The iodine Satellite (iSAT) Hall Thruster Demonstration Mission Concept and Development

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The use of iodine propellant for Hall thrusters has been studied and proposed by multiple organizations due to the potential mission benefits over xenon. In 2013, NASA Marshall Space Flight Center competitively selected a project for the maturation of an iodine flight operational feed system through the Technology Investment Program. Multiple partnerships and collaborations have allowed the team to expand the scope to include additional mission concept development and risk reduction to support a flight system demonstration, the iodine Satellite (iSAT). The iSAT project was initiated and is progressing towards a technology demonstration mission preliminary design review. The current status of the mission concept development and risk reduction efforts in support of this project is presented.

I. Introduction

Iodine has been considered as an alternative to xenon for more than a decade. [1,2] Under the support of 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.[3] Two distinct niches have been identified with key advantages when using iodine as opposed to the state-of-the-art xenon propellant; small satellites (<300kg) and exploration class mission electric propulsion. The flight applications benefit from the increased density of iodine over xenon, but also the reduced operating pressure from over 3000psi with xenon in some cases to less than 1psi with iodine. The operating pressure can have cost and risk advantages while also enabling the use of additive manufacturing and optimized form factors. Additionally, at high power, the condensable propellant may have significant advantages with ground testing performance and life validation testing.

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 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 current scope of work progresses towards a mission preliminary design review (PDR) of the baseline iSAT technology demonstration mission. The overall iSAT mission concept is a partnership with NASA Glenn Research Center (GRC) leading the propulsion subsystem development based on critical hardware delivered from Busek Co., and NASA MSFC designing, integrating and deliverying the flight system.

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II. Mission Concept Development

A range of mission studies have been completed to identify mission level advantages using iodine as the primary propellant.[4] In addition to iodine based missions for commercial, military, human and scientific exploration, multiple concepts have been developed for a low-cost high value technology demonstration mission. In general, flight demonstrations would not typically be expected for new Hall thruster developments. However, there are specific concerns regarding propellant control due to the propellant existing as a solid in the propellant tank and having the possibility to redeposit in the lines if the feed system temperature is too low. In addition, there are potential spacecraft-plume interactions unique to iodine and best evaluated in a flight test. The premise of a low-cost demonstration mission is to obtain flight experience with iodine to address these risks. This led to a basing of the low-cost demonstration missions on an iodine-fed derivative of the flight BHT-200 Hall thruster. At 200W, the Hall system can validate iodine system operation and characterize the spacecraft environment at much lower cost than implementing a higher power alternative. Demonstration missions with a 200W Hall thruster have been assessed for 6U and 12U platform in both Low-Earth Orbit (LEO) and on interplanetary trajectories.

A. 6U Low Earth Orbit Demonstration

The first technology demonstration mission concept assessed was for a 6U spacecraft. A ‘U’ is a SmallSat nomenclature for a CubeSat unit approximately 10cm x 10cm x 10cm with 1.33kg allocated to each U volume.[5] The 6U system demonstration is an appealing option for the lowest potential cost and higher flight opportunity solution. The iodine propulsion system and associated power systems make options less than 6U impractical. At 6U, the spacecraft packaging is still quite challenging and the spacecraft will be limited in application.

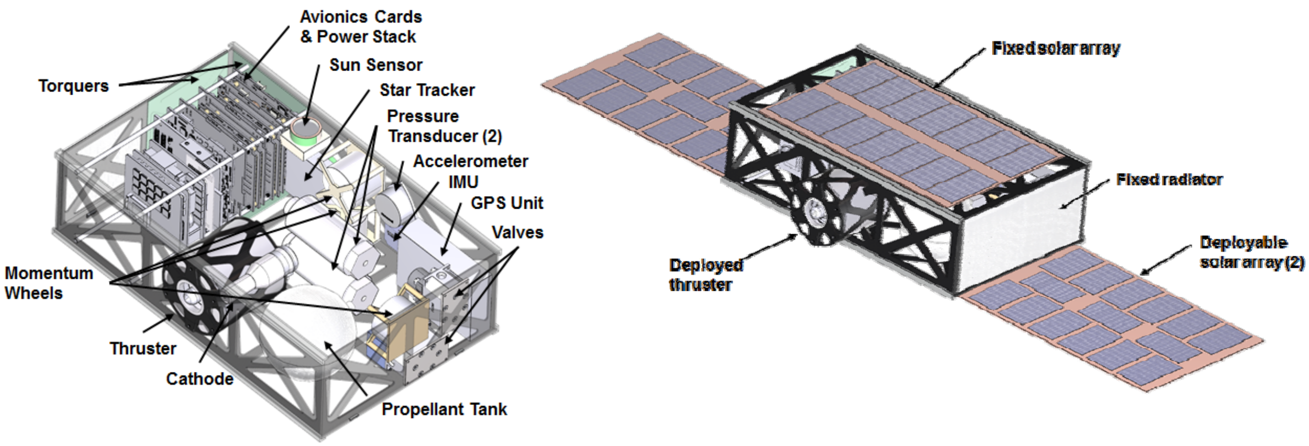

Figure 1. 6U iodine demonstration concept configuration.

In addition to extreme limitations on volume for any potential payload (i.e. plasma diagnostics or science utility), the 6U design includes significant risk for thermal design, volume for connectors and harnesses, and EMI/EMC risks. It also likely requires a deployment mechanism for the thruster and cathode so they are not within the spacecraft during operation. Beyond volume, the baseline concept also has a current best estimate (CBE) mass 9.5kg and predicted mass of 11.7kg after growth allowance. Given the limited utility, potentially unviable packaging options when connectors and harnesses are included and the high likelihood of exceeding the standard 10kg mass allocation, the 6U was not selected as the baseline concept.

