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RF PLASMA PROPULSION: UNLOCKING THE FULL POTENTIAL OF SMALL SATELLITES

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ABSTRACT

Small satellites are currently limited in capability by low ΔV propulsion systems. With the advent of radio frequency plasma thrusters, an electric propulsion technology scalable for nanosatellites, small satellite missions are no longer constrained by rideshare orbits and short mission lifetimes. By providing ΔV on the order of kilometers per second with RF plasma thrusters, new applications for small satellites are made possible. Some applications include mesh constellations from a single launch, very low-Earth orbit imaging, advanced debris mitigation, and formation flying. Here we provide an in-depth discussion of the Phase Four RF thruster performance, spacecraft design implications, and orbital maneuvers made possible by this technology. The maneuvers are broken down by mission segment, including deployment maneuvers, on-orbit operations, and end of mission servicing. We show how the enabled small satellite capabilities represent a paradigm shift in how the small satellite industry operates. The Phase Four RF thruster provides end users with propulsion and thereby the ability to optimize their missions.

INTRODUCTION

Small satellites are generally defined as satellites with a mass less than 500 kg [Ref 1] and can be separated into the subsets shown in Table 1. CubeSats, a standardized and common type of small satellites [Ref 2], are often in the nanosatellite and lower microsatellite mass categories.

Table 1: Small Satellite Subsets

Group Name	Mass [kg]
Minisatellite	100 to 500
Microsatellite	10 to 100
Nanosatellite	1 to 10

Small satellites already fulfill a wide variety of missions including Earth imagery, communications, weather data collection, asset tracking and global broadband internet. Mission needs determine an optimal satellite orbit that maximizes the value of the effort. However, most small satellites are launched as secondary payloads on launch vehicles and have little control over the orbital placement of their payload. As a result, small satellites must wait for a launcher that is conveniently launching to the correct altitude and orbital inclination, or they must settle with operations in a suboptimal location. With a capable small satellite propulsion system, these ride-share payloads can regain control of their orbital placement, as they can maneuver to their optimal location after being dropped off in a suboptimal spot. This prevents small satellites from having to compromise their launch time or orbital position. This paper introduces miniature radio frequency thrusters, a type of plasma propulsion system, and shows how they can expand small satellite capabilities accordingly.

RF ENGINE PERFORMANCE

Radio frequency thrusters work by directing heated plasma away from the thruster nozzle and pushing the system in the opposite direction. For the Phase Four RF thruster, xenon gas is injected as propellant into a plasma liner that is wrapped by an RF antenna. RF waves from the antenna efficiently ionize and heat the xenon plasma in the liner, causing it to expand thermally. The heated propellant expands outward and the thruster uses magnetic fields to direct the xenon plasma out of the nozzle, producing thrust.

RF thrusters are distinct from all other electric propulsion (EP) units. Most other EP systems, such as Gridded Ion Engines (GIEs) and Hall Effect Thrusters (HETs), operate by accelerating ions using imposed electric fields in the acceleration chamber. This process, though quite efficient, requires spacecraft to implement large DC power converters that do not fit in the mass, power or volume budget of small satellites. RF thrusters accelerate ionized gases (plasmas) by heating them efficiently via absorption of RF waves, similar to how microwave ovens heat water molecules. This process requires DC-RF power convertors, the core architectures of which have been dramatically miniaturized by the cellular phone industry [Ref 3].

GIE and HET systems are being investigated for use on smaller satellites [Ref 4], though nothing at the moment effectively scales down to nanosatellite systems. Other plasma-based propulsion systems or electric field driven propulsion systems are in development that use fundamentally different fuel storage architectures and low power requirements. However, these systems generally exhibit high efficiency at the cost of thrust performance and may be limited to very long duration maneuvers.

At the correct RF frequency, DC magnetic field strength, and plasma density, RF thrusters can achieve efficient plasma generation and extremely high power density with nanosatellite scale electronics. While systems exist or are in development for large spacecraft [Ref 5], Phase Four is utilizing the advancements in RF electronics miniaturization to develop a propulsion system small enough for nano-, mini- and microsatellites that can achieve 100+ mN/kW of thrust-to-power or upward to 1,000 seconds of specific impulse. The theoretical performance envelope of the Phase Four radio frequency thruster is shown in Figure 1.

