Ionic versus Chemical Propulsion: A Comparative Study

Ascher Oppenheim

Abstract:

As satellites become increasingly central to global communication and navigation, maintaining their precise orbital positioning has become a critical and recurring challenge. Satellites in geostationary orbit experience orbital drift caused by Earth's uneven gravitational field, requiring frequent station-keeping maneuvers throughout their operational lifetimes. This study compares two propulsion methods commonly used for these corrections—the SPT-140 Hall-effect ion thruster and the R-42 bipropellant rocket engine—to determine which is optimal for orbital drift correction. Using a representative scenario of a 6,600 kg communications satellite drifting 0.05° from its assigned position in geostationary orbit, both engines were evaluated under identical mission conditions across thrust output, specific impulse, and operational cost. A sensitivity analysis varied each thrust parameter from 50% to 150% of its standard value to assess reliability, and the thrust and impulse required for the maneuver were calculated and compared against each engine's capabilities. The results show that while the R-42 produces over 11,000 times more thrust, this excess power is a liability for fine maneuvering, limiting it to a burn of roughly 0.04 seconds compared to the SPT-140's controllable 489-second burn. The SPT-140's specific impulse of 2,100 seconds far exceeds the R-42's ~312 seconds, and despite its costlier xenon propellant, its high fuel efficiency reduces operating cost to approximately $1.00 per minute versus the R-42's $4,275.00. These findings indicate that the SPT-140 ion thruster is the superior choice for orbital drift correction, offering greater precision, efficiency, and cost-effectiveness for routine satellite station-keeping.

Intro:

As Space travel becomes more common and technology advances, humans have come to rely increasingly on the data and signals provided by satellites. They are the backbone of our communication systems and our navigation. Because of this, it is important to consider the optimal ways to maintain them. For many satellites in orbit, adjustments are required once they leave the atmosphere. To do so, they use smaller thrusters to propel them where they need to be. Two examples of such thrusters would be the Stationary Plasma Thruster (SPT-140), a Hall-Effect Ion thruster, or the R-42 Bipropellant rocket engine. These are the two thrusters selected for this case study, and they are compared to determine the optimal thruster type for orbital adjustments. In this study, we devised a scenario to replicate a realistic challenge. This study provides mission planners and aerospace engineers with a rigorous, evidence-based foundation for selecting the most efficient propulsion method; ultimately contributing to more efficient and cost-effective satellite operations.

Methods:

For the purpose of this study, both thrusters were evaluated under identical mission conditions with the goal of identifying which thruster would be the most optimal for standard maneuvers that take place during the operational lifetime of the average satellite. Values such as thrust, cost-efficiency, and specific impulse were calculated for each thruster.

In his textbook, *Rocket Propulsion Elements*, George P. Sutton defines thrust as “the force produced by the rocket propulsion system acting at the vehicle’s center of mass.” [1]. Thrust is represented by the equation $F = \dot{m} ve + (pe - pa)Ae$, where F is the thrust in Newtons, $\dot{m}$ is the propellant mass flow rate in kg/s, v_e is the exhaust velocity in m/s, p_e and p_a are the exit and ambient pressure, respectively, in Pa, and Ae is the exit area of the thruster in m^2. Cost-efficiency is represented by the equation $C = (\dot{m} * 60) * Pc$, where Pc is the propellant cost per kilogram. Lastly, Specific impulse (I_{sp}) is the measure of the amount of time that a rocket engine can generate thrust equal to the weight of its propellant [2].

The first engine source that was analyzed was the SPT-140 model Hall effect ion thruster. It is an ion thruster manufactured by OKB Fakel, a Russian aerospace company. While it was made in Russia, the SPT-140 is used in partnership with NASA and many other Western space agencies [3]. The SPT-140 operates in 5 stages. First, a hollow cathode ejects electrons. A positively charged anode attracts the negatively charged electrons into the discharge channel. Electromagnets at the channel's entrance create powerful magnetic fields that trap the electrons in a rapidly spinning tornado. Xenon propellant is pumped into the discharge channel, where xenon atoms collide with electrons to form ions, which are rapidly propelled out of the channel. The cathode then neutralizes the ions so that they do not get drawn back in by the electron field. Hall thrusters are incredibly useful due to their very high fuel efficiency. The specific impulse (I_{sp}) of the SPT-140 model Hall thruster at standard operating capacity (SOC) is 2100s [4]. However, while ion thrusters can deliver impressive impulse, their thrust is extremely low due to the mass flux of their propellant. The mass flow rate of the SPT-140 at SOC is on average 13 mg/s, or 1.3e-5 kg/s [4]. When converted, this comes out to less than one gram of propellant being ejected every minute. The actual thrust comes from the conservation of momentum and is derived from the exhaust velocity, or speed of the propellant as it exits the channel, and the propellant mass. For the SPT-140, the exit velocity averages around 21 km/s, with the mass being extremely small, as the propellant is Xenon[4][5]. These values are drastically different when looking at liquid-propelled rocket engines, or LPRE’s.