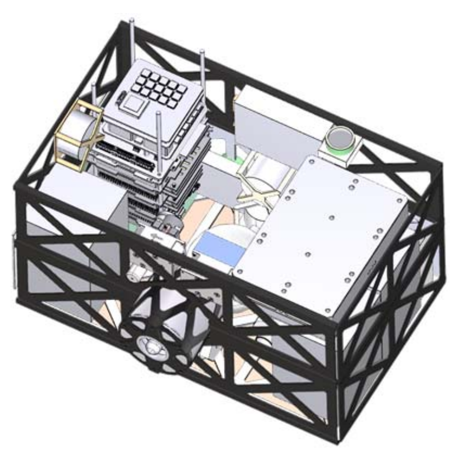

Figure 2. 12U interplanetary configuration.

B. 12U Interplanetary Demonstration

The concept of greatest interest to NASA MSFC was an interplanetary iSAT (iiSAT) spacecraft. The MSFC Advanced Concepts Office specifically assessed the viability of iiSAT for deployment as a secondary payload of the Space Launch System (SLS) Engineering Model first flight (EM-1), where after deployment the vehicle would perform an interplanetary mission objective. The specific concept addressed was a mission to a near-Earth asteroid. The SLS EM-1 opportunity is planning to qualify a 6U deployer, though a 12U deployer is also an option as long as the loaded deployer mass did not increase. At the time of the study, the constraints were a 12U volume and a mass of 14kg. A notional configuration of the 12U interplanetary iSAT is shown in figure 2. However, even without an instrument payload, the CBE mass of the interplanetary vehicle was over 14kg, though only limited time was spent on configuration design. The mass equipment list (MEL) estimated a CBE of 16.7kg for iiSAT and a 20kg predicted growth mass. While 20kg is the standard mass allocation for a 12U vehicle, it is not within the current options available for the SLS EM-1 opportunity. In addition exceeding the mass constraint, significant risks were identified for communications and the attitude control propulsion system. Because of the early "infeasible" decision, the team spent limited resources attempting to find a 12U interplanetary solution.

C. 12U Low Earth Orbit Demonstration

While a 6U LEO demonstration of an iodine-fed Hall thruster powered spacecraft is challenging by possible, increasing the size to a 12U LEO demonstration simplifies the entire mission architecture at the expense of reduced launch opportunities. Additionally, the 12U version of iSAT should allow for reasonable payload accommodations and demonstrate the utility and mission capability of an iodine SmallSat beyond simply demonstrating a component technology. For the 12U version we used a baseline set of three infrared cameras corresponding to a potential Earth science mission concept. The presence of the science payload forces the iSAT design to possess mass, power, volume, and data storage margins to accommodate instruments and helps in identifying the controlling requirements for future mission capabilities (e.g. pointing accuracy and stability). The design is still evolving as the project moves towards PDR, but the current spacecraft configuration is shown in figure 3; additional solar panel and structure removed for illustration purposes. The propulsion system is compartmentalized to simplify integration, isolating the thruster system and its large thermal loads from the rest of the spacecraft. The current configuration also simplifies some of the potential electromagnetic shielding challenges.

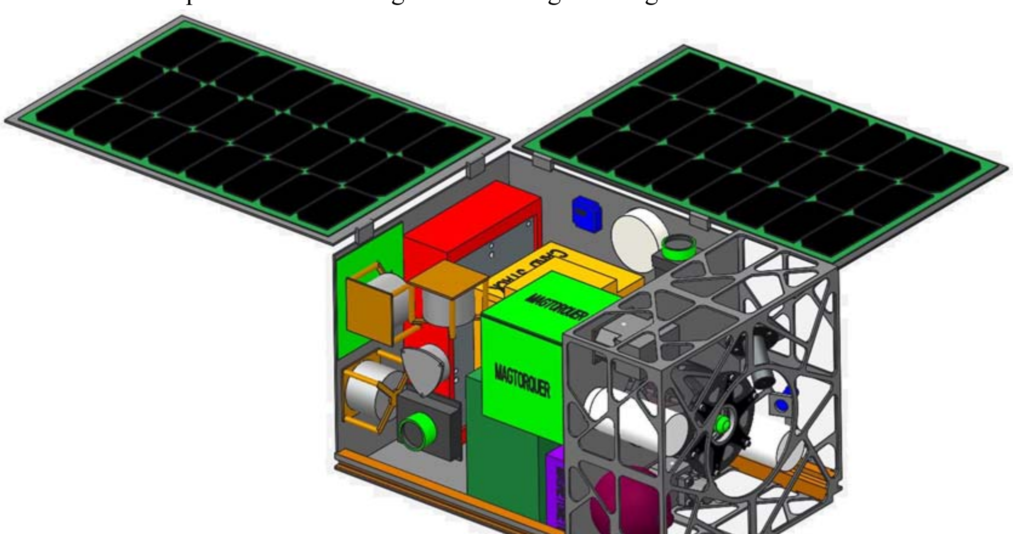

Figure 3. 12U LEO technology demonstration mission configuration of iSAT.

The cost impact of increasing from a 6U launch opportunity to a 12U launch opportunity can be up to \$1M; which would represent a significant fraction of the entire mission cost. This maximum cost impact assumes a 6U launch opportunity may be provided at no cost to the project. However, the expected cost impact is between \$0 and \$400k, with the latter being the cost difference between launching a 10kg and 20kg secondary payload. Increasing the available volume is expected simplify interfaces and reduce the risk of cost growth due to custom interfaces, thermal constraints and additional costs anticipated to trim grams and volume out of multiple components. The 12U LEO demonstration is the current baseline mission. The planned baseline mission intends to carry one science imaging instrument (as opposed to the three mentioned above) and use the remaining spacecraft resources for a plasma diagnostics package that remains to be defined. The baseline project schedule could allow for a flight opportunity in 2017.