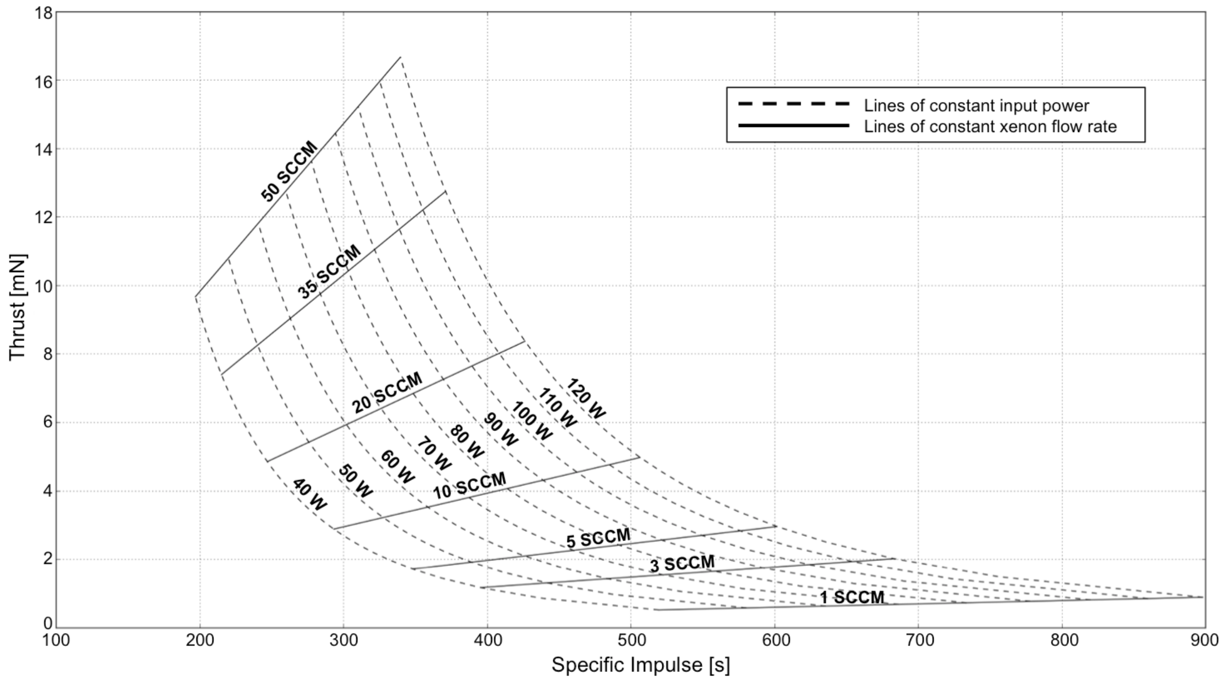

Figure 1: Theoretical Performance Envelope for the Phase Four Radio Frequency Thruster

The performance of the Phase Four RF thruster as compared to other propulsion solutions for nanosatellites is highlighted by the performance range over which it can perform. Figure 2 shows the thrust vs. specific impulse chart for several published nanosatellite propulsion systems. Systems such as ion thrusters represent high specific impulse but low thrust. On the other hand, cold gas and warm gas propulsion systems reach significantly higher thrust levels at the expense of specific impulse. With the ability to throttle between a wide range of thrust and specific impulse settings, the Phase Four RF thruster represents an otherwise vacant section of the performance curve. This allows nanosatellites to perform high thrust, low specific impulse burns for time sensitive maneuvers (e.g., collision avoidance) and low thrust, high specific impulse burns for better fuel efficiency (e.g., altitude raising), all in one mission with a single propulsion system.

