Advanced Pulsed Plasma Thruster Demonstration on MightySat Flight II.1

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Abstract

This paper describes the progress associated with a joint effort to demonstrate an advanced pulsed plasma thruster (PPT) on MightySat Flight II.1 to be launched in January, 1999. The PPT currently being developed for this flight represents a significant leap in technology compared to previous flight models. Although the MightySat II.1 launch vehicle is yet to be determined, the Space Shuttle Hitchhiker Eject System is the primary option under consideration. With this launch option, the PPT will be used to extend MightySat II.1 life from about 1-3 months to over one year by raising its operational orbit. The PPT is an ideal propulsion system for extending small satellite life because of its high specific impulse (>1000 sec), low system wet mass (<5 kg), and inert nature when unpowered (thus minimizing Shuttle integration issues). In addition to the life enhancement mission, the on-orbit operations have been specifically designed to rigorously test the PPT and to demonstrate its compatibility with the MightySat II.1 spacecraft in order to validate it for future DoD, NASA, and commercial satellites.

Introduction

This paper describes the progress associated with a joint government and industry effort to demonstrate an advanced pulsed plasma thruster (PPT) on the MightySat II.1 space flight to be launched in January, 1999. MightySat II.1 is a 275 lb. satellite to be manufactured by Spectrum Astro, Inc. of Gilbert, AZ under contract with the Space Experiments Directorate of the Air Force Phillips Laboratory at Kirtland AFB, NM.[1,2] Participants in the joint PPT flight demonstration effort include the Propulsion Directorate of the Phillips Laboratory, the NASA Lewis Research Center (NASA-LeRC), the Jet Propulsion Laboratory (JPL), and Olin Aerospace Company (OAC).

The PPT is an electric propulsion device which uses electric power to ionize and electromagnetically accelerate a plasma to high exhaust velocities, attaining a specific impulse in the 1000-2000 second range. The PPT is ideally suited to the propulsion needs of small satellites because it is compact, uses an inert solid propellant (Teflon™), is easily integrated to a spacecraft, and has a low system wet mass (<5 kg). Although PPTs have performed flawlessly on several satellites, PPT research and development essentially stopped in the 1970's. The PPT to be demonstrated on Flight II.1 represents a dramatic leap in capability compared to previous flight qualified models, and is being developed by OAC under a contract with NASA LeRC.[3,4]

Due to its efficient fuel consumption and low power requirements (1-150 W), the PPT can significantly enhance small satellite maneuvering capabilities. Potential applications include attitude control (including the complete replacement of a reaction wheel/momentum dumping system),[3,5] orbit maintenance, and orbit raising/repositioning.[6] The Phillips Laboratory's MightySat II Program Office has identified the Space Shuttle Hitchhiker Eject System (HES)[7] as the primary launcher for its small satellites.[1,2] With this launch option, the PPT on MightySat Flight II.1 will perform an orbit raising mission to significantly increase on-orbit life from about 1-3 months to over one year. The advanced PPT enables the use of the Shuttle HES as an affordable and reliable launcher for long-design-life small satellites.

In addition to the actual use of the PPT for extending the life of Flight II.1, the objectives of the MightySat II.1 demonstration are twofold. First, this flight will demonstrate advanced PPT performance and on-orbit life on a viable spacecraft. The performance and lifetime of the thruster will be demonstrated during a 1-3 month duration orbit raising maneuver at the beginning of the MightySat II.1 mission, and potentially during a second orbit raising maneuver near the end of the mission. The second objective is to demonstrate compatibility of the PPT with the spacecraft and optical sensor payloads. Potential integration issues include electromagnetic interference (EMI), thermal loading, and contamination of spacecraft surfaces. It should be emphasized that previous space flights have shown complete compatibility of the PPT system with the host spacecraft after many years of operational use. However, to demonstrate and characterize PPT plume compatibility with optically sensitive payloads and thermal surfaces, two quartz crystal microbalance (QCM) / calorimeter sensor packages will be used for measuring spacecraft surface deposition from the PPT exhaust plume. Additionally, this mission will serve as a pathfinder for demonstrating PPT compatibility with Shuttle integration requirements.

