Pulsed Plasma Propulsion for a Small Satellite: Mission COMPASS P^{3}OINT*

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Abstract

Pre-launch characterization and preparation of a Lincoln Experimental Satellite (LES 8/9) ablative pulsed plasma thruster (APPT) module for the COMPASS P^{3}OINT Mission are described. COMPASS P^{3}OINT is a joint project between the Electric Propulsion and Plasma Dynamics Lab (EPPDyL) of Princeton University and the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Science (IZMIRAN) to carry in-orbit investigations with an ablative pulsed plasma thruster onboard COMPASS, an IZMIRAN scientific microsatellite to be launched in October, 1996. The unmodified LES 8/9 APPT module produces impulse bits of 285 μN-s at an I_{sp} of 836 s using 25 W of power on average. The APPT module will be used to conduct in-orbit investigations of pulsed plasma propulsion as well as to provide attitude control of the satellite and a source of plasma for active space experiments. Details of the power, command, and telemetry signals required to operate the device on the COMPASS satellite are presented. Thermal control and various operational modes are also outlined. Operational modes include a combination of right and left nozzle pulse sequences for determining the performance and impulse bit of the APPT module in space. Documented pre-flight experiments include a temporary hardware addition that simulates the plasma discharge necessary for the pre-flight atmospheric integration test at IZMIRAN. Also described are the experimental measurements of the thrust efficiency, center of mass, and moments of inertia of the module.

1 Introduction

Over the past four years there has been a resurgence of interest[1] in ablative pulsed plasma thrusters (APPT's) due to a trend towards smaller satellites in the military, commercial and scientific sectors. Quite often these small satellites are power-limited to below 300 W. To date, only APPT's have the demonstrated ability of providing the mass-savings advantages of high specific impulse electric propulsion at and below these power levels.

Research and development efforts on APPT peaked in the mid-seventies but hopes for the availability of high power in space caused such efforts to all but cease in the eighties. Recent studies have demonstrated that even with off-the-shelf power storage and power processing technologies, the APPT can offer substantial mass-savings for common stationkeeping missions[2].

The state-of-the-art of flight-ready APPT technol-

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ogy of the mid-seventies is embodied in the Lincoln Experimental Satellites 8 and 9 Ablative Pulsed Plasma Thruster (LES 8/9 APPT) modules[3] which were built but were never flown due to scheduling constraints. A great deal of research work went into the design and construction of these modules[4, 5] including previous spaceflights[6, 7]. Although the LES 8/9 APPT modules did not go into space as planned, a few Teflon APPTs have flown in space in the eighties[8].

As part of an AFOSR-sponsored program to advance APPT technology to meet modern propulsion needs, Princeton University's EPPDyL is carrying research on two complementary fronts: 1) Fundamental studies (theoretical and experimental) of APPT ablation process, energy partitioning, scaling, circuit optimization and thrust efficiency, and 2) In-orbit investigations of APPT performance. In the present paper we discuss our efforts on the second front, particularly the use of a LES 8/9 APPT module onboard a Russian scientific satellite called COMPASS to be launched on October 28, 1996.

The part of the COMPASS project that deals with the APPT is called COMPASS P^{3}OINT for Pulsed Plasma Propulsion in-Orbit Investigation and Navigation Test. In this paper we first describe the objectives of the COMPASS P^{3}OINT mission and general aspects of the COMPASS satellite. We then go into the details of the preparation and characterization of the APPT module. In particular, we define the power, command, and telemetry signals necessary for the mission as well aspects of the required thermal control for the thruster. The operational modes and pulsing sequences that will be used during the mission are also presented.

Before delivering the flight module to IZMIRAN for satellite integration in August of this year, three instrumental steps have been accomplished. First, temporary internal and external hardware modifications have been made to allow a simulated discharge at atmospheric pressure for a pre-flight satellite integration test. Second, the efficiency of the LES 8/9 APPT has been measured over 436 pulses yielding an average impulse bit of 285 μN-s within 5 μN-s, an efficiency of 6.8%, and a specific impulse of 836 s. These performance measurements were made using the interferometric proximeter system (IPS) as described in ref [9, 10]. Third, all moments of inertia have been found experimentally to within 1.5% using a bifilar technique described here in detail as well as in ref [11, 12]. All three of these experiments are outlined in this paper.

2 COMPASS and the COMPASS P^{3}OINT Mission

2.1 Launch

A 70 kg scientific microsatellite called COMPASS belonging to the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Science (IZMIRAN) will be launched later this year from a Russian Navy submarine in the Barents sea using a 3-stage converted missile called Shtyl-2. The launch is scheduled for October 28, 1996 in connection with the celebration of the 300th anniversary of the formation of the Russian Navy. According to ref. [13], this will mark the first time a converted military ballistic missile is used to place a satellite in lower earth orbit (LEO). The satellite will be placed in a 400 km circular orbit with an inclination of 78-79°. The primary scientific goal of COMPASS is to conduct plasma studies related to earthquake precursors in the ionosphere. The satellite, however, will also include a LES 8/9 APPT module supplied, conditioned and adapted to COMPASS by Princeton University's EPPDyL.

2.2 Scientific Goals of COMPASS

During its minimum lifetime of six months, COMPASS aims at the following scientific goals:

- Studies of electromagnetic and plasma disturbances in the ionosphere as precursors to earthquake, volcanic eruptions and other large-scale natural disasters.
- Development of methods for the detection and monitoring of large-scale technological accidents from space using microsatellites.
- Investigation of the processes of electrodynamic interaction between the atmosphere, ionosphere and the Earth magnetosphere through passive and active space experiments.

2.3 General Objective of COMPASS P^{3}OINT

The part of the COMPASS project that deals with the APPT is called COMPASS P^{3}OINT and has the following objectives:

- Provide attitude adjustment and stabilization for COMPASS (pitch angle control, instrument orientation, drag compensation, etc.)

- Provide a source of high velocity plasma for ionospheric perturbation and active space experiments on COMPASS.
- Validation of APPT thrust and efficiency performance baselines inferred from attitude changes caused by APPT firings.
- Validation of APPT operation baselines.
- Investigation of on-orbit electromagnetic interference (EMI) from the APPT using the wave diagnostics on COMPASS.
- Provide on-orbit propulsion data to guide the scientific part of EPPDyL's AFOSR-sponsored research on APPT's.
- Provide hands-on astronautics and satellite integration education through the involvement of graduate and undergraduate students

2.4 COMPASS Scientific Payload

COMPASS has a suite of diagnostics intended for its scientific investigations. These instruments will be operating during the APPT firings providing scientific data about wave emission and particle energetics during the COMPASS P^{3}OINT mission. The instruments include:

- High frequency (HF) wave system for measuring waves in the range of 0.1-15 MHz
- An ultralow frequency (ULF)/ extremely low frequency (ELF) wave system for measuring in the 0.1 Hz-23 kHz range.
- Plasma diagnostics package for measuring plasma parameters
- Optical system consisting of two photometers and a TV camera
- A 3-axis DC magnetometer
- A particle spectrometer for high energy particles.

2.5 Satellite Power, Command, and Telemetry

The power supply consists of a set of solar panels and a buffer accumulator battery with a capacity of about 10 Ahr. During regular operation, the available power will be 40 W at 27 V on average.

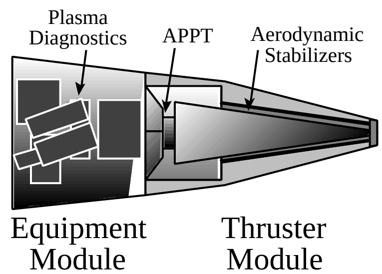

Figure 1: COMPASS Satellite in launch configuration.

Commands to COMPASS will be sent via the command line starting at IZMIRAN through a reserved line from the city of Sochi. Macintosh computers at IZMIRAN and Princeton linked through the Internet, provide means for communication and digital data transfers.

There are two modes of data collection: 1) Monitor Mode and 2) Data Recording Mode into the onboard 32 MB memory. The data is transmitted via the telemetry channel to the ground receiver stations at IZMIRAN in the city of Troitsk in the Moscow region. Another telemetry link will be to the city of Sochi. The data transmission rate exceeds 1 Mbit/s and the carrier frequency is 1.7 GHZ.