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 feed system maturation is the primary focus for FY14 and FY15 begins the formal qualification of the integrated propulsion system the iSAT project intends to demonstrate.

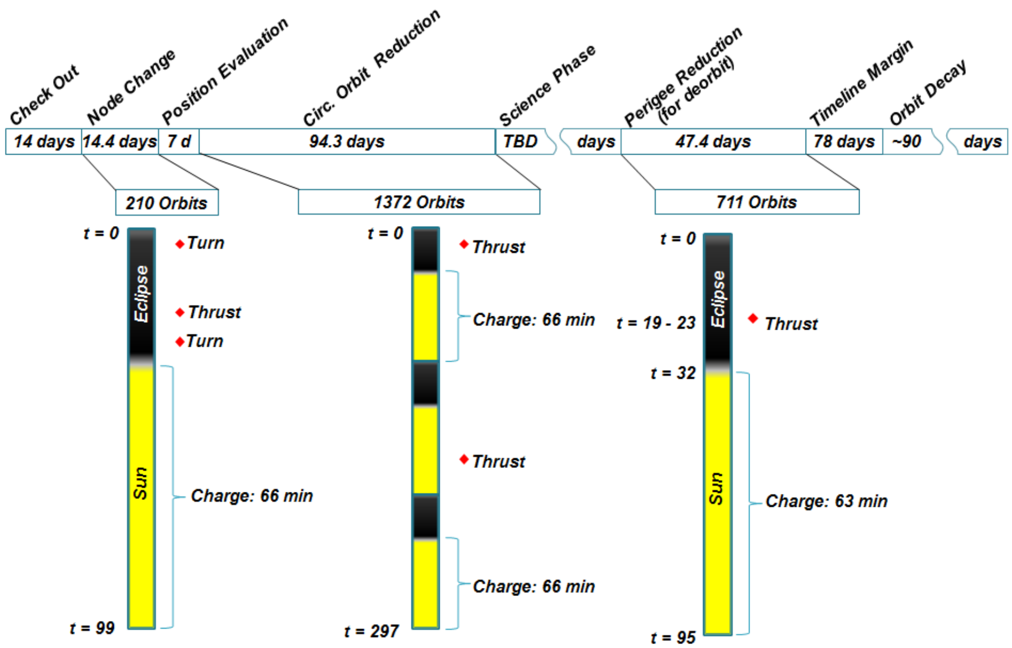

Figure 4. Basic mission Concept of Operations.

A. Concept of Operations

The mission concept of operations (CONOPS) is partially dependent on the orbit to which the iSAT vehicle is deployed. It is assumed based on the most likely manifest options that the spacecraft will be deployed into a sun-synchronous 600km circular orbit. However, deployment from the International Space Station is also held as an option. The spacecraft power and thermal management systems are designed for a wide range of altitudes and do not require a specific node (i.e. noon-midnight vs. 6AM-6PM). The basic CONOPS is illustrated in figure 4. An initial checkout period of two-weeks is planned. The vehicle will have significant battery charge available for deployment, correct for tip-off, and to operate the spacecraft for the time required to obtain the desired attitude control and begin communicating with the ground. The spacecraft will charge the power system while in sunlight, using momentum wheels and magnetic torque rods to rotate the vehicle to the required attitude and operating the thruster to perform maneuvers when appropriate. Most thrusting maneuvers will be on the order of 6 minutes. The first three months are spent performing propulsion systems testing. The vehicle will demonstrate node change capability and then lower the vehicle into a science mission orbit. Unlike the starting orbit, the science mission orbit is sufficiently low to meet orbital debris requirements, de-orbiting naturally within the required time.After a notional 6 month science phase, the iSAT vehicle will lower its orbital perigee again so that it re-enters within a few months.

B. 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 has engineering model hardware representative of all the propulsion subsystem components to allow early test and evaluation. The project will be performing significant integrated system testing prior to the mission PDR to address risks.

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.[3] 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.[6] 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 5.

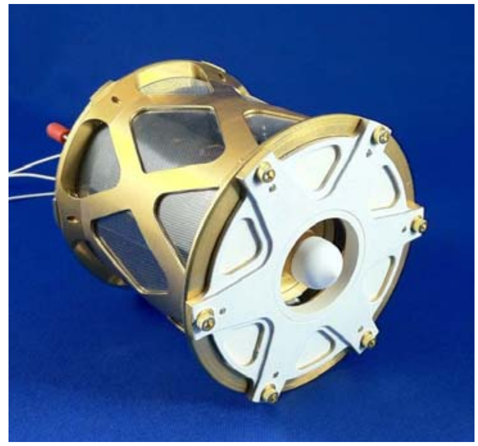

Figure 5. BHT-200-I EM Unit for iSAT.

2) Cathode

The cathode remains an 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 primarily to the system level efficiency. It is 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.[7] Colorado State University (CSU) 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 GRC has modified one cathode with diagnostics for ignition characterization testing. NASA GRC will perform cathode testing on an as-delivered unit and NASA MSFC will integrate one of the as-delivered cathodes into a propulsion system to operate a 200-W Hall thruster. The electride cathode is shown in figure 8. 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.

Figure 8. CSU delivered cathode and cathode operating on iodine.

