

The Iodine Satellite (iSat) Project Development towards Critical Design Review

IEPC-2015-303

*Presented at the 34th International Electric Propulsion Conference,
Kobe Convention Center • Kobe-Hyogo • Japan
July 4 – 10, 2015*

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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. 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 mission is a partnership between NASA MSFC, NASA GRC, and Busek Co, Inc., with the Air Force supporting the propulsion technology maturation. The team is working towards the critical design review in the final design and fabrication phase of the project. The current design shows positive technical performance margins in all areas. The iSat project is planned for launch readiness in the spring of 2017.

I. Introduction

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 (STMD), under the Small Spacecraft Technology Program (SSTP) approved the iodine Satellite (iSat) flight project for a rapid demonstration of iodine Hall thruster technology in a 12U configuration.¹ The mission is a partnership between NASA MSFC, NASA GRC, and Busek Co, Inc., with the Air Force supporting the propulsion technology maturation. The team is working towards the critical design review in the final design and fabrication phase of the project and the current design shows positive technical performance margins in all areas.

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Starting 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.² The results of testing indicate that iodine has comparable performance to that of the state-of-the-art (SOA) xenon. Additionally, changing the propellant to iodine does not require a modification to the power processing unit (PPU) discharge supply.

The iodine propellant has several advantages, with niches for low power volume constrained systems and at high power.³ The iSat system exploits these advantages for a low power secondary payload demonstration. The iodine is stored as a solid, with a density more than twice that of xenon. 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. The iSat mission demonstrates an order of magnitude increase in ΔV capability over the SOA for SmallSats. The project is working towards launch readiness in spring of 2017.

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

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. 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 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. To achieve full success, the mission must demonstrate a cumulative thruster duration of more than 80 hours, including individual maneuver requirements of more than 10 minutes at full power and 15 minutes at de-rated performance. The mission must also demonstrate propulsion altitude change greater than 250km and a propulsive node change; minimum success is no less than 100m/s of ΔV . 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 project will demonstrate twice the operational life of the highly successful TacSat-2 demonstration of the same thruster using xenon with a spacecraft <10% the mass.⁶

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 Grande⁷ 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. Mission Concept Overview and Development Status

The first detailed concept design of a low-cost iodine Hall demonstration mission was completed by the COMPASS team at NASA GRC in 2012. The concept was a 6U spacecraft with a modified BHT-200 thruster and repackaged compact power processing unit (PPU). The initial concept was power starved, included aggressive assumptions and required significant engineering development work, but it showed the viability of a low cost and high value approach to flight demonstrate the iodine Hall technology. Multiple iterations on concept designs followed the first look. As fidelity was increased, additional power was added, followed by deploying the thruster to assist with heat rejection, the battery grew in volume resulting in bus growth to a 12U, payloads were added and some of them later removed to accommodate system growth, heritage designs reincorporated, etc. The project is currently starting the third formal design and analysis cycle (DAC-3). The spacecraft concept evolution is illustrated in figure 1.

