PROPULSION INSTRUMENT ELECTRONICS AND SENSOR PACKAGE

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Abstract

Spacecraft operators and designers need to understand the interaction between thrusters and spacecraft, and the limitations of ground test facilities make it important to validate models with data obtained from on-orbit conditions. Toward this end, a sensor package will be manifested aboard an upcoming spacecraft flight for the purpose of developing a predictive capability for how electric propulsion thrusters interact with typical spacecraft. A small Hall thruster and a micro-PPT will be operated in orbit and several instruments will characterize the environment induced by the thrusters. An ion probe will determine the energy and species distributions and an electron probe will characterize the electron density and temperature of the back-flow region of the thruster plume. These data are intended for comparison with detailed numerical models in this region. Other instruments directly measure the effects of thruster operation on spacecraft thermal control surfaces, optical surfaces and solar arrays. Specifically, radiometric, photometric and solar-cell-based sensors are under development. All of the flight sensors are controlled by the Propulsion Instrument Electronics (PIE).

Introduction

The development status of a sensor package designed to observe the on-orbit operational influence of a Hall effect thruster and a micro Pulsed Plasma Thruster (μPPT) on an upcoming spacecraft flight is presented. Data collected from on-orbit will be used to validate models currently under development. The initial design and preliminary experimental results of the sensor prototypes and Propulsion Instrument Electronics (PIE) are discussed.

A critical part of the spacecraft sensor package is the characterization of interactions between the on-board thrusters and the spacecraft. These are significant because electric propulsion thrusters' exhaust products can be highly energetic, generating erosion and secondary deposition products wherever plume impingement occurs. In addition, wear materials are emitted from the thruster and flow through the plume to deposit on spacecraft surfaces. These effects can lead to degradation in optical surface properties, solar array performance, and radiator thermal properties. Several ground-based measurements have been made to assess these effects,[1,2] but the chamber effects dominate the measured signals in the back-flow region.

In response to this need, a collaborative program between the Air Force Research Laboratory (AFRL) and the Jet Propulsion Laboratory (JPL) was established to determine the effects of a Hall thruster and a μPPT on an upcoming spacecraft flight. This goal will be accomplished using a coordinated program of ground testing, on-board diagnostics, ground-based remote sensors, and a modeling effort by which extrapolations can be made to future systems. Figure 1 and Figure 2 show the current designs of the Hall thruster and μPPT respectively.

Based on the experiences from the Electric Propulsion Space Experiment (ESEX) mission,[3,4] a philosophy was developed for the appropriate measurement of effects on a host spacecraft from thruster operations. This includes several key points: maximize the number of measurements that can be conducted from remote observations (because they have a minimal impact on spacecraft design); perform direct measurements of critical engineering parameters (for example, thruster effects on optical surfaces) and thruster parameters (plume ion flux, for example); and finally, design the instrumentation such that the data are expected, from pre-flight analysis or test, to show a simple, trendable signal that characterizes the effect in question. Furthermore, the use of modeling and simulation throughout the program is key to describing the effects of these devices on generic spacecraft, as well as planning the logistics of the sensor design. Determining the location of the sensors on the spacecraft, for instance, can be aided dramatically even by first-order calculations of the plume flowfield and how it strikes other spacecraft surfaces.

Based on the above criteria, a set of measurements was identified very early in the program. These measurements focused on three classes of data: (1) direct engineering measurements of the contamination impact to the host spacecraft from the thrusters including thermal and optical surface degradation, and effects on thin film solar arrays; (2) plume characteristics to supply required modeling input data including electron and ion species in the exit plane and the plume; and (3) thruster performance data such as thrust, specific impulse, and efficiency. To address these measurement requirements, a suite of on-board sensors were baselined including: an ion probe, two electron sensors, six solar cells, ten radiometers, and ten photometers. Further ground-based tests such as communication tests,[5] or optical spectroscopy[6] may also be utilized.

Figure 3 shows the current layout of the sensors on a spacecraft propulsion panel, and their location relative to the Hall thruster and μPPT. Not shown are the Hall thruster internal components, which include the xenon flow system and the power processor, or the interface electronics unit for the onboard sensors. These smaller sensors (each with about 1cm^2 area) will be distributed around the propulsion panel and spacecraft zenith deck in coordination with the detailed spacecraft design.

