1.0 TECHNOLOGY NAME: Pulsed Plasma Thruster (PPT)

2.0 SPONSORSHIP: Modular and Multifunctional Systems (MAMS)

2.1 IPDT SPONSOR: NASA LeRC/Primex Aerospace Co. (PAC)/NASA GSFC

2.2 TEAM MEMBERS:

Bill Hayden/NASA/GSFC, (301)-286-8963

Frank Curran/NASA/LeRC, (216) 977-7424

W. Andrew Hoskins/PAC, (206) 885-5000

Charles Zakrzwski/NASA, GSFC (301) 286-3392

3.0 OVERVIEW

This plan outlines the approach which will be used to validate the Pulsed Plasma Thruster (PPT) as an attitude control device on the EO-1 spacecraft. The PPT is an electromagnetic thruster which utilizes Teflon for fuel and is capable of producing extremely small impulse bits at a high fuel efficiency.

The primary objective of the experiment is to show that the PPT can reliably control the pitch axis of the spacecraft while the spacecraft is in normal science mode and meet all of the EO-1 mission requirements.

To achieve the primary objective the engineering validation objective has been separated into three categories:

1) Demonstration of the control capability of the PPT system including the pointing accuracy, response characteristics, and stability

2) Confirmation of benign plume/spacecraft interaction and EMI effects

3) Verification of PPT ground performance tests.

4.0 INTRODUCTION

The Pulsed Plasma Thruster (PPT) is a propulsive device that, when used for attitude control, may offer significant advantages over current attitude control devices. The PPT offers a high specific impulse (900-1200s), very low impulse bits (10-1000 microN*sec), and the capability of operating over a low range of power levels (1-100 W). These characteristics can not be matched by any other state of the art propulsion system For missions which requiring propulsive momentum management (such as Geostationary or L2), the PPT is an excellent candidate as an attitude control device. For near earth missions requiring delta-V capability, the PPT may save the mass, power, and volume compared to the combination of momentum wheels, torquer bars, and a conventional propulsion system. The PPT may become very attractive for attitude control as spacecraft are reduced to the "micro-sat" level because of its scalability to low mass and power and the fact that the only moving part in the PPT is fuel bar/tension spring. The PPT requires minimal I&T effort because it is a simple, self-contained, bolt-on module. The Teflon fuel reduces ground handling costs and safety concerns and eliminates on-orbit fuel slosh concerns.

PPT's have been flown as delta-V thrusters for position control on several missions launched in the 70’s and 80’s. PPT's have never been utilized purely as an attitude control device. A program directed by NASA LeRC is currently improving the PPT technology by reducing the mass and volume of the PPT by approximately 50% and increasing the total impulse and thruster efficiency by nearly 200%. The new generation of PPTs being built by PAC for NASA LeRC will fly on the AirForce MightySat II.1 spacecraft as a delta-V device only. The EO-1 mission will be the first mission to fly and validate the PPT as an attitude control device.

5.0 TECHNOLOGY DESCRIPTION

The PPT is a small, self contained electromagnetic propulsion system for spacecraft. A coiled spring feeds a solid bar of Teflon between two electrodes. An "ignitor plug" is used to initiate the discharge of an energy storage capacitor. Plasma is created by the ablation of the Teflon propellant from the discharge of the energy storage capacitor across the electrodes. The plasma is accelerated by Lorenz forces, which arise from the self-induced magnetic field, to generate thrust at a high specific impulse. Multiple electrode/fuel bar assemblies can be driven by a common main capacitor and electronics to reduce mass.

For EO-1 one PPT module with two opposing electrode/fuel bar assemblies will be mounted with thrust vectors parallel to the spacecraft Z-axis. This will allow the PPT to produce positive and negative pitch torque with minimal average orbital delta-V effect. The PPT experiment will consist of disabling the use of the pitch wheel and pitch torquer bar and enabling the PPT to replace the wheel and torquer bar function.