3) Power Processing Unit

While the thruster is usually emphasized for technology development and mission benefits, the power processing unit (PPU) typically 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 the both NASA and AF SBIR programs. A key programmatic advantage for iodine Hall thrusters is that the thruster requires almost exactly the same voltage and current as the xenon model, permitting the direct use of PPUs that have already been designed and qualified for conventional xenon Hall thrusters. Unfortunately, the early xenonfeed system control and Digital Control Interface Unit (DCIU) functionality typically included in the PPU was not initally applicable to a iodine-fed system.

The PPU for the iSAT project is a derivative of the Compact PPU first developed under an Air Force effort, where a 200W-capable PPU was developed 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 GRC continued to invest under the SBIR program in a simplified PPU development. 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 3rd compact PPU iteration is planned for delivery in the fall of 2014. The 3rd PPU includes the feed system control capability for an iodine system discussed below. The iSAT project will leverage the previous 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 FPGAbased control of all outputs and telemetry. The compact PPU is shown in figure

6. The iSAT project has initiated software development for the control of the compact PPU and plans to perform integrated system testing in the fall of 2014.

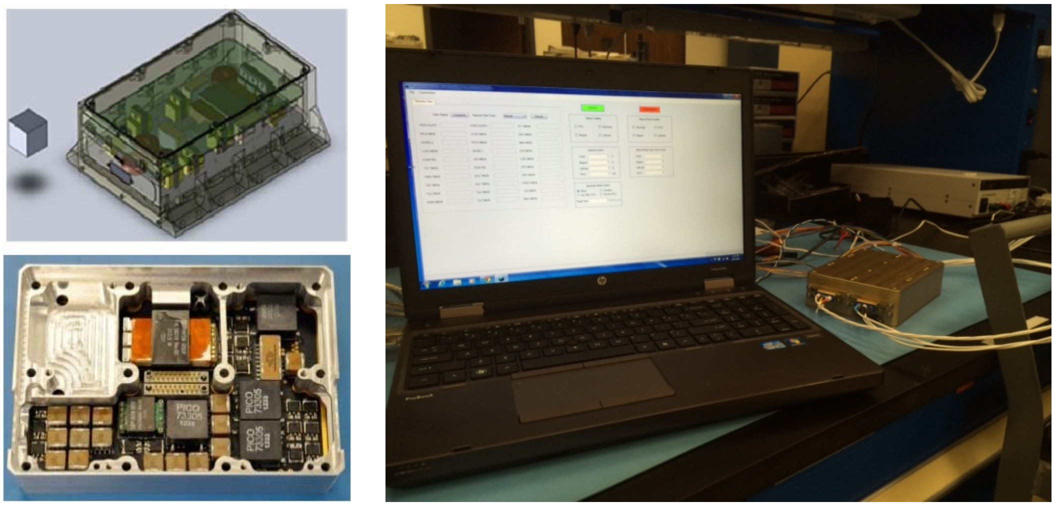

Figure 6. Current Compact PPU design with a 1" cube for scale (top-left), low-mass 200W PPU (bottom-left) and bench-top testing for control software development and early integration testing (right).

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. The efforts performed to-date are the subject of Ref. [8] 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 iodine in the propellant feed system starts as a solid in the propellant reservoir. The propellant is heated to achieve the desired pressure in the tank through sublimation (typically under 100 torr). The iodine vapor flows first through a latch valve and then through a proportional flow control valve (PFCV) which is an adjustable orifice that offers precise, fast response flow metering and control. Downstream of the PFCV, the flow is proportionally split to deliver the proper amount of iodine vapor to both the thruster and cathode. Special attention is required to minimize pressure drops in the line, which in addition to maintaining temperatures elevated above those in the propellant reservoir serves to minimize the danger of iodine deposition in the feed lines. In the present laboratory system testing a flow meter located in the line downstream of the PFCV and prior to the flow split is used to provide a measure of the iodine vapor flowrate in the system. After the thruster startup is complete, the flight feed system will switch from an open-loop control algorithm to a closed loop flow control based on the thruster discharge current. Schematics showing the basic layout for the laboratory propellant feed system and baseline flight feed system are found in figure 7. The laboratory system allows for testing control schemes that use either the iodine reservoir temperature (and commensurate vapor pressure) or the PFCV for propellant control. It is assumed that for larger spacecraft an additional PFCV valve could be used for independent control of the cathode and thruster flow rates, but for the CubeSat the additional valve mass and complexity required to yield optimal cathode flowrates is not justified.

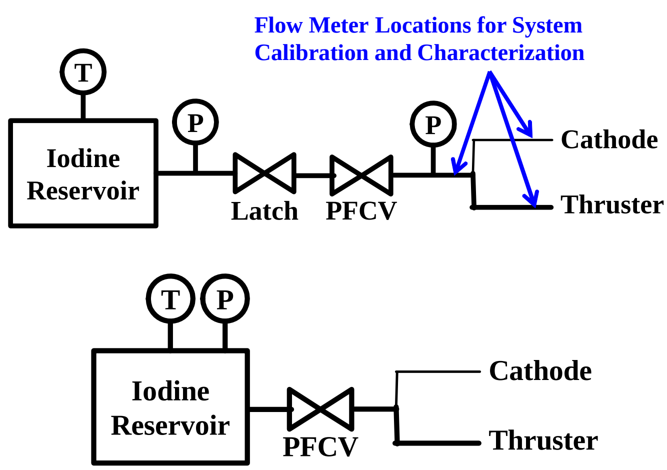

Figure 7. Characterization and calibration feed system schematic (top) and baseline flight system schematic (bottom).