The interface between the sensor suite and the spacecraft is managed by the Propulsion Instrument Electronics unit. The PIE inputs are the 28 V spacecraft power and an RS-422 digital interface for commands and telemetry. The PIE, designed and built by Broad Reach Engineering (BRE), provides the proper voltages and currents to drive the individual sensors, contains the signal processing and multiplexing circuits, and is responsible for the software interface for the sensors' command decoding and telemetry processing.

Finally, the critical design criteria for the sensors were mass and cost. The Propulsion Sensors element of the spacecraft, including the sensors, the PIE, the harness, fasteners, etc., carries a design limit of 2.0 kg. Furthermore, the development process is designed to minimize system cost by accepting risk consistent with a USAF class D space experiment, characterized by a proto-qualification testing approach, a single-string design, and limited parts selection. The following paragraphs describe each of the sensors types, provide a description of where they are located and the corresponding rationale, and describe the current status of each.

Contamination Measurements

The contamination measurements are loosely based on experience from the ESEX contamination data.[7-9] For ESEX, these measurements consisted of radiometers, thermoelectrically-cooled quartz crystal microbalances (TQCMs), and a solar array segment. Based on the mass and power constraints, radiometric sensors and solar cells were selected for this package. In addition, a photometer was added to address optical surface degradation. Each of these three sensors uses the sun as a relatively constant source, against which changes due to thruster operation are measured. All of the contamination sensors will be placed on sun-facing surfaces on the spacecraft in order to maximize their insolation exposure throughout the mission. These surfaces include the zenith deck itself, as well as on the propulsion panel, which faces both the sun and the thruster.

Radiometers

The radiometers are used to measure the effect of the thruster on the thermal properties of typical spacecraft surfaces. The basic design consists of a thin plate whose exposed surface is treated with a typical spacecraft material such as Kapton, thermal paint, or a radiator surface like silvered Teflon. The plate is thermally isolated from the spacecraft, such that the plate's temperature is strongly affected by the treatment's thermal properties. The temperatures of the surface and the spacecraft-radiometer junction are measured and recorded as a function of the solar illumination. As the surface material degrades from thruster operation, the emissivity and absorptivity of the material changes, and the temperature profile changes accordingly. Figure 4 shows a representation of this generic design.

Using this device to measure thruster effects depends on a thorough understanding of the nominal performance of the material in the orbit environment. For materials such as Z-93 white paint or silvered Teflon, the normal degradation from effects such as atomic oxygen is well characterized, so these materials make good candidates for these sensors. Because of the requirements for small dimensions, the temperature sensors themselves must also be relatively small in size. The current designs focus on the use of the Analog Devices AD590 temperature transducer. This device is flight qualified and will be used extensively elsewhere on the spacecraft. The AD590 sensors have well-characterized behavior over the expected temperature range, and have a convenient calibration curve of 1 micro-A per degree Kelvin. The radiometer design will be based on the same premise as the generic description above, but includes a more advanced designed to take advantage of weight savings. For example, the current design uses a bare AD590 die bonded to the sensor plate in order to reduce the plate's overall heat capacity. The AD590 die's mass is approximately 2 mg, which is small compared to the plate's mass of approximately 300 mg.

Solar Cells

The solar cell design can also be traced to the ESEX program. In this measurement, the voltage and current characteristics of the array are measured over the life of the mission to determine the performance degradation as a result of reduced surface transmission induced by thruster operation. For ESEX, only two points were measured for the array performance – the open circuit voltage and the short circuit current. While on orbit, data will be acquired over the entire I-V curve through a series of switchable load resistors.

Selection of the cell technology to be tested involves a trade between older, better-understood technologies such as silicon cells, and more advanced technologies likely to be used on future missions. The USAF research community is enthusiastic about spacecraft use of thin-film solar array technology. Figure 5, for instance, shows the thin-film technology that is baselined for the main spacecraft array. The thin-film arrays do not, however, have significant data on how they nominally perform on-orbit – making definitive statements about the Hall thruster impacts more difficult.

