Electric Propulsion and Electric Satellites

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May 11, 2017

Electric propulsion for satellites has proven to be a useful technique for orbit transfer and orbit stabilization. Although electric propulsion provides low thrust and therefore a very long transfer time, the Isp of electric thrusters are usually very high. This yields a very efficient and much cheaper transfer. Electric thrusters provide various types or propulsion split into two categories. The first category is ion and plasma drives which include electrostatic, electrothermal, and electromagnetic propulsion. The second category is non-ion drives including photonic, electrodynamic tether, and unconventional propulsion. There currently have been over 150 space crafts with electric propulsion starting back in 1962 and evolving into what we have today.

Nomenclature

a	= Acceleration (m/s^2)
A_e	= Exhaust area (m^2)
A_t	= Throat area (m^2)
c^*	= Characteristic velocity (m/s)
F	= Thrust
GTO	= Geostationary transfer orbit (geosynchronous transfer orbit)
GEO	= Geostationary stationary Earth orbit (GStO)
g	= Gravitational acceleration (9.806 m/s^2)
h	= Height (m)
Isp	= Specific impulse
kN	= kilonewton
LEO	= Low Earth Orbit
m_i, m_f	= Initial and final masses
m_p	= propellant mass
MR	= Mass ratio (m_i/m_f)
P	= Power (kW)
p_c	= Chamber pressure (MPa)
R_0	= Radius of Earth (6,376 km)
t	= Time (s)
T	= Temperature
ΔV	= Change in velocity
α	= Inclination
η	= efficiency

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I. Introduction and Brief History

Electric satellites have used a plethora of techniques and approaches to both produce thrust for orbital transfer and for station keeping. Electric propulsion was first introduced into the field in the 1960's, and in 1964 the world's first satellite with electric propulsion, the SERT 1, was sent to space. Over the 50 years of development electric propulsion techniques have been branched away from the original technique and into separate types and categories all being used in the satellite field. Electric propulsion has proven to be a more efficient and less expensive type of propulsion once a vehicle reaches orbit. However, electric propulsion is not yet used for early stages of rockets. The Isp for electric thrusters is very high but the force produced is not nearly high enough to be considered for first or second stages of rockets.

II. Types of Electric Propulsion

There are two primary categories of electric propulsion dividing thrusters as either ion and plasma drives or non-ion drives. Thrusters in these groups can then can be broken down into the different types of electric propulsion. Of the ion and plasma drives there are three primary styles of electric propulsion that are used today. These are electrostatic propulsion, electrothermal propulsion and electromagnetic propulsion. These are more widely used in the electric satellite field and have provided the thrust for multiple successfully operating satellites. Of the non-ion drives there are photonic thrusters, electrodynamic tethers, and unconventional propulsion techniques. The working versions of these are not as widely used and many techniques are still concept ideas that may prove to become successful thrusters in the future.

A. Ion and Plasma Drives

A.1 Electrostatic

Electrostatic propulsion utilizes a propellant that can be ionized. Common propellants for this type of electric propulsion are Cesium, Mercury, Xenon, Argon, etc. The propulsion in these type of thrusters is created by accelerating ions using an electric field and allowing those ions to pass through a grid. The ions are then neutralized by a stream of electrons to prevent any kind of charge build up on the bus. This technique provides a very low thrust but makes up for the lack of thrust by supplying very high specific impulses of around 3000-5000 seconds. Thrusters of this type are now being used more commonly for orbital transfer and orbital stabilization. The transfers using electrostatic propulsion have a far greater transfer time but they have been proven to be more efficient. This is determined because the high Isp allows for the bus to submit low thrust for long periods of time and use very little propellant. The ability to take only a fraction of the propellant mass to LEO and GEO makes the takeoff require less propellant as well. In the cases that time is not of great importance these type of thruster is one of the best choices for orbital maneuvers.

