A99-31127

AIAA 99-2291

PPT Development Efforts at Primex Aerospace Company

W. Andrew Hoskins, Michael J. Wilson,
Michael J. Willey, Nicole J. Meckel
Primex Aerospace Company
Redmond, WA

Mark Campbell and Seung Chung
University of Washington
Department of Aeronautics and Astronautics
Seattle, WA

35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
20–24 June 1999
Los Angeles, California

AIAA 99-2291

PPT DEVELOPMENT EFFORTS AT PRIMEX AEROSPACE COMPANY

W. Andrew Hoskins,* Michael J. Wilson,† Michael J. Willey,§ and Nicole J. Meckel,‡
Primex Aerospace Company
Redmond, WA

Mark Campell¶ and Seung Chung#
University of Washington
Department of Aeronautics and Astronautics
Seattle, WA

Abstract

Pulsed Plasma Thrusters (PPTs) are having an increasing appeal for a broad range of spacecraft propulsion applications that require either low thrust (<2 mN) in a compact system or very small, discrete impulse bits (~10 to 1000 μN-s) for control functions. This paper covers Primex funded PPT development efforts that represent an industrial complement to the significant PPT programs within the government and at university laboratories. The current outlook for PPT applications are discussed briefly. A modular test PPT has been built to serve as a flexible research tool for the broad range of potential applications and configurations. Extensive discussion is given to test facilities under development, particularly a thrust stand capable of measuring individual impulse bits targeted for the 100 uN-s range and lower. Finally, Primex is collaborating with the University of Washington to develop a mini-PPT propulsion system for a 13 kg satellite to be flown in 2001 under the AFOSR/DARPA University Nanosatellite Program. When this satellite is launched in 2001, it will be the smallest self propelled satellite ever flown.

Introduction

Pulsed Plasma Thrusters (PPTs) have an increasing appeal for a broad range of spacecraft propulsion applications that require either low thrust (<2 mN) in a compact system or very small, discrete impulse bits (~10 to 1000 μN-s) for control functions. A PPT developed at Primex Aerospace Company (PAC) under the NASA Glenn Research Center (GRC) PPT technology development program has been integrated on the Earth Observing-1 (EO-1) spacecraft.[1] This is the first flight PPT built in almost 20 years. Recently, GRC has selected a team from Unison Industries, PAC, and CU Aerospace to develop the next generation of PPT electronics, energy storage and discharge initiation.

This paper covers PAC funded PPT development efforts that represent an industrial complement to the significant PPT programs at NASA GRC, the Air Force Research Lab, and several universities. The increasing interest in PPTs for micro- and nano-satellites, as well as the fine control requirements of ST-3 class missions, has prompted a focus on very low I_{bit} PPTs. PAC has developed a Modular Test Unit (MTU) test thruster as a tool with the flexibility to investigate PPT behavior over the broad range of applications of interest. PAC is also working to prepare test capabilities, beginning with the development of a versatile thrust stand focussed on providing accurate thrust and impulse measurements below 100 μN-sec. With these tools in development, PAC is working with the University of Washington (UW) to develop a PPT propulsion system for the UW Dawgstar spacecraft. This system is building on the NASA GRC funded EO-1 design, but scaled to the Dawgstar's small satellite class (13 kg). When this satellite is launched in 2001 as part of the AFOSR/DARPA University Nanosatellite Program, it will be the smallest self propelled satellite ever flown.

* Principal Development Engineer., Senior Member
† Development Engineer, Member
‡ Senior Development Engineer., Member
§ Project Team Leader
¶ Assistant Professor, Senior Member
# Student, Member

PPT Overview and Applications

The PPT is one of the earliest electric propulsion technologies developed, with a successful flight history starting three decades ago and culminating in the successful TIP/NOVA flights of the 1980's.[2] A PPT uses an arc to ablate and accelerate a small amount of solid propellant, typically Teflon. The thruster itself consists of a propellant bar held between two electrodes. The power processing electronics use a 28 V spacecraft bus power to charge an energy storage capacitor to a desired energy. A discharge ignition circuit fires a spark plug to start the main discharge pulse. The details of PPT physics and configurations have been extensively reviewed elsewhere.[3]

For attitude and position control applications, the main advantage of using a PPT is its small impulse bit combined with high specific impulse. Furthermore, impulse bit can be throttled over a wide range by varying pulse energy or pulse rate. These features allow for continuous torque negation and very fine pointing and station keeping with much smaller propellant mass than other thruster technologies such as cold gas systems. Also, due to the relatively low density of stored gas, PPTs can have a significantly lower system volume than cold gas, which can be a more important consideration for small spacecraft.

Another advantage of the PPT is that the use of an inert propellant allows extended fueled storage and can eliminate the safety, handling, and leakage issues common to on-board fluids and their systems. Greater flexibility is provided to the spacecraft designer because of the simple spacecraft/PPT interface, which is limited to physical mounting hardware and electrical connections for power, commands and telemetry. Finally, with a single, slowly moving part, PPTs provide increased mechanical reliability relative to cycled, valved systems and momentum wheels, which create problems due to wheel jitter.

Applications for which PPTs have significant advantages include orbit raising for small spacecraft[4] and attitude control for a wide range of spacecraft[5, 6] Because of their limited thrust capability, missions that require a high slew rate, rapid delta velocity changes or significant drag makeup[7] are a challenge for PPTs, although they retain other advantages, such as propellant storability, and work is ongoing to improve PPTs thrust to power ratio.

The most promising new area of interest for PPTs over the past two years has been precision pointing and constellation maintenance,[8] with increasing opportunities on micro- and nano-satellite missions, where PPTs represent one of the only viable propulsion options. Because these areas put a premium on producing very small impulse bits at specific impulse levels high enough to keep the system mass acceptable, much more effort is being directed toward miniaturization of PPT technology and operation at lower pulse energies.

Modular Test Unit Development

To provide development testing over the broad range of applications and configurations of interest, PAC has built a test PPT, based on the EO-1 design. The Modular Test Unit (MTU), shown in Fig. 1, has several features that address anticipated PPT design issues.

To validate proposed designs with up to three orthogonal thrusters per capacitor, such as for the ST-3 and the UW Dawgstar missions, the MTU has three electrode pairs and the capability to mount the propellant bars at the 45° cant angle needed for thrust vector orthogonality. At the same time, all three pairs have the same thrust axis, allowing multiple thrust and/or impulse bit measurements during the same thrust stand test.

For research at low impulse bits, the MTU can be configured with miniaturized electrode pairs. In addition, the MTU electronics have been designed to provide a constant spark energy, independent of capacitor charge voltage, which was a limiting factor on low impulse pulses for EO-1. One of the first tests planned for the MTU is a characterization of PPT behavior at very low main capacitor energies and the full range of discharge energies and impulse bits possible with a constant spark energy.