The ultimate selection for the array to be flown as a part of the spacecraft sensor suite has not been made. Aside from the debate on silicon-based vs. thin-film technology, there is a secondary debate on what thin-film technology is most appropriate for this application. Further complications include limits on the amount of current output from the array segments to the PIE, predictions of expected on-orbit performance, and temperature effects on the array output.

Photometers

The final part of the contamination measurements suite is the photometers. These devices will be used to assess the impact of the Hall thruster on optical surfaces and coatings. The design features a photodiode collector that receives incident sunlight behind a silica window, which carries the optical coating of interest. Optical coatings under consideration include first surface reflectors, dielectric mirrors and filters, and anti-reflective coatings. Measuring the change in the collected sunlight as the mission progresses enables an assessment of the thruster impacts. Figure 6 shows an example of a photometer under consideration for this application.

The photometers are relatively low-risk items because there are numerous space-qualified applications already, such as sun sensors. The photometers will be sized according to the mass constraints of the sensor system, while ensuring that the widest range of data is acquired.

Plume Characterization Measurements

There are two primary motivations for these measurements: (1) to provide inputs and verification for current and future modeling efforts of Hall thrusters' interactions with spacecraft; and (2) to understand the Hall thruster plume characteristics in the space environment. As such, the instruments selected will measure the mass and energy distribution of xenon ions, the electron density and temperature in the near-field region of the thruster, and assess the current return path from the plume and ambient space plasma to the spacecraft. All of these sensors are currently in development and represent a significant part of the program effort.

Ion Probe

The ion probe under development will measure the mass and energy distribution of ions emitted from the thruster during operation. The primary ions of interest include Xe^+, and Xe^{++}, but may also include others as the design modeling effort matures. Figure 7 shows the critical components of the present prototype: ions enter the spectrometer through a system of input ion optics, pass through a pair of nested hemispherical section shells (energy analyzer) for energy-to-charge-ratio selection, are collimated by another ion lens, then become separated according to mass-to-charge-ratio by a yoked NdFeB permanent magnet (mass analyzer). Not shown is a microchannel plate detector, which may be required due to the low ion currents in the back-flow region.

Studies on the effectiveness of the present design have shown promising results; however, the interface between the instrument and the PIE remains a critical design issue. Other interface issues include shielding against stray electromagnetic emissions while maintaining the required level of sensitivity, and providing a complex system of voltage supplies and measurements with a low mass budget.

Measuring the low currents while maintaining an acceptable signal-to-noise ratio has been the greatest challenge to date. To address this issue up front, a breadboard of the current sensing circuitry was built and tested by BRE. This breadboard was successful in measuring current levels down to 1 nanoamp with a resolution of a 0.25 pico-amp, with relatively little noise on the telemetry. With this success in hand, the majority of work for the ion probe has focused on validating its functionality via an integrated firing with the thruster itself. Pending experiments will also more clearly identify the range of the expected current, enabling the flight design to be finalized. In particular, a microchannel plate may be added to amplify the current up to 1000 times.

Electron Probes

The electron probes are based on traditional Langmuir probe operation where the probe is biased with either a positive or negative voltage, and the collected current is recorded. For a spacecraft application, there are two probes – one mounted on a fixed boom off of the propulsion panel (see Figure 3), and the second mounted on the zenith deck. Both designs will have a voltage sweep range of +50V to –50V, and will be capable of measuring currents as high as 1 mA at 12 bit resolution. Both probes will be oriented into the RAM direction for at least 30 seconds per orbit (although the zenith deck probe will be in the RAM for much longer) in order to assess the ambient environment.

The boom mounted probe will be used to determine the electron temperature and density in the near-field region of the thruster plume. This sensor is a conducting cylinder (diameter = 0.4 mm, length = 15.2 mm), mounted 36 cm from the Hall thruster exit channel. The electron probe L/D = 40 and the total exposed surface area is 18.2 mm^2. Designs under consideration for mounting include a simple, fixed boom constructed of a composite tube to minimize weight, as well as a smaller boom mounted near the propulsion panel.

The primary purpose of the zenith deck probe will be used to determine the current return from the plasma environment. This probe is a 5 cm conducting disk which is electrically isolated and mounted directly to the spacecraft structure.

The instrumentation design schedule puts the detailed design of the two electron probes later in the process, because the sensors are relatively simple. The electron sensor is expected to be validated primarily against the Hall thruster, although other plasma sources may also be used as available.

