Systems-Level Trade Studies of a Dual-Mode SPT for Geosynchronous Communications Satellites[*][†]

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Electric propulsion has been shown, in theory and in practice, to provide significant mass benefits for geosynchronous communications satellites (GEOs). In particular, the Russian Hall-effect thruster SPT-140 is well-suited to the dual demands of GEO orbit raising and stationkeeping. The GEO mass benefits could be increased even further with a dual-mode SPT-140 subsystem, i.e. one that is designed for optimal performance in two different modes. This paper will present the results of systems-level trade studies of a dual-mode subsystem, based on the SPT-140 subsystem now under development, for GEO stationkeeping. The major factors that will be investigated are: propellant mass, spacecraft power budget, power processing unit architecture, thruster operating conditions, and thruster lifetime. It will be shown that significant benefits can be realized by adding only a single 600 V operating condition to the baseline 300 V operation. It will also be shown that a dual-mode subsystem can be tailored to operate within a strict spacecraft power budget, that additional mass gains are realized with a continuously variable discharge voltage, and that thruster operation at higher discharge voltages does not significantly reduce the thruster lifetime. Finally, a higher-I_{sp} operating condition can be used, most of the time, with little or no additional impact to the power system.

Introduction

Numerous studies have shown the considerable benefits of electric thrusters, specifically Hall and ion thrusters, for stationkeeping and orbit raising of geostationary satellites [1-6]. The studies almost invariably conclude that ion thrusters have an advantage for stationkeeping because of their higher specific impulse (I_{sp}), while Hall thrusters have an advantage for orbit raising because of their larger thrust and hence shorter trip times [1-4]. In addition, one study concluded that for a combined chemical-electric orbit-raising mission the optimum electric-thruster I_{sp} was close to that of a typical Hall thruster [7]. A separate study of combined orbit-raising/stationkeeping missions concluded that an optimum combined mission I_{sp} existed depending on the mission parameters [3], indicating the usefulness of a single variable-I_{sp} technology.

While state-of-the-art Hall thrusters have I_{sp}'s in the range of 1500-1800 sec [6,8] and ion thrusters operate best at I_{sp}'s greater than 2500 sec [9], each type of thruster can be designed to operate in the optimum range of the other. A recent study [1] specifically examined the benefits of constant-power, variable-I_{sp} Hall and ion thrusters for a combined orbit-raising/stationkeeping mission. This study (an outgrowth of the work in Ref. 3) found that Hall thrusters slightly outperformed the ion thrusters for the combined mission, largely because of the larger energy requirements (i.e. ΔV) of the orbit-raising phase of the mission. It also correctly noted that the lifetime impacts of operating outside of the normal I_{sp} range must be investigated for each type of thruster.

It is clear from these studies that, while Hall thrusters provide significant benefits for orbit raising and stationkeeping of geosynchronous communications satellites (GEOs), still greater benefits can be realized with increased I_{sp} for the stationkeeping portion of the mission. The study presented here will focus on the mass benefits of a variable-I_{sp} SPT-140 subsystem (i.e. a "dual-mode SPT") for GEO stationkeeping. An auxiliary benefit of the dual-mode SPT subsystem is flexible use of the spacecraft power system. A patent-pending system which uses available excess solar array power at the beginning of life, then scales back in power to reduce impact to the spacecraft batteries at the end of life, will be discussed. Finally, the impacts of operating at higher voltages on the SPT-140 lifetime will be assessed.

Assumptions and Methods

Thruster Performance Model

The performance of the SPT-140 at discharge voltages higher than the nominal 300 V operation point was modeled based on data taken from the SPT-140 DM3 tests performed at the NASA Glenn Research Center in 1999 [10]. Simple expressions, derived from basic performance equations and curve fit to the data, were used to model the thrust and I_{sp} based on thruster discharge current and voltage. These expressions, shown in Eqs. 1 and 2, are similar in functional form to relationships presented elsewhere [e.g. Ref. 11]:

$$T = 1.31 J_D \sqrt{V_D - 85.6} \quad \text{mN} \qquad (1)$$

$$I_{sp} = (101 + 1.37 J_D)\sqrt{V_D - 85.6} \quad \text{sec} \qquad (2)$$

where T is the thrust (in mN), I_{sp} is the specific impulse (in seconds), J_D is discharge current (in Amps), and V_D is discharge voltage (in Volts).

