testing to evaluate performance and characterize the thermal and heat transfer aspects of the battery will be completed in the summer/fall of 2016. The flight battery will be packaged in approximately a 7 cm x 7 cm x 16 cm aluminum box with an external wall thickness of 3 mm, shown in figure 8. The flight battery mass will be approximately 1.5 kilograms not including packaging, which is still being designed. A MSFC-designed cell balancing circuit was originally designed for the battery, but was removed to save power and considered unnecessary for the short duration and slow recharge rates of the mission operations.

E. Structures and Mechanical Subsystem

The iSat structure is defined to meet the standard interface of a Planetary Systems Corporation 12U CubeSat deployer. The iSat structure maximum outer dimensions are 365mm x 229mm x 212mm. After deployment, the iSat vehicle has spring loaded passive deployment mechanisms for the solar panels. The primary structure is fabricated from 7075 aluminum alloy with a hard anodized finish.

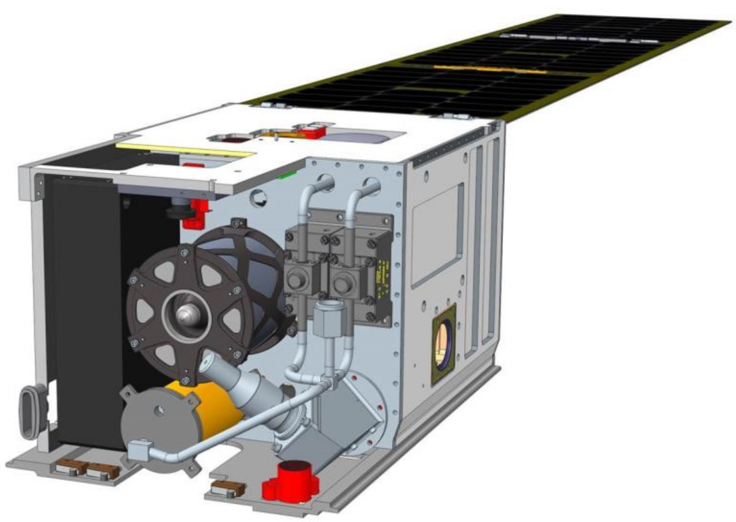

Figure 9. Basic configuration illustration for iSat.

The design challenges unique to iSat include handling the thermal loads from the thruster, the potential shielding needed for the electromagnetic interference / compatibility (EMI/EMC) environment, the overall power density within the spacecraft and the packaging of a large number of components within the limited volume available while still leaving clearances for standard connections. To meet these challenges the current design is based on two compartments, with the propulsion system in one compartment isolated from the rest of the vehicle. An open design is used for the thruster compartment to permit radiative cooling while the design leverages the compartment separation plate for EMI shielding. The design also allows useful viewing angles for the guidance, navigation and control (GN&C) sensors, the S-BD antenna, the GPS antenna, a thruster-imaging camera, and a payload complement of two photometers and three radiometers. The basic layout of the spacecraft is illustrated in figure 9.

F. Command and Data Handling Subsystem

Various components have been evaluated for the iSat command and data handling (C&DH) functions, but overall there are no commercial off the shelf (COTS) options that will meet all the iSat requirements. This is because typical CubeSat flight computers simply do not provide the interfaces required for the iSat subsystems. The baseline flight computer selected is the Andrews Space CORTEX 160 flight computer card. The card implements a Linux real time operating systems (RTOS) and includes five RS-422, three RS-485, two SPI, two I^2C and two parallel digital camera inputs. The board is designed for a 3 year lifetime and a 15krad total ionizing dose. Despite what it can provide over alternative COTS options, it lacks additional universal asynchronous receiver/transmitter (UART), pulsed width modulation and RS-232 capabilities required for the baseline C&DH architecture as illustrated in figure 10. The iSat project is leveraging available space on the auxiliary board to accommodate the additional C&DH needs. The auxiliary board will provide analog to digital conversion for an accelerometer and several RTDs. In addition it will a data bus conversion / bridge including RS-485 to UART for each of the reaction wheels, RS-485 to PWM for each of the magnetic torquers, RS-422 to RS-232 for the Earth Horizon Sensor (if included) and a conversion from RS-422 to an as-yet undefined interface for the science payloads and RF communications transceiver.