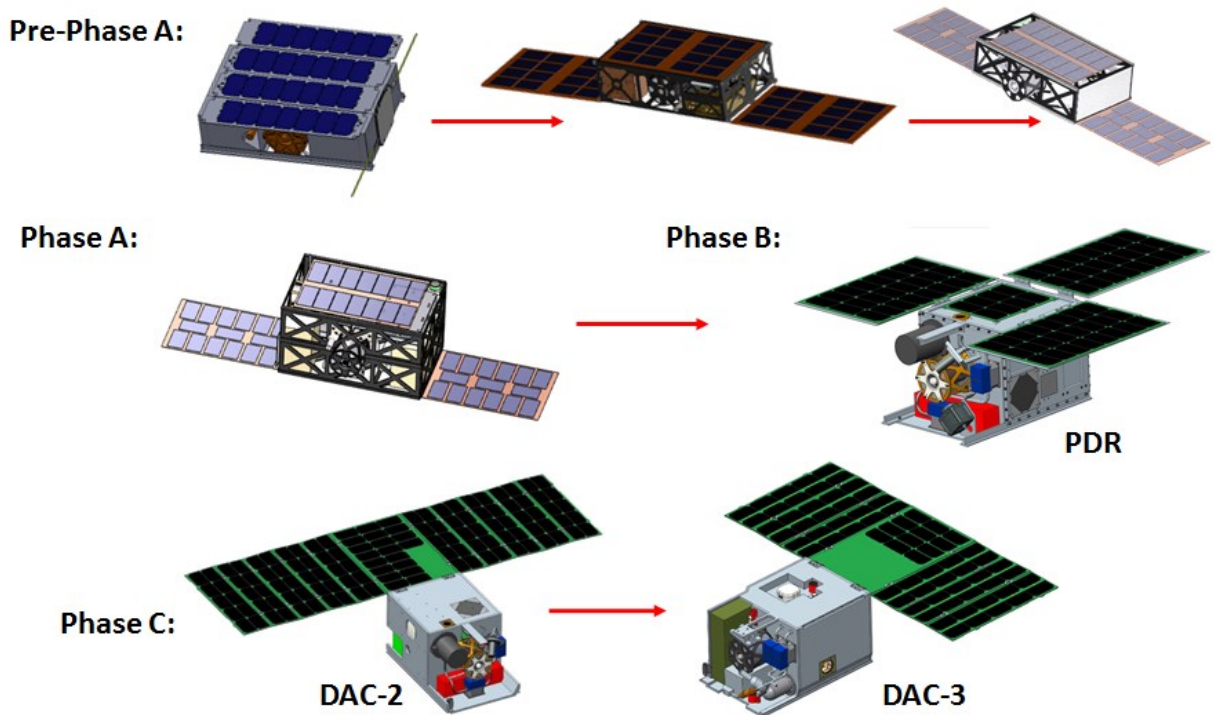


Figure 1. Concept design evolution of the iodine Hall demonstration system.

A. Concept of Operations

The mission concept of operations (CONOPS) is partially dependent on the orbit the iSat spacecraft is deployed. The baseline assumption is that the spacecraft will be deployed into a sun-synchronous 600km circular orbit. The altitude limit is set by no fault tolerance to orbital debris requirements. Even with a total mission failure at deployment, analysis shows that given iSat's ballistic coefficient, the spacecraft will naturally deorbit in less than 25 years. The spacecraft power and thermal management systems are designed to accommodate the full range of altitude and inclinations without any specific node requirements (e.g. noon-midnight vs. 6AM-6PM). The vehicle will have significant battery charge available for deployment, tip-off correction and attitude tracking; all performed without ground intervention. An initial check-out period of two weeks is planned. 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. After check-out, the spacecraft will transition to a more automated mode with sequences preprogrammed. The spacecraft will lower its altitude from a 600km circular orbit to a 300km circular orbit, perform a plane change maneuver, complete any final operational maneuvers and then continue to lower only perigee until achieving < 90day deorbit. The project is working with the National Reconnaissance Office (NRO) for a confirmed flight manifest, with Falcon 9 and Atlas V options available. With either launch vehicle, iSat will be deployed using the Planetary Systems Corporation (PSC) 12U deployer. The CONOPS are illustrated in figure 2.