2.6 The Structure of COMPASS

COMPASS consists of two main modules: an equipment module and a thruster module. Before launch, the two modules are collapsed into one overall structure that fits inside a conical canister with an elliptical bottom section. This configuration is necessitated by the limited space available in place of the warhead of the Shtyl-2 converted missile.

Schematics of COMPASS before and after deployment are shown in figures 1 and 2 respectively. After the capsule separates from the launcher, the deployment mechanism flips the thruster module 180 degrees (see figure 2) and deploys the aerodynamic stabilizers which are also covered on both sides with solar arrays.

The equipment module consists of two modular panels: 1) a panel with scientific equipment and 2) a panel of heat sink radiators for the service equipment. In addition to these two panels, the equipment module contains a longitudinal mechanical interface through which the module is attached to the launch capsule.

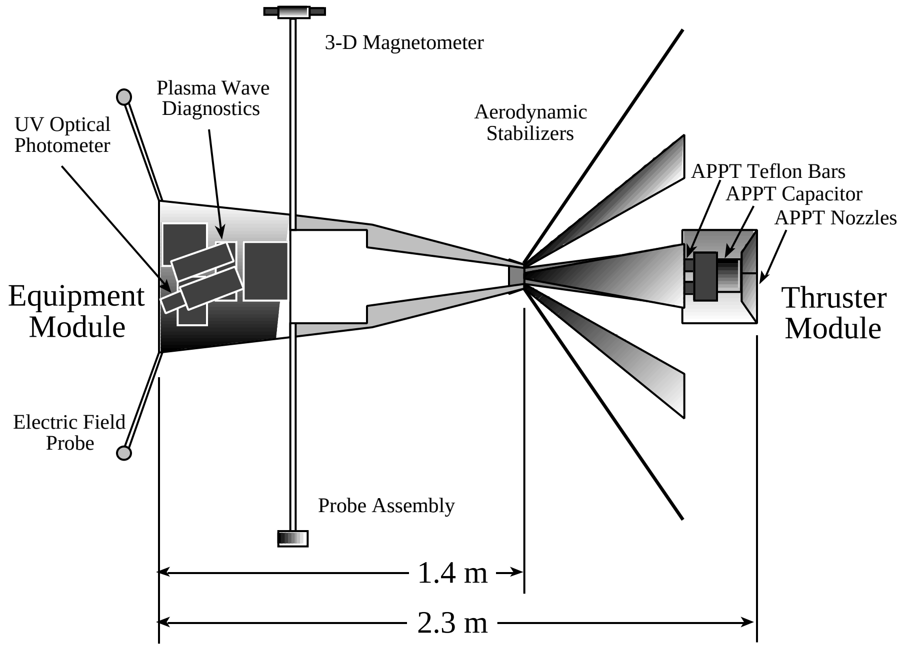

Figure 2: COMPASS Satellite in deployed configuration.

The thruster module consists of a stationary frame with a movable gimbal assembly on which the thrusters and the aerodynamic stabilizers are mounted along with the mechanism that allows deploying the stabilizers. The thrusters consist of one cold gas thruster operating with xenon and the APPT module of COMPASS P^{3}OINT described in detail in section 3 below.

A series of probes (Langmuir probe, magnetic and electric field antennas), are mounted on retractable booms that are retracted before launch into their housing on both the equipment and thruster modules.

The structure is made of aluminum alloy AMG-6 which does not require any protective anti-corrosion coating. The modular panels with heat pipes are also made of aluminum alloys. The booms that carry the probes are made of plastics. The aerodynamic stabilizers are made of honeycomb aluminum structure. All movable parts have anti-corrosion coatings.

The entire satellite is subjected to outgassing with a temperature above 70° C for about three days.

2.7 Thermal Management

The thermal management system for COMPASS excluding the APPT module is passive with heat rejection radiators expected to radiate 28 W into space while maintaining the equipment panel at 293° K within a range of 10° K under the least favorable sunlight/darkness conditions. The heat rejection system consists of an elliptical radiator with an area of .092 m^2, a set of thermal accumulators using .174 kg of ethyl alcohol and 4 heat pipes for enhanced heat conduction. The thermal management of the APPT module is described in section 3.3.

2.8 Stabilization and Attitude Control Systems

COMPASS will be placed initially in a 400 km orbit. The attitude control system is designed such that the microsatellite takes at least 6 months to degrade to an altitude of 250 km. All systems onboard have a lifetime exceeding 6 months.

A combination of gravitational and aerodynamic stabilization will be used to maintain spacecraft orientation within 10 degrees. The attitude of the spacecraft can be determined from the onboard solar sensors to within 1 degree.

Partial compensation for orbit degradation and further attitude control is supplied by a cold gas thruster operating with xenon at a thrust level between .1 and 1 N and the APPT module which provides impulses of

285 μN-s at an I_{sp} of 836 s using 25 W of power with a duty cycle of 0.89 Hz. Description of the APPT module, its preparation and pre-launch characterization are the subject of the rest of this paper.

2.9 Organizational Participation

While COMPASS P^{3}OINT is a joint collaboration between IZMIRAN and Princeton University's EPPDyL, COMPASS is an IZMIRAN project involving the participation of scientists from the Former Soviet Union, USA, Bulgaria, Poland, Slovakia and Hungary. Scientific payload integration is performed by IZMIRAN and M.V. Frunze Design Bureau Arsenal. The launcher and launch are the responsibilities of the State Rocket Center of the Makeev Design Bureau.

3 Description of APPT Module

Twelve LES 8/9 APPT modules were originally built for station keeping and orbital maneuvering duties aboard two Lincoln Lab Communications satellites [3]. Drawings of the top, bottom, side, front, and back of the APPT flight module can be found at the end of this paper in figures 7, 8, 9, 10, and 11.

The LES 8/9 APPT is parallel plate self-field plasma accelerator using Teflon, stored in a solid form, for propellant. It has two sets of electrodes, each offset at a 30 degree angle from center. As shown in figures 7 and 8, the Teflon rods are held in place on the rear edge of the electrodes by a negator spring and retaining shoulder. Energy is stored in one 1500 V, 17 μF silicon-mylar capacitor for a pulsed discharge that lasts 12 μs. Instantaneous power levels are on the order of 10 MW with peak current values near 20 kA. The average power consumption is close to 25 W at a pulse frequency near 1 Hz. The average impulse bit over the 10^7 pulse lifetime of the thruster is rated at about 300 μN-s with a specific impulse of 1000 s. Thrust efficiency is rated at about 7%[3]. Actual performance of the COMPASS P^{3}OINT flight module has been determined and is presented later in this paper.

The pulse begins when the main capacitor is fully charged and a TTL command signal is sent to the discharge initiation (DI) circuitry. One of four spark plugs (each set of electrodes have two spark plugs, one on the top and bottom of the cathode) fire, ablating a small amount of Teflon and allowing the main capacitor to discharge across the electrode gap. The completed plasma circuit ablates more Teflon and induces a magnetic field. The field interacts with the current sheet forcing it out of the thrust chamber producing the impulse bit.

This section of the paper documents the important module characteristics necessary for spacecraft integration and space flight. The center of mass and the moments of inertia for the thruster have been found experimentally and results are presented here. The electrical components are described further including the main capacitor circuit and the discharge initiation circuit. Thermal management is also discussed in this section of the paper.

3.1 Center of Mass and Moment of Inertia Calculations

The center of mass location along with the defined x, y, and z-axis of the APPT are shown in the module drawings at the end of this paper, figures 10 and 11. A bifilar technique (described in more detail later in the appendix) was used to find the moments of inertia of the LES 8/9 APPT. The bifilar method consists of hanging an object by two long wires, twisting the object a small amount, and measuring the period of oscillation about the vertical axis between the wires. Care must be taken to make sure the center of mass is exactly half way between the two wires so that the rotation is about a constant vertical axis that includes the center of mass. To determine the full moment of inertia matrix, including products of inertia, six measurements on six different axis are required. A coordinate transformation then produces the full matrix about the desired axis. For this analysis, in cases where non-linear simultaneous equations needed to be solved, they were solved numerically. The moment of inertia matrix, $\mathbf{I^O}$ is, in kg m^2,

$$\mathbf{I^O} = \begin{bmatrix} 3.78e-2 & 5.45e-4 & 5.78e-3 \\ 5.45e-4 & 5.63e-2 & 5.89e-3 \\ 7.78e-3 & 5.89e-3 & 4.90e-2 \end{bmatrix} \quad (1)$$

3.1.1 Moment of Inertia Error Calculations

The errors on the above results were obtained by numerically monitoring the solutions as the input values were varied throughout the respective uncertainty ranges. The percent uncertainty on all moments of inertia (the diagonal elements) was found to be 1.5%. The uncertainty of the products of inertia is 5%.