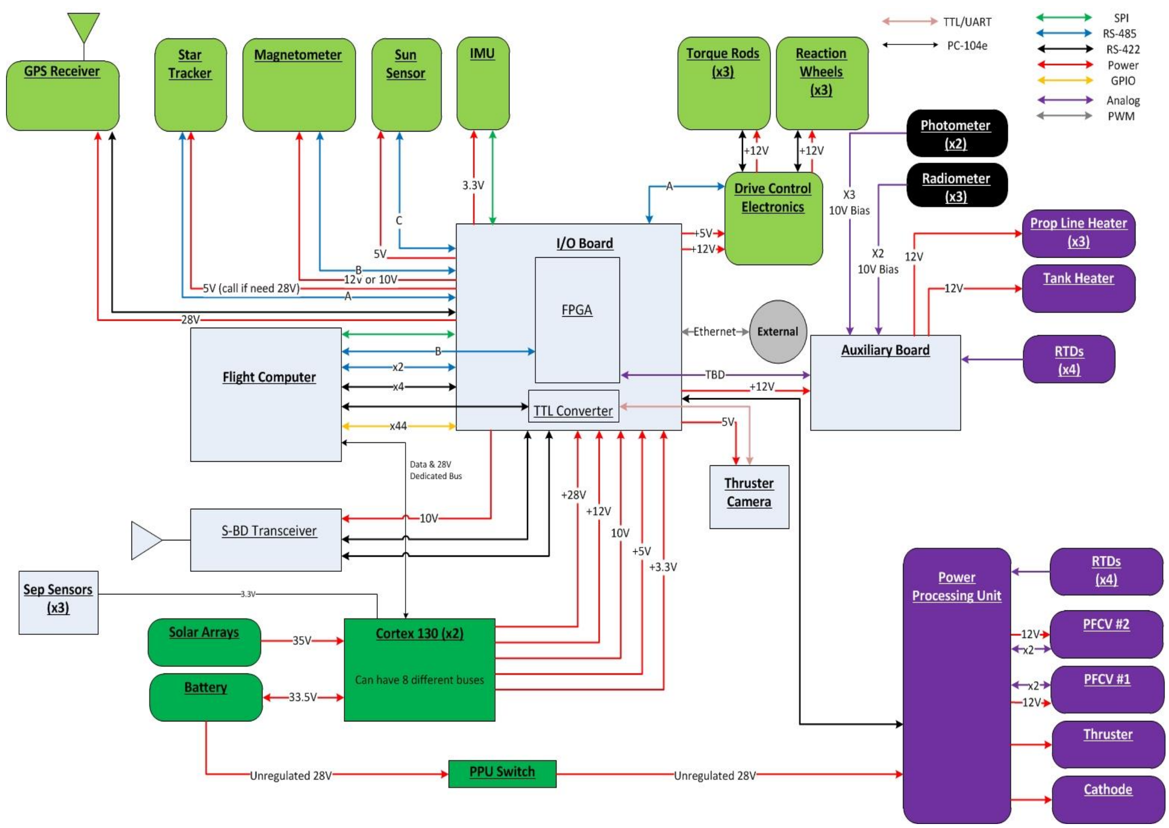

Figure 10. Preliminary C&DH architecture for iSAT.

Table 2. AD&C component options for iSat mission requirements.