Thruster current and voltage for this study were limited to an operating envelope chosen based on experience with the SPT-140 and other members of the SPT family [10,12,13]. These limits were represented by a triangular shape in current-voltage space, as shown in Fig. 1: the minimum discharge current was 6.67 A; the minimum discharge voltage was 250 V; and the third leg of the triangle was a line defined by the points 250 V, 20 A, and 600 V, 10 A. The thruster was allowed to operate only within the triangle of Fig. 1.
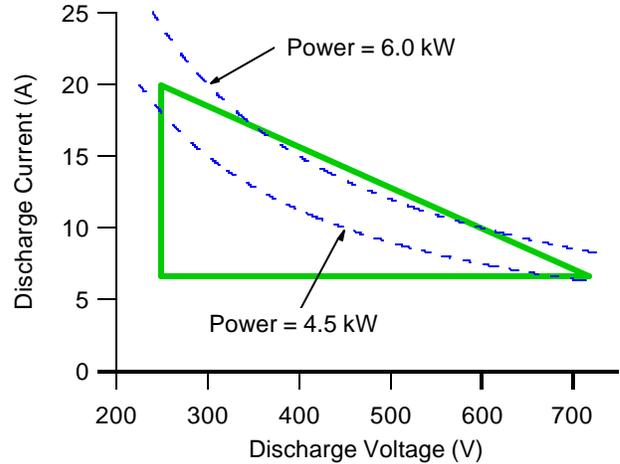

Fig. 1. Assumed Thruster Operation Envelope.

The SPT-140 requires a magnet power supply in addition to the discharge power supply. The magnet power during the DM3 testing varied with discharge current and voltage, but was typically in the range of 30-90 Watts [10]. For simplicity, the magnet power was not included in the propulsive power budget for this study.

PPU Architecture

Since members of the SPT family have already been shown to be adaptable for operation at higher voltages and powers, development of a dual-mode subsystem would largely be a PPU technology development effort. The PPU for the dual-mode SPT subsystem must be able to provide the different ranges of discharge current and voltage required by the thruster.

The PPU-140, which has been developed at SS/L in conjunction with the SPT-140 development, produces a constant discharge voltage of 300 V and is throttleable from 3.0 to 4.5 kW of discharge power. The discharge supply is made of three 1.5-kW anode converters operating in parallel in a zero-voltage switching mode [14]. The three anode converters together operate with an efficiency of greater than 95%.

Several new architecture options of varying complexity were considered for this study, and were compared to each other and the baseline PPU-140 configuration. The analyses presented here concentrated on three options for the PPU discharge voltage architecture. The first option was a "dual-mode" PPU that can operate at 300 or 600 V. This can be accomplished by "stacking"

the individual anode converters to provide either 300 V or twice that voltage. The second was a PPU which had a pair of "stacked" voltages, where the thruster could operate either at 300 or 600 V, or at 337.5 or 675 V. The 337.5/675 V stack was chosen to maximize the discharge voltage for stationkeeping at 4.5 kW, but in principle any other voltage stack could be considered. The third was a PPU with continuously variable voltage from 250 V to as high as 700 V.

For each PPU configuration, it was assumed that the discharge current was throttleable, as in the baseline PPU-140. Discharge power levels of up to 6.0 kW, a convenient multiple of the 1.5-kW anode blocks, were investigated.

Satellite and Mission Assumptions

Satellite and mission parameters were chosen based on a hypothetical high-power GEO satellite which might be designed, built, and launched within the next few to several years. The analysis was performed for the stationkeeping mission only, assuming that the required wet mass was delivered into the final orbit at the beginning of the spacecraft serviceable life, regardless of the orbit-raising method. A fifteen year mission life was assumed, with a spacecraft dry mass of 3500 kg.

North-south stationkeeping (NSSK) was performed by the SPT subsystem, with an average yearly ΔV requirement of 48.5 m/s. The thruster cant angle (i.e. the angle between the thruster centerline and the North-South direction) was 42.5°. A fixed PPU efficiency of 95% was assumed for all architectures. East-west stationkeeping (EWSK) was performed with the bipropellant system, and the propellant mass was tracked throughout mission life assuming a typical thruster specific impulse, cant angle, and ΔV requirement. Fixed xenon and bipropellant residuals were taken from a standard spacecraft propellant budget. The residuals account for in-orbit test, momentum wheel unloads, and dispersion in nominal thruster parameters.

