

Development of a Lightweight Pulsed Plasma Thruster Module for Solar Sail Attitude Control

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Abstract: This paper describes a preliminary development of a lightweight pulsed plasma thruster (PPT) module with an impulse bit of 150 $\mu\text{N}\cdot\text{s}$, named PPT150. A prototype PPT150 module, consisting of three thruster units and sharing a capacitor, was designed for attitude control of a 100-kg, 40-m class sailcraft with a moment of inertia of 2000 $\text{kg}\cdot\text{m}^2$ and with a solar pressure disturbance torque of 1 $\text{mN}\cdot\text{m}$. Such a 40-m sailcraft is mainly propelled by the 10-mN solar-radiation-pressure force and its attitude is controlled mainly by a primary propellantless attitude control system (ACS). A secondary ACS employing four tip-mounted PPT modules is proposed as a backup to such a propellantless ACS. The development of the PPT150 is one of the steps towards a ground validation experiment of a complete ACS integrated into a fully deployed 20-m scalable sailcraft of AEC-Able Engineering. The ground experiment is scheduled for early 2005 in the 30-m thermal vacuum chamber at the Plum Brook Space Power Facility of the NASA Glenn Research Center.

1. Introduction

1.1 Propellantless Solar Sail Propulsion

The prospect of space travel without the need to use any propellant for the primary propulsion system allows improvements over today's standard missions as well as the possibilities of entirely new opportunities of space exploration and utilization. Through NASA's In-Space Propulsion (ISP) Solar Sail program,¹ a variety of near-term solar sailing missions and the required sailcraft technologies are currently under rapid development and progress.^{2,3} The basic concept behind the solar sail propulsion is that photons from the Sun are reflected using a large lightweight sail that is like a mirror. The reflection and absorption of the photons increases the momentum of the spacecraft and thus creates a thrust. The thrust that is generated per square meter of sail is approximately 8 μN when about 1 AU away from the Sun. For example, a 40-m sailcraft is propelled by the solar-radiation-pressure force of approximately 0.01 N.

1.2 Attitude Control Problem of Solar Sail Spacecraft

The main need for attitude control arises from the fact that there will be an offset between the center of mass and the center of pressure on the spacecraft. This center-of-mass and center-of-pressure (cm/cp) offset will generate a disturbance torque that must be counteracted in order to maintain proper spacecraft attitude. This problem is similar to the typical thrust vector misalignment problem of various flight vehicles.²

A solar sail spacecraft in an earth-centered orbit is illustrated in Figure 1. The pitch and yaw are the two axes that affect the sun angle and allow the solar sail to be "tacked." The distinction between the pitch and yaw axis depends on the reference frame desired which is in part determined by the specific mission. A "pinwheel" motion about the roll axis also needs to be controlled. A much more in-depth analysis of solar sail attitude dynamics and control can be found in Ref. 2.

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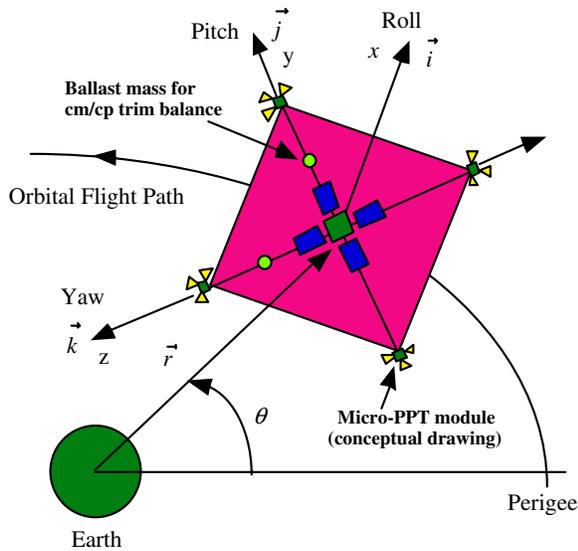


Figure 1. A baseline 40-m solar sail spacecraft in an earth-centered orbit.⁴

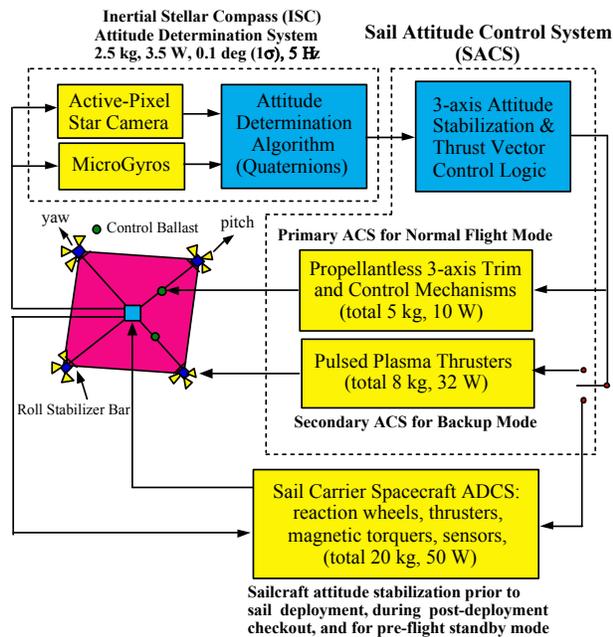


Figure 2. Robust sailcraft attitude control system architecture currently under development through NASA's In-Space Propulsion (ISP) Solar Sail Program.⁴