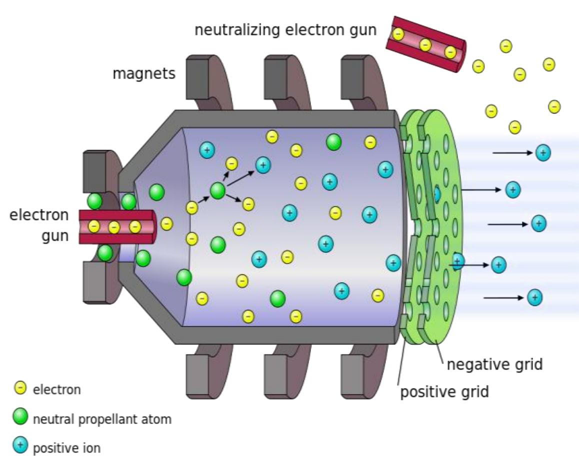


Figure 1: Gridded ion thruster (Wikipedia)

A.2 Electrothermal

Electrothermal propulsion works by using electric energy transfer heat to a propellant and increase its efficiency and Isp. This is done by heating an element in which the propellant is passed through. This element can be simply just heating the propellant or it can be heating a catalyst bed to aid in the propellant decomposition.

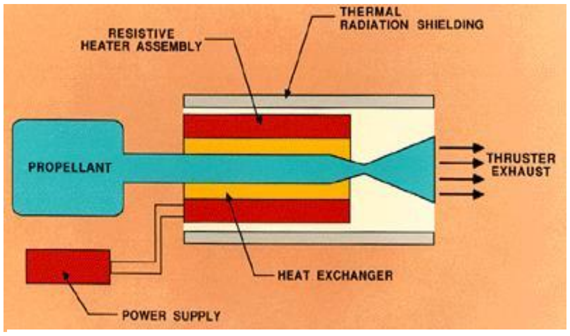


Figure 2: Resistojet thruster
http://currentpropulsionsystems.weebly.com

Some examples of Electrothermal propulsion are Arcjet, Microwave arcjet and Resistojet. This type of propulsion can be used with monopropellant and bipropellant rockets. The idea for this system is to aid what would normally be a cold gas system. Although this type of propulsion increases the Isp compared to chemical engines, the resulting Isp usually does not surpass 1000 seconds. This fall short of some of the other electric propulsion techniques but it allows for a greater thrust.

A.2 Electromagnetic

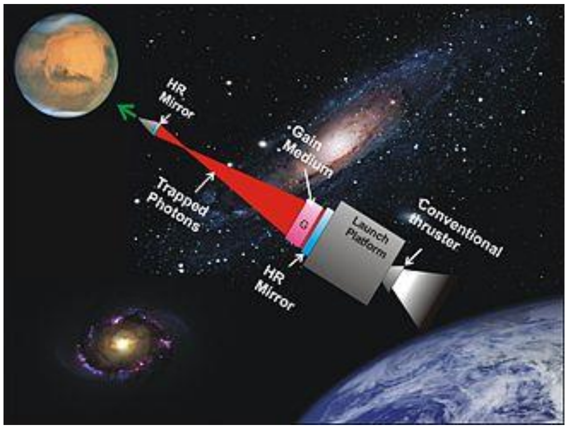
Electromagnetic propulsion utilizes plasma as its propellant. This is done by heating the propellant to temperatures of over 5000 degrees Kalvin. By suppling a magnetic field the conductive plasma portrays the Lorentz force. The plasma ions are accelerated via the magnetic forces created rather that needing an anode grid. This technique also allows the particles to become accelerated without becoming fully ionized resulting in a higher efficiency. Electromagnetic propulsion can create thrust levels up to 100 times larger than electrostatic propulsion can. The high Isp and relatively low thrust compared to chemical thrusters makes this type of thruster best suited for long orbital transfers. These thrusters are used similarly to electrostatic thrusters although they are not as common because of the higher difficulty of producing them and maintaining them.

Figure 3: Plasma propulsion engine, Lewis Research Center (Wikipedia)

B. Non-ion Drives

B.1 Photonic

This type of thruster produces all its thrust with the use of photons, thus avoid having to carry and expel and kind of propellant for propulsion. The types of propulsion in this category include laser propulsion techniques. Laser propulsion uses a solar sail type system that utilize laser shot from the ground to propel the bus. Photonic laser thrusters use a stationary mirror to shoot lasers and reflect off. The laser is amplified off the mirror and propels the bus via its solar sail.



