FINAL BACHELOR'S THESIS

TITLE : Review of small satellite propulsion systems for low Earth orbit missions

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ABSTRACT

The review article investigates the different propulsion technologies now in use or under development for small satellites designed for missions in low Earth orbit. It gives a general review of the various propulsion system types, including chemical, electric, and cold gas propulsion systems, as well as their salient features.Each system's benefits and drawbacks are also explored, along with the prospective missions for which it may be used. The assessment is concluded with a discussion of the prospective developments in propulsion technology, as well as how these developments may affect the possibilities and constraints of small satellite missions.

LEO: Low Earth Orbits

CPS: Chemical Propulsion

SPS: Solid Propulsion System

EPS: Electric Propulsion Systems

CGPS: Cold Gas Propulsion System

HTPD: Hydroxyl-Terminated PolyButadiene

HAN: Hydroxyl Ammonium Nitrate

HETs: Hall Effect Thrusters

PPTs: Pulsed Plasma Thrusters

FEEP: Field Emission Electric Propulsion

CGT: Busek Cold Gas Thruster

VLEO: Deorbiting very low Earth orbit

EDT: Electrodynamics Tether

GEO: Geostationary Orbit Missions

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1. Introduction

1.1. Background and motivation

Due to their many benefits, including cost effectiveness, shortened lead times, and enhanced accessibility to space, small satellites are increasingly being used for a variety of low Earth orbit (**LEO**) missions. The restricted size and power availability of the propulsion systems needed for small satellites, however, present significant difficulties. Therefore, it has become more crucial than ever to examine small satellite propulsion systems for **LEO** missions.

The goal of this thesis is to give a thorough analysis of the most cutting-edge propulsion technologies available for small satellites designed for **LEO** missions. This review's objectives are to assess the benefits and drawbacks of various propulsion technologies and to pinpoint any room for development. The possible influence of small satellite propulsion systems on the capabilities and constraints of small satellite missions will also be examined in this thesis.

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1.2. Objectives and scope of the paper

The primary objectives of this article are to provide an overview of small satellite propulsion systems for low Earth orbit missions, evaluate the advantages and disadvantages of different propulsion systems, and identify potential directions for small satellite propulsion technology progress.

This paper's scope covers a thorough analysis of the most cutting-edge propulsion technologies now employed for missions involving small satellites in low Earth orbit. The basic concepts of propulsion systems will be covered, along with other propulsion systems such as chemical, electric, solar sail, and cold gas systems. The report will also highlight the difficulties faced by small satellite propulsion systems and examine the performance and needs of the market's current propulsion systems.

Finding a viable propulsion system for deorbitation in low Earth orbit will be the main topic of this article. The consideration of small satellite propulsion systems potential future developments and how they could affect the capabilities and constraints of small satellite missions will round up the article.

2. Fundamentals of Small Satellite Propulsion Systems

2.1. Overview of propulsion systems for small satellites and CubeSats

Small satellites are satellites that weigh up to a few hundred kilograms and are used for a variety of tasks, including communication, scientific research, Earth observation, and technological demonstration. Small satellites' propulsion systems are essential for them to be able to maneuver in orbit, retain formation, and deorbit at the end of their useful lives.[1].

Small satellites include various types and sizes, such as minisatellites, microsatellites, nanosatellites and picosatellites [26].

SMALL SATELLITES	WEIGHT	DIMENSIONS
Minisatellite	100 - 500 kg	10 to 60 base pairs
Microsatellite	10-100 kg	450 x 450 x 550 mm
Nanosatellite	1-10 kg	10 x 10 x 10 cm
Picosatellite	Less than 1 kg	10 x 10 x 10 cm

Table 1. Types of small satellites [26]

Figure 1. Small satellites [2.1]

Small satellites known as "*CubeSats"* have a uniform form factor. In the late 1990s, Stanford University and California Polytechnic State University (Cal Poly) jointly developed them. A 10 cm x 10 cm x 10 cm cube with a maximum weight of 1.33 kg is the typical CubeSat form factor. To support heavier payloads, however, several sizes—referred to as *"3U," "6U," "12U,"* etc.—are also available[25].

CubeSats are made to be more affordable than more typical, bigger satellites, with lower development and launch costs. They may be constructed using readily available parts, and they are frequently employed for technological demonstrations, academic research, Earth observation, and other purposes. [25].