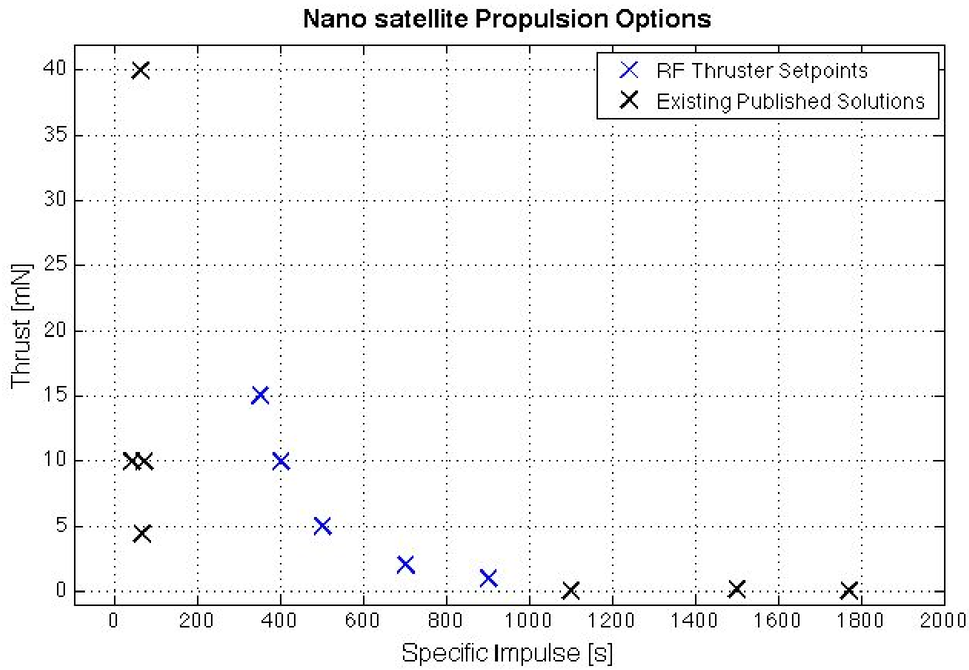

Figure 2: The Phase Four RF Thruster Setpoints Compared to Published Solutions for Nanosatellites [Ref 6]

Nanosatellites (1 to 10 kg) represent a subsection of small satellites. Legacy electric propulsion systems already exist for microsatellites (10 to 100 kg) and minisatellites (100 to 500 kg). To see how RF thrusters stack up against legacy systems, it is useful to analyze the total impulse delivered to the satellite as a function of the total mass of the propulsion system. Two primary factors contribute to total impulse: specific impulse and propellant mass; an increase in either parameter will increase total impulse. Designers must consider the mass of the propulsion system that includes the mass of the engine(s), tanks, plumbing, and drive electronics, as well as the mass of the propellant. This mass value often correlates with the cost of launching the satellite.

Figure 3 shows how the Phase Four RF propulsion system with variable propellant masses performs against two legacy hall thrusters, the Aerojet Rocketdyne T-40 [Ref 7] and the SPT-100 [Ref 8]. The propulsion mass values on this chart represent only the mass of the thruster and propellant, since it is assumed that each solution would connect to the same xenon feed system on a given satellite. At low mass values, the P4 RF propulsion system can deliver net impulse to a small satellite before existing hall thrusters can carry any propellant, which highlights the value case for nanosatellites and small microsatellites. As propulsion mass increases, the RF thruster still outperforms existing solutions that have higher specific impulse up to over 25 kg due to a significantly lower dry mass.