3.1.2 Center of Mass Misalignment

The center of mass was located by hanging the thruster by a wire and noting that the center of mass must align with the wire. Two such experiments locate the center of mass. Using the parallel axis theorem, the center of mass location must be known to an error of ϵ such that the bifilar pendulum is rotating about an axis a distance ϵ away from the x axis as described in section A.2. In this case the parallel axis theorem says that the error for a rigid body mass (m) is $m\epsilon^2$. For our case, $m\epsilon^2$ was much smaller then I^e_{xx} as determined in the experiment.

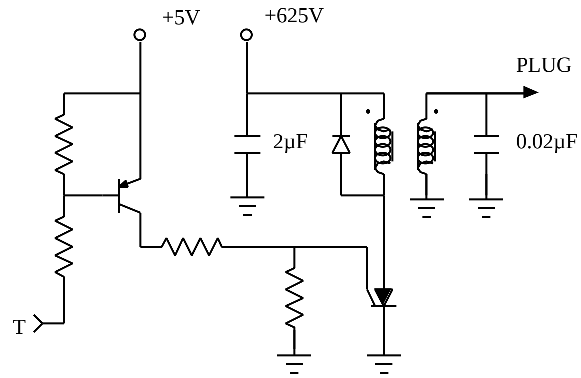

Figure 3: Fairchild Discharge Initiation (DI) circuit.

3.2 Electrical Components

The power processing unit used for charging the capacitors and the discharge initiation circuitry are located in the boxes behind the main capacitor (see figure 9.)

3.2.1 Power Processing and Main Capacitor Circuit

The 17 μF main capacitor is made of alternating layers of aluminum, mylar, paper, and mylar filled with 1016 Aroclor Oil. The capacitor is cylindrical in shape with a diameter of 12.7 cm, a height of 8.9 cm, and a mass of 1.93 kg. The capacitor was designed and constructed with care taken to provide the lowest internal inductance possible (<15 nh) while insuring at least a lifetime of 100 billion pulses[3].

The charging circuit uses a flyback type converter which keeps charging power constant. For the COMPASS P^{3}OINT flight module, the current and voltage supplied to the APPT power processing unit (PPU) was recorded during operation showing that the PPU uses 53 W regardless of the voltage. Charging lasts 0.48 s giving the PPU a total of 25.4 J. During testing, the 17 μF main capacitor was shown to store 17.7 J before the discharge. The pulse efficiency of the PPU is, therefore, 70% with the energy stored in the spark plug capacitors being neglected.

The entire circuit is also designed to have the lowest inductance possible. The main capacitor is connected *directly* to *both* sets of electrodes by two strip lines yielding an average inductance value during the discharge of 40 nh. Although the main capacitor is always connected to the electrodes, the circuit cannot be completed and the discharge cannot begin until a small amount of Teflon is ablated by the spark plugs, as described in the next section.

3.2.2 Discharge Initiation Circuit

In order to begin the discharge, a small amount of Teflon must be ablated by a smaller, higher voltage spark. Control of the spark plugs is handled by the Fairchild Discharge Initiation (DI) circuit as shown in figure 3. The circuit is duplicated for each of the four spark plugs although there are only two 625 V, 2 μF DI capacitors, one each for right and left nozzles. Logic circuitry inside the APPT permits only one spark plug to fire at a time. Each spark plug has its own 3000 V, 0.02 μF capacitor on the secondary side of the transformer.

3.3 Chassis Heater Control and Thermal Management

In both the operational and stand-by modes, the heating system of the APPT module may be switched on. The heating system has internal control circuitry and external temperature monitoring equipment designed to keep the thruster between -20° and 50° C. The APPT is designed to be thermally isolated from the rest of the spacecraft so that only the APPT heater control system is required for proper thermal management. When power is supplied to the thruster and the APPT module temperature drops below 50° C, the heater turns on. Above this temperature, the heater is off. The temperature of the APPT module is monitored by a thermistor (WSI Precision Thermistor 44031) mounted on the right side capacitor casing as shown in the thruster drawings (see figure 9).

4 Power, Command, and Telemetry

During the mission, power will be supplied by the batteries and solar panels on board the COMPASS satellite. Command will be supplied by ground control with computers on the satellite converting the information to APPT compatible command signals. Five telemetry signals will show the main capacitor and spark plug capacitor charging cycle voltages, the progression of both Teflon propellant bars, and the temperature of the main capacitor. More detail for each of these topics is presented in this section.

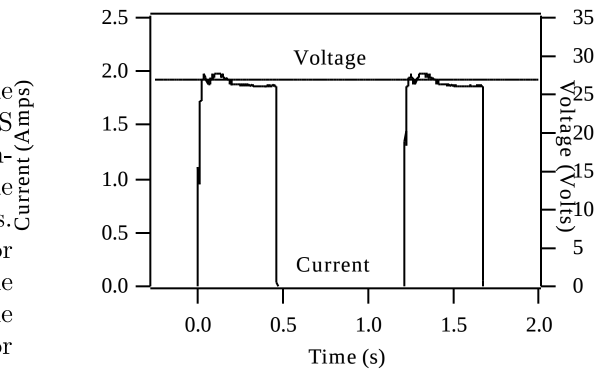

Figure 4: Voltage and current drawn from the power supply during charging of the APPT capacitors with a +27 V supply and the heaters off.

4.1 Power Requirements

The APPT requires an unregulated (not current limited) power supply providing 15-31 V. Peak current requirements can be above 3 A initially although normal operating conditions may only require 2 A depending on the power supply voltage. The APPT has internal circuitry to protect the satellite power supply from an internal short circuit. The results discussed in this paper use an unregulated +27 V (+/− 4 V) power supply as a baseline for the COMPASS Satellite power bus.

This sub-section of the report includes power requirements during capacitor charging and stand-by modes as well as heater power requirements. The average power required by the APPT module depends on the pulse rate and temperature conditions. With the heating system on and operating at a pulse rate of one discharge every 1.12 seconds (0.89 Hz) the APPT will use 25 W of power.

4.1.1 Power Processing Unit

The main discharge capacitor and the spark plug initiation capacitors are charged simultaneously at the beginning of the pulse sequence. During charging, the power supply remains at a constant voltage (+27 V) with a current of approximately 1.9 A for slightly less than 500 ms. At a power supply voltage of +23 V the APPT draws approximately 2.3 A. At a power supply voltage of +31 V the APPT draws approximately 1.7 A. Regardless of power supply voltage, the APPT uses approximately 53 W of power during charging. The 27 V signal is shown, as measured, graphically in figure 4. The average power consumed by the APPT depends on the pulse rate. For the current and voltage measurement experiments, our rate of operation was 1.2 seconds per shot (0.83 Hz) although faster rates of up to two pulses per second can be tolerated. The pulse rate for most of the operational modes of the flight module will be 0.89 Hz. The capacitors are charged in 0.48 s regardless of the power supply voltage or pulse frequency. The average power required for capacitor charging alone is equal to,

$$53W \times 0.48s \times f_{pulse}. \tag{2}$$

For the COMPASS P^{3}OINT Mission, an average power consumption of 25 W is desirable. Allowing for heater power and control circuit demands, this is obtained by setting the pulse frequency at 0.89 Hz.

4.1.2 Chassis Heater

The chassis heater control circuitry draws 5 mA of current whenever power is supplied to the APPT module. When the heater is activated, an additional 83 mA (at 27 V) is required to power a 325 Ω resistor. The heating system requires a total of 2.38 W when the heater is on and only 0.14 W when the heater is off with a power supply voltage of 27 V.