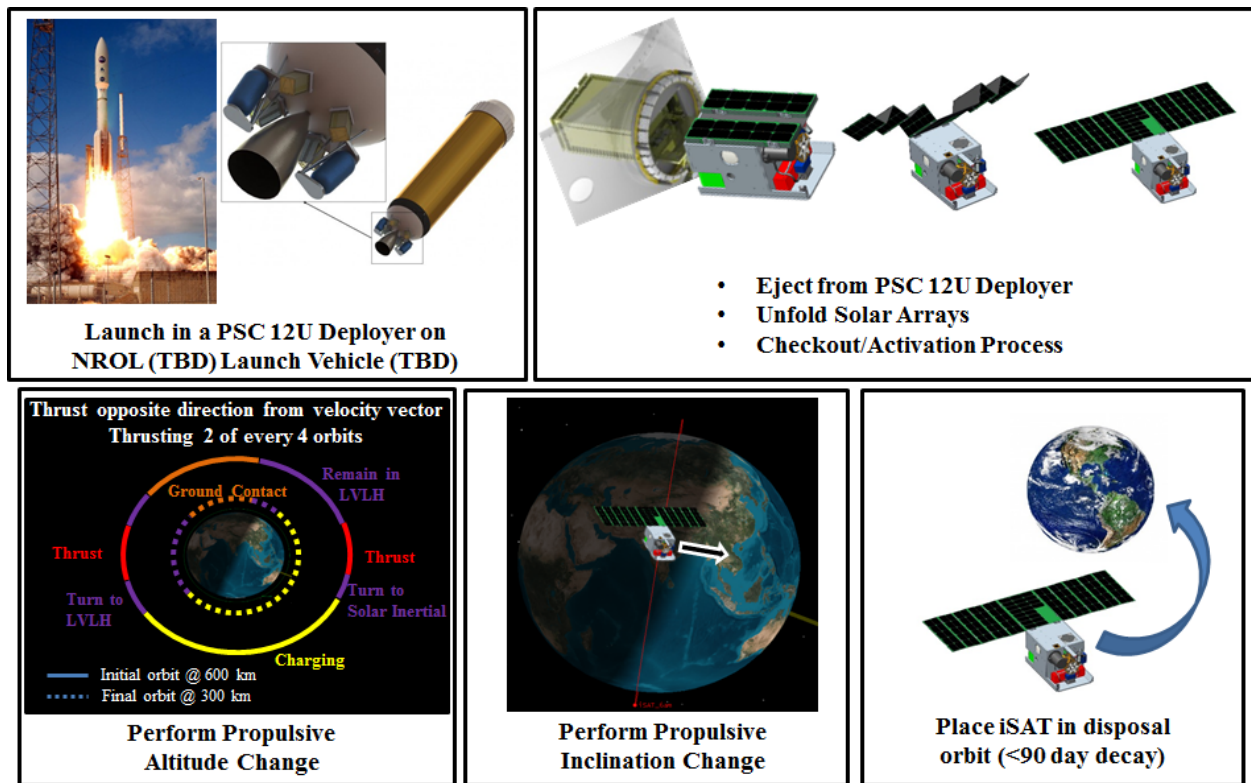


Figure 2. High level concept of operations.

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 is provided in Table 1.

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

TPM	Metric	Status at PDR	Status at start of DAC-3	Comments
X/Y/Z Margin	Planetary Sys. Envelope	GREEN	GREEN	Fits within envelope
Total ΔV	As determined by sim	GREEN	GREEN	Current ConOps requires 198.4 m/s without margin
Max Duration of Single 200W Burn	Max Duration Burn at 200W assuming one burn an orbit	RED	GREEN	Solar Array redesign, battery capacity increase, and ability to include charging orbits allows for this burn to be accomplished without exceed the 60% DoD
Max Duration of Single 100W Burn	Max Duration Burn at 100W assuming one burn an orbit	RED	GREEN	Solar Array redesign, battery capacity increase, and ability to include charging orbits allows for this burn to be accomplished without exceed the 60% DoD
Thruster Operation Duration	Total Cumulative run time of thruster during mission	GREEN	GREEN	Current ConOps has a runtime of 80+ hours.
Data Bandwidth	Available bits vs. Requested bits per day	GREEN	GREEN	Current S-BD solution exceeds data requests.
Battery SOC	Battery SOC for smallest repeatable interval of each mission phase	RED	GREEN	Battery currently dips to approximately 75% state of charge with current assumptions. Requirement is not to dip below 60% SOC.
Mass Margin	Total S/C mass vs Allocation	YELLOW	GREEN	Given that the spacecraft mass allocation is 24 kilograms, mass is not thought to be a driver. Spacecraft mass update is ongoing to incorporate DAC-2 results.
Available Payload Data	Available bits for the payload vs requested bits for the payload per day	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 orbit basis vs. allocated power	RED	GREEN	The diagnostic sensors do not require much power.

C. Propulsion Subsystem

The propulsion system is the core of the iSat mission. The propulsion system is not only the purpose of the project, but is a major driver for power, thermal management and attitude control. The iSat project has been working with engineering model hardware early in the project for risk mitigation with significant testing planned prior to system integrations. The thruster will undergo qualification and build a separate flight unit while the PPU will be a protoflight development.

1) Thruster

The thruster is a derivative of the BHT-200 flight thruster. The BHT-200 was the first American Hall effect thruster flow in space and launched in 2006 as a part of the TacSat-2 project. The thruster has been studied extensively and provides a good benchmark for comparing performance variances from the iodine version of the thruster; the BHT-200-I. The iodine thruster is distinguished from the nominal BHT-200 by the materials of construction, the geometry of the anode, and the presence of iodine-resistant coatings. The anode and gas flow lines are made from a non-magnetic, iodine-resistant alloy. The propellant voltage isolator is made from iodine-resistant metals and brazes. The gas distributor was also completely redesigned to allow the use of multiple materials. The BHT-200-I engineering model is shown in figure 3.

2) Cathode

The BHT-200 flight model is neutralized by a xenon fueled hollow cathode with a BaO⁻W emitter. For iSat, the BHT-200-I will be neutralized by an iodine fueled hollow cathode featuring a C12A7 electride emitter.⁸ The cathode will leverage the flight heritage design including the mounting structure, but the new emitter enables a significant increase in total system efficiency by reducing the power required for cathode conditioning.