A sailcraft attitude control system (ACS) currently under development through NASA's In-Space Propulsion Solar Sail program is illustrated in Figure 2. The proposed sailcraft ACS consists of a primary propellantless ACS and a secondary (backup) PPT-based ACS. The primary ACS employs control ballasts (approximately 1 kg each) running along mast lanyards for pitch/yaw trim balance and thrust vector control and also roll stabilizer bars at the mast tips for quadrant tilt control. The stability and robustness of such a primary propellantless ACS are further enhanced by a backup ACS utilizing tip-mounted, lightweight PPT modules. Such a PPT-based ACS can be employed for attitude recovery maneuvers from off-nominal conditions and for spin stabilization. It can also be employed as a backup to the conventional ACS of sail carrier spacecraft prior to sail deployment and during pre-flight sail checkout operation. Detailed discussions of the proposed sail ACS can be found in Refs. 3 and 4.

The solar disturbance torque that a solar sail experiences is small but nearly constant. This means that a small counteracting force with a proper moment arm length that can be constantly applied is one method of control. The solar disturbance torque can be countered by creating control torque about each axis (Figure 1). As the size of the sail increases, the disturbance torque scales as the cube of the sail size.

One approach to countering the small disturbance torque is to have small moveable surfaces on the tips, called control vanes, so that a varying force at the tip can be produced. Complications arise with this method when off-nominal maneuverability is desired. If the sun angle is not appropriate, such as would be the case for edge-on-sun flight where the solar sail is parallel to the sun's flux, control may become difficult. Another example would be exact positioning of the control vanes before deployment of the main sail. This may be difficult if the initial orientation does not benefit the use of control vanes due to the sun angle. Also, to be conservative, adopting a method to control the test of a solar sail that relies on the exact same technology does not provide any additional redundancy. If something unexpected were to occur that caused problems with the main sail, then this same problem may occur with the control system. This would be of no concern if solar sails were a more proven and accepted concept than they currently are. As it is, it seems more prudent to have a control system that is more reliable and more capable in a technology test where the main goal is a proof-of-concept of solar sails. This leads to a decision against the use of control vanes for the time being.

Standard small satellite thrusters such as cold gas thrusters or mini resistojets do not work as well for a

solar sail due to their low specific impulse (I_{sp}) and the relatively large total impulse required for even a modest solar sail flight. For instance, if a generic 100-s I_{sp} thruster were used for a one-year mission of an 80-m solar sail, the mass of the fuel alone for a single thruster would be about 4.6 kg. This weight is much higher than would be acceptable for the solar sail since mass is very critical for any solar sail flight.

Due to the above limitations and restrictions as well as many others,⁴ the control system will consist of a primary propellantless control device and secondary thrusters. The primary propellantless device is a control mass that will move along the length of the sail's masts, thereby changing the center of mass. With a different center of mass, the cm-cp offset is changed (either to negate its effect, or to cause a desired torque). Two control masses (each 1 kg) will be used. The secondary control device will be a thruster mounted at the tips of the masts. In order to meet the desired attributes of high specific impulse, low total mass, low volume, and (most importantly) reliability, a pulsed plasma thruster was selected. Also, due to the fact that the force from a tip-mounted thruster gains the moment arm length of the mast for its control torque, the use of tip-mounted control means that the scale of the required thrust with sail size increases by a smaller factor than the standard cubic relation. A simple model with these two control devices is shown in Figure 3.

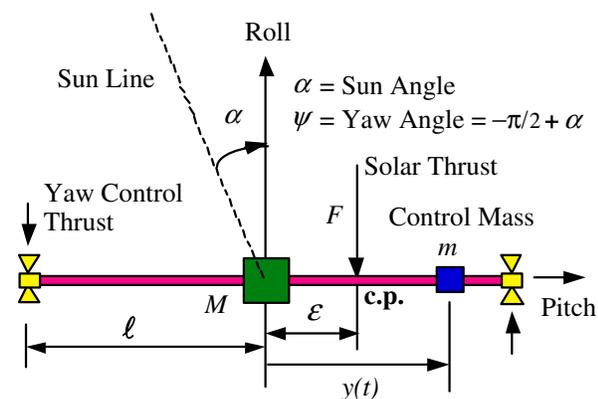


Figure 3. A simple dynamical model for an integrated trim balance and thrust vector control design.⁴

2. Pulsed Plasma Thrusters for Solar Sails

2.1 Overview of Pulsed Plasma Thrusters

A pulsed plasma thruster (PPT) is an unsteady electromagnetic device that delivers stored energy in short pulses. The available energy ablates, ionizes and subsequently accelerates the solid propellant, typically Teflon[®] (C_2F_4), via the electromagnetic Lorentz force,

$\mathbf{j} \times \mathbf{B}$. Due to its pulsed operation, typically 1 Hz, the average power required is only of the order of a few Watts.

