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Plasma propulsion for telecommunication satellites

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Abstract. Electric thrusters are used for in-space propulsion of spacecraft for a combination of practical and economic reasons. These devices that use electric power to accelerate the mass flow of the propellant at exhaust velocities are one or two order of magnitude faster than those achieved in conventional chemical propulsion. This feature results in significant propellant savings that allows longer mission times and heavier payloads, however, the thrusts achieved are lower for important electric power consumptions. The different electric thrusters that are currently used in Europe for both in-orbit corrections and also for orbit raising to the operational orbit from the separation stage of the launcher will be introduced. This propulsion system also serves to expel these vehicles from their orbit at the end of their useful life to control the increase of space debris in Earth orbit. Additionally, the characteristics of new low-power electric engines with thrust levels in the range 0.1-10 mN and electric power consumptions below 500 W will be discussed. These are required for flight formation, orbital corrections and end-of-life disposal in the new constellations of small satellites in low Earth orbit intended for planetary internet coverage and interactive television services.

1. Introduction

Plasma propulsion of telecommunication satellites is of increasing interest due to a combination of economic and practical factors [1-4]. Today, hundreds of different electric thrusters (EP) have been used successfully for orbit corrections as well as in deep-space scientific missions [5]. The main consumers of commercial plasma thrusters are large telecommunication satellites operated in a geostationary orbit (GEO, orbit altitude 35786 km). This equatorial orbit is reached by a sequence of different orbital maneuvers that consume propellant [1,6].

After the separation from third stage of its launch rocket the satellite is injected into an elliptical geosynchronous transfer orbit (GTO). Usually, a 400-500 N thrust is applied at its apogee to increment its speed in $\Delta v = 1.5$ km/s to move the satellite to a quasi-circular orbit on the equatorial plane of the Earth. The rising process from GTO orbit to GEO can take several steps where the inclination of the orbit plane with respect to the equator is also corrected [1,6].

Additional thrust is required to keep the satellite in its GEO working orbit. Orbital drag force is negligible at these altitudes; however, lunar and solar gravitational interactions and/or the irregular distribution of the Earth's mass can affect its orbital motion. To compensate these perturbations during all the time of the mission, which usually last 15 or 20 years, satellite thrusters are fired on a daily basis to deliver 80-100 mN. These maneuvers are currently denominated North-South (NSSK) and East-West (EWSK) *station keeping*. These in-orbit corrections are crucial for telecommunication satellites since its uplink and downlink high gain antennas must point along precise directions [6].

Eventually, it may also be necessary to move the satellite to avoid destructive collisions with objects in orbit. At its lifetime end, more thrust is finally applied to displace the satellite from GEO, since there is a limited number of slots (~400 satellites) available for in this orbit. It is preferable to increment its velocity in Δv = 3.0 m/s, raising its orbit in 300 km in order to avoid the eventual return to the Earth's atmosphere. This maneuver is intended to mitigate the proliferation of debris in lower LEO-MEO orbits [6]. This basic scheme is modified by a number of particular details of the mission, such as the latitude of the launch site, maximum thrust delivered by the launcher rocket, the inclination of its initial GTO orbit with respect to the Earth equatorial plane, etc.

However, telecommunication services are not restricted to GTO, for example, GPS systems operate in medium Earth orbits (MEO, altitudes from below 36000 km down to 2000 km). The new constellations of interconnected small satellites intended for interactive television and planetary internet coverage are being deployed in low Earth orbit (LEO, altitudes from 160 to 2000 km). In this last case the long-term interaction with the atmosphere is not negligible and LEO satellites need to be continuously operated to account for the orbital drag force. In this last case, the electric propulsion is the only propulsive technology available so far.

The Tsiolkovsky equation relates the ratio m_p/m_f between the mass of fuel $\Delta m = m_p$ needed to increase in Δv the velocity of a satellite with final mass m_f (dry mass) as,

$$\frac{\Delta v}{v_{ex}} = \left(1 + \frac{m_p}{m_f}\right) \qquad \text{or equivalently,} \qquad \frac{m_p}{m_f} = e^{\left(\Delta v/v_{ex}\right)}\text{-}1 \tag{1}$$

and $m_i = m_p + m_f$ is the initial mass of the system. Above equation can also be cast as,

$$\Delta v = I_{sp}\, g_o \ln\left(1 + \frac{m_p}{m_f}\right)$$

and this equation relates the increment Δv of satellite speed as required for the maneuver with the specific impulse $I_{sp} = v_{ex}/g_o$ of a specific thruster, where g_o is the standard Earth's gravity [8].