3) Power Processing Unit

The Power Processing Unit is also a major advancement over state of the art. The PPU includes a new topology for compact design. The compact PPU design started under an Air Force SBIR program under the Operationally Responsive Space (ORS) office. A 2nd and 3rd iteration of the compact PPU was funded to support two different NASA SBIR projects. The iSat 200W PPU and a NASA Game Changing Development 600W version are being built in parallel as the 4th and 5th design of the compact PPU. Both the 200W and 600W PPU are identical form factor with significant commonality between the two. The 200W PPU is essentially a 600W PPU optimized for lower power operation. The PPU has the same power requirements for operating a xenon thruster and can be used for future xenon mission applications. The PPU is also designed to include control of the feed system components described below. The intended functionality includes the control of three independent heater zones for the propellant lines, the tank heater, temperature sensors, pressure transducers and also perform on-board closed-loop flow control based on either discharge current or a pressure measurement. The PPU will use an RS422 interface, accept an input voltage range from 24-36V and leverage FPGA based control of all outputs and telemetry.

4) Feed System

The feed system is designed similarly to the Advanced Xenon Feed System.⁹ The core of the flow control is a pair of parallel flow paths with VACCO proportional flow control valves (PFCVs). The PFVCs have been modified from the xenon qualification valve to reduce the pressure drop, add internal heaters and temperature sensors, and material changes for iodine compatibility. NASA MSFC has been leading a larger effort for the feed system design of iodine based propulsion systems regardless of the thruster.

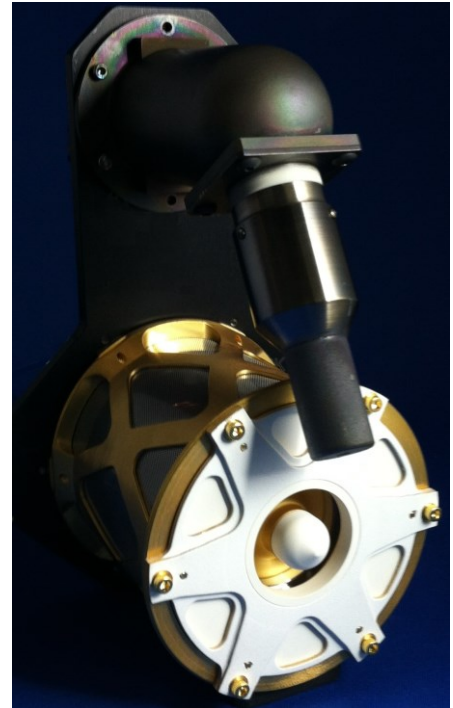


Figure 3. Engineering model BHT-200-I.

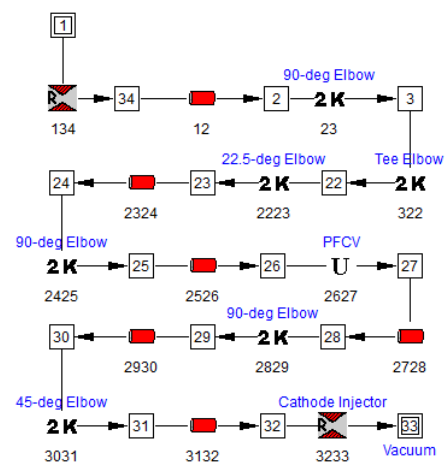


Figure 4. GFSSP cathode flow model.

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. A low pressure system, however, 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)¹⁰ 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. The diagram of the cathode flow channel for iSat is shown in figure 4 and the PFCV flow characterization setup in shown in figure 5.

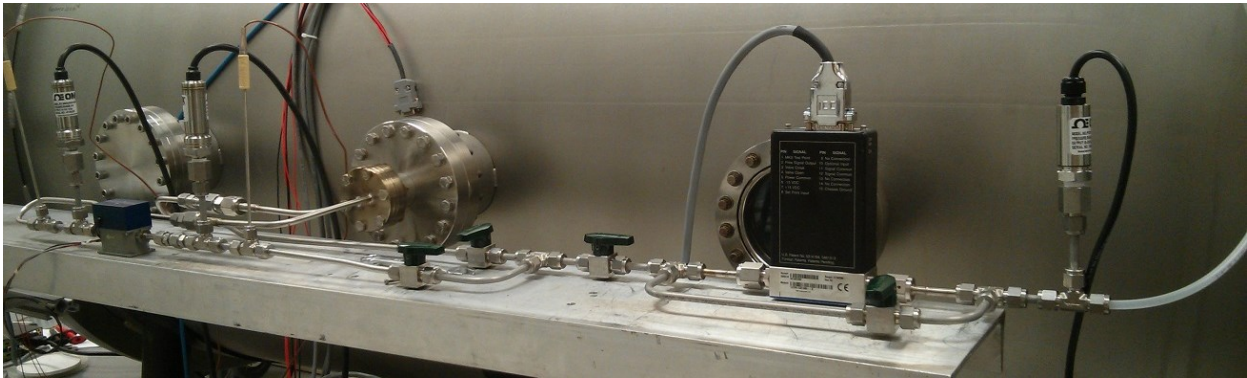


Figure 5. PFCV flow characterization setup.