The energy bursts are provided by a capacitor that can discharge its stored energy within microseconds while it is recharged during the idle interval between pulses, (~ 1 sec). This implies that 15 J of stored energy – utilizing 15 W of charging power for 1 second – would approximately provide 1.5 MW of power during a 10-microsecond pulse for ablation, ionization and acceleration of the plasma.

The arc discharge is initiated by a spark plug that aids voltage breakdown and provides current flow between the electrodes. The self-induced magnetic field interacts with the current to produce the Lorentz force. The force is of the order of a few Newtons, but since the PPT only fires for a very short period a more useful qualification is the impulse, often referred to as the impulse bit. This is the average thrust that is provided over a second. For example, if the PPT provided 10-N thrust (assumed constant for simplicity) over a 15- μ s time, this would be equivalent to a 150 μ N-s impulse bit which is equivalent to a 150 μ N continuous thrust over a 1-s period.

The major electronic components of a PPT are a capacitor, a power-processing unit (PPU), and a method for initiating the discharge. The capacitor is historically relatively large and usually consists of a large portion of the dry mass of a PPT. It is required to store the desired amount of energy to be released over the electrodes. The PPU is the device that converts the input voltage (typically a spacecraft bus voltage) to the higher voltage required. Voltages vary widely by design, but have historically fallen in the broad range of 600-10000 volts. The discharge unit is often a spark plug connected to a small capacitor so that energetic sparks may be released in order to create a small initial amount of plasma. The small amount of plasma is enough to complete the circuit in-between the electrodes so that the main capacitor can discharge. A schematic of a typical PPT is provided in Figure 4, and a representation of the force, equivalent circuit model, and typical current and voltage waveforms are shown in Figure 5.

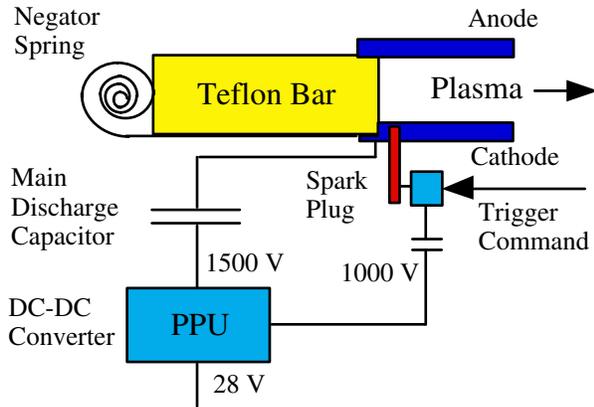


Figure 4. Schematic of a typical PPT.

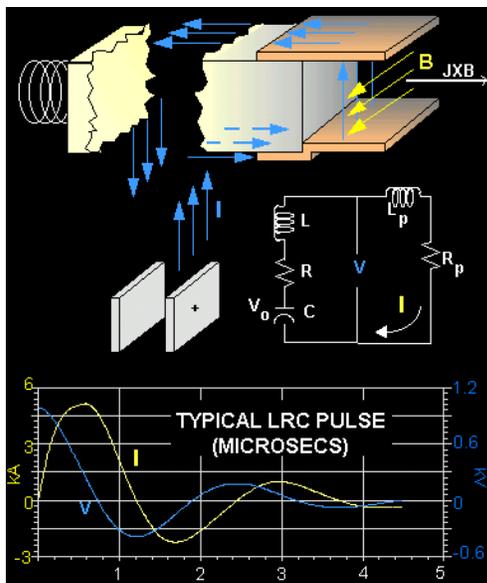


Figure 5. Operation of a PPT, its equivalent circuit representation, and typical current and voltage waveforms.

Many PPTs are configured with two parallel plate electrodes, though there are some with coaxial electrodes. The Teflon[®] is fed to the electrodes with a simple negator spring which constitutes the only moving part.

2.2 Benefits of a PPT

It is proposed that the small control force is provided by means of the pulsed thrust of a tip-mounted pulsed plasma thruster (PPT). The PPT will allow a higher I_{sp} than other small thrusters due to the fact that it is an electric thruster, but the size and power are both very small due to the fact that it operates in a pulsed manner, not continuously. The control of the

spacecraft must now be performed by altering the frequency of the pulses or the magnitude of the pulses (as opposed to the more standard variance of duration and magnitude). This does not introduce any problem since even a 1-Hz pulsing frequency is very quick when considering the overall slow dynamics of the spacecraft.

The PPTs are typically used on missions where the small impulse bit is desirable as well as the high I_{sp} (typically ranges from 300-1400 s). There is a good amount of interest and research in PPTs for use in small satellites and formation flying due to the low impulse bit and high I_{sp} .⁵ This is indeed the case for solar sails as well where the thrusters will be used for full three-axis attitude control as well as for maneuvers.

The history of PPT space flight can be dated back to the 1930s with major development initiating in the 60s. There have been many proven flights of various sizes since then. Included in the more recent history are the LES 6, LES 8/9, TIP-II, and EO-1 PPTs. All of these were actual space flights that utilized PPTs (the LES 8/9 was never flown, but was completely flight qualified) and all of them were successful without any failures in PPT performance. The EO-1 PPT was flown as a test of the technology and was operated for 33 hours of on-time⁶ to show its abilities to control the satellite while not interfering with sensitive equipment. The LES 6 PPT alone obtained 10 years of operation starting in 1968.⁷ PPTs can be designed and integrated quickly for a low cost, they are flight proven, and have the ability to act as a reliable backup or even a capable primary system. In fact, this research objective is to prove that PPTs are simple, robust, technically advanced, and are applicable for various solar sail missions, as well as the fact that a PPT can be made lightweight, at a low cost, in a small volume that will not consume much power—all of the desirable characteristics of a practical attitude control system.