The ratio m_p/m_f of equation (1) is represented in Figure (1) as a function of the exhaust speed. It shows that important reductions in the weight m_p of propellant for a fixed payload mass m_p as v_{ex} increases. For example, shuttle main engines deliver hot gases with v_{ex}~ 4.4 km/s and for a GTO-GEO transfer we obtain m_p/m_f = 0.405 which gives m_p = 405 kg for a 1000 kg satellite. Increasing v_{ex}~ 20 km/s this calculation leads to m_p/m_f = 0.078 reducing to m_p = 78 kg the weight of propellant.

The highest achievable gas speed in conventional chemical thrusters is limited to $v_{ex} \lesssim$ 5.5 km/s by the maximum energy stored per unit mass of the propellant [7]. Therefore, new technologies to circumvent this limitation are of paramount importance [1-4]. The rationale is to foster the economic competitiveness of satellite communication systems with longer mission times, higher thrusts $F = \dot{m}\, v_{ex}$ additional transmission channels and other services that can be made available using heavier payloads.

2. Electric propulsion systems

The electric propulsion (EP) systems make use of physical processes involving electric power to increment the velocity of a exhaust gas stream and/or to accelerate a plasma flow up to velocities over the upper bound of Figure (1), thus reducing the weight of required propellant.

Space engines are required to operate in a high vacuum environment and the basic scheme of a EP system is shown in Figure (2), where the central block symbolizes an idealized engine. The thrust $F = \dot{m}\, v_{ex}$ is delivered transforming the electric power W into the kinetic energy power,

$$P_b = \frac{dE_{kin}}{dt} = \frac{\dot{m}}{2} v_{ex}^2 = \frac{F^2}{2\,\dot{m}}$$

of the propellant substance (gas liquid or solid). Conventional space thrusters employ the energy stored in the chemical bounds of propellant molecules for this power conversion. This energy is extracted in EP systems from a independent electric power supply instead. Since the energy required for particle acceleration is provided by an external power supply, the exhaust speed v_{ex} in EP systems is less dependent of the chemical nature of the propellant. Therefore, the maximum exhaust velocity limit of v_{ex}~ 5.5 km/s for conventional chemical propulsion in Figure (1) can be surpassed.

Electric propulsion system are characterized by low thrusts $F = \dot{m}\, v_{ex}$ and high specific impulses $I_{sp} = v_{ex}/g_o$ whereas conventional chemical propulsion has lower I_{sp} but produce high thrusts. The maximum thrust values delivered under ideal conditions by the ion beam current I_b of single charged ions, that are accelerated across the electric potential drop V_{ac} can be estimated using,

$$F = \sqrt{\frac{2\, M_i}{e}}\; I_b\, \sqrt{V_{ac}}, \quad (2)$$

where M_i is the ion mass and e the elementary charge. Then, $W = I_b \times V_{ac}$ is the electric power consumption.

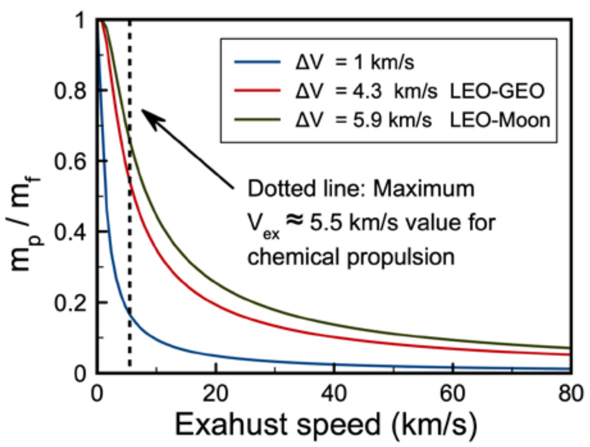

Figure 1. The mass fraction m_p/m_f in equation (1) as a function of the exhaust velocity v_{ex} of the propellant for typical of values of Δv

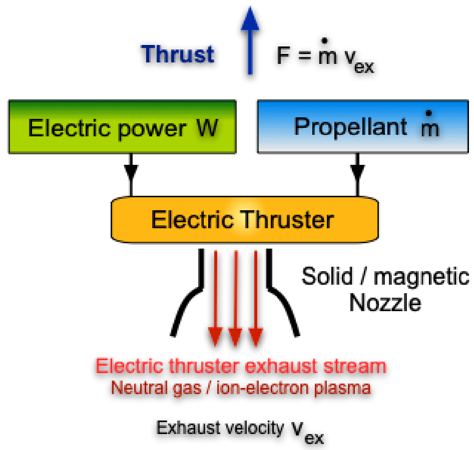

Figure 2. The scheme of a EP system with electric power W and propellant mass flow rate $\dot{m}$ consumption.