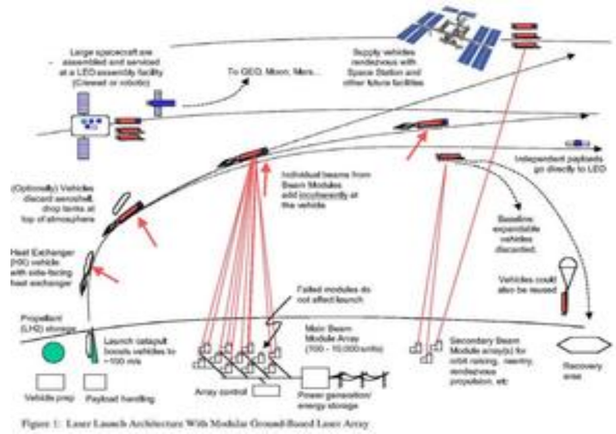


Figure 4,5: PLT (left), Laser Propulsion (right)
(Wikipedia)

B.2 Unconventional

There are some unconventional types of electric propulsion that don't fit in the other categories. These include quantum vacuum plasma thrusters, EM drives, and Cannae drives. These are mostly theoretical or are experimental only. These types of propulsion could be one of the prominent future type of electric propulsion but as of now we do not utilize any of these types of propulsion commercially.

C. Comparison of Electric Propulsion Types

III. Past and Current Bus with electric propulsion

A. SERT 1 (Electrostatic, 1964)

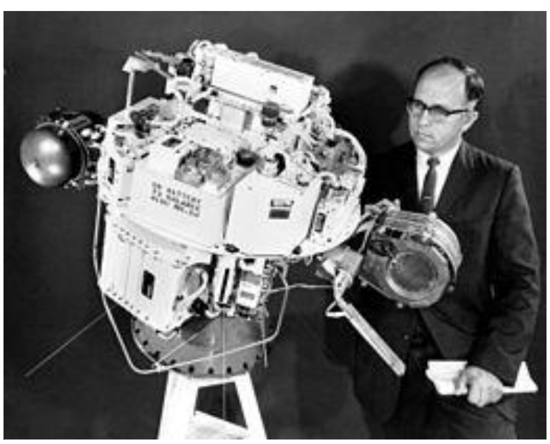


Figure 6: Program manager Raymond J. Rulis And SERT 1 (Wikipedia)

The SERT 1 was not only the first electric satellite it was also the first spacecraft to incorporate any kind of electric propulsion. The SERT 1 launched on July 20, 1964 on the Scout X-4 rocket. It was launched as an experimental satellite and therefor the satellite's total life was one day. The SERT 1 trialed two different gridded ion thrusters. The first was an 8-cm diameter cesium contact ion engine. This engine was designed to run off 0.6 kW of power and supply the satellite with a specific impulse of around 8050 second and provide a thrust of 5.6 mN. Unfortunately, there was a mishap with the electrical circuit which prevented the engine from starting. The second engine was a mercury electron bombardment ion engine. This engine was designed to run off 1.4 kW of power and produce 4900 second of specific impulse and produce 28 mN of thrust. The mercury engine did work and was activated approximately 840 seconds into the flight. This engine ran for 31 minutes becoming the first electric engine ever to operate in space. The model was corrected and improved into the SERT 2 which successfully operated from February 3, 1970 until 1981.

B. A2100 bus (GE-1) (Electrothermal, 1997)

The GE-1 was the first of the A2100 bus series. It consisted of three parts (GE-1,2,3). The A2100 bus series is Lockheed Martin's satellite series used in a plethora of different launches. The bus has been designed to be able to adapt to a large variety of needs. They have had over 100 different variations for their satellite with the first being in 1997 and current models still developing. the A2100 bus uses an electric propulsion system designed by Moog-ISP of the LEROS family. The LEROS 1c is the specific model that utilizes Hydrogen as the fuel and Nitrogen Tetroxide as the oxidizer. This engine can supply a thrust of about 460 N and a specific impulse of 325 seconds.

Figure 7:
Lockheed Martin's brochure
The A2100 bus model
(Lockheed Martin and
coloradospacenews.com)

Figure 8: the GE-1,2,3 bus series
(http://space.skyrocket.de)

C. 702 bus (702SP) (ABS-2A / Eutelsat 117 West B, 2015)

Figure 8: Both 702SP satellites in launch configuration (directory.eoportal.org and Boeing)

The 702-bus series has been in operation since 1996 and is still being used today. The 702SP is the most recently improved model which in 2015 was launch as a side by side setup. This was the first time in history two fully electric satellites were launch simultaneously and successfully into orbit. The two satellites were of different groups. The first was the ABS-2A from ABS in Bermuda, using the Xenon Ion Propulsion System (XIPS-25) electric propulsion engine. The second, the Satmex 7 later renamed the Eutelsat 115 West B, was of Satmex from Mexico also using the XIPS-25 engine. Both satellites successfully made the GTO to GEO transfer. The 702 series can be altered and launched from a variety of rockets. The 702SPs that were launched side by side were carried on SpaceX's Falcon 9 heavy rocket. The same two satellites from the same sponsors deployed a second successful mission a year later paving a new path for the future of electric satellites.