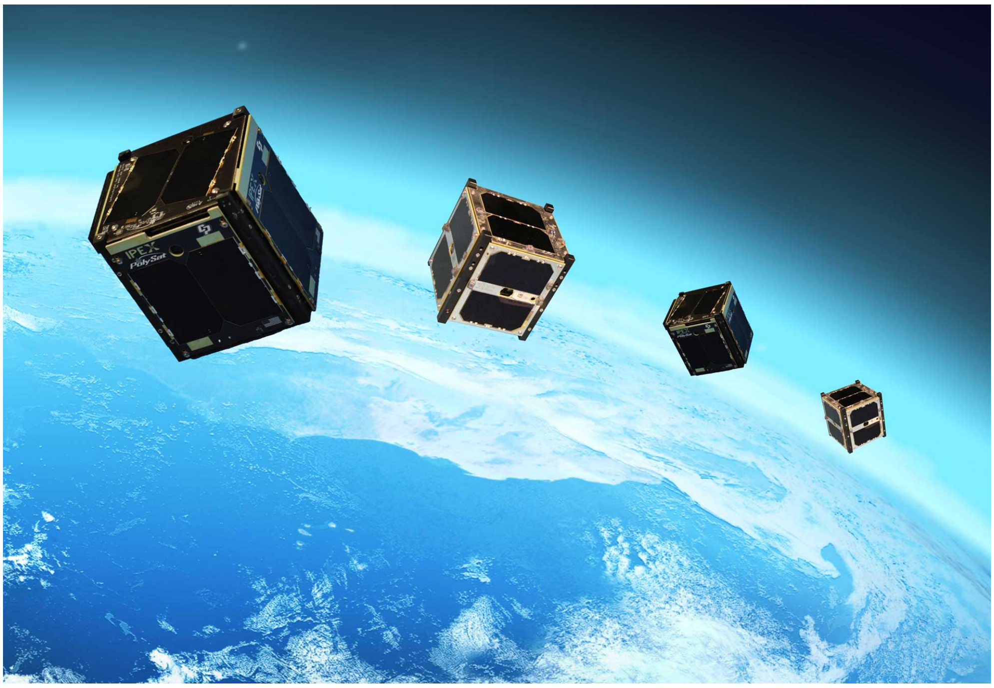

Figure 2. CubeSats [2.1.1]

2.2. Types of propulsion systems: chemical, electric, cold gas, and others

Small satellites can use a variety of propulsion systems, and the choice of one relies on the mission objectives, satellite mass, power budget, and cost, among other things. Several of the frequently employed propulsion technologies for small satellite are listed below:

- Chemical Propulsion: The oldest and most used kind of propulsion system is this one. It launches a propellant out of a nozzle and employs chemical processes to create thrust. High thrust and specific impulse are produced by this kind of propulsion system, but it also produces a lot of heat and needs a lot of fuel. Usually, far space missions and huge satellites employ this technology[2].

- Electric Propulsion: To generate thrust, this kind of propulsion system accelerates ions or plasma using electric fields or electromagnetic waves. While having a lesser thrust and requiring a lot more electricity, electric propulsion systems are more effective than chemical propulsion systems. Electric propulsion systems come in a variety of forms, including Hall Thrusters, Ion Thrusters, and Plasma Thrusters[2].

- Cold Gas Thrusters: Compressed gas, usually nitrogen or helium, is used in this kind of propulsion system to create thrust by ejecting the gas via a nozzle. Cold gas thrusters are straightforward, dependable, and inexpensive despite having a low specific impulse. They are primarily utilized for modest orbital modifications and attitude control.[2].

- Solar Sails: By reflecting or absorbing photons from the sun, this sort of propulsion system uses light to generate thrust. Solar sails are cheap, light, and have an endless source of fuel, but they have little thrust and need a lot of surface area. Long-duration missions or interplanetary missions generally employ solar sails[2].