5) Integrated Testing

Early in the project, the team is performing integrated system testing. Preliminary testing of short durations were performed at NASA MSFC while assessing interfaces, testing communication between the flight computer and the PPU and testing early designs of electric cathodes. In May of 2015, NASA GRC is performing a mission duration test (approximately 80 hours) of the engineering model thruster. The purpose of the mission duration test is to validate the design modifications of the engineering model thruster prior to building the qualification and flight model thrusters, map the performance of the thruster with both xenon and iodine over the thruster throttling range, map the plume of the thruster throughout the test duration, measure and record temperatures of selected components for thermal model validation, demonstrate feed system components and perform material testing concurrently.

During the 80 hour duration test the thruster telemetry will be continuously monitored and recorded. A Faraday probe and a Langmuir probe will be installed on a linear stage and will map the exhaust plume of the thruster. A CCD camera will also be installed on the linear stage and will take periodic close-up images of the thruster at prescribed intervals to document the status of the thruster and its coatings. The BHT-200-I EM thruster test will be performed at NASA GRC's Vacuum facility 7 (VF7). Vacuum facility 7 is an oil diffusion pump evacuated facility that is 10ft (3m) in diameter and is 15ft (4.6m) long. Vacuum facility 7 has been modified for compatibility with iodine propellant. Liquid nitrogen cooled chevrons will be used to collect the iodine propellant during thruster firing. After test completion, the iodine propellant will be vented through a dedicated iodine vent line. Figure 6 shows a photograph of the thruster installed on an inverted pendulum thrust stand.



Figure 6. Test setup at NASA GRC.

After a successful mission duration test, Busek will manufacture and deliver both a qualification thruster and a flight thruster. The qualification thruster will go through a standard qualification test sequence including test until failure. Busek will perform the thermal vacuum testing and NASA GRC will perform the remainder of the qualification testing including the life test; anticipated to be approximately 2,000hrs.

6) Material 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.

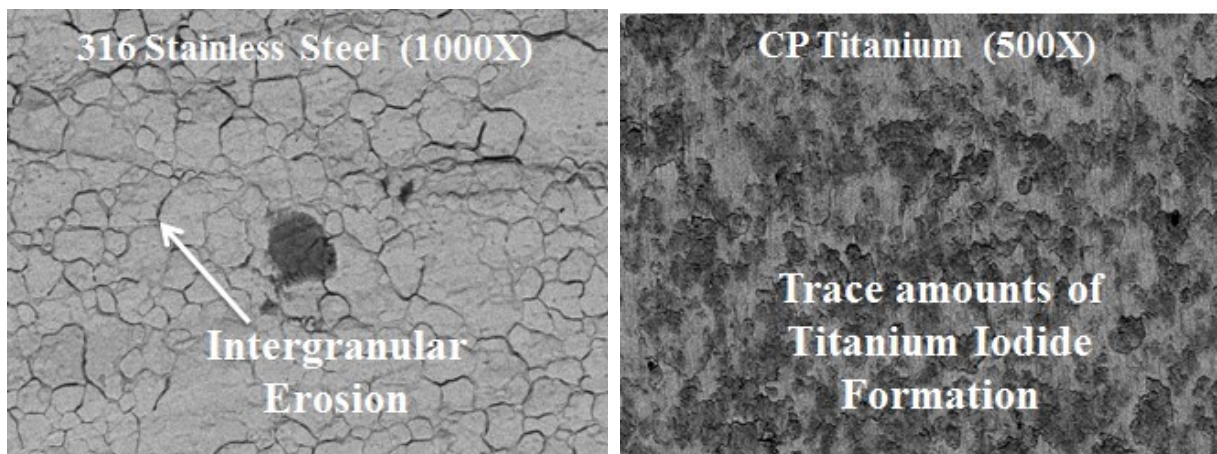


Figure 7. Preliminary results from one-week iodine exposure testing.

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 Spectrolab 28.3% efficiency Ultra Triple Junction (UTJ) cells to provide approximately 60W of power. The panels are strung to provide sufficient power including 25% design margin over the preliminary design requirement. 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.