IV. Propulsion Analysis Calculations (Example)

Parameter of a satellite are given as:

Given: fuel, grid (voltage applied, spacing, hole size, # of holes), eV loss, specific power plant mass, payload, burn time, tank mass, LEO height to GEO).

"Given parameters"

$At.Wt := 39.95 \quad At.no := 18 \quad At.Wn := \frac{At.Wt}{At.no} = 2.219 \quad At.m := 0.66 \cdot 10^{-25}$

$q.m := 24.13 \cdot 10^{5} \quad ionP1 := 15.8 \quad ionP2 := 22.63 \quad Isp.volt^{.5}\ 225$

$Va := 600 \quad D := 2 \cdot 10^{-3} \quad d := 5 \cdot 10^{-3} \quad h\# := 20000 \quad loss.ion := 300$

$B := 10 \quad OrbHi := 320 \quad paylM := 300 \quad tb := 90 \quad pro.m.tank := 10\%$

$eV := 1.6 \cdot 10^{-19} J \quad V.leo := 7720 \quad V.geo := 3070$

Calculations: Shown to calculate all other parameters and need dV for GEO transfer.

"thrust per hole" $F.hole := \left(3.14 \cdot \frac{D^2}{4}\right)\left(8 \cdot \frac{(8.854 \cdot 10^{-12})}{9}\right)\left(\frac{Va}{d}\right)^2 = 3.559 \cdot 10^{-7} N$

"total thrust" $Tot.F := h\# \cdot F.hole = 0.007\ N\ \sim 7\ mN$

"exit V" $Ve := (2\ (Va)\ (q.m))^{0.5} = 5.381 \cdot 10^4\ \frac{m}{s}$

"spacific imp." $Isp := \left(\frac{1}{9.81}\right) Ve = 5.485 \cdot 10^3 s$

"mas flow rate" $mfr := \frac{Tot.F}{Ve} = 1.323 \cdot 10^{-7}\ \frac{kg}{s}$

"sec per day" $s.day := 24 \cdot 60 \cdot 60 = 8.64 \cdot 10^4$

"propel. mass" $Pro.m := mfr \cdot tb \cdot s.day = 1.028\ kg$

"trhuster efficiency" $pro.eff := \left(1 + \frac{(loss.ion \cdot eV)}{(.5 \cdot At.m \cdot Ve^2)}\right)^{-1} = 0.666$

"power required" $P.req := \left(0.5 \cdot (mfr) \cdot \frac{Ve^2}{pro.eff}\right) = 287.683\ W \quad P := 0.287\ kW$

"power plant mass" $PP.m := B \cdot P = 2.87\ kg$

"mass ratio" $m.ratio := \frac{Pro.m}{(paylM + PP.m)} + 1 = 1.003$

"dV calulated" $dV := (\ln(m.ratio)) \cdot Ve = 182.42\ \frac{m}{s}$

"dV short of GEO" $dV.short := V.leo - dV - V.geo = 4.468 \cdot 10^3\ \frac{m}{s}$

".t ~ themal" ".e ~ electrical"

$E.t := 2500\ MW\ \sim 2.5 \cdot 10^6\ kW \quad Isp.t := 890\ s \quad F.t := 335\ N$

"efficiencies" $t.e.eff := .35 \quad eff := .60$

"elec. energy" $E.e := (E.t) \cdot (t.e.eff) \cdot 1000 = 8.75 \cdot 10^5\ kW \quad Isp.e := 5000\ s$

"exit V electric" $Ve.e := Isp.e \cdot 9.81 \frac{m}{s}$

"mas flow rate electric" $mfr := \frac{(E.e \cdot eff)}{0.5 \cdot Ve.e^2} = 4.364 \cdot 10^{-4}$

"trust electric" $F.e := mfr \cdot Ve.e = 21.407\ kN$

$Boltz := 5.67 \cdot 10^{-8}\ \frac{W}{m^2 \cdot K^4}$

"radiated power" $RP := \frac{Boltz \cdot 1000^4}{1000} = 56.7 \frac{kW}{m^2}$ "at 1000 K"