Another improvement incorporated in the MTU electronics is a selectable charge voltage limit that greatly reduces discharge energy variations due to temperature and input voltage. The EO-1 design was not originally designed for throttling, and discharge energy could only be roughly selected by controlling the length of the charge command. In the MTU electronics, capacitor voltage, and therefore discharge energy, is selected by a command bit. This change should allow control of impulse bit within a tighter band than was documented for EO-1.[1]

The MTU can be easily assembled, disassembled, and transported. The electrode mounting design can accommodate a wide range of configurations, and an adaptable capacitor mounting structure and open stripline access accommodates alternate capacitor geometries, while allowing in-situ discharge voltage measurements.

Early test plans include 5 J testing with a 1 cm x 1 cm electrode configuration and a dry (ceramic) rectilinear capacitor configuration to validate the UW Dawgstar PPT design approach (see below). In addition, characterization of the input voltage and temperature sensitivity of the discharge energy is planned to validate the new command approach. Finally, plume characterization, including investigation of alternate propellants and plume shields, and characterization of the light signature of the plume as a risk mitigation for the ST-3 application are under consideration.

Thrust Stand Development

In addition to the MTU test bed, PAC is developing test facilities and equipment for PPTs. The most critical need is the ability to take direct thrust and/or impulse bit measurements with adequate accuracy and resolution. This is especially challenging for the low impulse bit of pulsed microthrusters, for which the PPT is a subset. These challenges are further compounded due to recent interest in understanding issues related to off-axis thrust[9], shot-to-shot impulse bit variability, and the use of multi-accelerator thrusters.[8] All of these have significant implications requiring consideration during a thrust stand design.

PAC is building on 35 years of successful experience in developing thrust stand systems to develop a new versatile thrust stand for steady-state and pulsed microthrusters. The primary focus for this thrust stand is to accurately measure the impulse bits from PPTs, especially at the low range. This section describes the special considerations, design objectives, and status of the thrust stand and test facility being developed at PAC for microthrusters.

Background

Thrust stands are the most unique articles of test equipment used in electric propulsion. Perhaps the most important issue with thrust stands is that they can take several months to design, fabricate, install, and certify for testing. This encourages conservative design approaches that utilize the best traits and experience of previous designs. It also encourages design adaptability and flexibility so that a variety of thruster designs and configurations can be tested with a minimum amount of modification and test changes.

PAC has been successfully developing thrust stands for rocket engines for nearly 35 years. In fact, the first thrust stand developed by PAC was in the mid 1960s for testing the original gas-fed PPTs. After using the US Air Force's thrust stand during the millipound PPT effort,[10] PAC developed two permanent thrust stand facilities which are successfully used today for Arcjet testing.[11, 12] More recently, PAC has developed and commissioned a derivative of the well-known NASA-designed[13] four-bar linkage inverted pendulum thrust stand for testing Hall Current Thrusters.[14]

During the NASA GRC PPT development program, a compound pendulum thrust stand at PAC was used to measure the impulse bit of a breadboard PPT.[15] This thrust stand is normally used to measure the steady-state thrust of EHT resistojets. For the PPT, operation in a swinging pendular mode proved to be adequate for gross comparisons of impulse bit for different configurations. However, the long-term usefulness of the thrust stand for pulsed thrusters is limited by its accuracy, resolution, and inability to measure average thrust or low impulse bits.

As a result, PAC initiated an advanced thrust stand design study. The system will be built and implemented in stages. Design options that may have some foreseeable future benefit are being considered so that they are not precluded as a future modification.

Design Drivers and Objectives

A pulsed microthruster creates a number of unique issues that must be considered in a thrust stand design. These issues have been discussed in detail elsewhere[16-20] and is summarized briefly here. A pulsed thruster imparts highly transient forces to a thrust stand. This issue is compounded for very low impulse bits, which are highly susceptible to signal-to-noise limitations. These problems introduce a need for mechanical filtering, which can be introduced by having a thrust stand with a natural frequency much lower than the firing frequency of the thruster. As a result, all thrust stands built for pulsed thrusters to date are based on pendulum systems. This design results in the capability of measuring the impulse bit from a single pulse or the effective average thrust created by a continuous train of pulses at a constant pulse frequency. The measured displacement of the free-floating pendulum structure is then used as a means of comparison between the unknown engine thrust or impulse bit and the supplied calibration forces or impulses.

Tables 1 and 2 summarize the required and desired objectives of the thrust stand. Note that the resolution goals are linked to an acceptable uncertainty of the results. Resolution will improve with lower accuracy. The uncertainty is based on the recently standardized model that incorporates systematic and random uncertainties into a statistical coverage.[21, 22] The information is shown relative to a 95% confidence coverage. PAC intends on incorporating uncertainty models into all component calibrations and performance measurements on the thrust stand for maximizing data accuracy. PAC places the highest amount of concern over the quality and validity of its data, which is emphasized by the requirements that all performance measurements must be NIST-traceable and satisfy ISO-9001 requirements.

One of the most common oversights related to thrust stands is that they must resolve the thrust-to-weight of the system, not just the thrust. In addition to the thruster, this weight includes that of the floating element and any other diagnostics or test equipment that is part of it. The PAC thrust stand pendulum system may have to resolve a thrust-to-weight ratio as low as $3x10^{-8}$. This has significant implications on the sensitivity of the thrust stand to hysteresis and drift caused by mechanical shifting of the thrust stand and/or thermal expansion and creep of cabling.

The primary performance objective is to measure impulse bits at a much lower range than has been previously obtained with reasonable accuracy. One method being considered to alleviate this issue is to measure the average impulse bit from a fast train of pulses that appear as a single impulse to the thrust stand. Carrying out this technique will depend on the capability of individual thruster systems. Integral to this is the desire to measure shot to shot variability of the impulse bit. A very repeatable, controllable, and accurate impulse calibration system with a broad dynamic range is required.

The second performance objective of the design it to measure the effective average thrust of pulsed thrusters at a very low range. To obtain the needed accuracy, issues related to hysteresis and drift must be examined carefully. A very repeatable, controllable, and accurate steady force calibration system with a broad dynamic range is required.

Flexibility of the thrust stand is also critical. As a result, the design is addressing issues related to thruster size and weight, and the type of thruster being tested. Since there is a growing interest in all microthruster systems (Ion, Hall, Hydrazine, FEEP, etc.), alternate propellant systems and propellant storage/supply issues are being considered.

A variety of special considerations are being included in the design to maximize its usefulness at PAC. The first of these is to have the capability of testing multiple accelerators orientated along the same thrust axis during the same test. This requirement stems from the goal of obtaining the most amount of useful data from the MTU and similar thrusters in a short amount of time at minimum cost. Somewhat related to this is having the capability of conducting thrust vector measurement and/or testing multiple axis thrusters during a single test. This objective would require in-situ rotation of the thruster to re-orient the thrust vector to be measured along the sensitive axis of the thrust stand. As a result of these needs, the thrust stand design will be insensitive to the location of the thrust vector other than its angular orientation.