Performance Measurements

The final part of the on-board diagnostics will be used to measure the performance of the thrusters. The sensors to be used for these measurements are primarily those already included in the spacecraft Attitude and Direction Control System (ADCS) as well as ground-based techniques developed by the ESEX flight.[10] The ESEX performance measurements showed that the complications added by using an on-board accelerometer, for example, can be avoided by using existing means to measure thruster performance. The other measurements required for the thruster performance evaluation, such as flow rate, power input, etc. are all being measured by the operating telemetry within the system. The most recent ground measurements of thruster performance showed a thrust of 12.5 mN, an ISP of 1,391 sec, and an anode efficiency of over 41%. On-orbit performance is expected to be the same.

Sensor Suite Development

Designs for each of the sensors are settled and experimental testing of prototype hardware is progressing. The functionality of each sensor, with one exception, has been proven and the PIE unit, which not only controls each sensor but also collects the data, has been successfully tested with sensor simulators. Plans are being drawn to test flight-like sensor hardware with laboratory thrusters to validate their response and to provide ground-based data for comparison with data from on-orbit conditions.

The PIE drives the sensors, contains signal processing and multiplexing circuits, and serves as the communications interface. Prior to using the PIE with the sensor hardware, the PIE operation was validated through a series of tests to verify basic functionality, followed by operations with a set of sensor simulators. The functionality verification began with a set of basic tests such as grounding and isolation checks on the

PIE and associated cabling, before proceeding to powering the box with laboratory power supplies to ensure functionality and communication between the PIE and the control computer.

Once the basic functionality was established, the next set of tests was initiated which verified the design of the electronics against a set of sensor simulators. The sensor simulator hardware realistically imitates flight sensor inputs and outputs by sourcing appropriate voltages and currents to the PIE. These simulator output data are measured at the PIE, which saves the values to an internal memory cache. The PIE control computer interrogates the PIE memory and stores the data in a computer file on its local hard drive for subsequent analyses and comparison with the simulator generated input data. The simulator system was developed in conjunction with Naval Postgraduate School personnel.

Radiometers

Radiometer sensor function is simulated by sourcing currents from National Instruments FieldPoint modules and from a Keithley 2400 Source Meter Instrument. Additionally, supply voltages generated by the PIE for the AD590 temperature sensors are read and recorded throughout testing. The radiometer test plan was designed to fully explore the behavior of the PIE radiometer circuitry for various conditions. For example, basic functionality, linearity of response, channel cross-talk, and over range conditions were examined. In addition, three load cases were tested, max load, over range with short, and under range with open circuit. The results of these tests were satisfactory.

Solar Cells

Solar cell sensor function is simulated by sourcing currents from a Keithley 236 High Voltage/Current Source-Measure Unit to a network of resistors with the PIE measuring the resultant voltages. Additionally, voltages are sourced from the Keithley 236 to the PIE to check its response. The solar cell test plan was designed to fully explore the behavior of the PIE solar cell circuitry for various conditions. For example, basic functionality, linearity of response, and open circuit response were examined. In addition, current/voltage (IV) curve testing based on available IV Curves for the solar cells was tested. All data reviewed to date have shown good performance over the entire expected range of voltage, current, and temperature.

Photometers

Photometer sensor function is simulated by sourcing currents from National Instruments FieldPoint modules and, for high precision, from a Keithley 2400. Additionally, supply voltages generated by the PIE for the photodiodes are read and recorded throughout testing. The photometer test plan was designed to fully explore the behavior of the PIE photometer circuitry for various conditions. For example, basic functionality, linearity of response, channel cross-talk, and an over range condition were examined. In addition, four load cases were tested, max load, max load with short, open circuit, and over range to ensure the PIE could accommodate the different scenarios successfully.

Ion Probe

Ion probe sensor function is simulated by sourcing currents from Keithley 236, 2400, and 263 Calibrator/Source instruments. Additionally, supply voltages generated by the PIE for the ion probe are read and recorded throughout testing. In parallel to this effort, a prototype ion probe has been built and is undergoing operational testing in vacuum adjacent to an operating Hall thruster. Input lens and energy analyzer operation have been demonstrated. Total ion current collected after the energy analyzer yielded a preliminary signal-to-noise ratio of approximately 100 at a measurement location 75 degrees off of the HET axis. Demonstration of the intermediate lens and mass analyzer are pending.