The use of a thruster for control deters from the standard ideas for solar sail control due simply to the fact that they require propellant on an otherwise propellantless system. However, small electric thrusters such as a PPT require very small amounts of propellant and will give reliable control and maneuverability in all circumstances—even if the solar sail itself has failed in some manner.

2.3 PPT Sizing Requirements for a Solar Sail

For robust three-axis control of the solar sail with full redundancy, three PPTs will be placed at each mast tip. They will be placed orthogonal to each other, with two acting to counter the pitch or yaw disturbance (making them 180 degrees apart but in the same plane) and one

to counteract the roll. The two counteracting the pitch or yaw face opposite directions because the direction of the disturbance will be unknown until the solar sail is in space. By mounting this configuration at all four tips, then there is a redundant backup of each direction. A mass saving alternative (if redundant systems are deemed unnecessary) would be to use only two of the mast tips—one for pitch and one for yaw while both cover roll.

The requirements for the PPT on the solar sail are based on the anticipated maximum cm/cp offset and the total solar thrust that the sail will create. The multiplication of the cm/cp distance and the overall solar thrust gives the solar disturbance torque. The control torque must therefore be greater than this level, and thus an impulse bit of the PPT is found by dividing this control torque by mast length.

The total impulse is simply determined by multiplying the disturbance torque by the time it is active, and then dividing by the mast length. The above information is summarized in Table 1, with additional information for the required impulse bit of 150 $\mu\text{N}\cdot\text{s}$.

Table 1. Total impulse requirements (per year) of a 150 $\mu\text{N}\cdot\text{s}$ PPT.^{3,4}

Sail Size	40	80	m
Mast length	28	56	m
cm-cp offset*	0.1	0.2	m
Solar disturbance torque*	0.001	0.008	N-m
Control torque†	0.004	0.0084‡	N-m
Total impulse (required)	1126	4505	N-s
Total pulses (required)	7.5	30	million

* the normally worst case for untrimmed sailcraft

† using one thruster

‡ this torque can be doubled using a pair of thrusters

3. Design of a Prototype PPT Module

3.1 Description of the Prototype Development Project

The primary objective of the research project conducted at Arizona State University was to design and integrate a PPT that would be applicable to solar sail spacecraft in general. In addition, the project is to show the overall simplicity of the devices by not only creating a theoretical design, but also producing an initial working prototype within six-months. The prototype was designed and built in this short time period and is representative of the size and mass that should be expected of a more finalized version.

The design of a PPT is in general inherently difficult due to the lack of refined, in-depth knowledge of the physical operation. In order to create a PPT that has known thrust and specific impulse levels in a short amount of time (such as in under six months) is quite difficult. Much research has gone into trying to be able to mathematically model PPTs, but there is still more research needed.^{8,9} Due to the current lack of accurate models, physical testing of the device is often needed to know the characteristics of the thruster. However, it is indeed possible in the limited amount of time available to have a baseline design that is the most optimum considering what has been proven by tests or space flight. There have been an abundant number of flight qualified PPTs as well as lab test thrusters which provide a wide range of proven designs. Therefore, the approach to the design of a PPT for solar sail applications was a design reuse and optimization. An already proven thruster would be selected based on the lowest predicted mass for creating the size needed, and then modifications would be made in order to make it the desired smaller mass. Advances in electronics are always in rapid development, and thus allow easy improvements over previous generations of thrusters due simply to technology advancement in concurrent industries. This process allows for a design of essentially known characteristics to be rapidly developed and deployed. With the large number of PPTs already created and proven, a PPT can be easily found that matches almost any desired thrust level for solar sails—and many other satellites as well.

3.2 Design Comparison

In order to select the thruster that would provide the lowest mass, four modern PPTs that cover a range of sizes were compared—EO-1, TIP-II Nova, Dawgstar, and LES-8/9.^{10, 11, 12} Since there were different numbers of thrusters for each design, all designs were scaled to two thrusters—a typical baseline. Also, a specific mass in terms of energy (kg/J) was calculated. A specific mass in terms of energy was used as opposed to specific mass in terms of power due to the fact that PPTs are more defined by the energy levels since changing the firing frequency, which does not change the thruster significantly, can easily alter the power levels. Based on the specific mass, and the I_{bit}/J of each thruster, the total dry mass could be predicted for the design goal of 150 $\mu\text{N}\cdot\text{s}$.

Table 2. Dry masses of different baselines for a 150 mN-s Thruster.