Integral to all of the design objectives is the issue of cost. Up front NRE costs can be significant but usually pale in comparison to the long term costs. This is mostly due to the labor associated with multiple tests, manual thrust stand operation and control, and complex data acquisition and reduction. PAC is designing the system to minimize tests costs to the customer. PAC is also considering the use of a computer controlled system that will link control of the thruster to the thrust stand. This capability could potentially allow for automatic, unmanned operation that would yield the maximum amount of data needed in the minimum amount of time. Data acquisition and reduction may also be automated in this system. Considerations to the complexity of such a goal are being considered in continued design trades.

Design Status

Pendulum System

The primary decision to be made in the design is which pendulum system to use. The design must be insensitive to the radial location of the thrust vector. To meet this requirement, the pendulum will be based on a four-bar linkage system. Two-bar linkages require the calibration force to be located at the same radial distance as the thrust force from the single axis of rotation. This requirement stems from the fact that calibration is based on the moment arm of the system. However, four-bar linkages translate the thrust vector along the sensitive axis of the thrust stand to the coupler linkage (the free-floating platform) and its radial location relative to the stationary structure - removing the radial alignment requirement.

Presently, two different four-bar linkage pendulum systems are being considered: a horizontal pendulum system based on the two-bar linkage design at NASA GRC[17], and an improved version of the Watt's Pendulum originally developed at the University of Illinois at Urbana-Champaign.[19] Simplified drawings of these systems are presented in Fig. 2. The pros and cons of both designs are presently being studied.

Displacement Measurement

Since calibration is a function of pendulum displacement, measuring position is required. The most common method is to use a Linear Variable Differential Transducer (LVDT). Another option is to use laser interferometry[18]. PAC has selected to use a commercially purchased, NIST-traceable optical linear encoder. The device can measure displacements up to 20 mm at a resolution of 0.005 μm with a maximum linearity deviation of ±0.12 μm. Further benefits of this choice are discussed under the next section.

Steady Force Calibration
For steady force calibration, PAC examined the use of hanging weights over a pulley and various linear actuator technologies. The option of using hanging weights over a pulley as the primary calibration is not feasible because of its lack of direct NIST-traceability and, more importantly, because the hysteresis common to such designs is expected to be very problematic at the low force ranges. As a result, PAC has chosen to use a voice coil linear actuator. A highly specialized voice coil design is complete that will yield calibration capability from 1 – 2000 μN.

In a technique used successfully at PAC for more than 10 years[11, 14], the voice coil will be periodically removed and calibrated on a highly sensitive calibration stand. Since the thrust stand will operate in displacement mode, the voice coil will require calibration of the force constant versus position. Four techniques are being employed to mitigate issues related to misalignment. First, the voice coil is designed to have a fairly flat force constant, making it insensitive to small misalignments. Second, the optical encoder mounting will be integral to the design. The use of the encoder and its reference marker will ensure that the position of the voice coil's field assembly relative to the coil assembly will be the same in test as in calibration. Third, a precise alignment system will ensure radial and axial alignments are correct during installations. Fourth, the standard method of applying hanging weights over a pulley system in-situ will be used to verify proper installation. This will also verify that all electrical connections and systems unique to chamber installation are correct.

Impulse Bit Calibration
PAC has examined several options for impulse bit calibration. Each of these have been used successfully in the past. The first option considered was to roll balls down an inclined plane that would strike the thrust stand[23]. A more useful approach is to use an impact pendulum to strike the free-floating platform. Momentum transfer can then be measured directly using a force transducer[18, 19] or indirectly by measuring the instantaneous change in speed of the striking pendulum with a Ronchi ruling.[17, 24] The method selected by PAC is to use the voice coil linear actuator in a pulsed mode. The specialized design makes it feasible to incorporate an electronic timer into the control circuitry to apply a constant, desired force for a desired period of time.[25] The integration of this force signal will yield the applied impulse.

Critical to the effectiveness of an impulse calibration system is separating out non-repeatability of the calibration from that of shot-to-shot variability of a thruster. To do so, either a force transducer or a Ronchi ruling system will also be incorporated with an impact pendulum. Thus, two separate calibration methods will provide a more complete and accurate understanding of shot-to-shot variability of a thruster and the repeatability of a measurement by the thrust stand.

With a method of applying a known impulse bit, a method for calibrating pendulum response must also be incorporated. Several methods that have been used in the past and present are all available and are being considered:

1. Incorporate the area under the displacement curve for a critically damped or over-damped system.[16]
2. Measure the change in velocity directly from the change in position signal slope.[26]
3. Use an exponential decaying sinusoid curve fit.[18, 19]
4. Use an exponential decaying curve fit based on the peaks of each oscillation.[15, 27]
5. Use peak displacement of the first oscillation.[9, 17]

Damping Control
Since the thrust stand pendulum system will be essentially frictionless, there is a need to dampen out unwanted oscillations. This will be accomplished with either a second voice coil or the primary calibration voice coil in a position derivative feedback loop. The control system will be capable of turning this damper on or off as needed for the measurements being made.[17]

Balance Control
The expectation of very low thrust-to-weight ratios drives the need for careful balance control. Minute changes in the balance of the thrust stand along its sensitive axis will have a dramatic affect on thrust stand operation – causing significant drift and potential tare hysteresis. Balance issues will be mitigated with two methods. First, the pendulum arms (the side linkages) will utilize counterweights so that gravitational variations acting on the thruster will be counteracted by equal and opposite forces of the counterweights.[17] Second, an autoleveling system will be integral to the thrust stand framework. This method, developed by NASA GRC and already used successfully at PAC,[14] uses piezoelectric crystal stacks in a feedback control loop to highly sensitive inclinometers. Another benefit at PAC is the use of a highly specialized vacuum chamber system – where the mounting structure is isolated from the chamber and the local facility. This is described further in the next section.

Future Considerations

Two considerations are being examined for future modifications. The first is the possible addition of a rotary positioning stage on the free-floating platform to allow in-situ rotation of thrusters – allowing for the thrust measurement of off-axis thrust or for accelerators with different thrust vectors.

The second potential improvement is that of making the system wireless. One critical concern in obtaining very low performance measurements is the issue of cabling. Power, telemetry, and control are all needed on the floating element of the thrust stand. The inclusion of many wires and cables increases the chances that measurements will be affected by drift and hysteresis or that the system will be too stiff to yield enough displacement for an adequate signal-to-noise ratio. Supplementing these needs is the desire for diagnostics such as probes and thermocouples. PAC is designing the initial system for the present requirements without precluding future improvement. Options being examined include infrared, optical, and radio modem systems. Power supply options include the use of an on-board battery, supplying the power through electrically isolated flexures, or as the only wires on the system.

Vacuum Facility Development

PAC has recently commissioned a dedicated vacuum chamber for microthruster development, with near-term focus on PPTs. This chamber will house the thrust stand as well as providing forms of thruster testing including plume characterization, thermal vacuum tests, and EMI tests. This stainless steel chamber has a water-cooling jacket and a volume of 508 ft^3 (7.9 ft x 7.25 ft). Vacuum pressures of 10^{-6} are obtained with a combination of mechanical and cryogenic pumps.