Electron Probes

Electron probe sensor function is simulated by sourcing currents from Keithley 236 and 2400 precision power supplies. Additionally, the PIE measures voltage throughout the testing. The Keithley 236 and 2400 sense function is used to measure and record to a spreadsheet the voltage values for future comparison. The data recorded during this test indicated that the circuit sensed current normally within 130 micro amps of the commanded value.

Future Sensor Work

In general, the focus is shifting from developmental testing to the Engineering Model hardware design, fabrication, and test. The sensors are in various stages of final design and fabrication with a delivery planned later this year. Following fabrication and qualification, an interface verification with the engineering model PIE will be conducted, followed by tests with the thruster to validate the sensor response. Updates to the flight designs will then be incorporated at the critical design review, and flight hardware fabrication will be initiated. Typical flight qualification testing of the three assemblies will be conducted at the component level, including vibration, thermal cycling, and thermal vacuum. Once the qualification tests are complete, all of the flight hardware will be delivered to TRW for the final integration with the rest of the propulsion subsystem components on the panel.

Conclusions

The propulsion subsystem development effort is a challenging project designed to push technology towards advanced microsatellite applications, while maintaining cost and schedule constraints. A critical part of this effort is the measurement of the interactions between the thruster and the spacecraft, which will be accomplished by a suite of advanced, miniaturized sensors. The on-board sensors development is closely coupled with a ground test and modeling program to be able to produce an integration handbook for future Hall thruster systems. Development tests for all of the sensors and the PIE is ongoing, and preliminary tests show promising results.