The spacecraft power system was sized for an end-of-life power of 15 kW. A typical variation in solar array power output with season (e.g. accounting for the distance from the sun) and lifetime (e.g. accounting for radiation degradation) was assumed [15]. The payload and bus power consumption requirements were 13 kW. The batteries were sized at 11,250 Watt-hours. For simplicity, battery charge requirements were not included in the power budget.

Analysis Method

The fifteen-year satellite mission life was broken into sixty discrete seasonal periods (e.g. year five vernal equinox, year five summer solstice, etc.). Power availability, thruster operating parameters, and xenon mass requirements were determined uniquely for each season. The calculations were performed in the following manner, working backwards from the spacecraft end-of-life condition of 3500 kg dry mass plus propellant residuals.

The available power from the solar arrays was determined for the seasonal period from a lookup table, and the payload and bus power requirements were subtracted to yield the excess array power available for propulsive maneuvers. A decision about thruster operating conditions was made based on the excess array power, PPU architecture, and thruster operating envelope. The total propulsive power required, which included the PPU efficiency, was then determined. The difference between the excess array power and the propulsive power was the power required to be drawn from the batteries.

Thrust and I_{sp} were determined from Eqs. 1 and 2. The xenon mass required for NSSK during the season under question was then determined from the rocket equation using the I_{sp}, thruster cant angle, seasonal ΔV requirement, and the satellite wet mass. Assuming two burns per day (one burn each for two thrusters), the SPT burn time was approximated using the following expression:

$$t_{burn} = \frac{\Delta V_{NSSK} M_{wet}}{T} \qquad (3)$$

where ΔV_{NSSK} is the ΔV requirement per day per burn, M_{wet} is the satellite wet mass for the season under question, and T is the SPT thrust. Bipropellant mass requirements for EWSK were determined in a fashion similar to the xenon mass requirements. The satellite wet mass was updated every season by adding the propellant masses to the wet mass from the previous calculations. Finally, the battery depth-of-discharge was determined using the power draw required from the batteries, the SPT burn time, and the total battery capacity.

Analysis for Reduced Power System Impact
A unique feature of the dual-mode SPT subsystem is that it allows for flexible use of the spacecraft power system. Specifically, the SPT can draw more power and perform its functions more efficiently in the beginning of mission life, where excess solar array power is plentiful, and then scale back to a lower power near the end of life to reduce the impact on the power system.

For analysis of some of the cases presented here, a limit was set for the maximum power that could be drawn from the batteries, and the thruster operating conditions were chosen based on the excess array power available and that limit. For example, if the battery draw limit was set at 1500 W and the excess array power available was 2700 W, the total power available for propulsive maneuvers would be 4200 W. Accounting for the PPU efficiency, the thruster discharge power could then be as high as 3990 W.

Thruster discharge current and voltage could be varied within the allowable power range and operating envelope to select the optimum operating conditions. For this analysis, the optimum was always the highest discharge voltage (i.e. highest I_{sp}). For example, if the thruster discharge power was limited to 3990 W and the PPU architecture was chosen to allow any voltage up to 700 V, the thruster operating conditions would be 6.67 A and 598 V (i.e. the discharge voltage is maximized while maintaining the discharge current at its minimum level). As an additional example, if the thruster discharge power was limited to 3000 W and the PPU architecture was chosen to allow only voltages of 300 V and 600 V, the thruster operating conditions would be 300 V and 10 A (if 600 V was chosen the current would have been 5 A which is outside of the thruster operating limits of Fig. 1).

Results

The primary advantage of implementing a dual-mode SPT subsystem for GEO spacecraft is the reduction of xenon mass necessary for stationkeeping that accompanies the increase in thruster specific impulse. With this in mind, the first analysis that was performed bounded the xenon mass requirements for the stationkeeping mission. Shown in Table 1 are the results for several thruster operating conditions, assuming that all NSSK operations were performed at a single prescribed voltage and power level throughout the mission life. The thruster performance for each case is also shown in the table for reference.

Table 1 shows that the baseline SPT-140 subsystem requires a xenon mass of 244 kg for the stationkeeping mission. A marginal decrease in mass (12 kg) is realized by operating the baseline system at a higher power of 6.0 kW, but much greater achievements are made by operating at higher discharge voltages. The improvements over the baseline for the four higher-voltage cases are all greater than 60 kg, while the differences between those higher-voltage cases are 15 kg or less.