Pulsed Plasma Thruster	Predicted Dry Mass of 2 Thrusters at 150 microN-s (kg)
LES-8/9	2.42
TIP-II (NOVA)	2.51
Dawgstar	2.93
EO-1	0.88

A comparison of the specific impulse (I_{sp}) of each thruster is also needed since the lowest dry mass does not mean the lowest overall mass. For a decrease in the impulse bit, a decrease in the I_{sp} corresponds, but in an unpredictable way. There is data available for EO-1,¹⁵ and since it was a throttleable thruster, comparisons become much easier and more meaningful. At the same impulse bits, the EO-1 PPT has a higher I_{sp} than Dawgstar or TIP-II Nova. Therefore, a comparison of EO-1 and LES8/9 is the only needed comparison. Since LES 8/9 has a dry mass about three times that of EO-1, but the I_{sp} is higher, eventually the masses of the entire system (dry mass plus propellant mass) will be equal. However, the I_{sp} difference is very small. Using data from EO-1, for 150 μ N-s, an I_{sp} of 720 s could be obtained. Giving the unrealistic ability of the LES 8/9 to be scaled down to 150 μ N-s without a decrease in I_{sp} , the LES 8/9 is considered with a 1000-s I_{sp} . The result is that a total impulse of 50,482 N-s is required for the mass to be equal. This is a great deal higher than the currently envisioned solar sail flights and therefore means that the EO-1 will have the lowest mass of all the systems compared for solar sail flights currently envisioned.

3.3 Overview of Components

The mechanical structure of any PPT is not complex which is one of the very attractive aspects of PPTs. The structure simply consists of the electrodes and whatever structure is needed to hold them and the Teflon[®] in place. Other than that, the only structural consideration would be enclosing the hardware, and connecting it to the spacecraft.

The electronics are more complex in an in-depth look at each component, but the general architecture is very simple. A power is supplied and this goes through the power-processing unit (PPU). The PPU conditions the signal to the necessary current and voltage levels which is in turn connected to a capacitor. The capacitor charges (in typically under a second), which then causes a charge to be present on the electrodes, which are connected to the capacitor in parallel. Since there

is no medium to conduct current between the electrodes (the gap is much larger than that for breakdown in air or vacuum), the electrodes stay charged.

The discharge is initiated with a spark plug, which is placed in the cathode close to the Teflon surface. The spark plug is also connected to a capacitor in the same manner as is the electrodes, though this capacitor is of much smaller size and energy. The capacitor's charge is controlled by a switch, and when it is released the energetic spark starts the firing. The discharge initiation spark plug could be considered as a small PPT on its own, since it uses the same basic principles to start an initial spark.

3.4 Selection of Structure

The primary structural component that characterizes a PPT is the electrodes. In particular, their dimensions and the spacing between them are what affect the thruster characteristics. Copper is the material of choice as is typical in electromagnetic thrusters. Copper provides good conductivity and good resistance to erosion. The thickness of the electrodes is a balance between weight and erosion. As with any electromagnetic thruster, electrode erosion is an issue, however, since the PPT does not operate in steady state, the concerns are not very high and typically this has not proven to be a limiting factor especially in the thrust regime of interest. There are some empirical equations that can give approximations as to what the impulse bit and specific impulse would be, however these do not work in all cases. In order to design and assemble a thruster with known results in a few months, and without any form of testing, a design reuse of EO-1 geometry was used. The electrode gap, the length and width are all the same dimensions. The result is that the prototype has "known" values of I_{sp} and I_{bit} even though it has not been tested. This is because EO-1 had effectively proved all ranges of thrusters from 90 μ N-s to 860 μ N-s. Anything within this range can be built as a different thruster of lighter weight by changing the structure and electronics to suit the mission needed. For instance, in the case of this prototype, 3 orthogonal thrusters are needed instead of two along the same plane, and the power levels must be lowered so the electronics must all be changed. The material selected to hold the electrodes together was Ultem 2300.[®] Ultem 2300[®] is a plastic that provides good thermal and electrical insulation, while also being very radiation resistant.

3.5 Selection of Electronics

The electronics were selected based on the power requirements and the goal of reducing the mass. The electronics, consisting of the PPU and main capacitor are outlined here. A general discussion of discharge initiation electronics is outlined due to the fact that it is dependent on the spark plug used and those built for PPTs are proprietary.

Power Processing Unit: The power processing unit (PPU) is the device that converts a low voltage from the spacecraft bus (or elsewhere) to the appropriate high voltage needed for the PPT. Since the input voltage is usually a DC input, and the output is required to be a DC output, the PPU is often called a DC-DC converter. A DC-DC converter is a very vague term that includes all devices that convert between two DC voltages and is most typically found in voltage signal applications where it is used as a step down converter, meaning that the voltage is lowered across the converter—the opposite of what is desired in a PPT. The details of the components of the PPU are important because there are different ways to convert the voltage. The most commonly accepted means to do this efficiently with a PPT is by the use of transformers. A transformer not only provides the means of increasing the voltage, but also allows circuit isolation, which reduces electric noise since there is no physical connection between the two sides of the transformer. However, transformers are only operable in AC systems, so the DC signal must be converted. This is done with a Pulse Width Modulator (PWM). A PWM is an integrated circuit (IC) that creates a fast pulsing waveform from a constant input. A typical PWM may pulse square waves at 10-30 kHz. The use of diodes and transistors (such as a MOSFET) allows the AC current to be converted back to DC before the output. The setup is usually known as a push-pull circuit.¹³

For PPTs that have been proven in the past, a single PPU has been used and a tap-off was implemented for the discharge initiation. This is the most economical method in terms of mass, but one problem may be found in some instances. With the EO-1 PPT, they were unable to charge the discharge initiation capacitor enough while throttling to their lowest desired setting.¹² This is because their throttling was simply obtained by charging the capacitors for specified periods of time. This results in different energies and voltages that are used across the electrodes. So at the lowest charge duration, the discharge initiation capacitor did not receive enough energy. If more control is desired, two PPUs could be utilized to give complete charging independence. Since the power level requirements of

the discharge initiation circuit are much lower on flight models (typically a fraction of a watt), the second PPU can be much smaller in size and mass than the main PPU.