Component	Quantity	Power (per unit)	Mass (per unit)	Vendor, Part #
Reaction Wheels	3	Pitch - 1.8W Steady State Roll - 0.5W Steady State Yaw - 0.5W Steady State	0.288 kg	Blue Canyon Technologies RWp100
Torque Rods	3	1W Full Power >0.2W Expected Draw	~0.1 kg	Blue Canyon Technologies $0.6Am^2$
Digital Control Electronics	1	Peak Power 1.0 W Average power 0.75W	0.2 kg	Blue Canyon Technologies DCE
Star Tracker	1	Peak Power ≤ 1.25W Average Power ~1W	0.312 kg	Blue Canyon Technologies Nano Star Tracker
Inertial Measurement Unit (IMU)	1	0.1 W	0.007 kg	Epson M-G350-PD11
GPS	1	1 W	< 0.2 kg	Spacequest SQ-GPS-12-V1
Sun Sensor	1	Peak Power 0.13W Average Power 0.04W	0.034 kg	SSBV SS-411
Magnetometer	1	Peak Power 0.525W Average Power 0.405W	0.098 kg	Honeywell HMR2300

G. Attitude Control Subsystem

The Guidance, Navigation and Control (GN&C) subsystem provides the attitude control for the spacecraft during the various phases of the mission. The GN&C subsystem is responsible for pointing the solar panels at the sun while charging the battery, pointing the antenna at the ground during communication passes, and pointing the thruster in the proper direction to thrust events. The GN&C subsystem is designed to account for disturbances from a variety of sources. These disturbances include thrust vector misalignment, thruster magnetic dipole effects, thruster swirl torque, gravity gradient forces, aerodynamic drag, solar radiation pressure and any residual magnetic dipole when the thruster is not active.

The current configuration with the extended solar panels behind the main compartment drives the reaction wheel sizing to accommodate the large aerodynamic torques at the lowest operational altitudes. The GN&C architecture is based entirely on commercially off the shelf (COTS) components. GN&C sensors include a GPS receiver, magnetometer, digital sun sensor, and a star tracker. Attitude control through three 100 milliNewton-meter-second reaction wheels and leverages 0.6 Amp-meter-squared magnetic torque rods for momentum dumping. The GN&C software is developed in Matlab Simulink and will be autocoded for integration with flight software.

H. Thermal Control Subsystem

The iSAT thermal control system represents a key challenge for the project due to the high power density of the spacecraft, small amounts of available radiative surface area, and localized temperature requirements of the propulsion components. The vehicle must keep the gaseous iodine fuel at the high temperature of 120°C while thrusting, but maintain electronic components below 60°C. Even with the high power density and differing temperature requirements, the iSat team plans to only provide passive thermal control solutions. The thermal design is a driver for the current compartmentalized design with the propulsion system segregated from the remainder of the spacecraft, so that it is free to radiate heat to deep space. The primary structure is coated with a material to act as a radiator surface to maintain temperatures for components within the chassis, and radiators are used on the backside of the solar arrays. The high level thermal model is shown in figure 11.

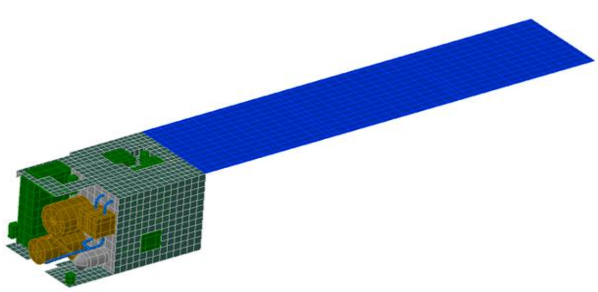

Figure 11. Thermal design configuration.

I. Communications Subsystem and Ground System

The iSat communication system provides both uplink and downlink capability through a single dual-frequency patch antenna. The downlink capability requirement for spacecraft bus health and status telemetry and thruster performance telemetry is approximately 70 MBytes/day. Due to the low data volume, and to minimize cost, the iSat spacecraft is planning to use an S-Band communication architecture for uplink and downlink. Using QPSK modulation with a nominal downlink data rate of 2.3 Mbits/sec, for a user information rate of approximately 1.5 Mbits/sec, the total daily data volume could be transferred down in under 7 minutes of ground station contact time per day. iSat may also employ a low-rate contingency-mode downlink data rate of around 30 Kbits/sec, in order to assure communication with the ground stations in the event of tumbling or unknown attitudes.