In addition to leading the PPT flight demonstration effort, the Phillips Laboratory Propulsion Directorate is primarily

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responsible for spacecraft integration and test, flight operations, and flight data analysis associated with the PPT. NASA-LeRC is leading the flight PPT development effort, and will be performing many of the ground based PPT performance, plume contamination, and flight qualification tests. OAC is responsible for developing, qualifying, and fabricating the flight PPT, under a contract with the NASA-LeRC. JPL will provide the flight contamination sensors and will lead the associated flight operations and data analysis efforts.

The Pulsed Plasma Thruster

The PPT is an electric propulsion device which uses electrical power to ionize and electromagnetically accelerate a plasma to high exhaust velocities (10-20 km/sec).[8-13] Its high specific impulse enables significant reduction in propellant mass requirements compared to monopropellant and cold gas systems.

A schematic of the PPT is shown in Figure 1. The thruster consists of a bar of Teflon™ propellant pressed against a lip between two electrodes by a negator spring (which is the only moving part). The negator spring serves to continually replenish the propellant as it is consumed. A power processing unit (PPU) charges a capacitor to voltages in the 1000-2000 V range using unregulated power from the spacecraft bus. The PPU also supplies a high voltage pulse to a spark plug which is used to ignite the discharge. Once the discharge is ignited, the energy stored in the capacitor (~40 J) powers a high current / short duration plasma discharge (~20 kA, ~5-10 microseconds). This discharge ablates and ionizes a small amount of Teflon™ from the face of the propellant bar and accelerates it to high exhaust velocities using the Lorentz force. The pulsed operation of the PPT allows it to function over an extremely wide range of input power levels with the same per-pulse performance. Average spacecraft bus power supplied to the PPT dictates the pulse rate, which is typically not more than 1-3 Hz.

PPTs have flown on LES 6,[8-10] TIP II & III,[11,12] NOVA I, II, III,[13,14] as well as on Japanese[15] and Chinese[16] spacecraft. PPTs have also been flight qualified for the LES 8/9[17,18] and SMS spacecraft.[19] These PPTs have performed flawlessly and would benefit the new generation of small satellites even at their low performance levels. Unfortunately for small satellite designers, these models are no longer available. Furthermore, the performance of previous flight-qualified models, even if they were available, is not well suited for the more ambitious life extension missions discussed in this paper, especially for >100 kg satellites. The absence of an off-the-shelf flight qualified PPT has recently spurred R&D programs at the Phillips Laboratory,[20] NASA-LeRC,[3,4,21] and OAC,[3,4,21] with goals to significantly increase performance and decrease system wet mass while maintaining flight heritage of previous designs.

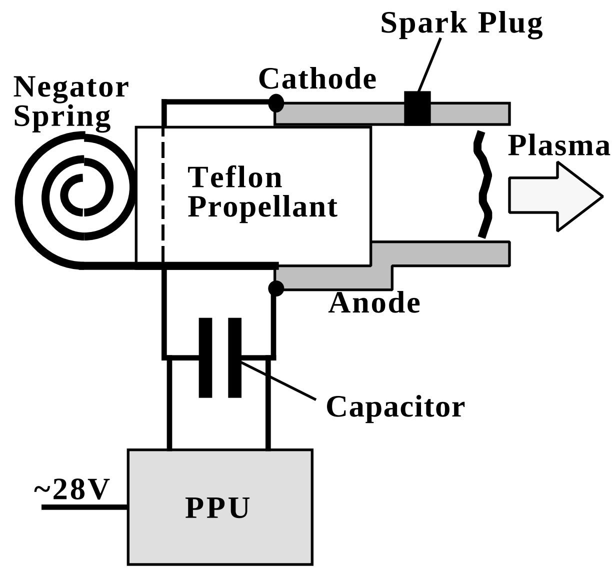

Figure 1: The pulsed plasma thruster

MightySat II.1 Spacecraft

MightySat II.1 is the first of five satellites (two of which are options) to be manufactured by Spectrum Astro, Inc. of Gilbert, AZ under contract with the Space Experiments Directorate of the Air Force Phillips Laboratory at Kirtland AFB, NM.[2] The primary objective of the MightySat II program is to provide timely and affordable access to space for Phillips Laboratory developed technologies. The planned launch date for Flight II.1 is in January, 1999, with the launch of each additional satellite following every 18-24 months.[2] The satellite bus is designed for one year of total on-orbit life. Due to uncertainty in the launch vehicle, the satellite will be designed for deployment from the Space Shuttle-HES as well as a variety of expendable launch vehicles (ELV's) that are being considered.