The other engine that was chosen for comparison is the R-42 890N (200 lbf) Bipropellant Rocket Engine, an LPRE made by Aerojet Rocketdyne [6]. The R-42 engine works in 2 steps. First, the fuel and oxidiser are pumped from their respective tanks, and once a valve opens, allowing them to enter the ignition chamber, they combine and ignite. The R-42 uses Monomethylhydrazine as fuel, and Nitrogen Tetroxide as the oxidiser [6]. This combination is hypergolic, meaning they spontaneously combust upon contact with each other, no external ignition required [7]. The ignited propellant is then funnelled through the R-42’s 160:1 expansion ratio nozzle, creating the thrust [6]. Traditional LPRE’s such as the R-42’s create large amounts of thrust at the cost of fuel efficiency. They require bigger fuel tanks, and therefore more weight, and they burn through it much faster than Ion propulsion. However, where they lack in I_{sp}, they make up for it with pure power. LPREs are traditionally used as first-stage boosters for launch vehicles, some examples being SpaceX’s Falcon 9. The Falcon 9 is capable of lifting up to 22,800 kg to Low-Earth-Orbit from static on Earth [8]. Chemical-propelled rockets are currently the only active methods of leaving Earth's atmosphere, a feat that ion thrusters are incapable of.

Common Issues can occur during space travel; things such as the Earth’s uneven gravitational fields can cause orbital drift, a change in path. This happens most often with satellites in orbit. For this case study, a 6,600 kg communications satellite in Geostationary

Earth orbit is evaluated, assigned to 100°W. Due to Earth’s uneven gravitational fields, it has drifted to 100.05°W over the course of two weeks. This change in positioning has caused a decay in signal quality because of dish alignment on the ground. The first step in the correction process is the retrograde burn, in which the satellite will fire its thrusters to rotate its body so the thrusters face the direction of travel, lowering its tangential velocity. The satellite will then slowly drift back toward the 100°W target point, eventually reaching it. However, at this point, due to its decreased velocity, the satellite is in a lower orbit, and so if left alone, it would sail past the target orbital point. This is when a prograde burn is engaged. In the prograde burn, the thrusters fire with the direction of travel and raise the altitude back to its original value. This scenario is one of the most common adjustments satellites have to make. Due to the Earth's uneven gravity, satellites in orbit will drift slightly over time, and these corrections must be made. The two thrusters we chose for this scenario were selected for two main reasons. Firstly, their size made them the right fit for orbital adjustments. The second reason being that these are the two main types of thrusters most commonly used in these scenarios. Chemical and Ionic propulsion are the competing methods of correcting orbital drift. To determine which method is superior for this scenario, we compared many parameters for each thruster.

RESULTS:

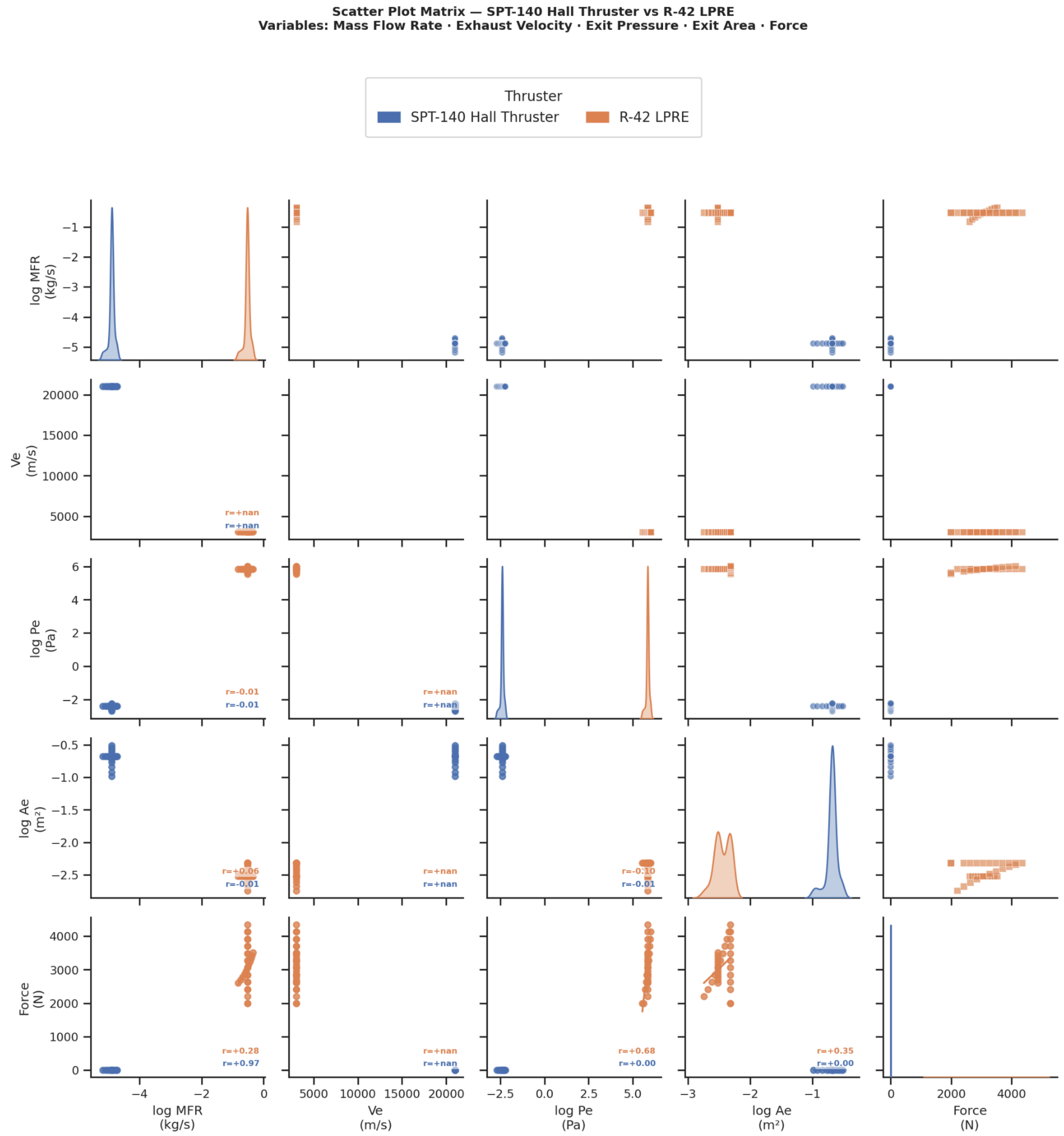


Figure 1: The effect each variable has on the thrust of an engine, by varying each parameter from 50-150% of its original value

Figure 1 displays the parameters we compared in a scatter plot matrix. To see their impact more clearly, the values are displayed as logarithms because many of them were so small that the graphs came up as single points or lines with little variation. In order to better understand the significance of each parameter and its effects on the thrust of a rocket engine, we varied the values from 50% to 150% of the standard values found in literature. The variations are demonstrated in Figure 1. We then calculated the thrust values and impulse required to execute the maneuvers for orbital drift correction, and compared the capabilities of each thruster to those requirements.