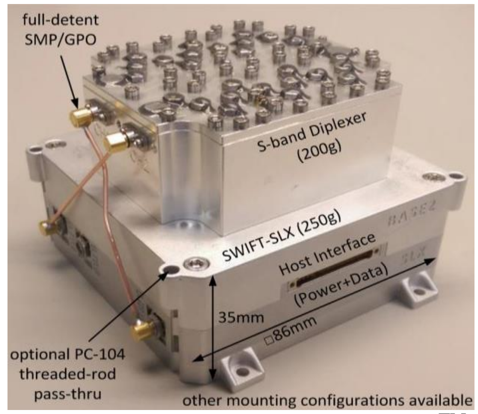

Figure 12. Tethers Unlimited SWIFT™ transceiver.

For practical and cost purposes, it is assumed the iSat vehicle will make contact with a maximum of three Near Earth Network (NEN) ground stations. The NEN is managed by Goddard Space Flight Center and is comprised of 15 NASA-owned and commercial ground stations. After initial planning with the NEN, the iSat anticipates using the Alaska Satellite Facility, the Wallops, Virginia Ground Station and White Sands, New Mexico Ground Station. The iSat team is currently working to secure a Stage 2 Certification from the National Telecommunications and Information Administration (NTIA). The iSat design is moving forward with an S-Band radio/diplexer solution from Tethers Unlimited, the SWIFT-SLX shown in figure 12, which was competitively procured. The transceiver will be coupled with one dual-frequency S-Band patch antenna, which will also be competitively procured. During nominal communications, the iSat should be able to receive the 56 Kbits/sec command uplink signal in any attitude, although it will have to actively point its patch antenna 'hemisphere' towards Earth in order to use the nominal high-rate 2.3 Mbits/sec downlink mode. If, for whatever reason, it cannot point the antenna towards ground, it should be able to successfully fall back to the low-rate 30 Kbits/sec downlink mode.

J. Flight Software

From a flight software perspective, iSat is utilizing an agile approach that allows the team to be more flexible in its approach to developing software. This approach has allowed the team to develop software as various documents mature. The requirements, architecture and design is housed in a single document name the Software Requirements Architecture and Design (SRAD) document. The iSat project is implementing a layered software architecture that uses an MSFC developed set of libraries called libSPRITE. The initial development began using Ares 1 flight software and has since been modified. The libSPRITE libraries have been used on six Nanolaunch flights, an effort to develop cost-effective launch vehicles for small payloads.

K. Launch Services

The iSat project has not been formally manifested for flight yet. The baseline approach is for the iSat project to procure industry launch services as a secondary payload. Multiple launch service providers have the capability for secondary spacecraft deployment, and there are multiple opportunities per year for a Sun-synchronous LEO deployment. The current rideshare opportunity under negotiation is with a department of defense provider through Spaceflight Services and likely on a Falcon 9 with excess payload capability and targeting a late calendar year 2017 launch.

L. Education and Public Outreach

The iSat project intends to execute a relatively large education and public outreach (E&PO) component to the small project. The iSat technology advances represent a significant new capability for the mission community due to the ability to perform large post-launch maneuvers. Leveraging the promise of SmallSats, the technology is intended to reach a wider market than a small segment of the space community. Additionally, the project provides an opportunity in increase awareness of electric propulsion in general; still relatively unknown to community at-large. The goals of the iSat E&PO include:

1) Inform the capabilities and limitations of electric propulsion with an emphasis on SmallSat application
2) Relate how iSAT fits within NASA’s future planetary, Earth science and exploration plans

3) See opportunities to build pubic familiarity with objectives and future use of electric propulsion and technologies developed as a part of the iSAT project
4) Provide access to relevant, accurate, clear, consistent and credible information and materials in a timely manner to both technical and non-technical communities
5) Transfer the project knowledge to the next generation through mentoring

The iSat project is leveraging NASA's ongoing enterprise of education and public engagement portals. The iSat project includes encouraging a generation of young people to embark on Science Technology Math and Engineering (STEM) careers that will prepare them to take part in future NASA projects. General public engagement is also a critical component of the E&PO effort toward improving science literacy while highlighting the technologies and capabilities of the iSat system. The project has provided intern opportunities for each fall, spring and summer sessions at the college level throughout the project lifecycle, conducted visits and development of educational activities for distribution at K-12 schools, participating in science camps and venues and a website and public media distribution of the project progress. The key message is the role of iSat technologies to enable future Earth science and solar system exploration.