6.0 TECHNICAL VALIDATION OBJECTIVES

The basic objective of the PPT experiment is to demonstrate that the PPT can be used as a reliable attitude control device for scientific spacecraft. The validation process will occur in several steps. The general approach is to start the validation by testing the PPT while still maintaining control with all three momentum wheels and then proceed in steps until only the PPT is controlling the pitch axis during the acquisition of scientific data by the primary instrument. The validation objectives are the following:

1) Demonstration of the control capability of the PPT system including the pointing accuracy, response characteristics, and stability

2) Confirmation of benign plume/spacecraft interaction and EMI effects.

3) Verification of PPT ground performance tests.

To minimize the risk that the operation of the PPT may have on the mission, the on-orbit validation of the PPT will not take place until the primary scientific/engineering objectives of the primary instrument have been achieved. It is desirable to test the health of the PPT as part of the initial on-orbit check-out of the spacecraft. If this is judged to be of significant risk to the mission, the PPT is designed to survive flight for a minimum of one year before it is operated.

6.1 CONTROL CAPABILITY DEMONSTRATION

6.1.1 Required In-Flight Data

Attitude rates
Attitude errors
Reaction wheel speeds
Command reaction wheel and PPT torques
Torque bar signals
TAM readings
Spacecraft Mode
Orbital Position

PPT main cap charge commands
PPT #1 spark plug fire commands
PPT #2 spark plug fire commands
PPT #1 electrode cumulative charge time
PPT #1 electrode fire counter
PPT #2 electrode cumulative charge time
PPT #2 electrode fire counter

6.1.2 Approach

Spacecraft attitude control telemetry will be used to verify the response of the spacecraft while the PPT is used for pitch axis control. Pointing accuracy, response characteristics, and stability will be evaluated and compared against simulated predictions for the PPT and actual behavior of the all wheel control system.

The control capability will be demonstrated in the following manner:

STEP	DESCRIPTION	DURATION
Establish all Wheel Performance Baseline	Collection of flight data to establish the performance of the all wheel control system. This sets a baseline with which to evaluate PPT control performance.	TBD-Taken during normal science mode.
PPT Calibration	Collection of gyro data while firing PPT via ground commands. Control of spacecraft maintained by all three wheels. Instrument stowed.	Estimate 1 day
PPT Calibration Evaluation	From calibration flight data determine torque magnitude and alignment. If necessary, adjust parameters in flight software (transformation matrix, PPT thrust constants, control law coefficients, etc.)	Estimate: 1 wk.
Transition from Pitch Wheel/Torquer to PPT control #1	Set pitch reaction wheel speed to zero (possibly by selecting advantageous orbital positions) and disable torquer. Enable autonomously on-board control logic to control with PPT. Instrument stowed.	Estimate 1 day
PPT Operation with Safed Instrument #1	Enable pitch axis control by PPT only with instrument in safe and stowed state.	Min. 1 day
(If Required) Transition from PPT to Pitch Wheel/Torquer control. #1	Disabled PPT control and enable the pitch wheel/ torquer bar.	Estimate 1 day
Control Evaluation #1	Evaluate pointing accuracy , response characteristic, and stability from flight data. Adjust flight software control constants if necessary	Estimate: 1 wk
(If Required) Transition from Pitch Wheel/Torquer to PPT control #2	Set pitch reaction wheel speed to zero(possibly by selecting advantageous orbital positions) and disable torquer. Enable autonomously on-board control logic to control with PPT. Instrument stowed.	Estimate 1 day
PPT Operation with Safed Instrument #2	Enable pitch axis control by PPT only with instrument in safe and stowed state.	Min. 1 day
(If Required) Transition from PPT to Pitch Wheel/Torquer control. #2	PPT control is disabled and the Pitch Wheel/ Torquer bar are enabled.	Estimate 1 day
Control Evaluation #2	Evaluate pointing accuracy , response characteristic, and stability from flight data. Verify flight software adjustments worked properly.	Estimate: 1 wk
(If Required) Transition from Pitch Wheel/Torquer to PPT control #3	Set pitch reaction wheel speed to zero(possibly by selecting advantageous orbital positions) and disable torquer. Enable autonomously on-board control logic to control with PPT. Instrument stowed.	Estimate 1 day
PPT Operation During Primary Instrument Image Taking	Operate PPT as pitch control device while primary instrument is taking data. Minimum of ten images from primary instrument required.	Min. 10 days Desired 1-2 months.