Early in the program, it was identified that no valve options existed for a flight operations system.

Under contract, Vacco designed, manufactured, and acceptance tested flight operational iodine latching and proportional flow control valves, and delivery occurred in December of 2013.. The valves are based on flight heritage xenon solutions but with increased internal flow passage diameters to minimize the pressure drop. Also, internal heaters were added to eliminate the dagners of deposition and wetted surface materials were changed for iodine material compatibility. Since power on SmallSats is limited, the valves are design to consume nearly zero power during steady state flow control.

Since the spring of 2014, MSFC has been testing the feed system components and calibrating system performance. The testing to date has primarily been with the components at atmosphere, flowing the iodine into the MSFC iodine vacuum test facility. All testing includes the DCIU / auxiliary control board for valve control. Integrated thruster/feed system testing in the vacuum environment is planned to occur in July 2014. In addition to testing the flow control from the propellant reservoir to the thruster and cathode, the project has also been testing tank-to-tank propellant transfer. In addition to basic feed system control and operation, the project is presently assessing general propellant transfer and propellant tank design sensitivities. The results hope to provide a design methodology to most efficiently heat the propellant in flight and specify ullage requirements to optimize input power versus initial flow rate requirements.

5) Digital Control Interface Unit / Auxiliary Board

The DCIU typically provides additional capability for the propulsion system including coordinating command, power and telemetry for the PPU and feed system. The earlier iterations of the PPU did not include the functionality to control the undefined iodine feed system. Therefore, MSFC designed and fabricated a DCIU to allow for testing of the feed system/DCIU system in the relevant environment, with power would be delivered to the thruster using either laboratory power supplies or a previously delivered PPU. Some of the DCIU functionality, including the valve drivers for an iodine latching valve and piezoelectric proportional flow control valves (PFCV), is already included in the 3rd PPU iteration under development. In addition to the DCIU functionality necessary for early testing, the iSAT project included additional avionics for health and system monitoring and to provide heater control. The board has it's own general interface capabilities and is now typically referred to as the auxiliary board.[8] It is unclear but currently doubtful that the auxiliary board functions can be completely absorbed within the iSAT flight system PPU. One limit is the volume available within the PPU, but the auxiliary board also provides custom avionics likely to change for future iodine flight systems, and as such these avionics should be maintained separately outside of any industry provided, flight-qualified PPU. Some of the additional functions included in iSAT are noted in the Command and Data Handling Subsystem section, Section III E.

6) Materials Testing

While it extends beyond the propulsion system, the iSAT program has initiated a materials characterization campaign to address compatibility concerns associated with the use and potential redeposition of the iodine propellant. The existing literature on material compatibility with iodine is incomplete and insufficient at the conditions of interest. Two basic tests are planned: active iodine flow testing and iodine static bath testing. These tests are for iodine compatability prior to iodionization. Material coupons are also planned for testing during active thruster operation.

The iSAT project is testing a wide range of materials including both metallic and non-metallic materials that may be used in fabricating the iSAT system but, more generally, these are typical spacecraft materials that may come in contact with iodine during future missions. The materials include stainless steel alloys, aluminum alloys with and without coatings, paints used for thermal control, Viton, Buna, Teflon, titanium, composites, multi-layer insulation (MLI), glass, various film coatings, solar cells, circuit boards with and without coatings, connectors and wires with standard coatings.

The active flow testing will place the samples in a tube furnace to continuously flow iodine across the coupon at the desired temperature. Samples will be intermittently removed to characterize the rate of iodine-induce corrosion. Pre- and post-test examinations may include the use of an optical microscope and a scanning electron microscope. Samples will also undergo dynamic mechanical analysis, thermo-mechanical analysis and differential scanning calorimetry. Finally, the samples will have the emissivity and absorptivity measured both before and after iodine exposure to inform the spacecraft thermal design. The static bath testing will yield a long-duration soak in iodine vapor, with measurements being the same as those performed before and after the active flow testing. Initial results are planned for the fall of 2014.

C. Electrical Power Subsystem

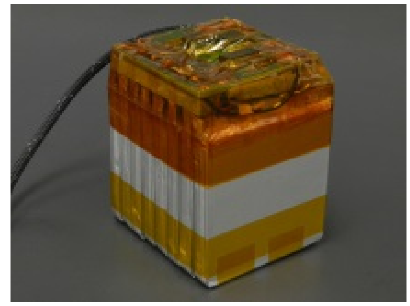

Figure 9. EM battery for testing.

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 Spectrolab 28.3% efficiency ultra triple junction cells to provide 60W of power. The panels are strung to provide an open circuit voltage of nearly 40V to permit recharging of the battery. MSFC has also designed and manufactured custom power management and distribution boards for iSAT. The power distribution board provides regulated DC voltages at 28V, +/- 15V, 12V, 5V and 3.3V to meet the needs of the various spacecraft components. The power distribution board may also need to provide a 6V output for the IR camera payload. In addition to providing power to the power distribution board, the battery also provides unregulated power directly to the PPU. The power management board includes circuitry for peak power tracking, battery charging control and health monitoring.

The battery was identified as a risk item in the original iodine Hall technology demonstration proposal. The battery selected is an industry-provided battery that uses lithium polymer cells. This type of battery cell has flight heritage on multiple CubeSat and Air Force SmallSat missions. For iSAT, the cell choice is driven by the high energy density, the capability to provide a high current (~10A), and the ability to recharge quickly. MSFC performed bread-board battery testing early in the project and is presently testing the engineering model battery pack, shown in figure 9. Complete testing to evaluate performance and characterize the thermal and heat transfer aspects of the battery will be completed in the fall of 2014 prior to the PDR. The flight battery will have a volume and mass is approximately 1/3 U and 0.77 kg respectively, with a maximum energy storage of 170 Whr.