4.2 Command Signals

The APPT requires two digital command signals, one for each nozzle, to begin the pulsing sequence on either nozzle. The command signal is a standard 5 V TTL signal dropping to ground (0 V) to begin the pulsing sequence. Only one of the nozzles will be commanded to fire at any time; the other will receive a constant 5 V signal. A measured command signal

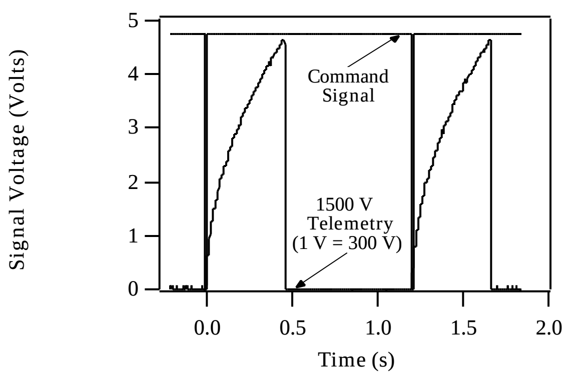

Figure 5: Trigger signal history shown along with the 1500 V telemetry output from the APPT module.

along with a sample telemetry signal from the 1530 V capacitor are shown in figure 5.

The pulsing sequence begins with the 0 V command signal lasting approximately 15 ms. At that point, the main discharge capacitor and one of the two discharge initiation capacitors begin to charge. In approximately 0.5 s, both the main capacitor and the spark plug capacitors reach their required voltages, 1530 V and 635 V, respectively. During this time, no other external command signals will be followed. The voltages on the capacitors are monitored by internal circuitry that, when charging is completed, commands an SCR to close and fire one of the spark plugs on the appropriate side of the thruster. There are four spark plugs, one on the top and bottom half of each nozzle. When one nozzle is commanded to fire, the top and bottom spark plugs of that nozzle will alternate automatically for even propellant ablation.

4.3 Telemetry Signals

For the COMPASS P^{3}OINT Mission, the APPT requires five analog telemetry signals. Two of the telemetry signals will monitor the 1530 V capacitor and the 635 V capacitor voltages. These signals will be sampled at a minimum rate of 1000 samples per second to insure the maximum voltage on the capacitor charging cycle is recorded. The range for both telemetry signals is 0-5 V. For the 1530 V capacitor, the voltage is reduced by a 300:1 voltage divider. For the 635 V capacitors, the voltage is reduced by a 125:1 voltage divider. Both reductions are made internally.

Two other telemetry channels will monitor the progression of the right and left teflon propellant bars. The end of the teflon bars have a metal plate that joins two resistive strips. The resistance in the completed circuit *increases* linearly with the progression of the teflon bar. The resistance varies from 80 Ω when no shots have been fired to 6 kΩ when all the propellant has been used. The resistance of both propellant strips will be monitored by an external circuit. Since the teflon bars will move a very small amount per pulse, this resistance will be measured only once every 200 pulses with a resolution of 1 Ω.

The final signal will come from monitoring one of the two telemetry thermistors located on the exterior of the main capacitor. The resistance of the thermistor varies as a function of temperature. At -20°C the resistance is 78 kΩ. At 50°C the resistance is 3900 Ω. The resistance of the telemetry thermistor will be monitored by an external circuit.

5 Operation Modes

During the mission, there will be various scenarios for operating the thruster. These operational modes are defined here. A table of operational modes is also included at the end of this paper in figure 12. All "right" or "left" side conventions are shown on the APPT module drawings.

5.1 Power off

In this mode, no power is supplied to the APPT module. The control circuitry will be off, the heaters will not have power, and no command or telemetry signals will be monitored.

5.2 Stand-by

In this mode, the APPT is supplied +27 V from the satellite power bus. The power conditioning circuitry and the chassis heater control will be activated using a total of 0.68 W. The heating system will turn on when the APPT module temperature drops below 50°C. The heating system uses an extra 2.24 W of power when the heater is on. Only the thruster temperature will be monitored on telemetry channels.

5.3 Mode Rs: Right single pulse

In this mode, the APPT will be activated for a single pulse of the right nozzle. During the charging cycle lasting approximately 500 ms, the APPT will use close to 53 W of power. Heating circuitry will also be activated if temperatures drop below 50°C. Both capacitor voltage telemetries and the thruster temperature will be recorded during this mode.

5.4 Mode Rm: Right multiple pulse

In this mode, the APPT will be activated for multiple pulses of the right nozzle at a set rate, 0.89 Hz, to match satellite power supply requirements (25 W with heaters on.) The power conditioning circuitry and the chassis heater control will be activated using a total of 0.68 W during off-charging periods. Both capacitor voltage telemetries, the resistance of the right Teflon bar strip, and the thruster temperature will be recorded during this mode.

5.5 Mode Ra: Right automatic pulse

In this mode, the APPT will be activated for multiple pulses of the right nozzle at an automatic rate set internally by the APPT power conditioning circuitry. This rate corresponds to the maximum allowable pulse frequency, 2.08 Hz. Accordingly, the capacitors will be continually charged and discharged using 53 W of power on average (contingent on COMPASS power supply duty cycle and limitations.) The chassis heater control will also be activated using 0.14 W at 27 V. Although it is not expected in this mode, if the heating system turns on, it will use an extra 2.24 W of power. Both 1530 V and 635 V capacitor telemetry signals, the resistance of the right Teflon bar strip, and the thermistor temperature will be recorded in this mode of operation.

5.6 Mode Ls, Lm, and La

These three modes: left single pulse, left multiple pulse, and left automatic pulse are exactly similar to the right single pulse, right multiple pulse, and right automatic pulse modes, respectively, described in the previous sections. All pulse commands will be sent to the left nozzle only for all of these operational modes.

5.7 Mode Am: Alternate multiple pulse

In this mode, the APPT will be activated for multiple pulses alternating between the right and left nozzles. Command signals will be sent to both nozzles at a frequency of .45 Hz. Average power consumption with heaters on will still have a maximum value of 25 W. The two signals must be 180° out of phase to insure that only one nozzle is commanded to fire at a time.

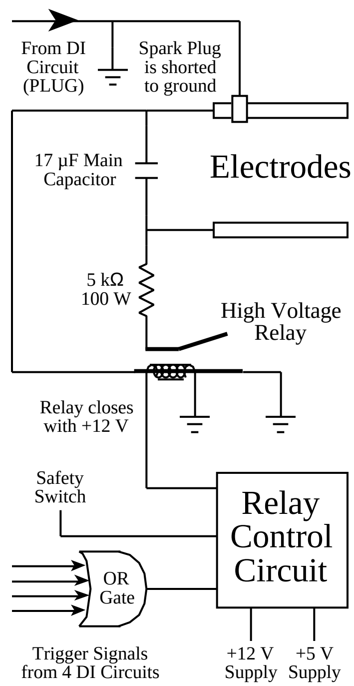

Figure 6: External hardware for relay discharge circuit.

All telemetry channels will be recorded in this mode of operation.

6 APPT Module Preparation and Integration Test

The integration of the LES 8/9 APPT with the Compass Point Satellite includes a final test at atmospheric pressure of all flight-ready electrical components. The LES 8/9 APPT was designed to operate at pressures below 10^{-5} Torr and cannot fully function at atmospheric pressure. Therefore, the flight module circuitry had to be temporarily modified for the test. The requirements for the modifications were: to make the test pulse replicate the real discharge as much as possible, to make the test safe for the operators, and to insure the module could return to normal operating condition after the modifications were removed. All three requirements have been met by installing an external high voltage relay that closes when the command signal is sent to the discharge initiation circuitry. A diagram of the external hardware is shown in figure 6. The relay is connected in series with a 5 kΩ resistance (maximum allowed power

100 W) and the 17 μF main capacitor of the APPT module. The entire package including the relay, resistor, and control circuit is mounted in a small box on the right side of the thruster. The spark plugs of the discharge initiation circuitry are shorted internally, and a cover has been placed over the nozzles to insure safe operation. Finally, the modifications have been kept as simple as possible for easy removal after the integration test.

The relay control circuit is connected to the four spark plug TTL control lines, a safety switch, a 12 V and 5 V power supply, and the relay coil. The control lines are taken off of the main logic board input to the discharge initiation (DI) circuitry. When any of the four spark plug command lines increase to 5 V triggering the spark plug to fire, the relay is closed discharging the main capacitor through the 5 kΩ resistor. A safety switch can also be turned on at any time to close the relay and discharge the capacitor. The control circuit is powered by a 5 V supply with the relay requiring 12 V to close.