The PPT control objectives are to meet the Normal Science mission mode functional ACS requirements listed below:

Point Accuracy	> 0.25 deg
Jitter	> 5 arc-sec, 1 sigma for frequencies > 10 Hz.

6.1.3 Anticipated Results

Actual attitude control characteristics will closely match the simulated predictions.

6.1.4 I and T Data:

The before-flight data required for the overall validation of the PPT as an attitude control device consists of ACS simulations and I&T tests. Listed below are the major tasks and associated goals required.

TASKS	GOAL
SIMULATIONS:	
One-Dimensional	Assess performance with respect to control approach, minimum and maximum impulse, and command quantization. Provide performance estimates, pointing performance, torque authority, and fuel consumption.
High-Fidelity	Confirm all ACS performance estimates by incorporating PPT model in full-up high fidelity spacecraft simulation which will include all disturbance torques, cross-axis torque coupling, flexible body modes, misalignment effects, etc.
Thruster Performance Test	Confirm PPT performance assumptions used in simulations by making thruster level thrust and specific impulse measurements.
PPT End-to-End Tests	Confirm command path from spacecraft processor to flight PPT as part of ACS I&T end-to-end tests.

6.1.5 Rationale:

Only actual flight data can provide the type of credence required for many potential scientific and commercial payloads to use PPT as an attitude control device.

6.2 CONFIRMATION OF BENIGN PLUME/SPACECRAFT INTERACTION AND EMI EFFECTS

6.2.1 Required In-Flight Data:

ACS:
- Three Axis Magnetometer (TAM) output
- GPS signals
- Course Sun Sensor signals
- Star Imager signals

Power:
- Solar Array Voltages
- Solar Array Current
- Spacecraft Bus Voltage
- Spacecraft Bus Current

Advanced Land Imager Instrument:
- Image data from both wedge and grating chips
- Detector chip test patterns

LEISA Atmospheric Corrector Instrument:- Image data

Lightweight Flexible Solar Array: -Voltage
-Current

Communications: - X-band transceiver signal
- S-band transceiver signal

6.2.2 Approach:

Spacecraft and instrument telemetry which may be susceptible to plume contamination or EMI effects will be monitored and trended before, during, and after PPT operations. To minimize the impact to spacecraft resources, plume and EMI diagnostic instruments were not added to the spacecraft.

It is desired to operate the PPT continuously for one month or longer in order to improve the examination of the cumulative effect the exhaust plume may have on the spacecraft and primary instruments.

6.2.3 Anticipated Results:

Spacecraft subsystems and instrument will not show anomalous telemetry above predictions.

6.2.4 I and T Data:

Before flight the plume and EMI characteristics of the PPT and their interaction with the spacecraft will be well understood. Ground tests will be performed on an engineering model . Theoretical modeling will be performed if necessary. The flight unit will be tested to insure that its characteristics are very similar to units used in the comprehensive tests.

ACTIVITY	PURPOSE
Plume Mapping	Plume density distribution and species concentrations will be measured.
EMI Mapping	Radiative EMI will be measured . Induced magnetic fields for a TAM will be mapped.
Contamination Measurements with Spacecraft Mock-up	Interaction of PPT with spacecraft structure will be determined. Surface depositions will be measured
Theoretical Modeling PPT plume on EO-1	Interaction of PPT with spacecraft components which could not be experimentally measured will be determined using theoretical code.
Plume Measurement of PPT flight unit	Confirm flight PPT plume characteristics
EMI measurement of PPT flight unit	Confirm flight PPT EMI characteristics
Spacecraft I&T EMI measurements-TBD	Test for conducted EMI effects during spacecraft I&T.

6.2.5 Rationale:

In-flight data of spacecraft subsystems and instrument will verify the ability of the PPT to operate as an attitude control device that is benign to scientific instruments and other spacecraft subsystems.