D. 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.

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 mesh 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) and payload optics . The basic layout of the spacecraft is illustrated in figure 10.

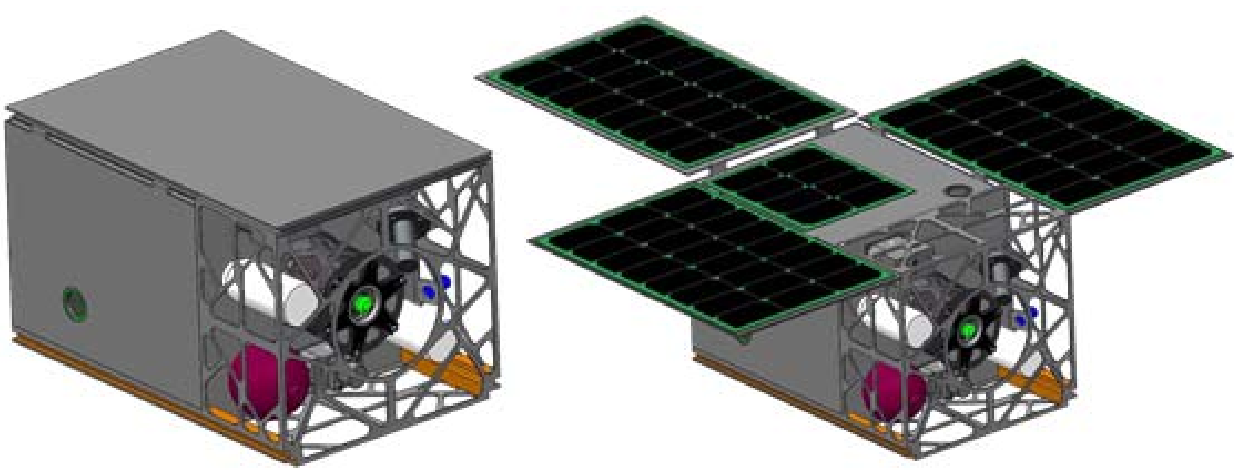

Figure 10. Basic configuration illustration for iSAT.

E. 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 11. The iSAT project intends to use 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 interace for the science payloads and RF communications transceiver.

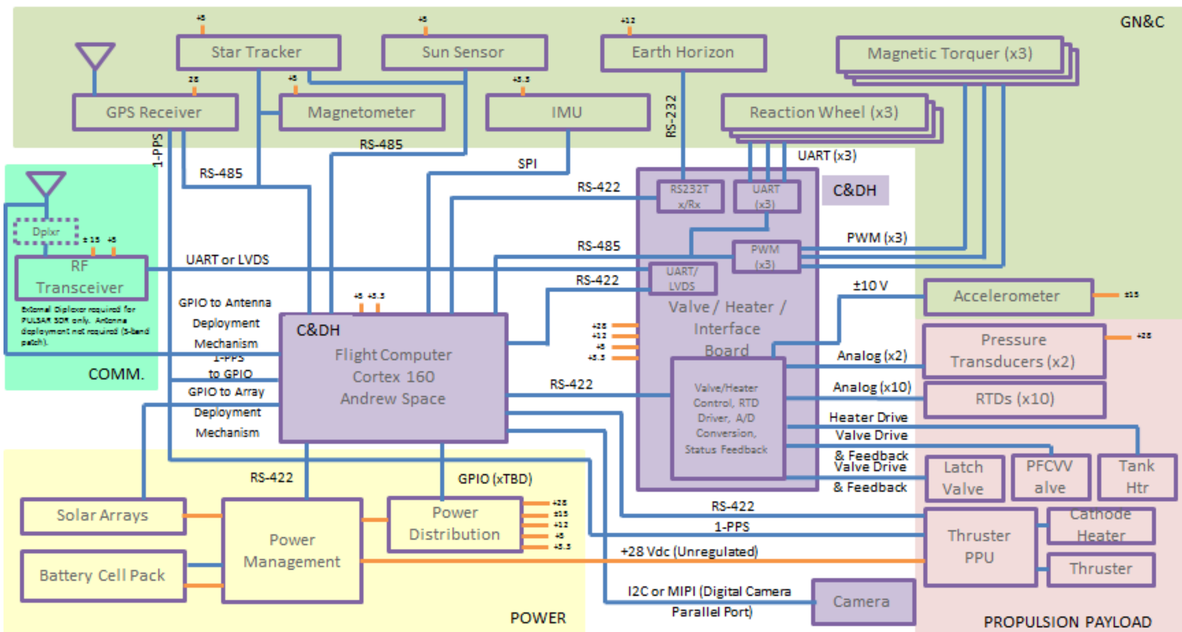

Figure 11. Preliminary C&DH architecture for iSAT.

F. Attitude Control Subsystem

The attitude determination and control (AD&C) subsystem is based entirely on COTS components. The thruster on iSAT is not gimbaled, so the AD&C system provides all the attitude control for the vehicle during maneuvers. This system is also responsible for spacecraft pointing while charging the battery system and during the science phase of the orbit. Disturbances include thrust vector misalignment, thruster magnetic dipole effects, thruster swirl torque, gravity gradient forces, aerodynamic drag, radiation pressure and any residual magnetic dipole when the thruster is not active. The disturbance torques budget that drives the sizing of the AD&C system is shown in table 1. The iSAT vehicle is assumed to be deployed with a possible maximum tip-off rate of up to 5 degrees/s. The system provides attitude control through three 30 mN-m-sec reaction wheels and leverages magnetic torquers for momentum dumping. Based on these requirements, the notional AD&C COTS system components given in table 2 were identified to meet the mission needs.