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 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 2015. The flight battery will be packaged in approximately a 7 cm x 7 cm x 16 cm aluminum box with a wall thickness of 3 mm. The flight battery mass will be approximately 1.5 kilograms not including packaging, which is still being designed. The battery will also be packaged with a MSFC-designed cell balancing circuit. The cell balancing circuit will be built with commercial parts to conserve volume, but will include a higher grade bypass in case of circuit failure.

E. Structures and Mechanical Subsystems

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 ejection, the iSat vehicle has spring loaded passive deployment mechanisms for the solar panels. The design will also allow for a commanded deployment mechanism if required by the launch vehicle. The primary structure is fabricated in-house from 7075 aluminum alloy with a hard anodized finish.

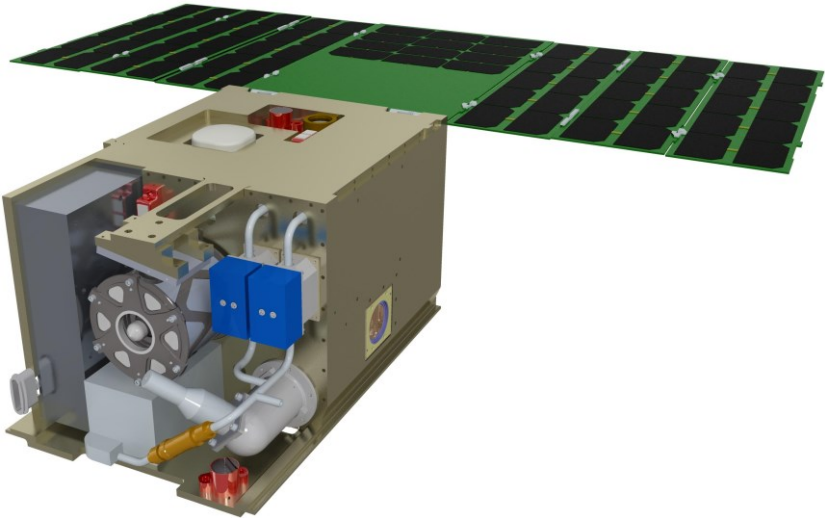


Figure 8. Basic configuration illustration for iSat.

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. The thruster compartment is exposed to space 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 8.

F. Thermal Control Subsystem

The iSat thermal control system represented 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 was the 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. The primary structure also functions as the spacecraft bus radiators. The solar arrays will radiate their own heat. Early thermal analysis indicates the passive solution can keep all components within the allowable limits of military grade electronic components. The current design is for the outer exposed surfaces to be covered with silver Teflon tape to increase radiator effectiveness.

G. Attitude Determination and Control

The attitude determination and control (AD&C) subsystem is based entirely on commercially off the shelf (COTS) components. The thruster on iSat is not gimballed, 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 communication passes. 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 preliminary design was driven by thruster misalignment and worst case magnetic dipole torques. The new configuration with the extended solar panels behind the main compartment drives the reaction wheel sizing to accommodate the aerodynamic loads at the lowest operational altitudes, slew requirements and solar radiation pressure. The iSat vehicle is assumed to be deployed with a possible maximum tip-off rate of up to 5 degrees/s. The system performs attitude control through three 100 mN-m-sec reaction wheels and leverages 0.6 Am² magnetic torque rods for momentum dumping. Several of the components remain to be competitively procured. However, AD&C COTS system components have been identified to meet the mission needs for the notional system and are identified in table 2.

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 \leq 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

H. Command and Data Handling

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 I²C 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 9. The iSat project intends to use available space on in-house designed I/O Board to accommodate the additional C&DH needs. The I/O board will provide an FPGA to do analog to digital conversion as required. Additionally, the I/O board will serve as a data bus conversion / bridge as shown in Figure 9.

The C&DH subsystem will also include an auxiliary board that performs two functions: host circuitry to operate the payload sensors and mimic the minimum heater control circuitry provided by the PPU. The payload circuitry is based on a design provided by the Air Force Research Laboratory from TacSat-2. The heater control circuitry provides the ability to control four separate heaters based on output from four RTDs, which is intended to operate the feed system tank heater and three independent propellant feed line heaters. The circuitry is included as a risk mitigation measure due to the fact that the PPU is still under development.