For the thrust stand, the most important aspect of the this vacuum chamber is that the interior mounting posts are vibrationally isolated from the chamber and the surrounding facility. As Fig. 3 shows, this is accomplished by passing the posts directly through the floor of the vacuum chamber and into a 784 ft^3 concrete seismic block. Flexible bellows provide a vibration-free vacuum seal at this location. The seismic block is separated from the surrounding facility by a 2" gap filled with a polymer that further reduces vibration concerns. The advantage of this design is that this large seismic mass will isolate the thrust stand from facility vibrations and make it less sensitive to drift caused by facility shifting and thermal transients.

Mini-PPT Development

Using these tools and building on the experience with the GRC funded EO-1 PPT development, PAC is assisting the University of Washington (UW) in developing a mini-PPT system for a 13 kg satellite to be flown in 2001 under their University Nanosatellite program. This satellite will be the smallest ever flown with active propulsion. The mini-PPT concept provides a new option for active control of small spacecraft, as well as allowing distributed placement of thrusters on small structures on larger spacecraft.

University Nanosatellite Program

In response to the increasing need for a low cost, versatile science and communications platforms, the Air Force Research Laboratory (AFRL) initiated the TechSat 21 program that will demonstrate the feasibility of using distributed micro-satellite systems to do the work of a large, dedicated satellite platform.[28] To support TechSat 21 objectives, the University Nanosatellite Program, funded by AFOSR and DARPA (with additional funding from NASA), is a two-year program with a goal of designing, building, and flying nanosatellites. The UW and nine other universities are working towards a shuttle launch in Nov 2001.

The "UW Dawgstar" is a 13 kg satellite designed to be the most functional small satellite ever built. The UW is collaborating with PAC on the propulsion system and PAC is providing consultation for the overall spacecraft design. The UW has teamed with Utah State University (USU) and Virginia Polytechnic Institute (VPI) to form a cluster of three nanosatellites called the ION-F, or Ionospheric Observation Nanosatellite Formation. The name ION-F also denotes the two operational goals of the cluster: investigating global ionospheric effects with distributed satellite measurements and demonstrating formation keeping and maneuvering.

Formation Flight

Relative positional control of multiple spacecraft is an enabling technology for missions requiring distributed measurement. For example, EO-1 will formation fly with LandSat-7 to perform paired imagery. ST-3 will use precision formation flight to perform stellar optical interferometry. TechSat 21, will perform sparse-aperture sensing with 8 to 16 small satellites in a side-by-side formation. The ION-F science mission of distributed ionospheric impedance measurements is an example of distributed in-situ space science. The baseline mission for ION-F includes two types of formations - leader follower and same ground track - and formation maneuvering between the two.

UW Dawgstar Spacecraft Design

Although still at a preliminary design stage, the spacecraft will have a hexagonal bus (see Fig. 4) 18" in diameter and 10" in height, with an aluminum isogrid top and bottom, and truss sides with lightweight graphite/epoxy composite panels. The on-board processor will be a Tattletale Motorola board. Commercial off-the-shelf transmitters and receivers will be used, and cross-links and 10m accuracy GPS will be designed in collaboration with APL. Body mounted, high efficiency GaAs solar cells will provide 18 W of orbit averaged power. Ni-Cad batteries will be used for energy storage. Attitude sensors will include a three-axis rate gyro, two horizon sensors and a sun sensor. The propulsion system is described below.

UW Dawgstar Propulsion Trade Study

Only two propulsion system options are suited for the UW Dawgstar due to the mission's mass and power requirements: PPTs and cold-gas propulsion.[29]

Although twelve thrusters are typically used to provide full six degree of freedom control, fewer thrusters can be used where redundancy is not necessary. This results in mass reduction of the thruster system, especially for the PPT. To approach the propulsion system mass target of 2.5 kg, eight canted thrusters were assumed. The placement of the thrusters on the nanosatellite structure is illustrated in Fig. 5 for the PPT option. Thrusters are paired, and the thrust vectors for each pair are set 90° apart. In the case of the PPT this is accomplished by cutting the propellant bar surfaces at a 45° angle, similar to the LES 8/9 PPT configuration.[30]

Thrusters in this configuration can control attitude in all three axes and translation in two axes. Although the system does not have direct control of z-axis (nadir) translation, position in this direction cannot be de-coupled from orbital (x-axis) velocity anyway due to the orbital mechanics. Furthermore, z-axis translation could be indirectly accomplished by a 90° rotation and then a translation maneuver. There is full redundancy in yaw and some redundancy in roll and pitch control. In the case of a thruster or thruster cluster failure, attitude can be maintained with the remaining functional thrusters. Also, thrusters can be fired to produce pure rotation or both rotation and translation.

Cold-gas Propulsion System

Cold gas systems, which simply release high-pressure gas through a nozzle, have been used on several missions over the past 35 years. As originally proposed for the Pluto Fast Flyby spacecraft,[31] there were to be 24, 11-gm thrusters that would share less than 1.5 kg of nitrogen propellant. Its propulsion system mass was reduced from the original design mass of 20 kg to 9.9 kg through the use of miniaturized pressure regulators and valves and a composite propellant tank. These types of mass reductions would also be necessary to implement a cold gas system onboard the Dawgstar.

A propellant mass of 1 kg of GN_2 can provide approximately 49 m/s of ΔV or approximately 1.6 hours of continuous thrusting (73.8 days of 1 Hz pulsing). Assuming an average temperature of 10°C and a storage pressure of 2000 psig, the volume of the tank for this mass of GN_2 is approximately 200 in^3, corresponding to a spherical ID of 5.3 in.

The cold gas system studied for Dawgstar is shown schematically in Fig 6. Since Dawgstar has a short development time and a low budget and must meet Eastern and Western Range safety requirements, all components must be off-the-shelf products. Fortunately, a miniature cold gas thruster, latch valve, and pressure regulator have already been developed for the Pluto Fast Flyby mission. The miniature cold gas thruster is the Moog 58E135, developed by Moog Space Products in conjunction with the NASA Jet Propulsion Laboratory. The measured thrust and minimum impulse bit of this thruster at 5 psig are 4.5 mN and 100 μN-s, respectively[31]. Due to the diminishing performance of the cold gas system over its lifetime, an average I_{sp} of 65 sec is assumed. Table 3 lists the mass of the propulsion components appropriate for the Dawgstar.

Pulsed Plasma Thrusters

The PPT system concept for the UW Dawgstar is primarily based on a scaled version of the EO-1 PPT. The system, also shown in Fig. 6, consists of eight thrusters arranged in pairs around four energy storage capacitors. A single charge converter unit can charge any of the high voltage capacitors through a set of high voltage switches. Each thruster has a dedicated discharge initiation (DI) circuit with igniter. The combination of capacitor charged and igniter fired determines which thruster is fired.