The xenon mass savings shown in Table 1, however, come at a cost to the spacecraft power system. The power system impact, which for this analysis was quantified by maximum battery draw and depth-of-discharge (DoD), is shown in Table 2 for the same mission cases as shown in Table 1. The maximum

Table 1. Effects of Discharge Voltage and Power on Xenon Mass Requirements
(Operation at Fixed Voltage and Power).

Discharge Voltage (V)	Discharge Power (kW)	Thrust (mN)	I_{sp} (sec)	Xenon Mass Required for Stationkeeping Mission (kg)	Mass Savings Compared to Baseline (kg)
300	4.5	288	1780	244	0
600	4.5	223	2524	180	64
675*	4.5	212	2674	171	73
300	6.0	384	1880	232	12
600	6.0	297	2601	175	69
700	6.0	278	2795	165	79

* This is the highest discharge voltage allowed based on the thruster operating envelope of Fig. 1.

Table 2. Effects of Discharge Voltage and Power On Spacecraft Power System
(Operation at Fixed Voltage and Power).

Discharge Voltage (V)	Discharge Power (kW)	Maximum Thruster Firing Time (min)	Maximum Battery Draw (W)	Maximum Battery DoD (%)
300	4.5	20	3350	9.4
600	4.5	26	3350	12.2
675	4.5	27	3350	12.8
300	6.0	15	4930	10.4
600	6.0	19	4930	13.4
700	6.0	21	4930	14.3

battery draw is a large fraction of the thruster discharge power, indicating that near the end of spacecraft life where less excess power is available, most of the thruster power must be supplied by the batteries. The firing time increases in Table 2, due to the reduced thrust at higher voltages, cause the battery DoD increases at constant power.

Power System Flexibility
The xenon mass calculations shown in Table 1 indicate the best-case mass savings for the given satellite assumptions, while the battery calculations in Table 2 show the worst-case impact to the satellite power system. The xenon mass and battery impacts can be traded against each other, however, with flexible use of the spacecraft power available for propulsive maneuvers. This is accomplished by limiting the thruster discharge power, which reduces the impact to the spacecraft power system but also reduces the I_{sp}, thus increasing the xenon mass required for stationkeeping.

Xenon mass and power system impacts were investigated for the three PPU architecture options discussed previously, where the maximum battery draw was limited to a pre-determined level. The results are compared in Table 3 to the baseline SPT-140 subsystem for a maximum discharge power of 4.5 kW and a maximum battery draw of 1500 W.

The xenon mass savings for the simplest of the alternative PPU architectures, the dual-mode, is 38 kg while the greatest savings of 65 kg is achieved with the continuously variable voltage supply. The relatively large difference in mass savings between those two architectures is a result of the voltage variation scheme: if the maximum pre-set battery draw limit would barely be exceeded at 600 V with the minimum allowable discharge current, for example, the dual-mode architecture must drop down to 300 V while the variable voltage architecture could simply ramp down the voltage to 599 V and retain a mass-saving high I_{sp}. The xenon mass for the baseline PPU architecture

Table 3. Xenon Mass and Power System Impact Comparison
(Operation at 4.5 kW Maximum Power and Fixed Battery Draw Limit)

PPU Voltage Architecture	Allowable Discharge Voltage (V)	Battery Draw Limit (W)	Maximum Battery DoD (%)	Xenon Mass (kg)	Mass Savings Compared to Baseline (kg)
Baseline	300	1500	6.9	247	0
Dual-Mode	300, 600	1500	6.9	209	38
Stacked Pair	300, 600 337.5, 675	1500	7.2	200	47
Continuously Variable	250-675	1500	7.7	182	65

increases by three kilograms with the imposed battery draw limit, compared to operation at a fixed 4.5-kW discharge power, and the maximum DoD decreases from 9.4% to 6.9%. Maximum DoD increases slightly with PPU complexity compared to the baseline PPU.