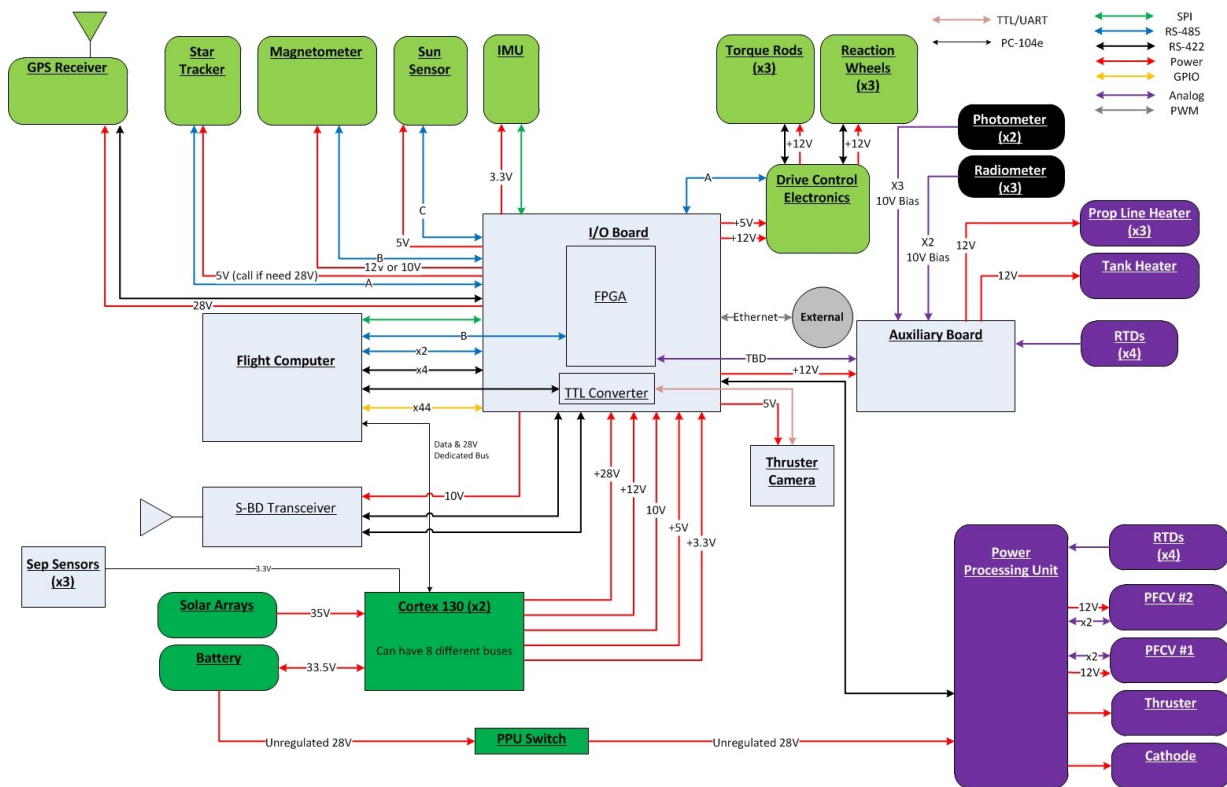


Figure 9. Baseline command and data handling architecture.

I. Communications and Ground System

The iSat communication system provides both uplink and downlink capability through a single patch antenna. The downlink capability requirement for spacecraft bus health and status telemetry and thruster performance telemetry is approximately 0.2 Mbps. Due to the low data rate, the iSat spacecraft is planning to use an S-BD communication architecture for uplink and downlink. Even with an assumed BPSK modulation, which limits S-BD downlink to 2.5 Mbps, an S-BD architecture allows for >10x margin on the data rate. 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 McMurdo, Antarctica 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 assumed S-BD radio/diplexer solution from Tethers Unlimited, the SWIFT-SLX. The transceiver will be coupled with a single S-BD patch antenna. While the SWIFT-SLX meets the requirements, the transceiver will be competitively procured.

J. Flight Software

From a flight software perspective, iSat will be utilizing an agile approach that is defined by sprints and epics (sometimes referred to as “scrums”). Each epic is focused on building out a core functionality of the software. The epics are comprised of two week sprints, during which the entire development effort is focused on completing discrete tasks. These tasks are managed in a master “To Do” list, which provides continuity between the sprints and evolves to match changing priorities or tasks. The flight software team will be using OpenProject to manage tasks and schedule and will be providing status updates to the project at the completion of each sprint. This approach is less reliant on having a thorough and complete set of requirements at the beginning of the development process and allows the requirements to be developed as the spacecraft and planned operations are matured. The flight software team will derive requirements from multiple sources, including component interface definitions, system-level requirements, the concept of operations, interface agreements with the ground systems and GNC subsystem, and other interactions with the rest of the team. These requirements are maintained in a Software Requirements Document, which is a configuration managed product.