Capacitors: The capacitor is the main component of a PPT. Important considerations in the capacitor are size, mass, inductance, and polarization. The inductance is important because of the effect on the oscillation of the current. A PPT naturally creates an oscillating current waveform, which results in a detrimental effect on overall performance.¹⁴ It is very difficult to prevent this entirely, but it should still be paid attention to in the design. The capacitor should be non-polar. This means that the capacitor should be able to be charged with a current and voltage from either direction—it should not matter which leads are connected to the high and low potentials. If the capacitor is polar (meaning that current is only allowed to flow one direction), failure will be likely due to the fact that current will travel in the opposite direction as the circuit oscillates. Due to this restriction, most aluminum electrolytic capacitors will not work.

For the desired energy and voltage levels of this prototype (about 20 J at 1000 V, though it is will be operated at a lower voltage) as well as the need for non-polarization, no single commercial-off-the-shelf (COTS) product could be found. This means that a custom capacitor must be built—if a single capacitor must be used. The major drawback of this is simply time since a custom capacitor may take at least 8-12 weeks to create. Also, the cost may be much higher than necessary, as usually minimum purchase amounts are set requiring the purchase of more capacitors than needed.

However, it is relatively straightforward to create an array of COTS capacitors if time is limited. The first capacitor that this prototype used was an array of 36 COTS products. There are many drawbacks regarding using an array compared to a single capacitor. The array will be much larger and heavier than a single capacitor, and the array will likely have higher uncertainties and much more inductance. However, the time and money saved may be worthwhile if these tradeoffs are acceptable—as with a proof of concept design.

Spark Plug: The discharge of the plasma is started with an energetic spark from a spark plug. The spark plug typically has operated around 1000 V but this varies as time goes on due to the spark plug itself physically changing (ever so slightly) with each fire.^{10, 16} The spark plug fires with energy stored from a capacitor in order to create a higher energy spark so

that it may ablate the Teflon to provide enough conduction for the main arc. Typically, the spark plug capacitor is charged from a tap-off of the PPU, which provides a lower voltage from the transformer than the main capacitors. In the case of the main capacitor being of lower voltage than the spark plug capacitor, than the tap-off will no longer work as effectively and a different approach must be used, such as an additional transformer to increase the voltage for the spark plug. Due to the low energies required for the spark plug, the size of the additional transformer should be relatively small.

4. Cost and Procurement of Components

4.1 Component Cost

The prototype built in two phases: one was with almost exclusively COTS products, which leads to a low cost and quick turnaround time, and the second was with some custom made products that allowed for better representation of a space flight ready module. Shown below in Table 3 are the total costs of components, as well as the times from order to receipt.

Table 3. Component cost and receipt times.

ITEM	COST	Receipt Time
COTS Capacitor	\$400	1 week
Custom Capacitor	Sample	10 weeks
PPU	\$800	3 weeks
Thruster Assembly	\$4,000	6 weeks
Fuel	\$300	1 week
Misc Electronics	\$100	N/A
Total =	\$5,600	

As can be seen from the table, the most expensive part that accounted for 72% of the total cost was the thruster assembly. Of the \$4,000 that was spent on the thruster assembly, 98% of it was for the professional machine shop to produce the electrodes and the thruster. By comparison, the other 2% of the cost was the in team fabrication of one model of the thruster out of acrylic as well as an overall housing container for three thrusters and all equipment.

Exact pricing on custom capacitors is unknown, but it is expected that these will be a similar price as the thruster assembly and the lead-time is anticipated to be 8-12 weeks. One generic quote was received for a \$3,000 minimum expenditure amount in order to build any custom capacitor. The lead times may be the largest constraint on building a PPT but they are relatively short. This is because the custom components (such as capacitors and transformers) are commonly manufactured to specification throughout

other industries. Both the price and lead time of all custom components will increase in large amounts for more flight-qualified devices as compared to these predictions based on standard requests for products.

The cost of the fuel is for a 12 x 24 x 1 in (L x W x T) block, which is approximately 11 kg.

The discharge initiation unit was not priced due to it having the longest timeframe to get a typical flight unit. A sample testing spark plug from unison was used, but the additional electronics for control were not used.