The simple calculations in table (1) show the high electric power required to achieve substantial thrusts. Only 95.9 mN are obtained with 2.25 kW of electric power required to accelerate the current I_b = 1.5 A current of Xenon ions through V_{ac} = 1.5 kV voltage drop. This maximum value drops to 54.6 mN for Argon gas because of its lower atomic mass. As the electric power available on board of spacecrafts is limited, this restricts until now the applications of electric propulsion to low thrust and/or long time maneuvers.

Electric thrusters can be roughly classified in terms of the physical principle for the acceleration of propellant as shows the scheme of table (2). According on the specific field of application, thrusters falling into one of these three categories can be more or less attractive according to their specific performances such as, delivered thrust, electric power consumptions, etc.

Microwave and radiofrequency plasma thrusters are also currently included in this category [2,5], since in a ionized gas (electron and ion plasma) electromagnetic waves can transfer energy to ions by different physical mechanisms (helicon wave, electron cyclotron resonance, etc) increasing the ion temperature. Since the motion of ions can be restricted along the magnetic field lines, the imparted momentum increases when plasma jet expands through a *magnetic nozzle* configuration [6]. Ions are accelerated whereas the contribution of electrons to the momentum transfer remains small. Hence, the

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subsequent plasma flow expansion into the vacuum through magnetic and/or solid nozzles transforms their kinetic energy into thrust.

Table 1. The ideal thrusts and velocities from equation (2) for single ionized Xenon and Argon ion currents I_b with speeds v_i over the limit of Figure (1) accelerated by the potential drops of V_{ac} 0.5, 1.0 and 1.5 kV voltages.

		0.5 kV		1.0 kV		1.5 kV	
	I_b (A)	v_i (km/s)	F (mN)	v_i (km/s)	F (mN)	v_i (km/s)	F (mN)
Xenon	0.5	27.35	18.4	38.67	26.1	47.37	32
	1.0		36.9		52.2		63.9
	1.5		55.3		78.3		95.9
Argon	0.5	49.08	10.5	69.41	14.9	85.11	18.2
	1.0		21.0		29.7		36.4
	1.5		31.5		44.6		54.6

Table 2. Non-exhaustive classification of EP thrusters where M and M_i are respectively the masses of molecule and ion. The acceleration potential is V_{ac} the neutral gas or ion temperature is T and J the electric current density. The acronyms are; ECR, electron cyclotron resonance thruster; GIE, gridded ion engine; FEEP, field emission electric propulsion; HET, Hall effect thruster, HEMPT, highly efficient multistage plasma thruster. The applied-field (AF) and self-field (SF) are variants of the magnetoplasmadynamic MPD thruster.

Physical principles			**Thruster**
Electrothermal	$v_{ex} \sim \sqrt{\frac{T}{M}}$	Solid nozzle	Arcjet Resistojet
		Magnetic nozzle	Helicon Vasimir ECR
Electrostatic	$v_{ex} \sim \sqrt{\frac{2\ e\ V_{ac}}{M_i}}$	Externally applied electric field	GIE Colloid FEEP
		Self-consistent electric field	HET HEMPT Multi-Cusp
Electromagnetic	$v_{ex} \sim \frac{J}{\dot{m}}$	Steady plasma flow	AF-MPD SF-MPD
		Unsteady plasma flow	Pulsed