The iSat project is implementing a layered software architecture that is heavily dependent on an MSFC developed set of libraries called libSPRITE. The initial development began using Ares 1 flight software and has since been modified. From a flight perspective, the libraries have been used on six Nanolaunch flights, an effort to develop cost-effective launch vehicles for small payloads. While libSPRITE is comprised of multiple libraries, the heart of libSPRITE is the Simple RunTime eXecutive (SRTX). The libraries have also been used in “hardware in the loop” tests for various projects. This can be run on a single machine (the single machine can be multiprocessor or multicore), provides a task scheduler, and provides a deterministic publish subscribe mechanism. An open source release of libSPRITE is coming soon.

K. Hardware in the Loop / Software in the Loop Testing

A unique capability of NASA MSFC that will be used extensively during the iSat project is the Small Projects Rapid Integration and Test Environment (SPRITE)¹¹. The unit is a Portable Hardware in the Loop (PHIL) and software in the loop capability. The unit connects directly to the spacecraft flight computer for mission simulations and will be used for dynamic feedback for all subsystem components. The SPRITE system allows for a low-cost test environment comparable to significantly larger projects and enables significant risk reduction for a low cost Class D mission. The first SPRITE test with the iSat system is shown in figure 10. The first test included the SPRITE unit, an engineering model of the flight computer, power management and distribution boards, a digital control interface unit (DCIU), a Busek compact PPU, the engineering model thruster and a laboratory model cathode and occurred prior to mission PDR.



Figure 10. Preliminary SPRITE testing for iSat.

L. Launch Services

The iSat project has not been manifested for flight yet. The baseline approach has been 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 project has completed preliminary negotiations with a commercial launch provider. Also, the NRO has offered a commitment to launch the iSat system. The NRO has multiple opportunities in the time of interest. Some of the options include launch loads significantly higher than GEVS, but an interface suppression ring would be available prior to the iSat launch date. The iSat system is designed to accommodate any of the launch options as dictated by the program. The iSat is expected to obtain a formal manifest agreement in 2015 for a launch in the summer of 2017.

M. Education and Public Outreach

The iSat project is executing a relatively large education and public outreach (E&PO) component to the small project; primarily through team volunteer efforts and existing NASA engagement opportunities. 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 to increase awareness of electric propulsion in general; still relatively unknown to the 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 public 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, shown in figure 11, 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, a website and public media distribution of the project progress. The key message is the role of iSat technologies to enable future science and solar system exploration.



Figure 11. The iSat table at a NASA public outreach event in Alabama.

IV. Near-Term Activities

The iSat project is working towards two primary goals in FY15: successful completion of the CDR and procurement of long-lead subsystem elements. The iSat project will be performing all the necessary component design, analysis, development and risk-reduction testing, and product development to support an iSat CDR in August of 2015. From a spacecraft bus perspective, the iSat project is focused on procuring engineering units for all components to complete a build-up of an Avionics Test Bed (ATB) also within FY15. The ATB will serve as a “flat sat” ground capability that will allow the flight software team to exercise its code on actual iSat hardware. Additionally, development-level testing will be completed on the iSat power and C&DH cards to determine the conducted EMI/EMC emissions and identify the need for any additional shielding. Finally, the iSat project will build an engineering unit of the battery and begin simulating the spacecraft loads on that battery to characterize its performance over time.

Specifically on the propulsion, GRC will begin a mission duration test (approximately 80hrs) of the engineering model of the BHT-200-I using some of the same hardware developed for feed system testing. The test will also include samples of hard-anodized 7075 aluminum placed at various points in the chamber to evaluate the effect of the thruster plume on the aluminum. The primary goal of the test is to validate the design modification from the flight heritage thruster. Upon completion of the test, the thruster will be removed and undergo post-test analyses. Following a successful test, the build of the qualification model thruster will be initiated. MSFC is updating the feed system modeling with design and testing of an engineering model propellant tank. At the same time, Busek is continuing development of the PPU and procurement of long-lead EEE parts and cathode maturation.

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. Since PDR, the project has significantly reduced risk and has improved all technical performance metrics. The project team has made and continues to make significant progress towards risk reduction. The iSat project is scheduled for a mission CDR in August of 2015 and is targeting a flight opportunity in 2017.

Acknowledgments

This work is sponsored by NASA's Space Technology Mission Directorate and is managed by the Small Spacecraft Technology Program at the NASA Ames Research Center. The authors wish to thank the entire iSat team for their input and progress to date.

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