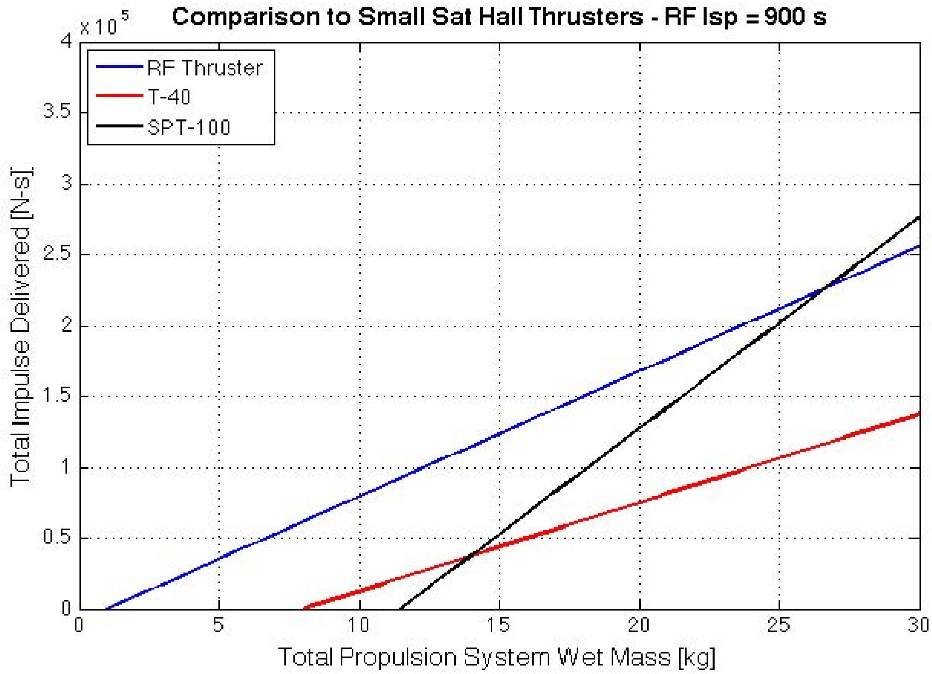

Figure 3: A Radio Frequency Thruster Compared with Legacy Small Satellite Hall Thrusters

ENABLED MANEUVERS

Propulsion system performance drives a satellite's ability to maneuver in space. Change in satellite velocity, or ΔV, while not the only figure of merit for orbital design, is a useful figure to assess how much a spacecraft can change its orbit. For perspective, Table 2 shows the approximate ΔV required for a few common orbital maneuvers.

Table 2: Approximate ΔV Required for Three Common Maneuvers [Ref 9]

Orbit before Maneuver	Orbit after Maneuver	Approximate ΔV [m/s]
600 km circular	600 km circular with 60° phase offset after 10 days	84
600 km circular	600 km apogee with 100 km perigee	142
250 km circular at 23° inclination ("parking orbit")	Geostationary	4,300

Satellite ΔV capability depends on the satellite's dry mass, propellant mass, and the specific impulse of the propulsion system. Figure 4 shows the ΔV provided by the P4 radio frequency thruster to satellites with various propellant mass fractions (propellant mass divided by total satellite mass). The chart trades ΔV with approximate burn time - a critical consideration in satellite and mission design.