Table 1. Disturbance Torque Budget.

Disturbance Torque	Axis	Angular Momentum (mN-m-s)	
		During 10min Maneuver	During Orbit
Thrust Vector Misalignment	Y/Z	21.6	-
Thruster Magnetic Dipole	Y/Z	30	-
Thruster Swirl Torque	X	6	-
Gravity Gradient	-	-	1.3
Aerodynamic Drag	-	-	0.0052
Solar Radiation Pressure	-	-	0.15
Thruster-off residual magnetic dipole	Y/Z		7.2

Table 2. AD&C component options for iSAT preliminary design.

Component	Quantity	Power (per unit)	Mass (per unit)	Vendor, part #
Reaction Wheels (pitch/yaw/roll axes)	3	1.5 W (peak) 0.4 W (steady state)	0.185 kg	Sinclair (RW-0.03-4)
Star Tracker	1	1.0 W (peak) 0.5 W (avg)	0.085 kg	Sinclair (ST-16)
Inertial Measurement Unit (IMU)	1	0.1 W (3.3 V @ 30 mA)	0.007 kg	Epson (M-G350-PD11)
Magnetic Torquers	3	0.2 W	0.065 kg	TBD
GPS	1	1 W	< 0.2 kg	Spacequest
Accelerometer	1	0.5 W	0.075 kg	Honeywell (QA-3000)
Sun Sensor	1	0.13 W (peak) 0.04 W (avg)	0.034 kg	Sinclair (SS-411)
Magnetometer	1	0.4 W	0.2 kg	SSBV
Earth Horizon Sensor	1	0.36 W	0.085 kg	Maryland Aerospace (MAI-SES)

G. Thermal Control Subsystem

The iSAT thermal control system represents a key challenge for the project due to the energy density of the spacecraft. The vehicle must address the direct heat load of the thruster, with competing desires to keep the spacecraft at modest temperatures while maintaining the feed system and propellant tank at elevated temperatures. In addition to the propulsion system, the power system generates significant waste heat during operation. Even with the high power density, 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 it is isolated and free to radiate to free space. Radiator surfaces are included on the primary structure and on the backside of the solar arrays. The system relies on conductive straps for heat transport. Early thermal analysis, shown in figure 12, indicates the passive solution can keep all components within the allowable limits of military grade electronic components.

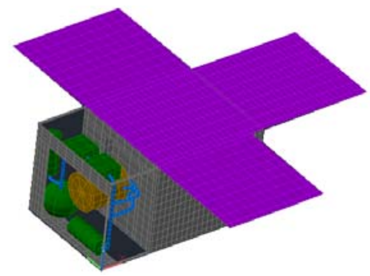

Figure 12. Thermal design.

H. Communications Subsystem and Ground System

The communications subsystem is a subsystem that is not driven by the propulsion system demonstration mission objective. Instead, the secondary objective for the iSAT vehicle to demonstrate mission capability through the inclusion of imaging payloads is the primary driver for data rates. The iSAT communication system provides both uplink and downlink capability. The downlink capability for spacecraft bus health and status telemetry and thruster performance telemetry is negligible compared to that of a science imaging payload. Consequently, we plan to allow for the maximum data return possible within the project constraints. The baseline data volume generated is approximately 6000 Mbytes/day with the science payload generating 98% of the data. 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. For initial planning, the iSAT anticipates using no more than three stations, notionally the Alaska Satellite Facility, the Virginia Ground Station and Kongsberg Satellite Services. Communications analysis predicts an average of 193 minutes of ground contact per day, of which iSAT planning assumes access for one-third of the available time to conservatively estimate 64 minutes for data transfer.The data requirement therefore leads to a communication system downlink capability of approximately 12.7 Mbps leading iSAT to an S-BD uplink and X-BD downlink architecture. The stations chosen all have both S-BD and X-BD capability, which is compatible with the iSAT communications system.

The iSAT team is still in the process of completing the communication trade study to identify the best technical solution. To meet the iSAT requirements before exceeding the available mass and volume, a solution must have a mass of less than 3.5kg and a volume under 2U in addition to a power consumption less than 30W. Note that on iSAT there is significant power available relative to typical CubeSats since the power system is sized for the propulsion system, leaving much excess power available during the science phase of the mission. An industry survey was completed, but unfortunately no COTS solutions can meet all of the iSAT requirements. However, the team has found existing S-BD receiver and X-BD transmitters that could be repackaged for iSAT. Additionally, we are considering use of the Programmable Ultra Lightweight System Adaptable Radio (PULSAR).[9] The iSAT team would remove redundant functionality from PULSAR for a custom iSAT solution. The communication trade study is planned for completion in the fall of 2014. The PULSAR 1.1U configuration is shown in figure 13. With the removed functionality, the iSAT solution would have a lower volume.

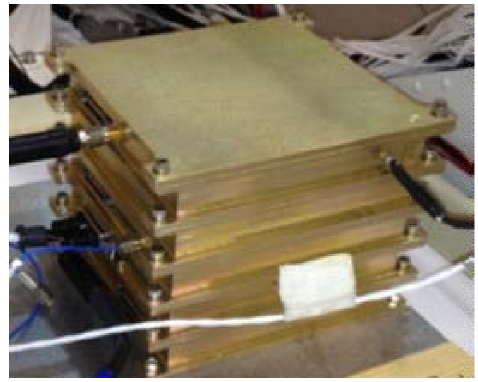

Figure 13. PULSAR 1.1U test unit.