For this test, the spark plugs are shorted to ground for safety reasons. This will not allow them to spark and no other discharges will take place at atmospheric pressure. During the test, the main capacitor will reach its normal value of 1500 V and, therefore, requires the electrodes to be covered by a plexiglass shield. All wires to the capacitors and DI circuitry are internal to the APPT module. The relay control circuitry is compact and mounted inside a shielded metal box that has been attached to the module. The wires carrying the spark plug trigger signals to the control circuit are each twisted with a ground wire to insure shielding from EMI and eliminate false signals. All additions, both internal and external, can be removed with minimal effort.

7 Efficiency of the APPT

The efficiency of any electric propulsion device is important for scaling relations and mission planning as well as providing a measure for improvement with new ideas and innovations. For pulsed plasma thrusters, the thrust efficiency is defined as the ratio of the average kinetic energy of the exhaust beam to the energy stored before the discharge. The kinetic energy in the exhaust beam is usually defined by using the impulse bit, I_{bit}, as follows:

$$I_{bit} = m_{bit}\bar{u}_e, \tag{3}$$

$$E_{beam} = \frac{1}{2}m_{bit}\bar{u}_e^2 = \frac{I_{bit}^2}{2m_{bit}}, \tag{4}$$

where the mass bit, m_{bit} is defined as the amount of mass ablated per shot and $\bar{u}_e$ is the effective exhaust velocity. The LES 8/9 APPT uses a capacitor for its energy storage device so the stored energy is a function of the capacitance, C, and the initial voltage, V_0,

$$E_{stored} = \frac{1}{2}CV_0^2. \tag{5}$$

The efficiency, η, for the APPT is then,

$$\eta \equiv \frac{E_{beam}}{E_{stored}} = \frac{I_{bit}^2}{m_{bit}CV_0^2}. \tag{6}$$

The efficiency has been found experimentally by measuring these quantities. Full details can be found in another paper at this conference[10]. A brief explanation will also be given here. The impulse bit is measured by mounting the APPT on a horizontal swing-arm thrust stand and monitoring the velocity of the arm before and after the discharge. The velocity is found through the derivative of a position measurement given by a laser interferometric proximeter system (IPS). Individual impulse bit measurements can be made[9] although for these tests, an average value was used. In fact, all quantities are taken over an average of 300-400 pulses to allow a significant amount of mass to be ablated for accurate measurement. The mass bit is determined by weighing the teflon propellant bar before and after the series of pulses. Repeated removal and replacing of the bar showed no significant erosion. An accurate count of the number of pulses is kept to determine the mass bit. The capacitance is assumed to be 17 μF and the initial voltage is given from the 1530 V telemetry signal.

A series of 436 thruster pulses produced the following results: an average impulse bit of 285 μN-s$\pm$1.7% and an average mass bit of 34.77 μg$\pm$0.7%. With an initial voltage of 1420 V$\pm$1% and a capacitance of 17 μF, the thrust efficiency of the APPT module is 6.8%.

8 Conclusions

Preparation has been made for the October, 1996 space flight of an LES 8/9 APPT module. The thruster will be launched on board IZMIRAN's COMPASS satellite with the experiment being called Mission COMPASS P^{3}OINT. The flight module has been described here including general characteristics and information regarding power, command, and telemetry. Aspects of thermal control have been addressed and operational modes during the mission have been defined. To prepare for pre-flight integration, the moments of inertia and the center of gravity of the APPT module were found, a circuit permitting an atmospheric electrical test was developed, and the performance of the flight module was measured. The module is now ready for the system integration meeting in August.

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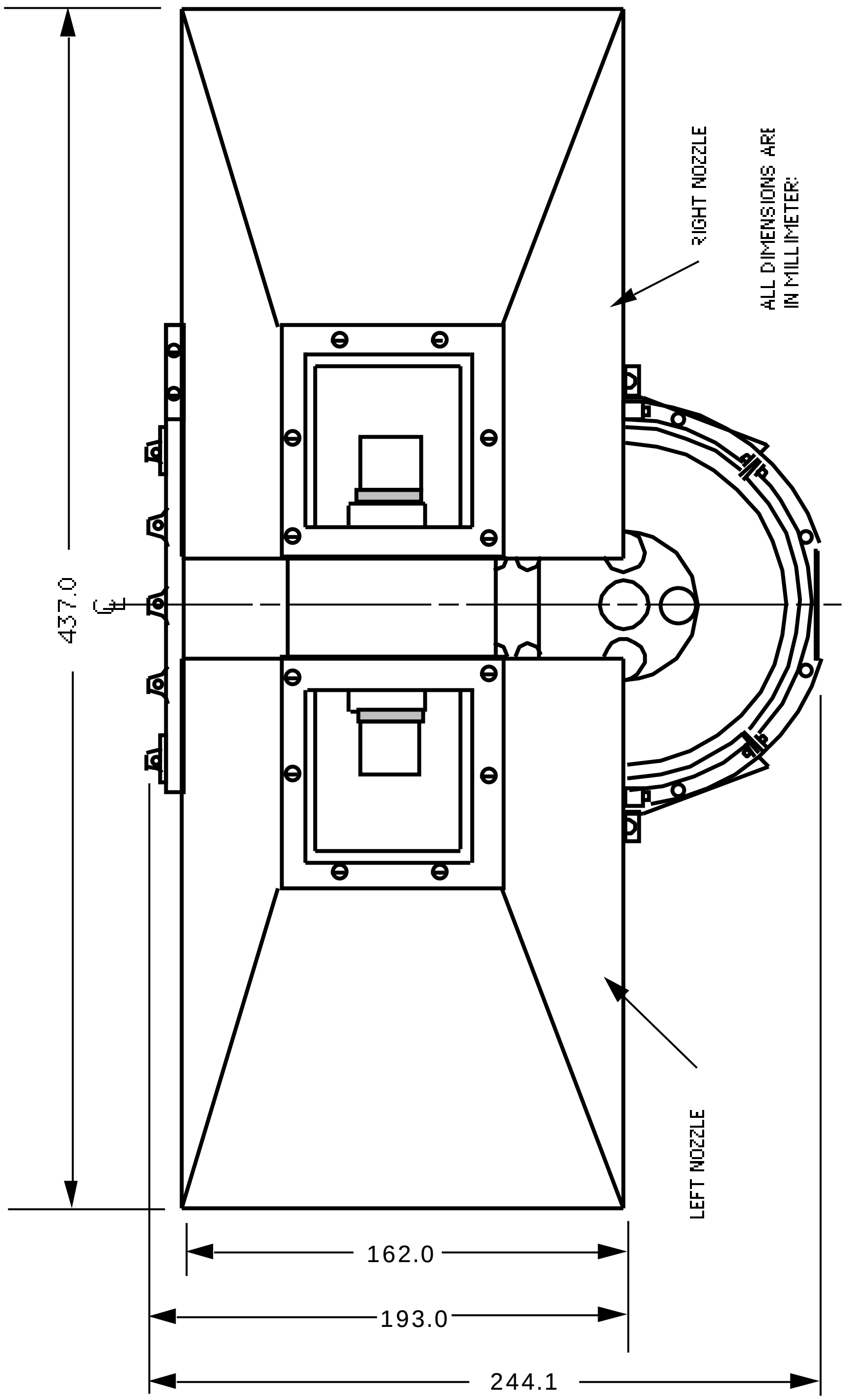

Figure 7: Drawing number 1, front view of APPT.