Figure 2 shows the variation in xenon mass and maximum DoD with battery draw limit for the dual-mode architecture at a maximum thruster power of 4.5 kW. For this case, the maximum battery draw possible is 3350 W, corresponding to thruster operation at 600 V for the whole mission life (see Table 2). Note that xenon mass is sensitive to the battery draw limit: a limit of 2000 W would increase the mass savings shown in Table 3 for this case from 38 kg to 56 kg. Recall that the maximum savings possible from Table 1 was 73 kg (i.e. operation at 675 V throughout the mission life with no battery draw limit).
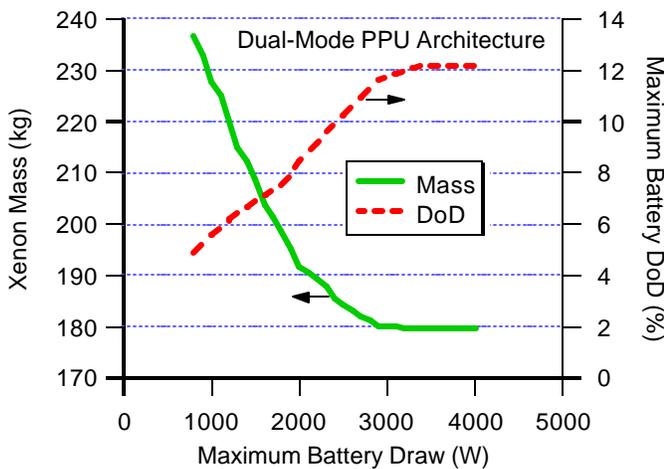

Fig. 2. Effect of Battery Draw Limit on Xenon Mass and Battery DoD for Dual-Mode PPU Architecture.

The sensitivity of xenon mass to maximum battery draw becomes clear when the thruster operating conditions over the whole sixty-season spacecraft mission are considered. Shown in Fig. 3 are the number of seasons of operation at 300 V and at 600 V as a function of battery draw limit for the same mission conditions as Fig. 2. As the battery draw limit is increased from 1000 W, more and more of the thruster operation is performed at the 600-V condition with its higher I_{sp}, and thus more propellant mass is saved.

Figure 4 shows the mass savings possible for each of the PPU architecture options relative to the baseline
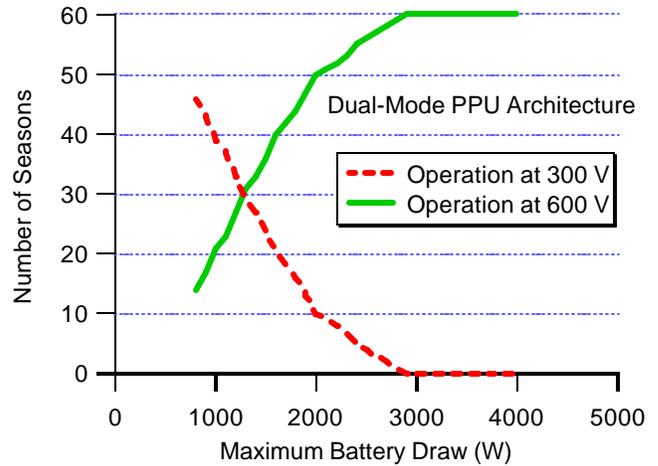

Fig. 3. Effect of Battery Draw Limit on Thruster Operating Conditions for Dual-Mode PPU Architecture.

PPU-140 as a function of maximum battery draw limit for operation at 4.5 kW maximum. It can be seen that the simplest of the PPU options, the dual-mode, captures the bulk of the mass savings at all but the lowest battery draw limits. If the battery draw is not restricted, the variable voltage supply saves only an extra 8 kg of mass. Thus, significant mass gains can be achieved with the relatively simple dual-mode PPU. Larger gains are possible with a continuously-variable power supply, but at the expense of much greater PPU complexity and thus development costs.

Note that, although the analyses presented here have been performed with a limit on the maximum battery
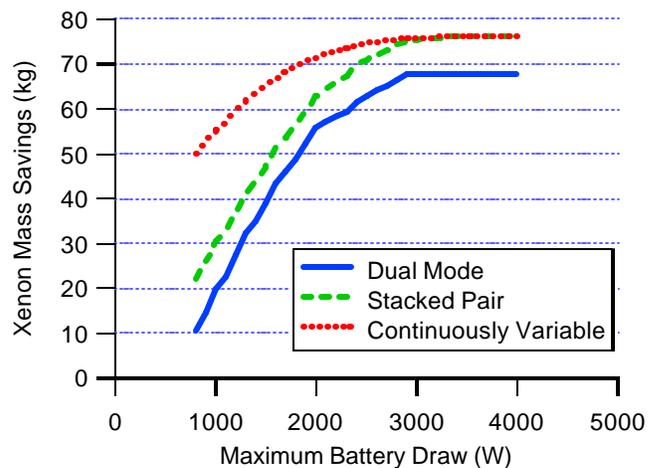

Fig. 4. Xenon Mass Savings for Three PPU Architectures Compared to Baseline PPU-140.