Figure 2 shows a scale drawing of the MightySat II.1 spacecraft, along with preliminary characteristics. It is a class D satellite[22] with a total power of approximately 325 W and a mass of 275 lb. The spacecraft is 3-axis stabilized, utilizes a UHF communication system, and has electrical power provided by two 2-D articulated silicon arrays (26 ft^2) on a 28 V unregulated bus. The command and data handling system centers around a VME (Versa Module Eurocard) specificiation computer card backplane with two sets of 21-slot card cages housing all of the spacecraft electronics. Payloads are mounted either inside or on top of the spacecraft bus, which has approximate dimensions of 20 x 24 x 12 inches.

There are eleven payloads on MightySat II.1 including the PPT and its own diagnostic package, the Plume Diagnostic Experiment (PDE), which is designed to measure PPT plume effects on the spacecraft. MightySat II.1 has two optical sensor payloads, the Fourier Transform Hyperspectral Imager (HSI), and the Total and Ultraviolet Irradiance Radiometer (TUVIR), which may also be used at the end of life to observe PPT plume effects.

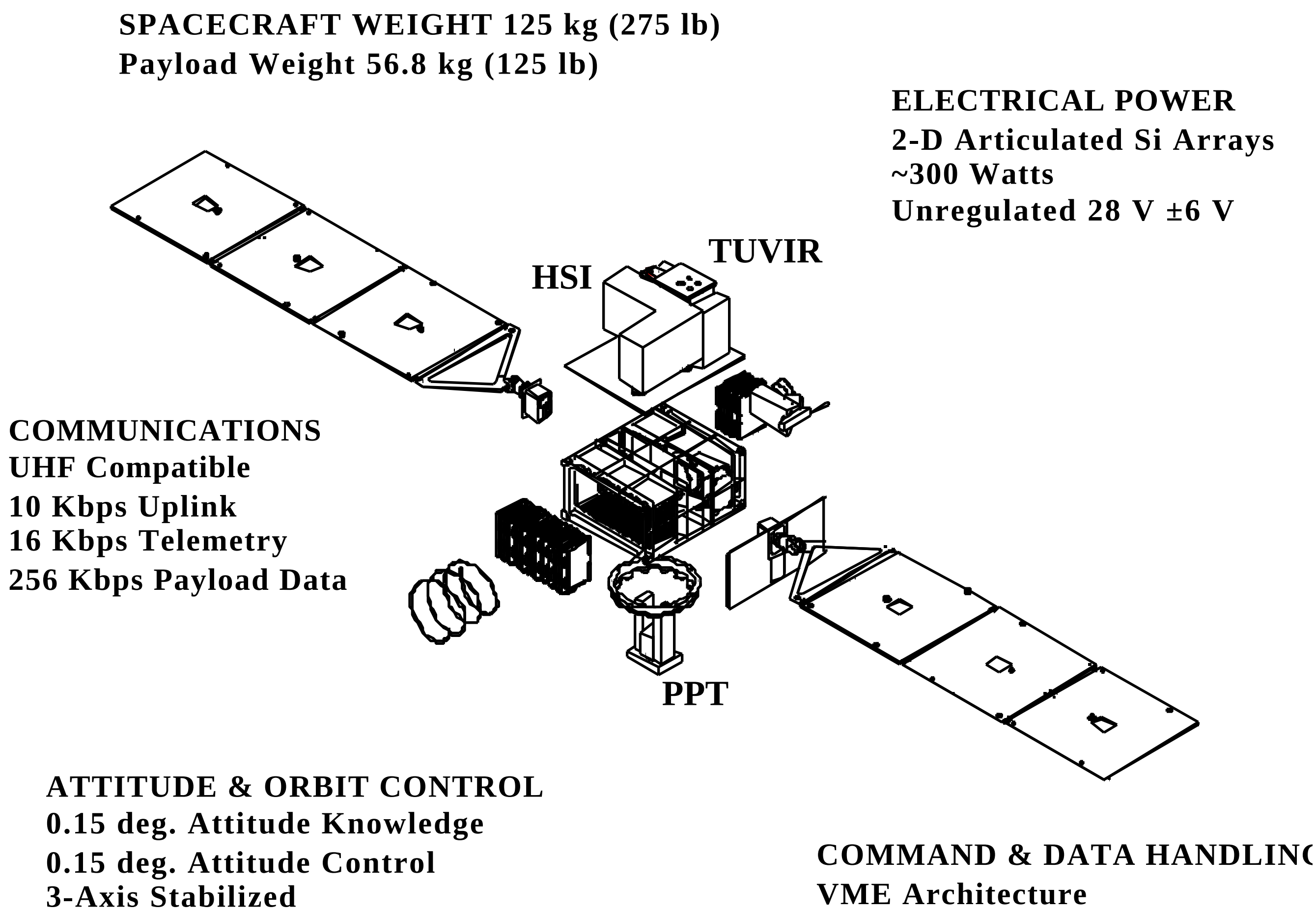

Figure 2: Exploded view of the MightySat II.1 spacecraft showing experiment locations and general spacecraft information

General design requirements of the PPT system on the MightySat II.1 spacecraft design are threefold. First, in order to minimize impacts on the attitude control system, the PPT is aligned with the spacecraft center of mass. Second, to maximize the ability to raise the satellite orbit, articulated solar arrays are required in order to decouple the need to align the arrays with the sun and align the PPT with the spacecraft velocity vector. Finally, the PPT system requires the flight software to have the sophistication necessary to autonomously operate the PPT while in sunlight for many orbits between ground contacts. Additionally, the impact of the PPT on the spacecraft thermal design is currently being assessed.

Mission Analysis