The specific impulse of the EO-1 PPT ranges from 650–1400 sec at capacitor charges of 8.5–56 J, respectively.[1] For a nominal 5 J charge for the mini-PPT, the I_{sp} is conservatively assumed to be 500 s, although extrapolation of the EO-1 data suggests 600 s at 5 J and the reduced propellant face area of the mini-PPT could increase the actual I_{sp} further. The nominal I_{bit} is assumed to be 70 μN-s from extrapolation of the EO-1 data. No throttling of the PPT is assumed, although it can be accomplished to add dynamic range between maximum thrust and minimum I_{bit}, if required later. Due to the high I_{sp} of the PPT, the propellant mass required for ΔV is only 2.7 g-s/m. The effective thrust of a pair of thrusters firing simultaneously is 140 μN at a 1 Hz pulse rate. The mass of the propellant was sized to a pulse capacity of approximately four million. At a firing frequency of 1 Hz, each thruster has sufficient propellant to fire continuously for about 45 days, or 392 days for the system. With an 80% PPU efficiency and a pair of thrusters charging simultaneously for a coupled impulse, the peak input power requirement is 12.5 W.

Table 4 summarizes the preliminary total system mass, broken down by components and with qualitative contingencies included. The electronics mass, including the DI circuits, is conservatively estimated to be that of the EO-1 design with slight reductions in the magnetics mass due to the reduced power handling requirement. This is in keeping with the extremely cost limited nature of the project, which requires the delta design effort to be minimal. However, the UW and PAC have recently won a separate grant from the Washington Technology Center, to be matched with funding from PAC, to miniaturize the electronics, which accounts for 45% of the estimated system mass.

Propulsion System Comparison

The results of the PPT and cold-gas system comparison are summarized in Table 5. Both PPT and cold-gas thrusters provide enough thrust to compensate for maximum translational disturbances, due mostly to the Dawgstar's drag of 0.042 mN. Dawgstar has enough power to support an eight-thruster PPT system. Even with conservative EO-1 based masses, the PPT system has a lower mass due to its lower I_{bit} and higher I_{sp}, providing better pointing accuracy and much more ΔV for a given propellant mass than the cold-gas system.

The PPT is a more attractive system compared to the cold-gas system's larger mass and volume, problems inherent to a high-pressure system, and the limited miniaturization capability due to the flow characteristic of gases and liquids. Also, PPTs do not suffer from propellant leakage, which has a history to cause cold-gas systems to fail. The PPT has a simple feed system with minimal moving parts, leading to high mechanical reliability. Also, PPT system mass can be further reduced by decreasing the size of the electronics, the most massive component of this PPT system.

Conclusion

PPTs continue to have increasing appeal for a broad range of spacecraft propulsion applications. With the upcoming launch of a PPT on the EO-1 spacecraft in December of this year, PPTs have again achieved a flight ready status, but with significant technical improvements and a wider array of potential missions. These missions include general attitude control for almost any spacecraft, as will be demonstrated on EO-1, as well as orbit raising of small low earth orbit satellites. However, PPTs are an even strong contender for new formation flying applications, such as ST-3 and ION-F.

PAC is continuing efforts started under the GRC PPT technology development program, both as part of the follow-on PPT program and as internal PAC initiatives. These efforts represent a critical industrial complement to the ongoing PPT programs within NASA and the Air Force and at several universities. PAC has built a versatile test thruster, the MTU, for validation of a wide range of PPT configurations. In addition, PAC continues to invest in test capabilities, most notably the effort in progress to build a micro-thruster thrust stand capable of measuring individual impulse bits at least as low as 50 μN-s with a ±5 μN-s uncertainty.

Future work on the thrust stand depends on the level and direction of interest in microthrusters. Immediate plans are to select the pendulum type. Once requirements become firm, the system will be designed without precluding future needs. Once complete, the system will be built, installed, and made operational. The validity of the system will be certified by testing a LES-8/9 PPT, which has the most performance data of any PPT available. Another option for certification will be to use the MTU test bed PPT and compare its performance to that measured elsewhere. Upgrades to the system will occur in a timely fashion as warranted by future needs.

Finally, PAC has recently entered into a collaboration with the University of Washington to develop a complete PPT propulsion system for the 13 kg Dawgstar nanosatellite. The PPT was selected over cold gas in a trade study that showed advantages for the PPT in mass, delta velocity capability, minimum impulse bit, storability, and safety. This propulsion system will provide control in three rotational and two translational directions, making the Dawgstar the smallest satellite ever to have active self propulsion capability.

Acknowledgements

We would like to acknowledge the students of Professors Bruckner's and Campbell's AA420/421 space design class for their efforts on the preliminary design of the Dawgstar satellite, especially their work on defining the PPT system configuration.

References

1) Benson, S. W., et al., "Development of a PPT for the EO-1 Spacecraft," AIAA paper 99-2276, *35th Joint Propulsion Conference*, June 1999.

2) Ebert, W. L., Kowal, S. J., and Sloan, R. F., "Operational Nova Spacecraft Teflon Pulsed Plasma Thruster System," AIAA Paper 89-2497, *25th Joint Propulsion Conference*, July 1989, see also AIAA A89-46876.

3) Burton, R. L., and Turchi, P. J., "Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 14, No. 5, Sep.-Oct. 1998, pp. 716-735.

4) LeDuc, J. R., et al., "Mission Planning, Hardware Development, and Ground Testing for the Pulsed Plasma Thruster (PPT) Flight Demonstration on MightySat II.1," AIAA Paper 97-2779, *33rd Joint Propulsion Conference*, July 1997.

5) Cassady, R. J., Myers, R. M., and Osborne, R. D., "Pulsed Plasma Thrusters for Spacecraft Attitude Control," *Proceedings of the Proceedings of the 1996 JANNAF Propulsion Meeting*, Dec. 1996.

6) Cassady, R. J., et al., "New Attitude Control Strategies Using Pulsed Plasma Thruster Systems," AAS 98-065, Feb. 1998.

7) Urban, M., et al., "Investigation of Propulsion System Requirements for Spartan Lite," SSC98-V111-5, *12th AIAA/USU Conference on Small Satellites*, Sep. 1998.

8) Cassady, R. J., et al., "Pulsed Plasma Thruster for the New Millennium Space Interferometer Experiment DS-3," AIAA Paper 98-3326, *34th Joint Propulsion Conference*, July 1998.

9) Arrington, L. A., and Haag, T. W., "Multi-Axis Thrust Measurements of the EO-1 Pulsed Plasma Thruster," AIAA Paper 99-2290, *35th Joint Propulsion Conference*, June 1999.

10) Cassady, R. J., "Pulsed Plasma Mission Endurance Test," Rocket Research Co., AL-TR-88-105, Aug. 1989.

11) Morren, W. E., and Lichon, P. J., "Low-Power Arcjet Test Facility Impacts," AIAA Paper 92-3532, *28th Joint Propulsion Conference*, July 1992.