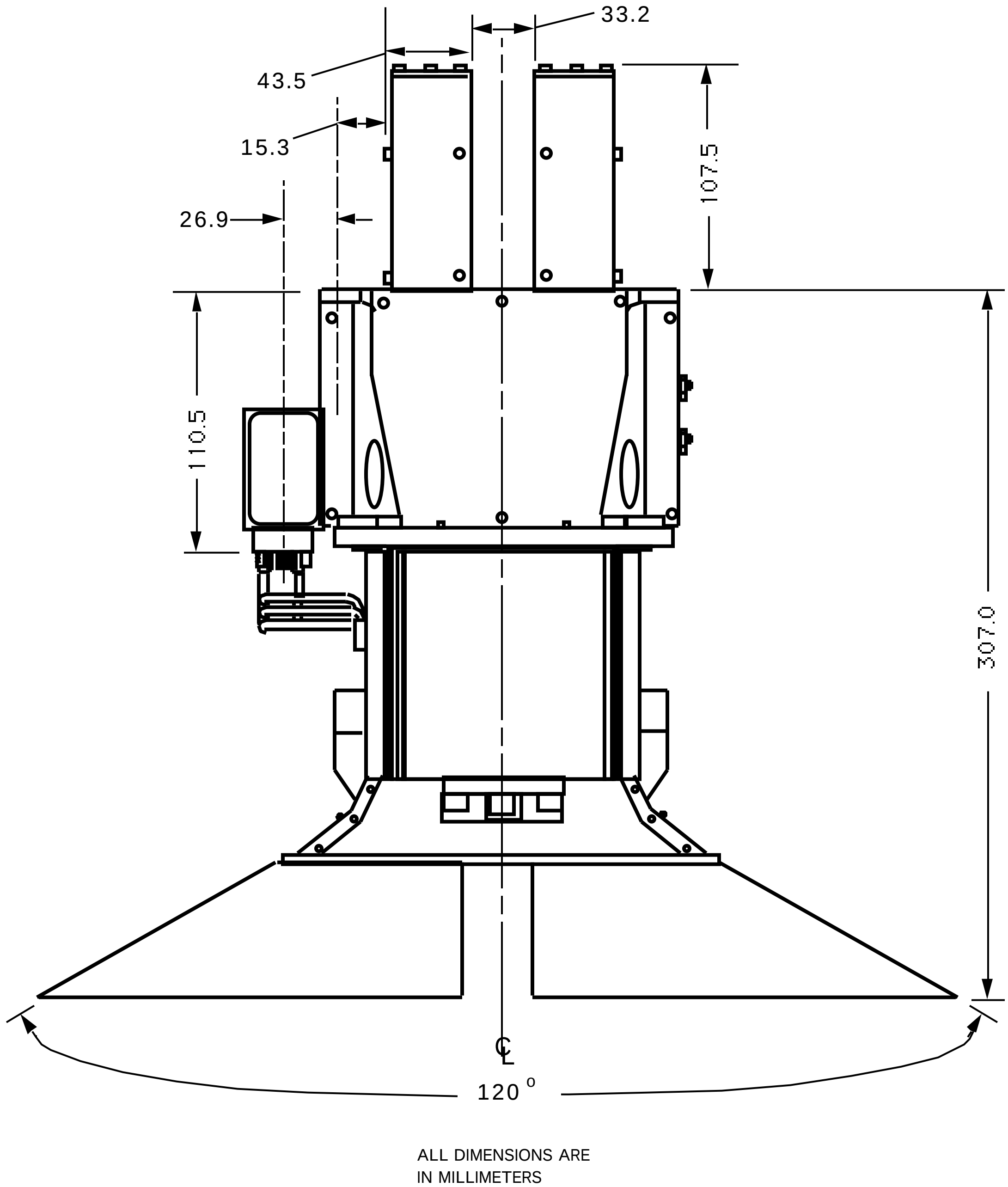

Figure 8: Drawing number 2, bottom view of APPT.

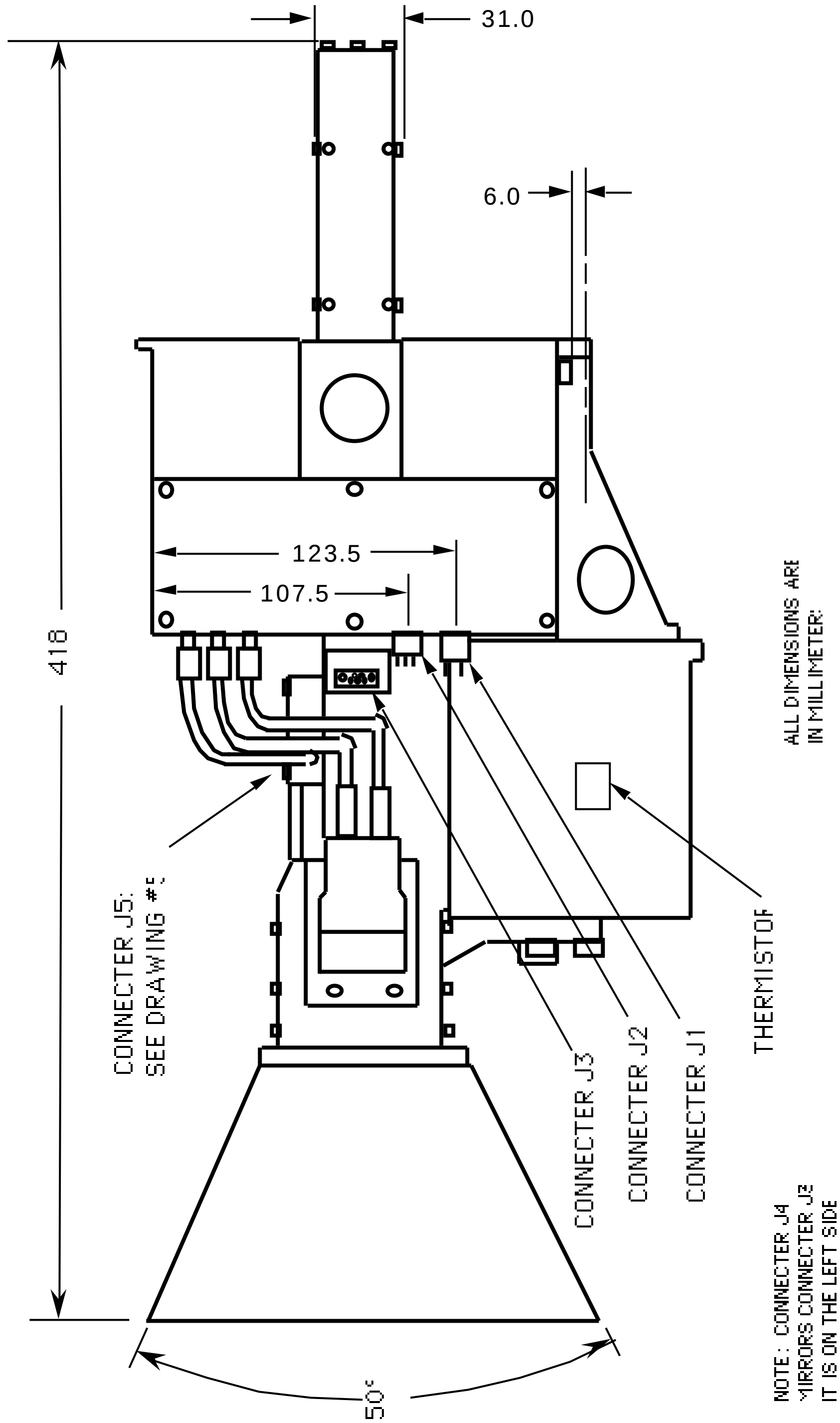

Figure 9: Drawing number 3, side view of APPT.