4.2 Procurement of Components

Power Processing Unit: A PPU for the prototype PPT was obtained from UltraVolt. It is capable of 1000 V and 30 W output from a 23-30 V input (9-32 V derated). The PPUs from UltraVolt have efficiencies as high as 92%. The baseline off-the-shelf model (without additional add-ons such as RF shielding and Mu-Metal shielding) has a mass of 142 g, and has dimensions of 94 x 38.1 x 19.6 mm (L x W x H). These sizes are also applicable for voltages up to 6000 V, which indicates that some decrease in size and mass should be possible for the 1000 V model.

Capacitor: For this prototype, both a single capacitor and a capacitor array were used. The capacitor array was built from 36 Cornell Dubilier series 935 capacitors that were direct from the shelf and therefore the only delay was the shipping time. These capacitors were rated at 10 μ F and 400 V each. The single capacitor was a custom sample that Dearborn Electronics was kind enough to provide in 10 weeks. It was in fact larger than what will be used (50 μ F was provided when 40 μ F will be used), but it still had a surprisingly small mass at only 250 grams with dimensions of 2 x 4.5 inches (diameter x length).

Propellant: Teflon[®] (C₂F₄) is used as the solid propellant. The advantage of using Teflon[®] is that it is a self-contained, non-hazardous solid and for many missions of PPTs, the entire amount of fuel can fit in the palm of your hand. It can be easily obtained in rod, tube, or sheet form and this prototype's Teflon[®] was received from Scientific Commodities Incorporated. The propellant cost shown above is for a sheet that was 12 x 24 x 1 inches (L x W x T). This is approximately 11 kg, which is much more than needed for any mission that would be flown.

Spark Plug: Previous PPTs received much of their electronics including the spark plug and related circuitry from Aerojet-Redmond Division (formerly

Primex Aerospace). From several contacts with Aerojet it would appear that they no longer provide the spark plugs and related circuitry. Many lab thrusters use spark plugs from Unison, and they will provide the desired equipment for the prototype. Flight models are not available for prototypes due to the fact that they are custom and proprietary products that usually take a long time to obtain (several months). Due to this, an accurate weight for a flight model is unknown at this time. The spark plug used for testing consisted of a testing sample provided by Unison that was connected to a capacitor of approximately 1 μF at 1000 V. A manual switch was used to initiate the spark plug.

5. A Prototype PPT Model: PPT150

A prototype model, named PPT150, should be capable of delivering a 150 $\mu\text{N}\cdot\text{s}$ impulse bit, and an Isp of 700 s. It will utilize about 17 W of power assuming an 80% efficiency in delivering power. The mass of the entire 3-thruster setup is predicted to be less than 2 kg, as shown in Table 4, which shows the weights of an optimized design as well as the prototype constructed. The prototype has thicker construction of the thruster assembly as well as additional electronics for easy testing. The total mass will be dependent on the mission due to the fuel weight (see Figure 6 for fuel weights of missions).

Table 4. Dry masses of PPT components (not including propellant, * indicates predicted mass).

ITEM	Optimized Mass (kg)	Prototype Mass (kg)
Three Thruster Assembly	0.706	1.15
Capacitor	0.250	0.250
PPU	0.142	0.284
Discharge Circuit *	0.375	0.375
Misc	---	0.391
Total	1.473	2.45

As can be seen, the major contributor of dry mass is the weight of the thruster assembly, which is unordinary for electric propulsion. This is in part due to the fact that there are three thrusters sharing the same electronics. However, there is the possibility of decreasing the mass of the thruster assembly by means such as decreasing the thickness of the electrodes (assuming testing shows such an ability will not hinder lifetime).

The capacitor weight will be smaller for a finalized version since the weight shown is for the capacitor used in the prototype, which was larger than necessary (since the exact decrease in mass is unknown, the known prototype mass was simply used for the optimized mass). This indicates that recent advances in capacitor creation techniques and technology may significantly benefit future PPTs since the mass has been decreased a good amount.

The fuel weight for control is dependent on the mission desired. Several potential missions have been proposed, and some are summarized in Table 5 below. The values of total impulse are for a single pitch/yaw thruster, plus the roll thruster. Figure 6 then shows the corresponding propellant mass needed for solar disturbance correction for a single three-thruster unit.

The propellant mass becomes quite a bit higher for much longer missions and larger sails as discussed in Section 1. For longer missions or larger sails, it is easy to scale the designed PPT up to provide a higher impulse bit and higher specific impulse. The trade-off would be with the increased dry mass of the capacitor and PPU and should be considered for larger total impulse missions.

Table 5. Possible solar sail missions (* total impulse is for solar sail disturbance correction only) ^{3,4}

Case	Mission Description	Life	Size	Total Impulse*
LSS	1600 km sun-synchronous	90 days	40 m	417 N-s
GTO	2,000 x 40,000 km elliptic	90 days	40 m	417 N-s
GEO	36,000 km circular orbit	90 days	40 m	417 N-s
EMX	Earth Magnetotail Explorer	5 years	40 m	8445 N-s
LIS	Lagrangian Point, 0.95 AU	5 years	80 m	33790 N-s

Control Propellant for Select Solar Sail Missions

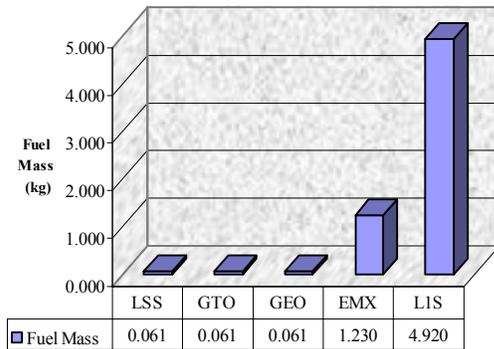


Figure 6. Fuel masses for conceived missions.