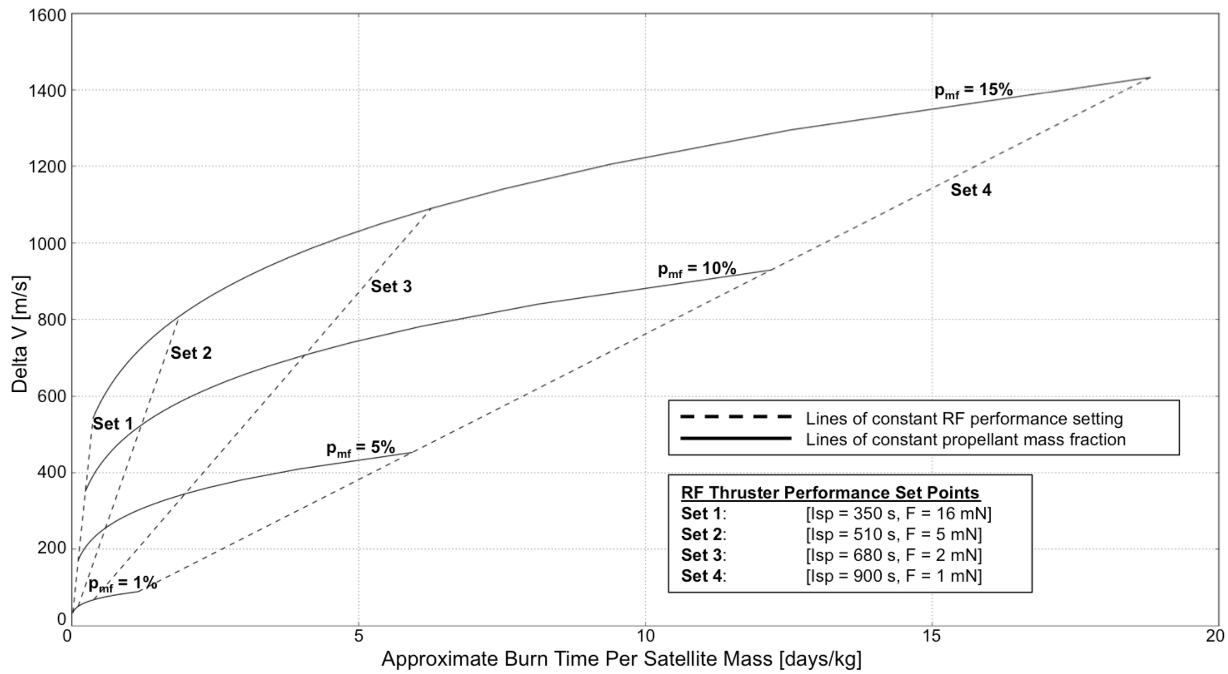

Figure 4: The P4 RF Thruster ΔV and Burn Time for Various Performance Set Points and Propellant Mass Fractions

This section also uses duty cycle - defined as the percentage of time per orbit the propulsion system must fire - to give a deeper look at the missions enabled by radio frequency thrusters. For example, a mission at 600 km circular altitude with 5% propulsion duty cycle must fire about 4.8 minutes per orbit.

The following overview of maneuvers enabled the P4 RF thruster is separated into the three primary segments of satellite missions: deployment, operation, and disposal. The detailed maneuvers have been performed by large satellites for decades and are now used by minisatellites and large microsatellites. Critically, novel aspects of orbital operations are 1) the ability to perform sophisticated and rapid maneuvers with nanosatellites and 2) the ability for nano-, micro-, and minisatellites to perform these maneuvers at a fraction of the cost of legacy systems.

Deployment

The deployment phase begins when a spacecraft separates from its launch vehicle and ends when the satellite reaches its operational orbit. Large satellites use dedicated launch vehicles to get reasonably close to their operational orbit before separation, but small satellites do not always have this option. Most small satellites are launched as secondary payloads that leave their operators little control over the separation orbit and, if their satellite lacks propulsion, little or no ability to change that orbit.

With propulsion, Earth-orbiting satellites often use a combination of the following three maneuvers to reach their operational orbit: orbit phasing, altitude changes, and plane changes. Orbit phasing involves a series of altitude changes to move a satellite to a different position on the same orbit, which can distribute several co-located satellites around the Earth for improved coverage. Altitude changes involve the increase or decrease of a satellite's distance from the Earth's surface, a valuable capability for achieving broader sensor coverage or higher resolution. Finally, plane change maneuvers modify a satellite's inclination angle.

Although the P4 RF thruster enables small satellites to perform all three deployment maneuvers described above, the following study focuses on orbit phasing. For example, take two 11.5 kg CubeSats deployed at the same location on a 600 km circular orbit (a relatively common CubeSat mass and deployment orbit). The objective is to use the P4 radio frequency thruster to position these satellites 180° apart. Table 3 shows a full description of the mission.

Table 3: Orbit Phasing Mission Details

Mission	Remote Sensing
Spacecraft Mass [kg]	11.5
Circular Altitude [km]	600
Thrust [mN]	2.0
Specific Impulse [s]	500
RF Power [W]	50
Xe Propellant Mass [g]	100

In this configuration, the two satellites will achieve their nominal positioning in 9.5 days using about 80 g of propellant. For comparison, the same maneuver would take approximately 6 months to perform with the existing technique of using differential drag [Ref 10].

Operation

Once a satellite reaches its operational orbit, operators usually want to maintain the satellite in that orbit. Orbital perturbations such as atmospheric drag, solar radiation pressure, and third-body gravitational effects make this nearly impossible without propulsion. Operators might also want to modify their satellite's operational orbit to avoid colliding with other satellites. Both of these operational maneuvers can be performed with the Phase Four radio frequency propulsion system.