The *electrostatic* thrusters first use electric power to ionize the propellant neutral gas (an electron-ion plasma) and momentum is directly imparted to heavy ions by a stationary electric field. As shows equation (2) ions can reach high velocities moving in the field produce by electrodes (usually metallic grids) connected to high voltage power supplies. Biased electrodes are employed *gridded ion engines* (GIE, also called Kaufman thrusters) to produce currents of ions accelerated by metallic meshes connected to high voltages. Similarly, highly charged micro-droplets of polar liquids accelerated under kV-range voltages drops in *colloid* thrusters. The *field emission electric propulsion* (FEEP) produces the electric field ionization of a liquid metal (cesium, indium or mercury) and ions are later accelerated by a externally imposed strong electric field. Alternatively, non-equilibrium discharge plasmas can develop internal self-consistent electric fields that can accelerate ions to velocities well over the limit for chemical propulsion indicated in Figure (1). The *Hall effect thruster* (HET) (also called closed-drift thrusters), the *Highly Efficient Multistage Plasma Thruster* (HEMPT) and other similar *Multi-Cusp* designs make use of this basic principle.

The propellant gas is also ionized in the *electromagnetic* propulsion and this plasma is accelerated by the interaction of current flowing through with steady or pulsed electric and magnetic fields established by, either, the currents itself and/or external means. In *magnetoplasmadynamic* (MPD) thrusters charged particles are fed into the exhaust chamber were are accelerated by the Lorentz force resulting from the interaction of a magnetic field (externally applied or self-induced) and the electric current that flows through the plasma. The applied-field (AF) thrusters have magnetic rings surrounding the exhaust chamber whereas self-field (SF) thrusters have a cathode along through the centerline of the chamber. Other *pulsed plasma* configurations accelerates the ions in a cycle produced by the ablation and sublimation of solid propellants (teflon) which is accelerated by the Lorentz force by a time dependent electron current.

3. Plasma thrusters for telecommunication satellites

The largest commercial market for electric propulsion is until now the large telecommunication satellites. These are delivered into GTO orbit by the launcher and the maneuvers to reach the GEO operational orbit are performed using on-board propulsion. Using conventional chemical propulsion this GTO-GEO orbit transfer takes typically one week, but the required propellant represents 50\% of the satellite weight. This orbit raising lasts up to six months using electric propulsion with reductions of 40\% in weight that can be used to accommodate more payloads to deliver other services to customers. In addition, electric propulsion is currently employed to deliver the low thrusts required for NSSK orbit corrections in GEO operation since the mass savings of the propellant extends the operational life of the satellite.

Leading electric propulsion technologies for telecommunication satellites in terms of performance in Europe are Gridded Ion Engines, Hall Effect Thrusters and HEMPT [2,7-10]. They operate in steady state, delivering typical thrusts below 500 mN, specific impulses from thousands of seconds to tens of thousands of seconds, higher than *resistojets* and *arcjets*, with electric power consumptions in the range of hundreds of watts up to tens of kilowatts. Microwave based engines as the Helicon [9] or electron cyclotron resonance thrusters [2,9] still are in an early development stages. The low power micropropulsion technologies for precise positioning of nanosatellites, such as FEEP or colloid thrusters [10] are also cited in table (2) but are not employed in telecommunication satellites because of their low thrusts.

However, these commercial systems have excessive electric power consumptions to be of use in the new constellations of satellites that are being deployed in low orbit. Services such as interactive television, automatic vehicle driving or coverage of ships on the high seas require high quality internet access with planetary coverage.

This objective can only be achieved efficiently by means of constellations of small satellites that describe precise orbits, acting simultaneously and inter-connected in a planetary network. For this purpose, several projects (OneWeb, Starlink, O3b, SpaceX, etc.) are deploying groups of satellites (reaching up to 1,000 units) that communicate with the Earth's surface through mass-produced, low-cost terminals. Their trajectories will experience deviations, breaking the formation and thus interrupting downlink/uplink data traffic.

Low power in-space electric propulsion will be essential and is the only the technology available so far for orbital maneuvers, station keeping, flight formation and/or end-of-life disposal of these small satellites (50-250 Kg) intended for global internet coverage. They roughly require of thrust levels in the range 0.1-10 mN and electric power consumptions below 500 W. This propulsion system also serves to expel these vehicles from their orbit at the end of their useful life and to control the increase of space debris in LEO. The low-power version of HET, HEMT and different GIE conceptions are under development to meet this challenge as well as new ideas [11,12] that can address this technological gap.

4. Concluding remarks

New ideas appear constantly in the field of electric propulsion where basic plasma physics connects with aerospace technology. Although basic principles were established long ago, technological advances in power electronics, materials physics and other fields have made possible important advances in recent years.

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