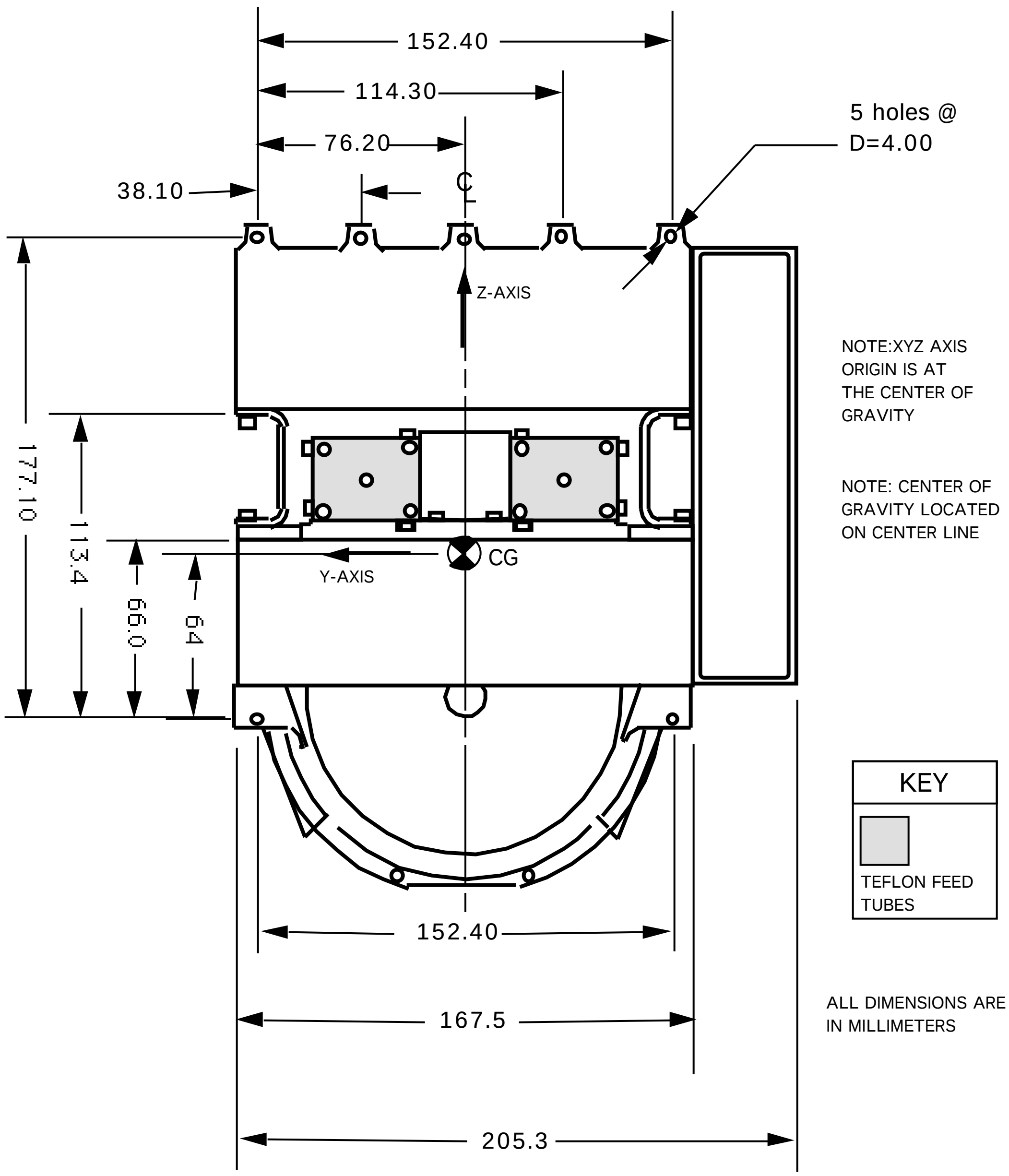

Figure 10: Drawing number 4, back view of APPT.

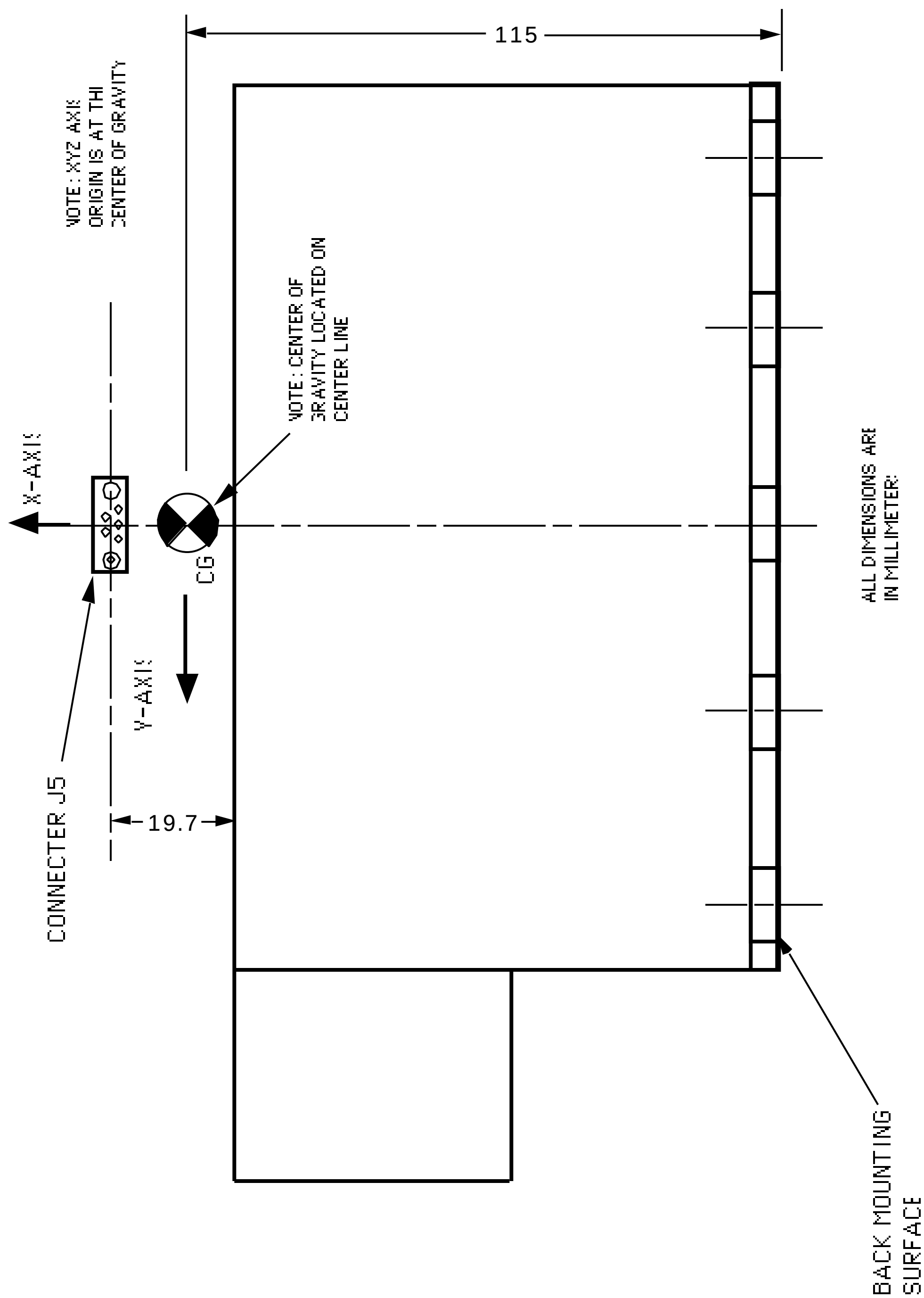

Figure 11: Drawing number 5, top view of APPT.

Mode of Operation	Mode Description	Average Power (W)	Right Nozzle Command Signal	Left Nozzle Command Signal	Thermistor Telemetry	Right Teflon Bar Resistance Telemetry	Left Teflon Bar Resistance Telemetry	1530 V and 635 V Telemetry
Power Off	No power supplied to APPT module	None	None	None	Not required	Not required	Not required	Not required
Stand-By	27 V to APPT power bus, no command signals	0.68 (heater of) 2.92 (heater on)	5 V constant	5 V constant	Yes	Not required	Not required	Not required
Mode Rs: Right single pulse	Right nozzle, single pulse	53.0 plus heater (for 0.5 s charge)	One 0 V signal for 15 ms	5 V constant	Yes	Not required	Not required	Yes
Mode Rm: Right mult. pulse	Right nozzle, multiple pulses	22.8 (heater of) 25.0 (heater on)	Mult. 0 V signals at 0.89 Hz	5 V constant	Yes	Yes	Not required	Yes
Mode Ra: Right auto. pulse	Right nozzle, multiple pulses, automatic rate	53.2 (heater of) 55.4 (heater on)	Continuous 0 V signal	5 V constant	Yes	Yes	Not required	Yes
Mode Ls: Left single pulse	Left nozzle, single pulse	53.0 plus heater (for 0.5 s charge)	5 V constant	One 0 V signal for 15 ms	Yes	Not required	Not required	Yes
Mode Lm: Left mult. pulse	Left nozzle, multiple pulses	22.8 (heater of) 25.0 (heater on)	5 V constant	Mult. 0 V signals at 0.89 Hz	Yes	Not required	Yes	Yes
Mode La: Left auto. pulse	Left nozzle, multiple pulses, automatic rate	53.2 (heater of) 55.4 (heater on)	5 V constant	Continuous 0 V signal	Yes	Not required	Yes	Yes
Mode Am: Alt. mult. pulse	Alternate nozzles, multiple pulses	22.8 (heater of) 25.0 (heater on)	Mult. 0 V signals at 0.45 Hz (180° out of phase with left signal)	Mult. 0 V signals at 0.45 Hz (180° out of phase with right signal)	Yes	Yes	Yes	Yes