"surface area" $As := \frac{E.e \cdot 0.40}{RP} = 6.173 \cdot 10^3\ m^2$

V. Future

A. Photon Laser Thruster

The Photon Laser Thruster along with other electric propulsion techniques of the unconventional type make up a large portion of recent research and development in the field. The Photon Laser Thruster makes use of a stationary laser in which it fires a laser towards. The laser is reflected and amplified, and in returns to the satellite. The satellite utilized a solar sail to then use the returning amplified beam of photons to propel forward. The photon propulsion systems are not being utilized commercially yet but they are theoretically one of the most efficient forms of travel even with a very minimal thrust. The future may incorporate these types of systems more in long travels and far explorations but the use of these for quick changes in orbit or for lower orbit propulsion is thought to be unfeasible.

VI. Conclusion

The electric propulsion movement is the future of both satellite and of space exploration. The efficiency of these system far surpasses the down side of having low thrust once the space vehicle reaches orbit and beyond. This technology has been developing for over 50 years and it is having yet to slow down. This shows that the world sees this step of using electricity over chemical propulsion as vital to improving our ability to utilized space.

Acknowledgments

This paper reports in part the development of today's electric propulsion alongside the history and implementation of electric satellites. The information portrayed is credit to reference noted web sources and information gathered from Dr. Kantha's notes of rocket propulsion.

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Appendix A

A1. SERT 1

Table 1: Bus Details

Parameter	Value	Comments
First Launch Date	July 20, 1964	
Operational Timeline	One time launch	
Launch Vehicle	Scout X-4	
LxWxH (m)	?	unlisted
Mass (kg)	?	unlisted
Thrusters	Cesium contact ion engine, Mercury electron bombardment engine	Two separate engines
Thruster mass (kg)	?	Per thruster
Propellant Mass GTO-GEO (kg)	Never achieved	
Power	Batteries	

Table 2: Propulsion Details (Cesium Engine)

Parameter	Value	Comments
Propulsion type	Gridded ion thruster	Electrostatic
Fuel	Cesium	
Total Input Power (W)	600	
Thrust Vac (mN)	5.6	
I_{sp} Vac (s)	8050	

Table 3: Propulsion Details (Mercury Engine)

Parameter	Value	Comments
Propulsion type	Gridded ion thruster	Electrostatic
Fuel	Mercury	
Total Input Power (W)	1400	
Thrust Vac (mN)	28	
I_{sp} Vac (s)	4900	

A2. A2100 bus (GE-1)

Table 4: Bus Details

Parameter	Value	Comments
First Launch Date	1996	
Operational Timeline	15+ years	
Launch Vehicle	Multiple (Atlas 2A)	
LxWxH (m)	1.83x1.85x22.2	
Mass (kg)	~1,300	
Thrusters	LEROS 1c	
Engine mass (kg)	4.3	Per thruster
Propellant Mass GTO-GEO (kg)	?	
Power	Solar array, batteries	

Table 5: Propulsion Details

Parameter	Value	Comments
Propulsion type	Liquid apogee	Electrothermal
Fuel	Hydrazine	
Oxidizer	Nitrogen Tetroxide	
Thrust Vac (N)	460	
I_{sp} Vac (s)	325	

A3. 702 bus (702SP)

Table 6: Bus Details

Parameter	Value (SP)	Comments
First Launch Date	1997 (2012)	
Operational Timeline	15 years	
Launch Vehicle	Multiple (Falcon-9)	
LxWxH (m)	1.8x1.9x3.5	
Mass (kg)	~1,500	
Payload Mass (kg)	~500	
Thrusters	Xenon Ion Propulsion System	4x25cm thrusters
Thruster mass (kg)	16	Per thruster
Propellant Mass GTO-GEO (kg)	400 kg	
Power	Solar array, Li-Ion batteries	

Table 7: Propulsion Details

Parameter	Value	Comments
Propulsion type	Gridded ion thruster	Electrostatic
Fuel	Xenon	
Total Input Power (W)	2200-4500	
Grid Diameter (cm)	25	
Utilization Efficiency (%)	82	
Electrical Efficiency (%)	87	
Thrust Vac (mN)	80-165	
I_{sp} Vac (s)	3500	