12) Zube, D. M., et al., "Initial On-Orbit Performance of Hydrazine Arcjets on A2100(TM) Satellites," AIAA Paper 99-2272, *35th Joint Propulsion Conference*, June 1999.

13) Haag, T. W., and Curran, F. M., "Arcjet Starting Reliability: A Multistart Test on Hydrogen / Nitrogen Mixtures," AIAA Paper 870-1061, *19th International Electric Propulsion Conference*, May 1987.

14) Wilson, F., et al., "Development Status of the BPT Family of Hall Thruster Systems," AIAA Paper 99-2573, *35th Joint Propulsion Conference*, June 1999.

15) Meckel, N. J., et al., "Improved Pulsed Plasma Thruster Systems for Satellite Propulsion," AIAA Paper 96-2735, *32nd Joint Propulsion Conference*, July 1996.

16) Stark, K. W., et al., "Design and Development of a Micropound Extended Range Thrust Stand (MERTS)," NASA Goddard Space Flight Center, NASA TN D-7029, Aug. 1971.

17) Haag, T. W., "PPT Thrust Stand," AIAA Paper 95-2917, *31st Joint Propulsion Conference*, July 1995, see also NASA TM 107066.

18) Cubbin, E. A., et al., "Pulsed Thrust Measurements Using Laser Interferometry," AIAA Paper 96-2985, *32nd Joint Propulsion Conference*, July 1996.

19) Wilson, M. J., Bushman, S. S., and Burton, R. L., "A Compact Thrust Stand for Pulsed Plasma Thrusters," IEPC Paper 97-122, *25th International Electric Propulsion Conference*, Aug. 1997.

20) McFall, K. A., Spanjers, G. G., and Schilling, J. H., "Pulsed Thruster Thrust Stand Measurement Evaluations," AIAA Paper 98-3805, *34th Joint Propulsion Conference*, July 1998.

21) Dieck, R. H., *Measurement Uncertainty - Methods and Applications,* 2nd ed., Instrument Society of American, Research Triangle Park. NC, 1997.

22) "American National Standard for Expressing Uncertainty - U.S. Guide to the Expression of Uncertainty in Measurement," National Conference of Standards Laboratories, American National Standards Institute, ANSI/NCSL Z540-2-1997, Feb. 1998.

23) "Thrust Stand Operations Manual," Fairchild Republic Co., November 1976.

24) Burton, R. L., et al., "Investigation of a Pulsed Electrothermal Thruster," GT-Devices, Inc., NASA CR-168266, Oct. 1983, see also GTD 83-10.

25) Williams, T. E., and Callens, R. A., "Performance Testing of a Solid Propellant Pulsed Plasma Microthruster," AIAA Paper 72-460, *9th Electric Propulsion Conference*, Apr. 1972.

26) Bushman, S. S., Burton, R. L., and Antonsen, E. L., "Arc Measurements and Performance Characteristics of a Coaxial Pulsed Plasma Thruster," AIAA Paper 98-3660, *34th Joint Propulsion Conference*, July 1998.

27) Solbes, A., and Vondra, R. J., "Performance Study of a Solid Fuel-Pulsed Electric Microthruster," *Journal of Spacecraft and Rockets*, Vol. 10, No. 6, June 1972, pp. 406-410, see also AIAA Paper 72-458.

28) Cobb, R., "TechSat 21, Space Missions Using Distributed Micro-Satellite Systems," *University Nanosatellite Kickoff meeting*, Jan. 1999.

29) de Groot, W. A., "Propulsion Options for Primary Thrust and Attitude Control of Microspacecraft," NASA CR 98-206608, *COSPAR Colloquium on Scientific Microsatellites*, Dec. 1997.

30) Vondra, R. J., "The MIT Lincoln Laboratory Pulsed Plasma Thruster - A Final Report on the LES-8/9 Pulsed Plasma Thruster," AIAA Paper 76-998, *12th International Electric Propulsion Conference*, Nov. 1976.

31) Morash, D. H., and Strand, L., "Miniature Propulsion Componentes for the Pluto Fast Flyby Spacecraft," *30th Joint Propulsion Conference*, June 1994.

Table 1.
Design Objectives for the PAC Microthruster Thrust Stand

Issue	Required	Desired
Impulse Bit		
Single Pulse [a,d]	50 – 1000 ± 5 μN-sec	5 – 2000 ± 1 μN-sec
Multiple Pulse Average[a,d]	10 – 1000 ± 2 μN-sec	1 – 2000 ± 1 μN-sec
Average Thrust	50 – 1000 μN ± 5 μN	10 – 2000 μN ± 1μN
Thruster Specifics		
Weight	≤ 10 kg	≤ 15 kg
Dimensions	12"L x 8"W x 8"H	18"L x 18"W x 18"H
Propellant	Solid	Solid, Liquid, Gas
Special Considerations		
Thrust-to-Weight [c]	$\geq 10^{-7}$	$\geq 10^{-8}$
Testing multiple accelerators (with same thrust axis)	*Single test*	*Single test*
Thrust vector measurement (*and/or testing multiple axis accelerators*)	From test-to-test (*Setup changes*)	In-situ during single test (*In-situ rotation*)
Shot to shot variability measurement	Performed manually	Automated by computer
Test duration	Measured by hours	Measured by days
Data Reduction	Performed manually	Automated by computer

(a) = Resolution shown with respect to the total uncertainty shown for the low end of the range.
(b) = Obtained by rapid pulsing of thruster, simulating a single pulse.
(c) = Includes weight of free-floating platform and all thruster systems and diagnostics attached to it.
(d) = Uncertainty given by ASME//ISO standard: $U_{95} = \pm t_{95}\left[(B_R/2)^2 + \left(S_{\bar{X},R}\right)^2\right]^{1/2}$ (Ref: [21])

Table 2.
Foreseeable Electrical Requirements for the Microthruster Thrust Stand

Description	Amp-Current Requirement	Number Required
28 VDC Power Supply	10 Amps max	1
28 VDC P.S. Return	10 Amps max	1
Capacitor Charge Command	< 1 Amp	1
DI Commands	< 1 Amp	3 – 5
Return for Commands	< 1 Amp	1
Force Transducer	< 1 Amp	2
Cap Voltage Telemetry	use of voltage divider	1
Thruster rotation motor*	< 1 Amp	5

* Not an immediate requirement

Table 3.
Summary of cold gas propulsion system mass.

Components	Number of Units	Mass per Unit (kg)	Mass Contingency (%)	Total Mass Including Contingency
Tank	1	2.040	30	2.652
Service Valve	1	0.018	30	0.023
Pressure Transducer	1	0.060	30	0.078
Filter	1	0.024	30	0.031
Latch Valve	2	0.100	30	0.260
Pressure Regulator	1	0.100	30	0.130
Cold Gas Thruster	8	0.008	30	0.083
Tubing	1	0.110	30	0.143
Propellant (GN_2)	1	1.000	10	1.100
TOTAL				4.579

Table 4.
Propulsion system mass summary.