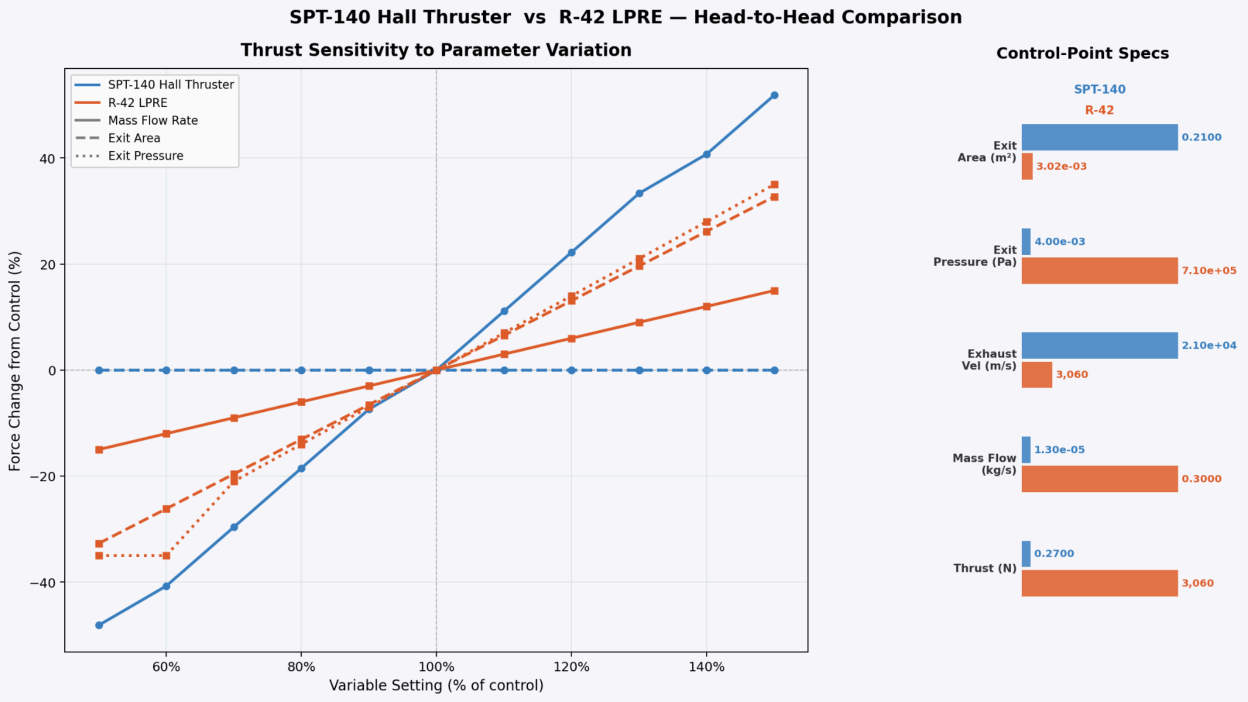


Figure 2: A head-to-head comparison of how the variation of each parameter affects the thrust output of each thruster

The sensitivity curves on the left show how each engine's thrust changes (as % from its control baseline) when each parameter is varied from 50% to 150%. The key insight is immediately visible: The R-42 responds strongly to all three variables with steep slopes across mass flow rate, exit area, and exit pressure, while the SPT-140 only responds to mass flow rate (flat lines for exit area and exit pressure, meaning those variables are essentially irrelevant to its thrust in near-vacuum). On the right of Figure 2, the control point spec bars show the raw control point values normalized within each parameter, so both thrusters are readable on the same axis despite their orders-of-magnitude differences. From here, the core tradeoff is clear. The R-42 produces almost 11,000 times more thrust, but it burns propellant at almost 23,00 times the rate as the SPT-140. The variation also helped to show the reliability of each thruster. If something in the satellite gets damaged and affects a parameter, such as mass flow rate or exit area, seeing how that might affect the thruster's thrust output is useful for determining which thruster is optimal for orbital drift correction.

The second comparison was of the cost efficiency of each thruster. Figure 3 models the cost efficiency of each thruster using the equation $Ce = (\dot{m} * 60) * Pc$