An additional component that was researched was a propellant feed system. Usually Teflon[®] is simply fed with a spring which is very simple and works very well. However, with the fact that one of the three thrusters in the box may be using very little fuel means that one of the thrusters may have fuel loaded that is almost completely unused. Therefore, for longer missions a propellant feed system that stores all the Teflon[®] and distributes it to the thrusters as needed may result in a mass savings. This research is still underway, but initial models indicate that this will be possible simply using springs which retains the initial inherent benefit of a simple, low-failure propellant feed system while eliminating the fuel wasted due to unknown flight conditions.

Figure 7 shows a prototype PPT150 with custom thruster assemblies and a custom capacitor. A PPT150 with fuel for a longer solar sailing mission is also illustrated in Figure 8.

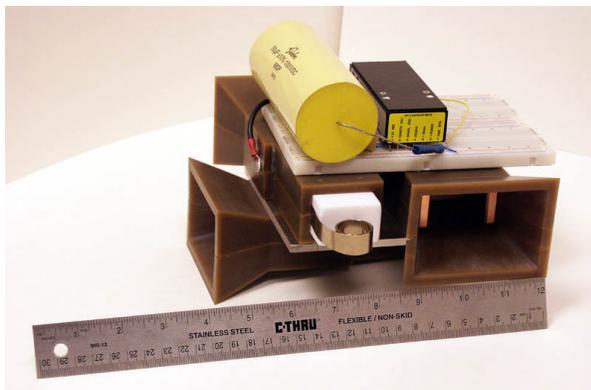


Figure 7. A prototype PPT150 with propellant for a baseline 40 m solar sail spacecraft.

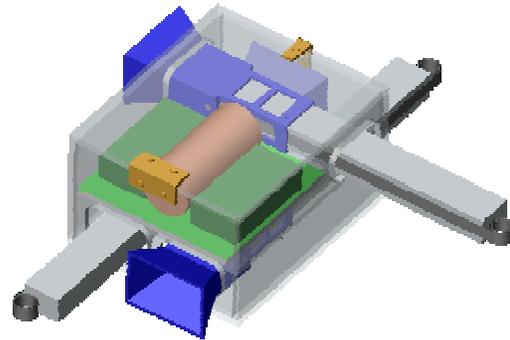


Figure 8. A prototype design of PPT150, shown with propellant for a longer solar sailing mission.

Preliminary testing of the prototype in vacuum at 1×10^{-6} torr was performed. This was done with electronics exterior to the vacuum due to the current need for some manual control. The testing resulted in several successful firings of the prototype, one of which is shown in Figure 9.



Figure 9. Vacuum test of PPT150 utilizing acrylic housing for visualization.

Table 6. Summary of PPT150 characteristics.

Impulse Bit	150 μ N-s
Isp	700 s
Energy	13 J
Power at 1 Hz	17 W
Total module mass	< 2 kg

5. PPT Contamination Issues

As with all thrusters, PPTs are not perfect by any means. Besides their low efficiencies of under 10%, there have been other concerns that are constantly

questioned, but have been tested and proved irrelevant in almost all cases. The biggest concern is the effect of the Teflon plasma on the spacecraft itself. Numerous tests have been conducted to determine if there is any possibility of sensitive equipment being disturbed by the PPT. All of these tests have indicated that the level of contamination is very low for objects that are behind the thruster. The reader is referred to Refs. 17-20 for more detailed analysis of the issue of spacecraft contamination using electric propulsion.

Also, as with many thrusters, the direction of thrust is not identical to that which may be desired. EO-1 did in-depth testing of this factor and they found that they had thrust components in the direction of the anode, and the resulting bias angles were 5.3 degrees, and 3.6 degrees.¹⁵ These effects are small, especially considering that there will be shot to shot variations in the thrust. Again, the EO-1 tests showed that these variations ranged from 9.5% to 20% for their thruster tested in a vacuum chamber.

6. Conclusions

Pulsed plasma thrusters have numerous advantages that render them a viable option for various sized satellites, as well as solar sails. Not only do they have high specific impulse, but they also utilize solid propellant, which makes the volume smaller than other propulsion systems with gas storage tanks, as well as the fact that they are very reliable due to the few simple components that have low failure rates. However, the major advantage comes from the sheer simplicity and robustness. The technology is at the point where it can be easily designed and implemented for a large number of missions—even though it is not anywhere near as researched and optimized as other electric propulsions (such as the ion thruster). Even though no consistently reliable design equations exist for accurate prediction of thrust and efficiency, there are enough designs that have been validated and proven to serve as a backbone for any new designs. The incredible simplicity of PPTs allows for these new designs to be implemented quickly and reliably—a working prototype in less than six months. This PPT that was designed and prototyped within six months is also applicable to a variety solar sail missions due to its low cost, low mass, low volume, and low power.

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