IV. Near-Term Activities

The iSat project has a large number of activities to be completed in the remainder of FY16. However, the critical near-term activities are the path and completion of the integrated critical design review. During July, NASA Glenn will be leading integrated propulsion system development testing primarily to demonstrate reliable ignition of the selected cathode emitter, but also demonstrate system cycle testing, feed system control, operational functionality of the MSFC control board, demonstrate closed loop control using discharge current, and thermal characterization for model correlation. Following the propulsion testing, a propulsion CDR is planned for August to review all of the propulsion components prior to the project level integrated CDR planned for late August.

V. Summary

Multiple institutions within government and industry are advocating the use of iodine Hall thruster technology, especially for SmallSat application. The iSAT project leverages past and present Air Force, and NASA investments to reduce risk in the application of iodine Hall thruster technology through a demonstration mission. The project team has made and continues to make significant progress towards risk reduction including flight-like operational feed system demonstration, DCIU development and testing, integration propulsion system testing, materials testing, power control and distribution avionics design and development, battery testing, preliminary flight software development, structural design and analysis and thermal design and analyses. Critical propulsion testing is occurring in the near-term to demonstrate reliable cathode ignition and system operation. The project is on track for a critical design review in August 2016 prior to beginning the integration and test phase of the project. Finally, the project is working towards a flight demonstration with a launch expected in the end of calendar year 2017.

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References

[1] Tverdokhlebov, O.S.; and Semenkin, A.V.: Iodine Propellant for Electric Propulsion—To Be Or Not To Be. AIAA 2001–3350, 2001.

[2] Dressler, R.; Chiu, Y.-H.; and Levandier, D.: Propellant Alternatives for Ion and Hall Effect Thrusters. AIAA 2000–0602, 2000.

[3] Dankanich, J. W., Szabo, J., Pote, B., Oleson, S., and Kamhawi, H., "Mission and System Advatages of Iodine Hall Thrusters," 50th Joint Propulsin Conference, July 28-30, 2014.

[4] Tverdokhlebov, O.S.; and Semenkin, A.V.: Iodine Propellant for Electric Propulsion—To Be Or Not To Be. AIAA 2001–3350, 2001.

[5] Dressler, R.; Chiu, Y.-H.; and Levandier, D., "Propellant Alternatives for Ion and Hall Effect Thrusters," AIAA 2000–0602, 2000.

[6] Maly, J. R., "ESPA: The EELV Secondary Payload Adaptor," Moog CSA Engineering Form 500-705 July, 2010.

[7] Szabo, J., et al., "Performance Evaluation of an Iodine Vapor Hall Thruster," AIAA 2011-5891, 47th AIAA Joint Propulsion Conference, San Diego, CA, July 31 – August 3, 2011.

[8] Szabo, J., Robin, M., Paintal, S., Pote, B., Hruby, V., and Freeman, C., "Iodine Propellant Space Propulsion," IEPC-2013-311, 33rd International Electric Propulsion Conference, Washington D.C., October 6-10, 2013.

[9] Rand, L., P., and Williams, J. D., "Instant Start Electride Hallow Cathode," IEPC-2013-305, 33rd International Electric Propulsion Conference, Washington, D.C. October 6-10, 2013.

[10] Polzin, K. A., and Peeples, S., "Iodine Hall Thruster Propellant Feed System for a CubeSat," 50th Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

[11] Dankanich, J. W., Cardin, J., Dien, A., Kamhawi, H., Netwall, C. J., and Osborn, M., "Advanced Xenon Feed System (AXFS) Development and Hot-fire Testing," AIAA 2009-4910, 45th JPC, Denver, CO, August 2-5, 2009.

[12] A.K. Majumdar, A.C. LeClair, R. Moore, P.A. Schallhorn, "Generalized Fluid System Simulation Program, Version 6.0", NASA/TM—2013–217492, October 2013.