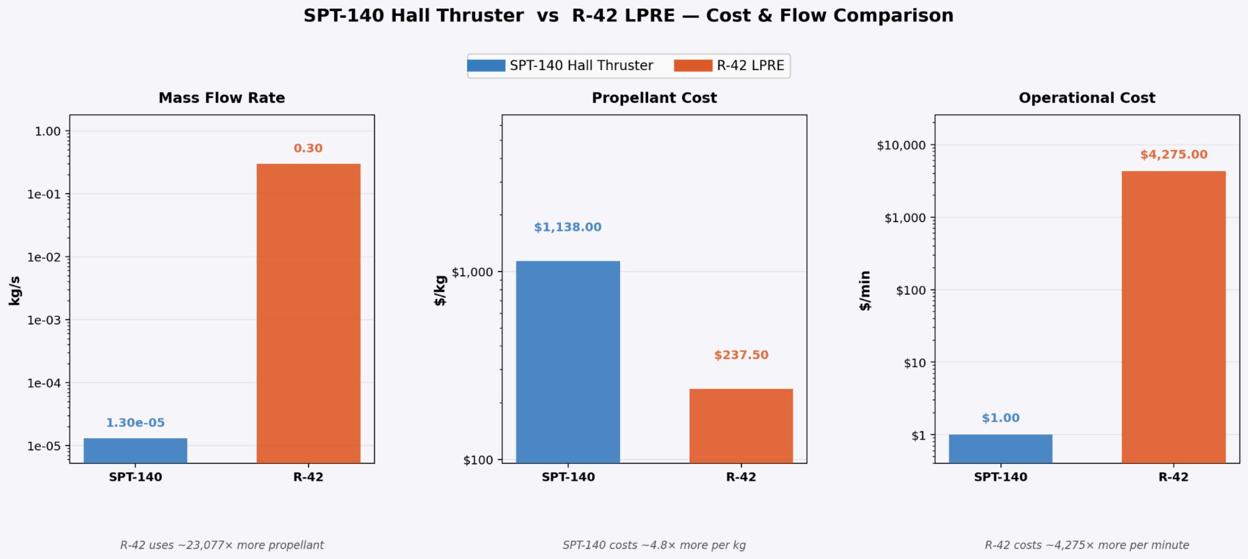
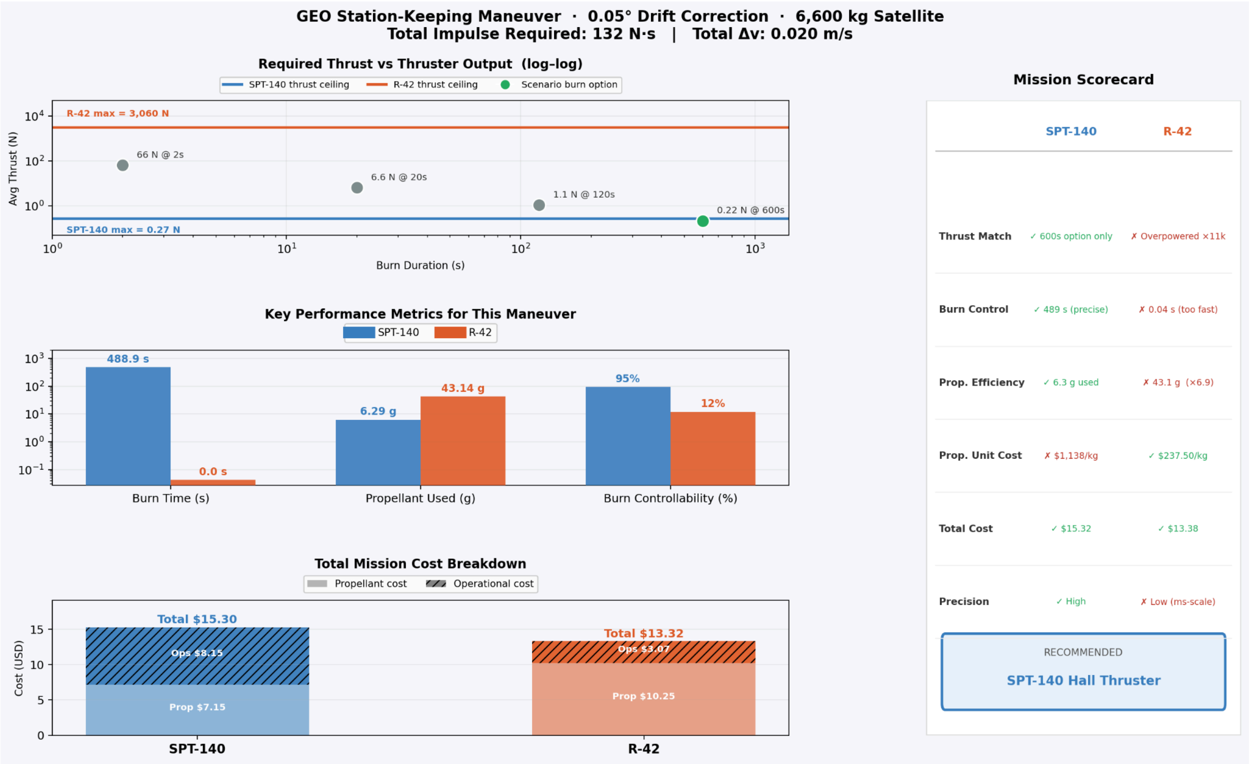


Figure 3: The Mass flow rate, the propellant cost, and the operational cost of both thrusters are compared.

. Figure 3 demonstrates that while the SPT-140's propellant, Xenon, costs approximately 4.8 times the amount that the propellant for the R-42 does. This is offset by the SPT-140's fuel efficiency, which lowers the operational cost significantly. So much so that the R-42 costs approximately $4,275.00 per minute, while the only SPT-140 costs $1.00 every minute to operate at standard capacity.

As a final evaluation, Figure 4 takes the steps, thrust, burn duration, and impulse required for an orbital drift correction in GEO, and analyzes the capabilities of each thruster in order to determine which one is optimal.