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draw while the DoD was allowed to vary, it is straightforward to perform a similar analysis in which the maximum DoD is fixed while the battery draw is allowed to vary.

Thruster Lifetime

The primary life-limiting factor for the SPT is erosion of the ceramic discharge chamber walls from incident ion sputtering. At higher operating discharge voltages, the ion energies and thus sputter yields will increase, hence the concern over thruster lifetime. Thruster lifetime as measured by total impulse does in fact decrease with increasing discharge voltage [16]. At constant power, however, the discharge current and thus ion current impacting the walls will be reduced, counteracting the higher sputter yields.

Reference 16 presents a thruster lifetime scaling expression for thrusters of different geometries and powers which accounts for the higher ion energies and higher doubly-charged ion fractions that are present when operating at higher discharge voltages. For thrusters of identical geometries (or for the same thruster operated at different powers) the scaling expression reduces to:

$$tP = t_0 P_0 \qquad (4)$$

where t is the thruster lifetime, P is the thruster discharge power, and $t_0 P_0$ represents the lifetime-power product at some reference condition. The SPT-140 lifetime is greater than 6300 hours at the 300 V, 15 A operating condition [8], which gives a reference condition of 2.8×10^7 W-hrs.

Equation 4 was generalized for this study to account for operation at many different power levels over the life of a single SPT-140 type thruster. The generalized criteria for thruster lifetime is:

$$\sum_n t_n P_n \leq 2.8 \times 10^7 \text{ W - hrs} \qquad (5)$$

where P_n and t_n are the power levels and cumulative thruster firing times for the nth season. The time-power product is summed over all seasons and must be less than the reference time-power product for the thruster in order to achieve the mission within the design lifetime. Equation 5 provides a guideline for estimating thruster life requirements, and should be verified by additional work.

Table 4 shows the thruster life requirements (in time-power product) for the stationkeeping mission for several PPU architectures at a 4.5-kW maximum power. It can be seen that the life requirements are well below the design life of the thruster of 2.8×10^7 W-hrs. The higher-voltage cases in general have larger life requirements because, for the same power level, the thruster must fire for a longer duration to achieve the same impulse. Even for the continuously variable voltage case where the stationkeeping mission uses 10^7 W-hrs, there is still sufficient life for 4000 hours (i.e. 167 days) of orbit-raising at 4.5 kW and 300 V. Note that operation in the battery-limited dual-mode case only uses 16% more life than the baseline case.

Table 4. Thruster Life Required for Stationkeeping with Different PPU Architectures – 4.5 kW Maximum Power.

PPU Voltage Architecture	Allowable Discharge Voltage (V)	Battery Draw limit (W)	Thruster Life Required for Stationkeeping Mission (W-hrs)
Baseline	300	None	8.1×10^6
Dual-Mode	300, 600	None*	1.0×10^7
Dual-Mode	300, 600	1500	9.4×10^6
Stacked Pair	300, 600 350, 700	1500	9.7×10^6
Continuously Variable	250-700	1500	1.0×10^7

*This option is equivalent to operating solely at 600 V.

Conclusions

The analyses presented here indicate that there is much to be gained from a dual-mode SPT subsystem for large geosynchronous communications satellites. For the stationkeeping mission considered in this study, xenon mass savings of nearly 80 kg are possible with a thruster of the SPT-140 type when operating at 6.0 kW and 700 V. Retaining the design heritage of the PPU-140 and SPT-140 at the 4.5-kW operating power, however, only reduces the possible mass savings to 73 kg. It was shown that a tailored SPT subsystem can utilize excess solar array at the beginning of the spacecraft life, thereby decreasing the xenon mass required for stationkeeping, then reduce its power consumption near the end of life to minimize the impact to the power subsystem. The relatively simple PPU modification of adding a 600 V operating point to the nominal 300 V point captures the majority of the xenon mass savings and power system flexibility. Greater performance can be achieved by utilizing successively more complex PPU architectures. Finally, based on a generalized thruster lifetime scaling relationship, it was shown that operation of the SPT-140 at 600 V or greater for stationkeeping does not significantly reduce the thruster lifetime and leaves ample life for substantial electric orbit raising.

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