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Figures

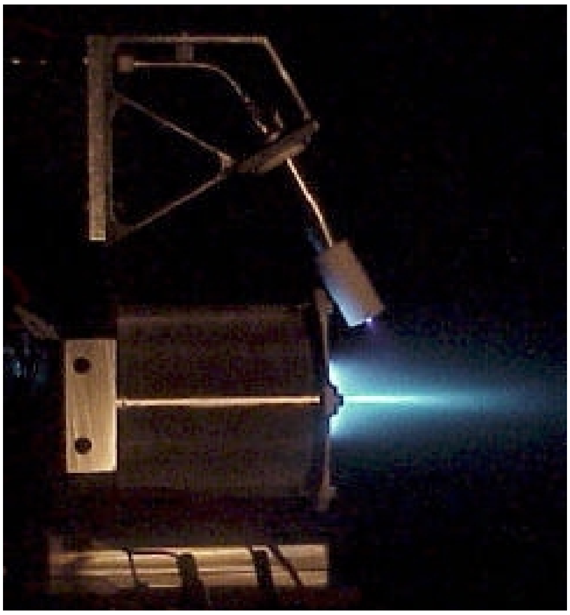

Figure 1 – Hall Thruster and Cathode

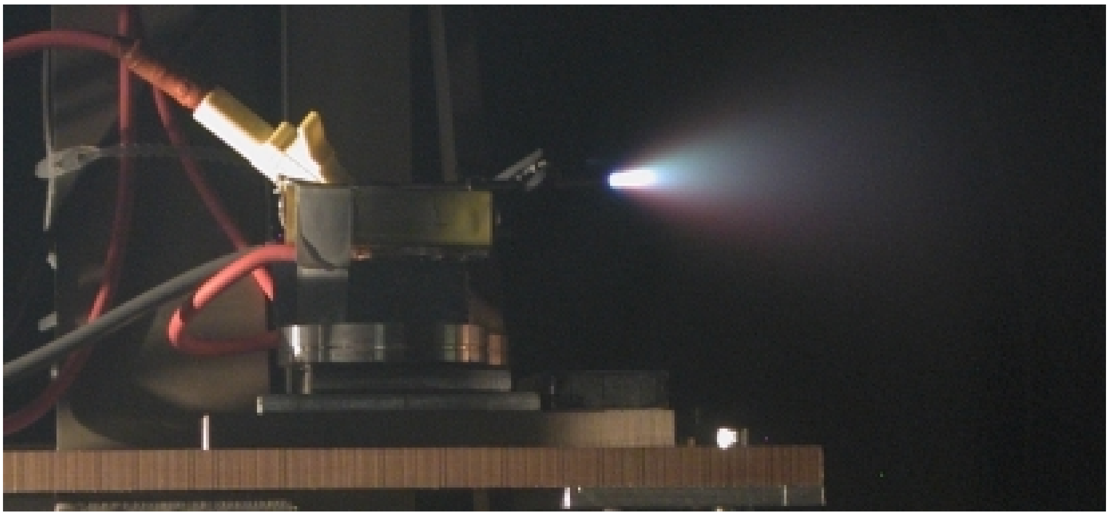

Figure 2 – μPPT

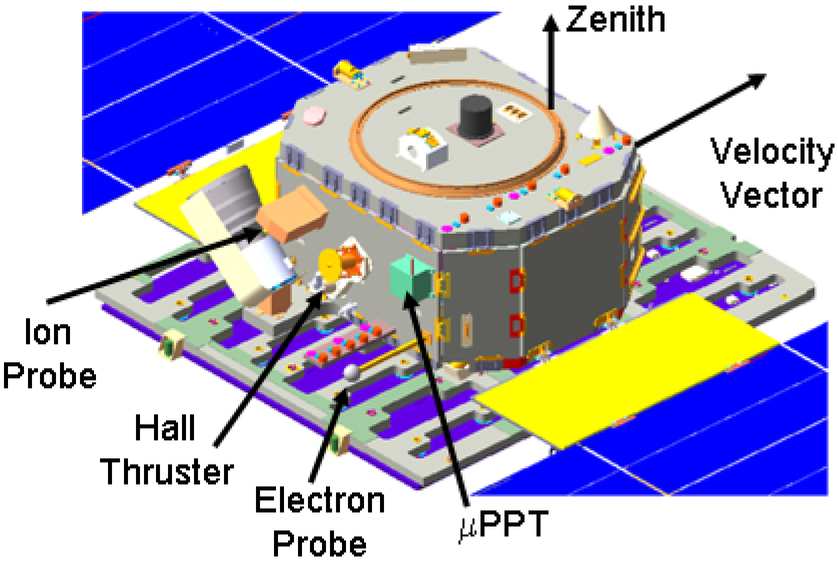

Figure 3 – Layout of the Propulsion Subsystem Sensors

Figure 4 – Generic Radiometer Design for Contamination Measurements

Figure 5 – Thin-Film Solar Array Technology Similar to that used on the main array

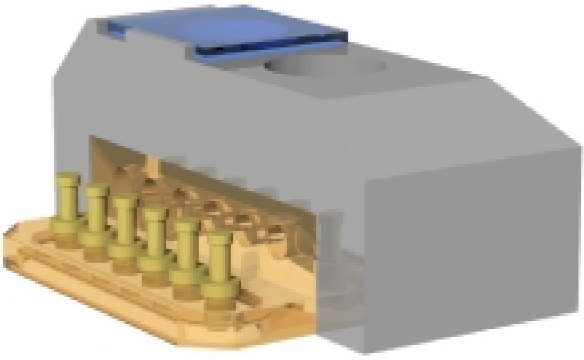

Figure 6 – Example of Photometer to be Used for Contamination Measurements

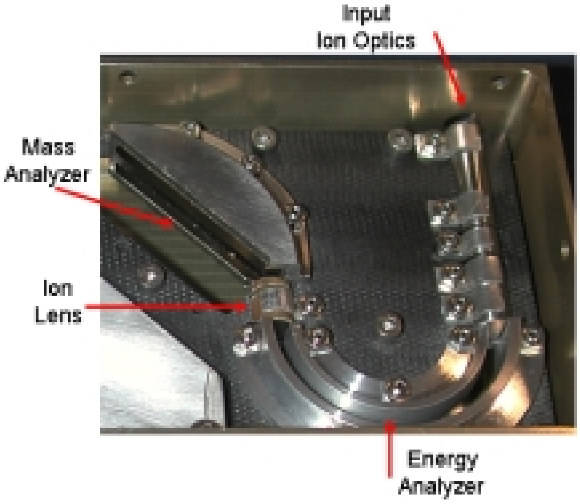

Figure 7 – Prototype of the Ion Probe

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