The primary mission of the PPT is to extend MightySat II.1 on-orbit life to greater than one year. Although the launch vehicle has yet to be determined, the worst-case scenario in terms of on-orbit life is the use of the Space Shuttle HES. On-orbit life without propulsion, at Shuttle-deployed altitudes, is less than 100 days for typical small satellites. For many Shuttle-deployed small satellites, the PPT is well suited for extending satellite life to 1-2 years.[6] Unfortunately, the large cross-sectional area and mass of MightySat II.1, in conjunction with the fact that it will be launched near solar maximum, presents an extremely demanding mission for the PPT. PPT power handling capability, total impulse, and performance are required to be much greater than that ever flown or flight qualified before.

Orbital analysis was performed to determine the most efficient PPT thrusting strategy for extending the on-orbit life of Shuttle-deployed satellites.[6] Three primary strategies were identified, with the appellations of Hold, Lift & Coast, and Lift & Hold. The Hold strategy consists of using the PPT at the Shuttle-deployed altitude to provide an orbit-averaged thrust to exactly compensate for the drag force. The disadvantage of the Hold strategy is that the power requirements at Shuttle-deployed altitudes are typically too high. An alternative strategy, Lift & Coast, requires that all payload power be devoted to the PPT at the beginning of the mission to raise the satellite to a higher altitude. Lift & Coast requires the least amount of propellant (and thus total impulse) of all strategies considered. Additionally, it requires no power once the orbit raising mission is complete. The disadvantage of Lift & Coast is the inability to operate the payload(s) during this orbit raising mission, which typically has a duration of 1-3 months. Lift & Hold consists of using the PPT at full power to raise the satellite to an altitude where the Hold power requirements are much more manageable. This strategy provides a compromise between Hold and Lift & Coast by reducing the trip time during the Lift phase and reducing the power requirements for the subsequent Hold phase.