A specific case is extending the time a satellite can maintain a certain orbit before its altitude decays due to atmospheric drag (i.e., mission lifetime extension). Figure 5 shows the lifetime performance for a 10 kg CubeSat using a P4 RF thruster with 120 W input power, 500 grams of xenon propellant, and the theoretical performance from Figure 1. The chart shows how the satellite can achieve longer mission lifetime with more specific impulse but must spend more time maneuvering. Alternatively, the RF system at higher thrust setting decreases the propulsion duty cycle, providing more time for operating the satellite's payload. For perspective, the same satellite at 300 km would re-enter the Earth's atmosphere in about two weeks without propulsion due to atmospheric drag.

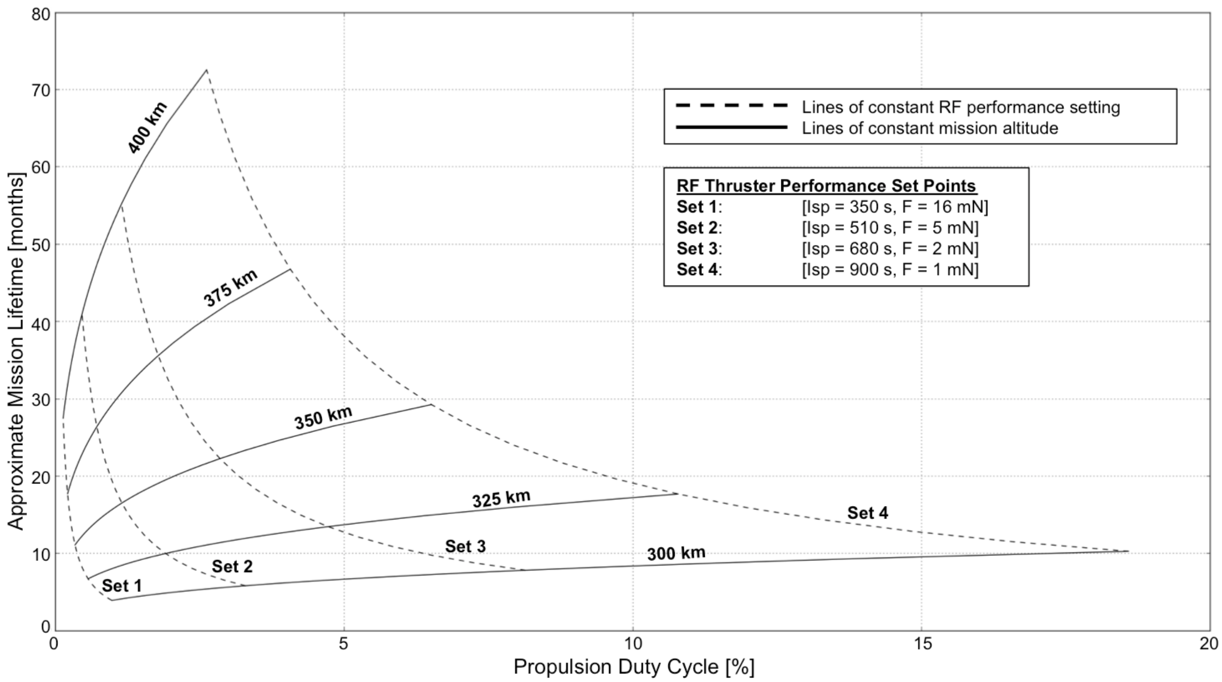

Figure 5: Mission Lifetime Extension Performance with an RF Thruster

Disposal

NASA guidelines require a satellite in low-Earth orbit to re-enter the atmosphere within 25 years after the end of its mission [Ref 11]. This guideline is in place to limit orbital debris, and it also limits how high a spacecraft can fly if that spacecraft has no de-orbiting ability. Satellites without propulsion must rely on atmospheric drag to de-orbit, and the atmospheric drag force is often too small to meet the 25 year requirement at altitudes roughly 600 km and above [Ref 12]. The P4 RF thruster enables disposal maneuvers for small satellites, which in low-Earth orbit involves decreasing the satellite's perigee to a low enough altitude that it re-enters within the required timeframe. More importantly, on-board propulsion enables small satellites to reach disposal at a fraction of the 25 year requirement, thus limiting orbital debris and promoting the responsible stewardship of space.