*Right and left conventions are shown on APPT module drawings
**Timing and duration of Ra and La modes depend on COMPASS power supply constraints

Figure 12: Table of APPT Operational Modes

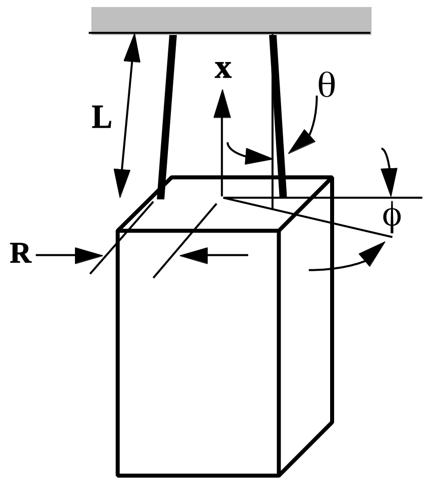

Figure 13: A simplified bifilar pendulum

Appendix

A The Bifilar Method for Measuring the Moment of Inertia

The center of mass and moment of inertia properties of the APPT were needed for the design and integration of the COMPASS Satellite. A method known as the *bifilar pendulum technique* was used to determine these properties. A bifilar pendulum consists of a rigid body suspended by two wires or filaments as shown in figure 13. The dynamical equations of motion in the general case are nonlinear and complicated. The equations of motion can be greatly simplified provided that certain assumptions are not violated. In this case, knowing the natural twisting period of the pendulum system about the vertical axis allows for the calculation of the moment of inertia of the body about this axis. Performing this experiment about six sufficiently different axis of the rigid body allows one to obtain the full moment of inertia tensor.

A.1 Equations of Motion

The non-linear bifilar pendulum equations of motion are most thoroughly treated in ref [11]. However, if care is taken, a simplified model will accurately describe the bifilar pendulum dynamics and yields an expression for the moment of inertia about the vertical axis in terms of the period and other measurable values.

A.2 Simplified Model

Figure 13 shows the simplified bifilar pendulum configuration. This model assumes that the axis of rotation passes vertically through the center of mass and that it is equidistant from the two wires. In this case, the wires have the same tension equal to one half of the weight (W) of the body. The wires provide a restoring force whenever the rigid body is rotated about the x axis. The sum of moments (M_x) from the wires, for small displacements, is:

$$\Sigma M_x = WRsin(\theta) \approx WR\theta. \tag{7}$$

The desired moment of inertia about the x axis (I_{xx}) can be introduced using Newton's Law,

$$WR\theta = I_{xx}\ddot{\phi}. \tag{8}$$

Using the geometric relation

$$L\theta = R\phi \tag{9}$$

an equation of motion for the θ dimension can be written:

$$\ddot{\theta} = \frac{WR^2}{LI_{xx}}\theta. \tag{10}$$

This simple harmonic oscillator system has a natural frequency (ω) given by

$$\omega = \sqrt{\frac{WR^2}{LI_{xx}}}. \tag{11}$$

Rearranging eq.. 11, using $D = 2R$, and writing τ for the natural period gives an expression for I_{xx} in terms all measurable quantities:

$$I_{xx} = \frac{WD^2\tau^2}{16\pi^2 L}. \tag{12}$$

A.3 Torsional Correction

A correction to Eq.. 12 must be made to account for the torsional effects of the wires. Modifying Eq.8 to account for this additional torque gives

$$WR\theta + 2\frac{GJ}{L}\phi = I_{xx}\ddot{\phi} \tag{13}$$

where G is the shear modulus and J is the polar moment of inertia of the wire. The expression GJ/L

is the twisting spring constant k_{eff} of the wire according to strain theory. Combining Eq.. 9 and 13 and solving the harmonic system gives the correction term for I_{xx} as

$$I_{torsion} = \frac{GJ\tau^2}{2\pi^2 L} = \frac{k_{eff}\tau^2}{2\pi^2} \tag{14}$$

which agrees with ref.[12]. The final equation used for I_{xx} is

$$I_{xx} = \frac{WD^2\tau^2}{16\pi^2 L} + \frac{k_{eff}\tau^2}{2\pi^2} \tag{15}$$

A.3.1 Torsional Spring Constant Measurement

k_{eff} can be measured experimentally by suspending an object from one of the wires and measuring the torsional period. By knowing the moment of inertia (I_{test}) of the test body, the harmonic relation

$$\frac{2\pi}{\tau_n} = \sqrt{\frac{k_{eff}}{I_{test}}} \tag{16}$$

and the natural period (τ_n) by experiment, k_{eff} can be obtained and used in eq. 14.

B Moment of Inertia Matrix

Section A.1 provides a means of determining the moment of inertia of the thruster about a vertical axis. In order to construct the full moment of inertia tensor (**I**), the experiment must be repeated with the thruster suspended in six different orientations. Since **I** is a symmetric matrix, three of the nine elements are repeated. Once six moments of inertia have been measured about six sufficiently different axis on the thruster, **I** can be determined for any coordinate system desired. **I** is constructed from the measured values through the use of a rotation transformation.

B.1 Rotation Transformation

The moment of inertia tensor transforms under a rotation according to the following relation[14]

$$\mathbf{I^a} = (\mathbf{R^{ab}})^{-1}\mathbf{I^b}\mathbf{R^{ab}} \tag{17}$$

where R^{ab} transforms from the a frame to the b frame. This equation allows a measured moment of inertia about an arbitrary axis to be related to the moments of inertia about the desired axes. Several such measurements must be made to determine the entire moment of inertia tensor in the desired frame.

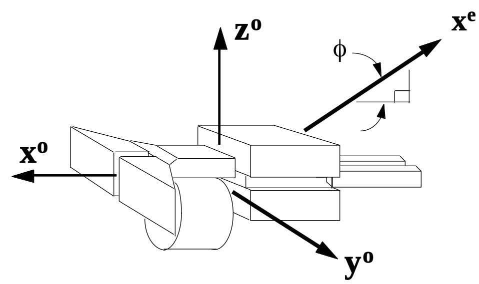

Figure 14: The LES 8/9 APPT reference frame and a sample x axis orientation.

B.2 Selecting the Necessary Independent Measurements

Six orientations of the thruster need to be selected. Each experiment will provide a value for the moment of inertia I_{xx} about the x^e axis as labeled in figure 13 and will provide one equation of the form of eq. 17,

$$\begin{bmatrix} I^e_{xx} & - & - \\ - & - & - \\ - & - & - \end{bmatrix} = (\mathbf{R^{eo}})^{-1} \begin{bmatrix} I^o_{xx} & I^o_{xy} & I^o_{xz} \\ I^o_{yx} & I^o_{yy} & I^o_{yz} \\ I^o_{zx} & I^o_{zy} & I^o_{zz} \end{bmatrix} \mathbf{R^{eo}} \tag{18}$$

where I^o represents the moment of inertia tensor of the thruster in the desired frame. Figure 14 shows the **o** frame and an x^e axis for which the moment of inertia (I_{xx}) is measured in one experimental configuration. For example, a right handed rotation of the o frame about the y^o axis (see figure 14) of amount ϕ would align the x^o axis and the x^e axis of the experiment. Such a rotation is represented by the rotation matrix

$$R^{eo} = \begin{bmatrix} cos\phi & 0 & sin\phi \\ 0 & 1 & 0 \\ -sin\phi & 0 & cos\phi \end{bmatrix}. \tag{19}$$

Placing this into eq. 18 and writing the expression for the element I^e_{xx} gives

$$c^2 I^o_{xx} - 2scI^o_{xz} + s^2 I^o_{zz} = I^e_{xx} \tag{20}$$

where c and s represent the cosine and sine respectively of the angle ϕ. One can see that after three different values of I^e_{xx} have been obtained from experiment I^o_{xx}, I^o_{xz} and I^o_{zz} can be solved for and another measurement in the xz plane would be redundant. In this case, I^o_{xy} and I^o_{yy} can then be obtained from two different measurements of the moment of inertia in the xy plane and lastly I^o_{yz} from a measurement in the yz plane.

All moments of inertia for the flight model have been found using this method. The results are presented in section 3.1.