I. Launch Services

The iSAT project has not been 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 iSAT project may also leverage a deployment opportunity from the International Space Station. An ISS deployment does not impact the primary objectives, however, the secondary science objectives include imaging of polar ice and higher latitude observations. Ideally launch service procurement will occur after the iSAT Critical Design Review, notionally March, 2015.

J. 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

Figure 13. The iSAT table at a NASA public outreach event in Alabama.

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. Planned efforts include intern participation at the college level, 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 FY14. The team continues to progress towards the PDR and complete all required analyses, technology assessments, trade studies materials testing, while developing the required systems engineering products. The iSAT project has on-hand all hardware necessary for an integrated propulsion system test. The team has manufactured a test plate for an integrated propulsion system characterization planned for the end of the summer at NASA GRC. The test plate fixture is complete and integration is ongoing. The project will demonstrate a flight-like feed system while operating the thruster and cathode first at NASA MSFC, and then at NASA GRC in VF-2 on a thrust stand. The test plate configuration for near-term GRC thrust stand testing and system characterization and test hardware in shown in figure 14.The project intends to demonstrate the full iSAT propulsion system throughput requirement by test prior to mission the PDR. Finally, the project intends to perform an integrated test at NASA MSFC to coincide with the PDR to demonstrating additional control hardware in the loop; leveraging the flight computer to control thruster start-up, long duration maneuvers and health and monitoring of the system. The system test at MSFC plans to leverage the Small Projects Rapid Integration and Test Environment (SPRITE).[10]

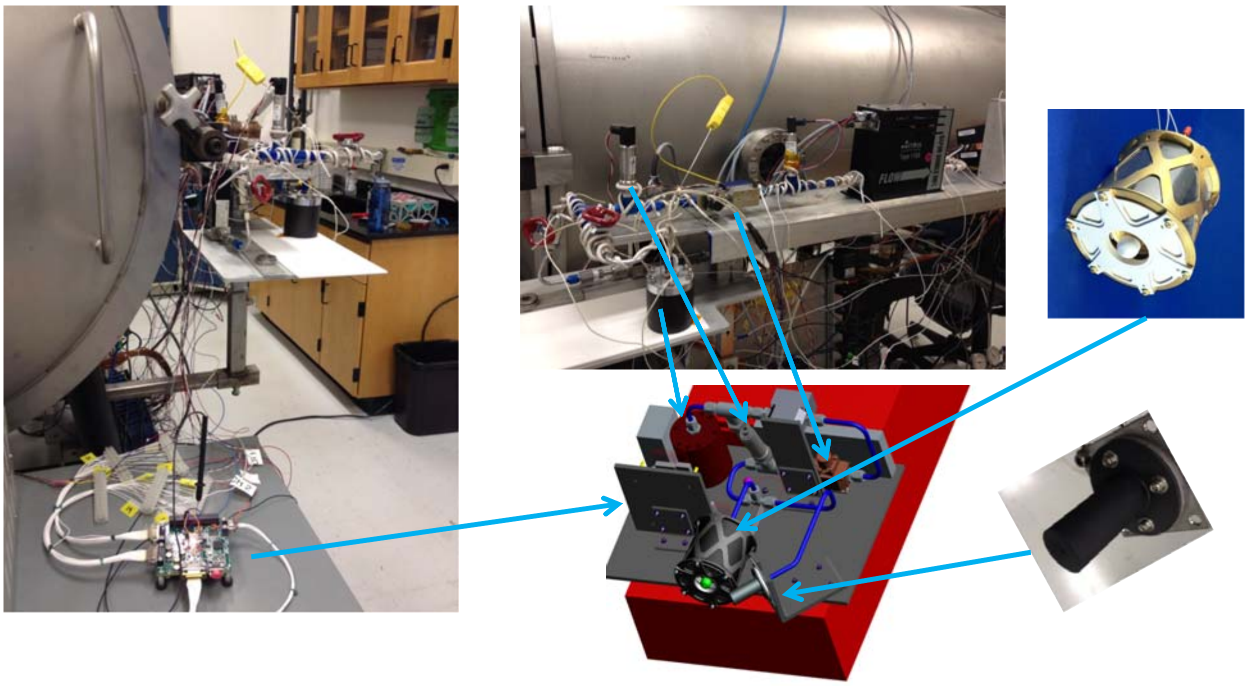

Figure 14. Near-term test configuration for GRC thrust stand measurements and system characterization.

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. A systems-level hardware in the loop test of the propulsion system hardware and avionics will be performed prior to the mission PDR. The iSAT project is scheduled for a mission PDR in September of 2014 and is targeting a flight opportunity in 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] 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.

[4] 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.

[5] Lee, S., et al., "CubeSat Design Specification Rev. 13," The CubeSat Program, Cal Poly SLO, February 20, 2014.

[6] 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.

[7] 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.

[8] 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.

[9] Sims, H., Varnavas, K., and Eberly, E., "Programmable Ultra Lightweight System Adaptable Radio (PULSAR) Low Cost Telemetry – Access from Space," SSC13-II-4, 27th AIAA/USU Conference on Small Satellites, Logan, UT, August 10 – 15, 2013.

[10] Rakoczy, J., Heater, D., and Lee, A., "Small Projects Rapid Integration and Test Environment (SPRITE): Application for Increasing Robustness," NATO CSO STO AVT-210 Specialist Meeting on Risk and Reliability Assessment and Validation for Mall Spacecraft, Karlstad, Sweden, May 13-16, 2013.