6.3 VERIFICATION OF PPT PERFORMANCE

6.3.1 Required data:

Attitude rates	PPT main cap charge commands
Attitude errors	PPT #1 spark plug fire commands
PPT main cap voltage	PPT #2 spark plug fire commands
PPT spark plug voltages	PPT #1 electrode cumulative charge time
PPT temperatures	PPT #1 electrode fire counter
PIO voltage	PPT #2 electrode cumulative charge time
PPT fuel gauge readings	PPT #2 electrode fire counter
PPT power	

6.3.2 Approach:

In-flight data will be used to assess the performance of the PPT. The PPT firing commands and PPT voltages will be used to calculate predicted fuel use which will be compared to the actual fuel gauge readings. Using the spacecraft attitude rates with fuel consumption, thrust and specific impulse parameters may be estimated.

On-orbit operation of the PPT for the minimum required duration of approximately three days allows fuel consumption to be determined to only approximately 10%. It is desired to operate the PPT for one month or longer to improve PPT performance verification.

6.3.3 Anticipated Results:

The on-orbit performance of the PPT will closely match ground test measurements.

6.3.4 Supporting I&T Data:

PPT performance measurements will be made during acceptance testing of the PPT flight unit. Thrust, specific impulse, and input power will be measured for the various levels of charge expected on-orbit.

6.3.5 Rationale:

Ground tests measurements of electric propulsion devices are inherently limited because the chamber in which they must be made. In-flight validation of thrusters performance is useful to validate ground measurements.

7.0 SCIENTIFIC VALIDATION OBJECTIVES

TBD from Scientist

8.0 SCHEDULE

8.1 GROUND VALIDATION SCHEDULE

The completion dates for the major components of the ground validation of the PPT experiment are given below:

ACS Simulation	6/13/97
Engineering Unit EMI tests	6/19/97
Engineering Unit Contamination Tests	7/16/97
Engineering Unit Life Tests	9/4/97
Flight Unit Performance #1 Tests	11/14/97
Flight Unit EMI Tests	11/28/97
Flight Unit Contamination/Life Tests	12/12/97
Flight Unit Performance #2 Tests	12/26/97
Flight Unit Integration Tests	5/30/98
PPT End-to End Tests	12/31/98

8.2 ON-ORBIT VALIDATION SCHEDULE

PPT experiment will be performed after instrument has fulfilled its minimum mission requirements. It is desirable, but not required, to verify the operation of the PPT during the initial on-orbit check-out phase of the spacecraft. After the primary instrument has achieved its fundamental objectives the PPT experiment will be performed. The baseline on-orbit schedule of PPT experimental activities, which will be initiated within 1 year of launch, is given below:

DAY NO.	ACTIVITIES
1	Initiate PPT Experiment - PPT Calibration
2-8	PPT Calibration Evaluation
9	Transition from Pitch Wheel to PPT Control #1
10	PPT Operation with Instrument Safed #1
11	Transition from PPT control to Pitch Wheel (If Needed)
12-19	Control Evaluation #1
20	Transition from Pitch Wheel to PPT Control #2 (If Needed)
21	PPT Operation with Instrument Safed #2 (If Needed)
22	Transition from PPT control to Pitch Wheel #2 (If Needed)
23-30	Control Evaluation #2 (If Needed)
31	Transition from Pitch Wheel to PPT Control #2 (If Needed)
32-42	PPT Operation with Instrument Taking Science Data
43	Transition from PPT control to Pitch Wheel #3

9.0 REQUIRED MANPOWER

Manpower requirements above those included as part of the spacecraft team during spacecraft I&T and on-orbit operations consists of technical support from PPT vendor for approximately two months during s/c I&T and one month for on-orbit operations.

10.0 REQUIRED FACILITIES

All test facility requirements for the validation of the PPT technology during the development of the hardware will be provide by NASA LeRC and PAC. The baseline approach to integrate and test the PPT at the spacecraft level will not require special tests facilities. Special tests facilities may be required if the EO-1 project requires verification of EMI interactions by testing the PPT once it is integrated to the spacecraft.

11.0 SIGNATURES

IPDT Provider

Project Scientist

Project Manager

GSFC Program Manager

NMP Program Manager