Component	QTY	Mass(kg)
EMI Filter	1	0.094
Charge Converter	1	0.100
High Voltage Switches	4	0.220
PPU Housing (Al)	1	0.270
DI Circuits w/ igniters	8	1.000
Capacitors (ceramic or mica)	4	0.544
Capacitor/ DI housing (Al)	1	0.144
Sets of Electrodes	8	0.110
Strip Lines	4	0.160
Teflon Propellant Bars (Side)	4	0.228
Propellant Housings	4	0.160
Teflon Propellant Bars (Corners)	4	0.256
Propellant Housings	4	0.190
Feed Springs	8	0.320
TOTAL		3.800

Table 5.
Comparison of PPT and Cold Gas Propulsion Systems

Propulsion System	Total Mass (kg)	I_{sp} (s)	I_{bit} (μN-s)	T (mN)	Propellant Mass per ΔV (g-s/m)	ΔV Time Duration (s^2/m)	Total Impulse (N-s)	Peak Power (W)
PPT †	3.80	500	70	0.14	2.7	$1.43x10^5$	2370	12.5
Cold Gas	4.58	65	100	4.5	20	$2.22x10^3$	640	10.1

† The performance of the PPT was analyzed assuming a pair of thrusters firing at a 1 Hz frequency.

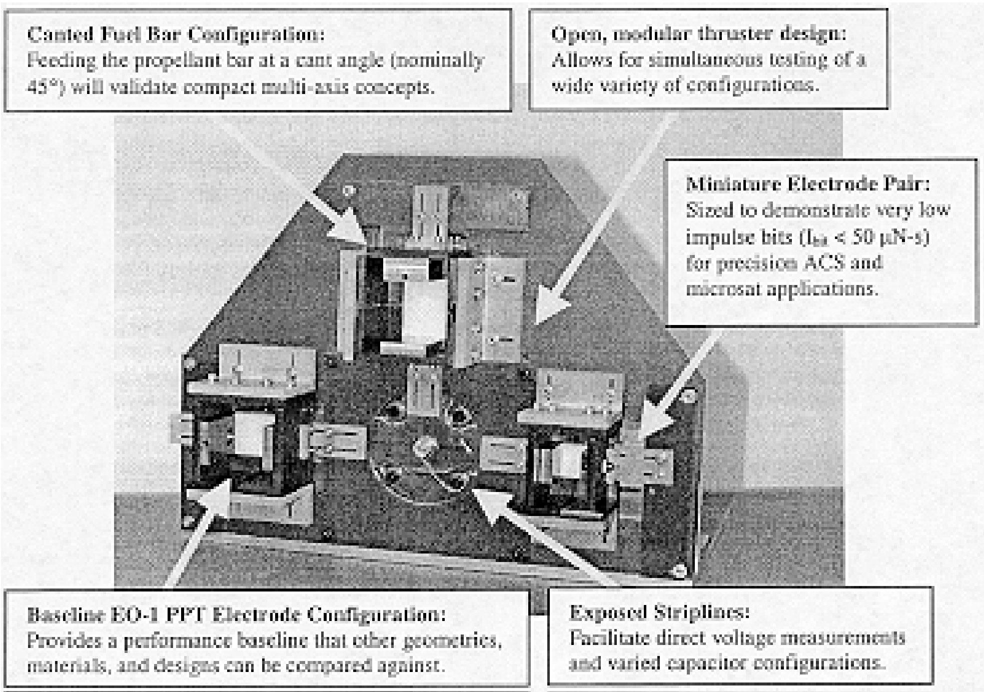


Figure 1. PAC's Modular Test Unit (MTU).

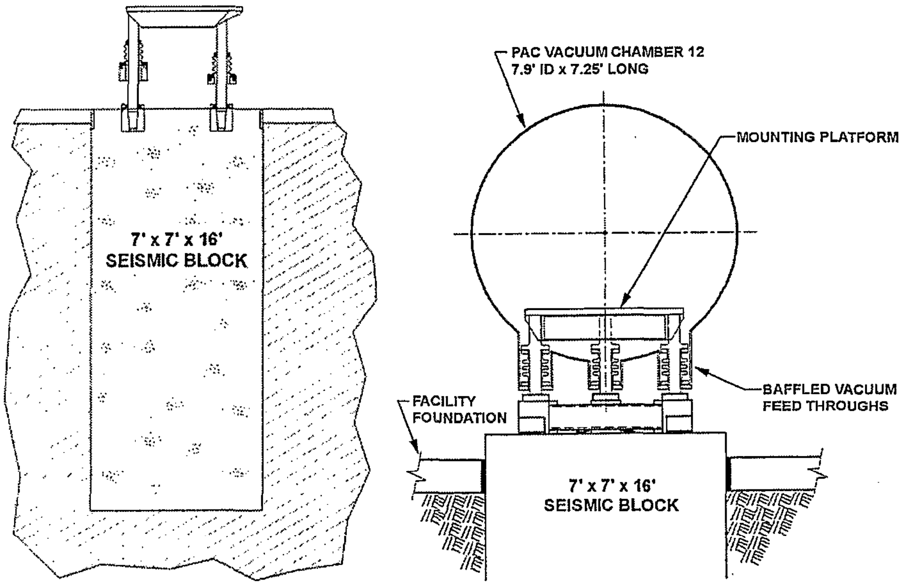
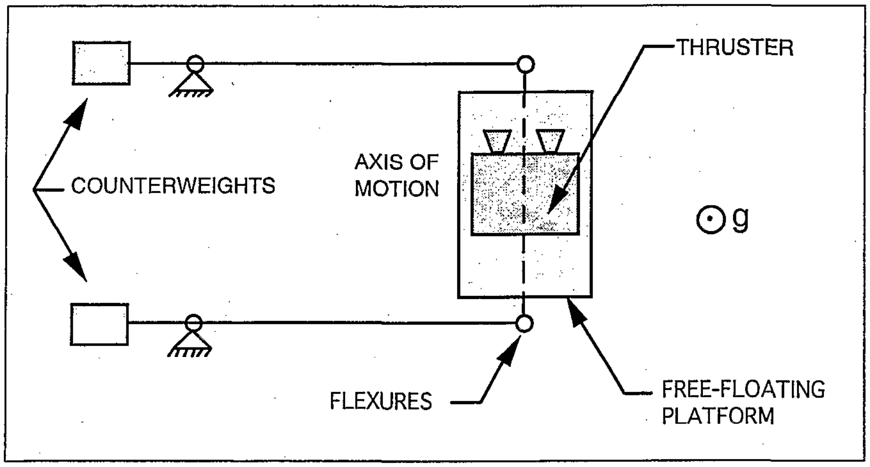
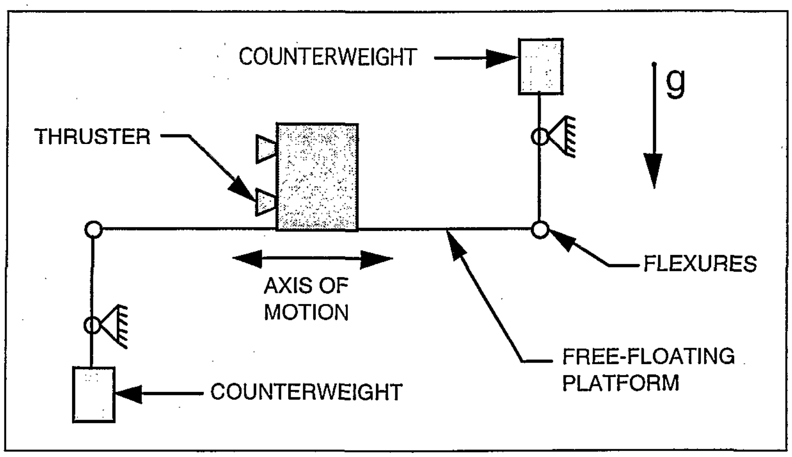