	SPT-140	R-42
Thrust Match	✓ 600s option only	✗ Overpowered ×11k
Burn Control	✓ 489 s (precise)	✗ 0.04 s (too fast)
Prop. Efficiency	✓ 6.3 g used	✗ 43.1 g (×6.9)
Prop. Unit Cost	✗ $1,138/kg	✓ $237.50/kg
Total Cost	✓ $15.32	✓ $13.38
Precision	✓ High	✗ Low (ms-scale)

Figure 4: Final comparison of the requirements for orbital drift correction and the evaluation of each thruster if put in that scenario

The R-42 actually produces too much thrust, making it sub-optimal for orbital drift correction. Because it is so powerful, it is much less precise, with a maximum burn time of 0.04 seconds, while the SPT-140 can burn for 489 seconds in order to produce the necessary thrust. The propellant for the R-42 is actually much cheaper, however that advantage is offset by its impulse of ~305s, compared to the SPT-140's impulse of 2100s [6][4]. Its impulse gives it a much longer operational lifetime than traditional chemical thrusters and reduces its operational cost significantly. Due to its precision, impulse, and therefore cost efficiency, we have determined that the SPT-140 ion thruster is the optimal choice for orbital drift correction, and therefore, use on a satellite.

CONCLUSION:

The SPT-140 ion thruster and the R-42 liquid propellant rocket engine were compared in order to determine which one is optimal for correcting orbital drift for a 6,600kg communications satellite in GEO. This is an incredibly common scenario, and so determining the optimal thruster for use in these satellites is important for cost savings, mission longevity, and overall operational efficiency. The two thrusters were evaluated based on thrust output, specific impulse, and operational cost. Although the R-42 produces over 11,000 times more thrust, that power proved to be a disadvantage rather than a strength, forcing a burn time of only about 0.04 seconds, which leaves little room for the fine control this maneuver demands. The SPT-140, on the other hand, could carry out the same correction over roughly 489 seconds, allowing for far greater precision. The SPT-140's specific impulse of 2100s exceeds that of the R-42 by over 1750s, allowing it to extract far more useful impulse from each kilogram of propellant. And even though its Xenon fuel costs 4.8 times more per kilogram, it uses so little that the operating costs fall to only $1.00 per minute against the R-42's $4275.00. For a correction that must be repeated many times throughout the lifetime of a satellite, those savings in cost efficiency compound quickly, which is why we determined the SPT-140 ion thruster to be the superior option for orbital drift correction. Still, this study covered only one scenario and two engines; future work could test larger or more varied maneuvers where chemical propulsion might regain its edge, include newer electric propulsion designs, and validate these values against real satellite telemetry. This is work that will only grow more important as orbital space becomes increasingly crowded and the demand for efficient, cost-effective satellite operations continues to rise.

References:

[1] Sutton, G. P., Biblarz, O., & Morehart, J. H. (2026). *Rocket propulsion elements*. John Wiley & Sons.
[2] Specific Impulse. (n.d.). Retrieved June 23, 2026, from https://www.grc.nasa.gov/WWW/k-12/airplane/specimp.html
[3] Manzella, D. (1997). *Performance Evaluation of the SPT-140* (Vol. 206301). National Aeronautics and Space Administration, Lewis Research Center.
[4] Lazurenko, A., Vial, V., Bouchoule, A., Skrylnikov, A., Kozlov, V., & Kim, V. (2006). Dual-mode operation of stationary plasma thrusters. *Journal of propulsion and power*, *22*(1), 38-475.
[5] Kieckhafer, A., & King, L. B. (2007). Energetics of propellant options for high-power Hall thrusters. *Journal of propulsion and power*, *23*(1), 21-26.
[6] Aerojet Rocketdyne. (n.d.). *R-4D-11 490N (300:1) bipropellant rocket engine* [Data sheet]. SatCatalog. Retrieved June 23, 2026, from https://satcatalog.s3.amazonaws.com/components/1015/SatCatalog_-_Aerojet_Rocketdyne_-_R-4D-11_490N_300-to-1_-_Datasheet.pdf
[7] Matsuura, Y., Iihara, S., & Tashiro, Y. (2014). Hypergolic propellant ignition phenomenon associated with two-phase oxidizer flow injection. *Journal of Propulsion and Power*, *30*(5), 1399-1409.
[8] SpaceX. (n.d.). SpaceX. https://www.spacex.com/vehicles/falcon-9