Table 4 shows the maximum altitude at which a satellite can end its operational life and still perform a controlled de-orbit maneuver. The analysis assumes a microsatellite with 50 kg dry mass and a P4 RF thruster operating at specific impulse of 800 s. The maximum mission altitude is a function of the remaining propellant onboard the satellite. At mission end, the satellite would perform a series of retrograde burns (i.e., thrust vector directed opposite the satellite's velocity vector) to lower its perigee to a low enough value, approximately 75 km, that the spacecraft will immediately re-enter the atmosphere.

Table 4: De-Orbit Altitude for a 50 kg Microsatellite with an RF Thruster at 800s Isp

Remaining Propellant [kg Xe]	De-Orbit Delta V [m/s]	De-Orbit Altitude [km]
1.0	155	629
1.5	232	939
2.0	308	1,276
2.5	383	1,645
3.0	457	2,051

BLENDED MANEUVERABILITY SERVICE

As more stakeholders in industry, government, and academia build and operate their own small satellites, it is no longer sufficient for propulsion companies to provide only a propulsion hardware subsystem. Instead, a blended approach between propulsion hardware and trajectory design enables a more seamless satellite maneuverability experience for the operator.

With propulsion solutions such as RF thrusters, future small satellites will be more maneuverable than their predecessors, enabling exotic constellations such as swarms of spacecraft flying in formation. More ΔV does not instantly guarantee mission success. An operator must maneuver strategically to maximize this benefit, which is often done with trajectory optimization. Most established aerospace companies have this capability in house, but many new entrants do not. Furthermore, all entities can benefit from a more streamlined connection between satellite requirements and the needs of the end user.

As an example, consider an operator flying a constellation of small satellites used to take images of Earth. The satellites are equipped with RF thrusters and can decrease their altitude to capture higher resolution, higher frequency imagery of specific areas. Currently when the operator decides to focus on a high value target, they must identify which satellite(s) to maneuver, plan the burn sequence, set each burn time, and then execute the maneuver. With a blended maneuverability service, the operator simply enters the desired coordinates and the maneuverability service does the rest. This solution saves valuable time and minimizes the amount of propellant required to execute the maneuver, potentially increasing the operational lifetime of the constellation.

Delivering such a maneuverability service is not without its hurdles, including power requirements, communication systems, coordination between space tracking entities, and even cyber security. Nevertheless, this effort will ease the burden on satellite operators and ensure a safer transition to highly maneuverable small satellites.

SUMMARY

The rapid increase of small satellites has generated a demand for miniature, highly capable propulsion systems. Radio frequency thrusters, which use radio waves to generate a plasma, represent a solution that can meet this demand. Based on theoretical models, the Phase Four RF thruster can provide specific impulse between 350 and 900 s and thrust between 1 and 16 mN, filling a critical gap in the nanosatellite propulsion field. Due to a low dry mass, RF propulsion systems can scale up to effectively compete with ~30 kg hall thrusters.

A wide performance envelope enables the P4 RF thruster to perform a wide range of critical maneuvers, including those used during satellite deployment, operation, and disposal. For deployment, RF thrusters can phase two remote sensing satellites from 0° to 180° in roughly 10 days, which would take several months with differential drag. A 6U satellite in a 400 km circular orbit can remain at that orbit between roughly 30 and 70 months using a radio frequency thruster, depending on the desired propulsion duty cycle. Low-Earth orbiting satellites must re-enter the atmosphere within 25 years of mission end, and a 50 kg satellite, with a P4 RF thruster and 3 kg of remaining propellant, can end its operational life at over 2,000 km and still meet this requirement.

To responsibly and safely handle the increased density of small satellites on orbit, we outline a maneuverability solution that blends the hardware of the propulsion system with trajectory optimization algorithms. Such a service could interface with space traffic entities, regulators, and other satellite operators to most effectively use miniature propulsion systems like RF thrusters, thus decreasing the risk of collision and increasing the value of these satellites.

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