Figure 3. PAC Vacuum Chamber 12. A 784 ft^3 concrete block acts as a large seismic mass to remove facility vibrations from reaching the mounting platform in the chamber. Flexible bellows isolate the platform posts from the chamber while providing a vacuum feed through seal.



(a) TOP VIEW OF A HORIZONTAL 4-BAR PENDULUM



(b) SIDE VIEW OF WATT'S PENDULUM

Figure 2. Simplified drawings of the four-bar linkage pendulum systems being considered for the PAC microthruster thrust stand. Both operate as torsional pendulums. (a) is a top view of a horizontal pendulum and (b) is a side view of Watt's straight-line motion pendulum. Note the difference in how gravity acts on the two systems. The benefits and drawbacks of both systems are being considered.

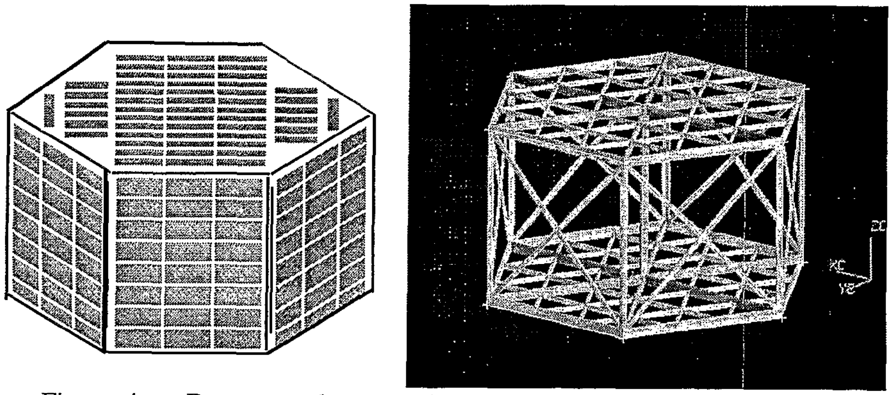


Figure. 4 Dawgstar solar array placement and structural design.

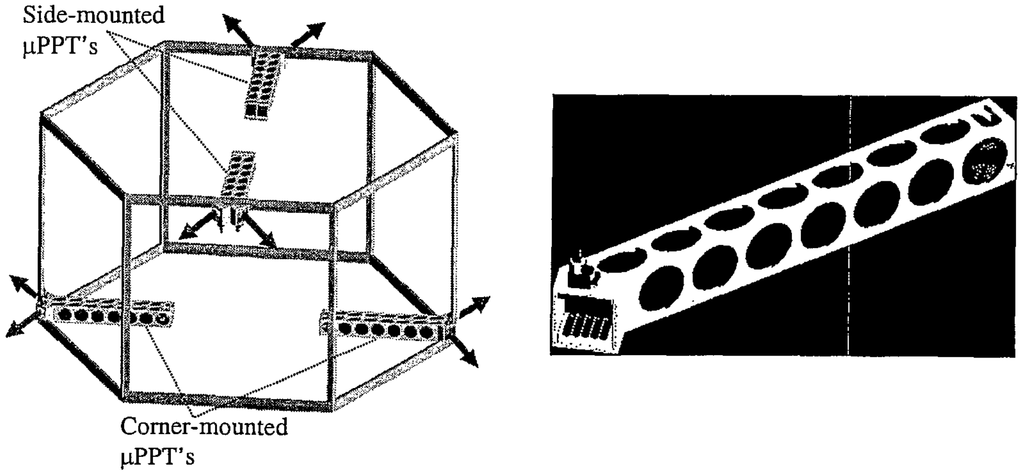


Figure 5. Configuration of the UW Dawgstar PPT system with preliminary single accelerator design. (Propellant bar is 7 in long with 0.325 in^2 fuel face and 45° cant angle).

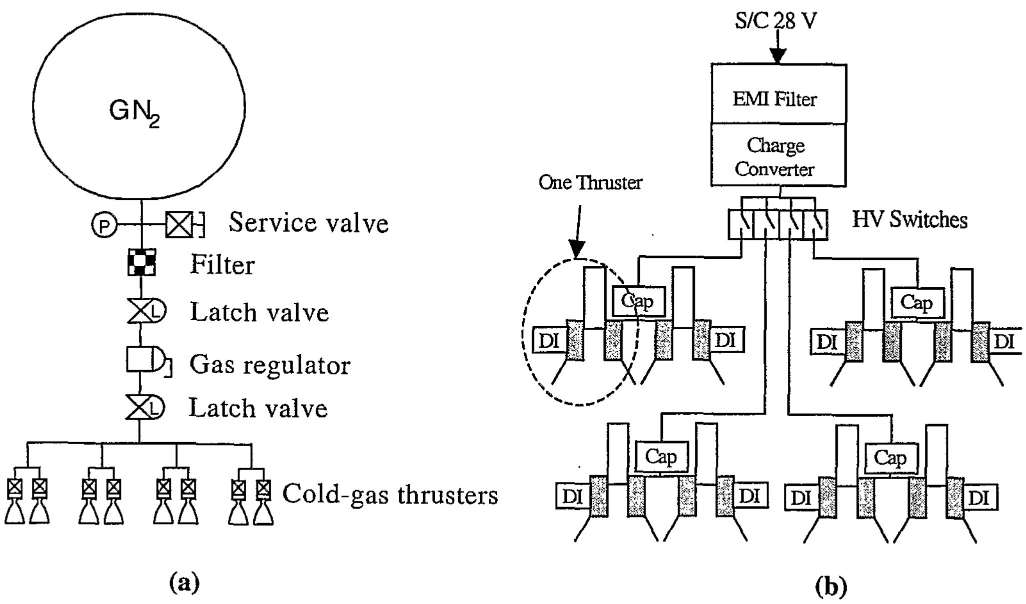


Figure 6. Schematics of the (a) cold-gas and (b) PPT propulsion system options for UW Dawgstar.