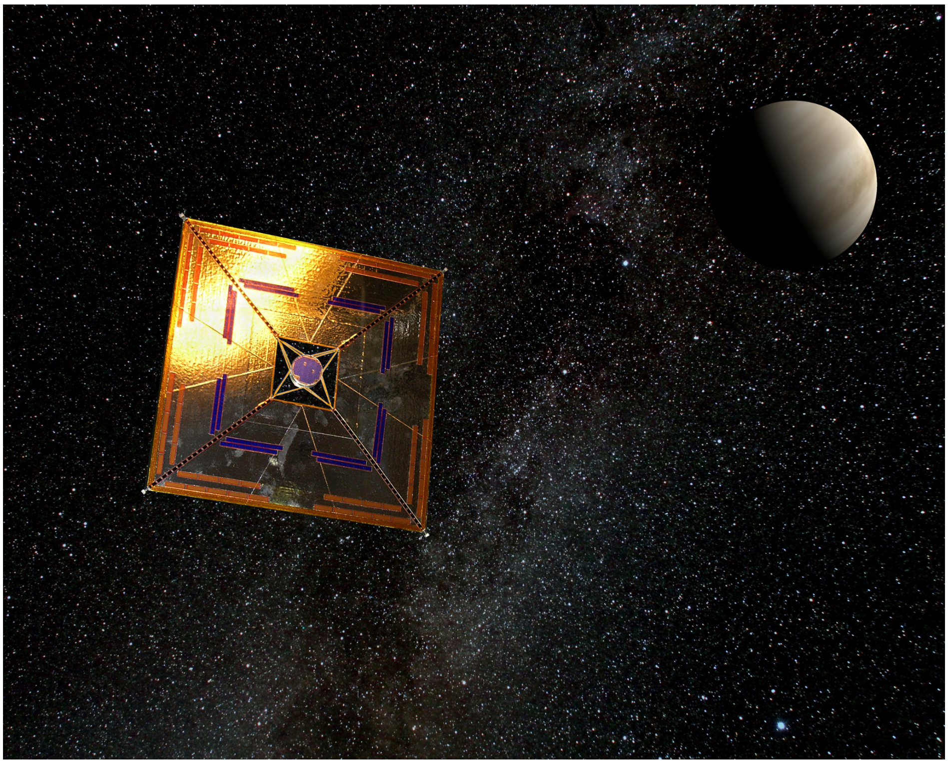

Figure 3. Solar Sails [2.2]

➢ Hybrid Propulsion: The great performance and versatility of this kind of propulsion system are achieved by combining two or more propulsion systems. For instance, a hybrid propulsion system can combine electric and cold gas thrusters to provide high thrust and high specific impulse [2].

Figure 4. Hybrid Propulsion [2.3]

ENGINE TYPE	THRUST	SPECIFIC IMPULSE
Hydrazine	0.5-4 N	150-250 s
Cold Gas	10 mN - 10 N	65-70 s
Non-toxic Propulsion	0.1-27 N	220-250 s
Pulsed Plasma and Vacuum Arc	1-1300 µN	500-3000 s
Thrusters Electrospray	10-120 µN	500-5000 s
Hall Effect Thrusters	10-50 mN	1000-2000 s
Ion Engines	1-10 mN	1000-3500 s
Solar Sails	0.25-0.6 mN	N/A

Table 2. Propulsion system types for small spacecraft [4].

2.3. Key parameters and performance metrics

The primary characteristics and performance indicators of small satellite propulsion systems vary depending on the particular design. However, the following broad criteria and performance indicators are frequently employed to assess the effectiveness of small satellite propulsion systems.:

- ➢ Thrust: This is the propulsion system's force, which is commonly expressed in Newtons (N) or pounds-force (lbf). The thrust is a crucial factor since it affects the satellite's acceleration and mobility[3].

- ➢ Specific Impulse (Isp): The ratio of thrust to propellant mass flow rate serves as a gauge for the propulsion system's effectiveness. Specific impulse, which expresses how long a particular quantity of propellant can deliver thrust, is commonly expressed as seconds (s) or meters per second (m/s)[3].

- ➢ Delta-V (Δv): The change in velocity that a propulsion system may give a satellite is known as delta-V. It establishes the satellite's capability to carry out orbital movements, including orbital insertion, orbital repositioning, and station-keeping. M/s, or meters per second, is used to express delta-V. The delta-V capabilities of small satellite propulsion systems are typically restricted, falling in the range of a few hundred to a few thousand meters per second [3].

- ➢ Power: It is commonly expressed in watts (W) and represents the amount of electrical power needed by the propulsion system to function. For electric propulsion systems, which need a lot of electricity to function, power is a crucial parameter[3].

- ➢ Mass: The mass of the whole propulsion system, including the propellant, tanks, engines, and other parts, is represented by this number. For small satellites, the mass is a crucial factor since it determines the satellite's overall size and weight, which is measured in kilograms (kg) or pounds (Ibs)[3].

- ➢ Reliability: This is the likelihood that the propulsion system will work as designed without any problems. As small satellites are frequently employed for vital tasks including Earth observation, communication, and scientific research, reliability is a crucial factor. It's expressed in (%)[3].

The primary characteristics and performance indicators of small satellite propulsion systems are generally determined by the particular kind of propulsion system being employed and the mission requirements. To satisfy the small satellite's mass, power, and cost limits while achieving the necessary mission objectives, the propulsion system should be chosen and its characteristics adjusted [3].

3. Description of propulsion systems for Small Satellites

The three most crucial propulsion systems for small satellites are those that will be discussed below for low Earth orbits (**LEO**) of up to a few hundred kilometers, when drag forces are significant.

3.1. Chemical propulsion systems

One of the most popular forms of propulsion systems for small satellites is the chemical propulsion system (**CPS**). These technologies produce propulsion and launch the satellite into orbit via a chemical reaction. **CPS** may be divided into solid and liquid propulsion systems, respectively[4].

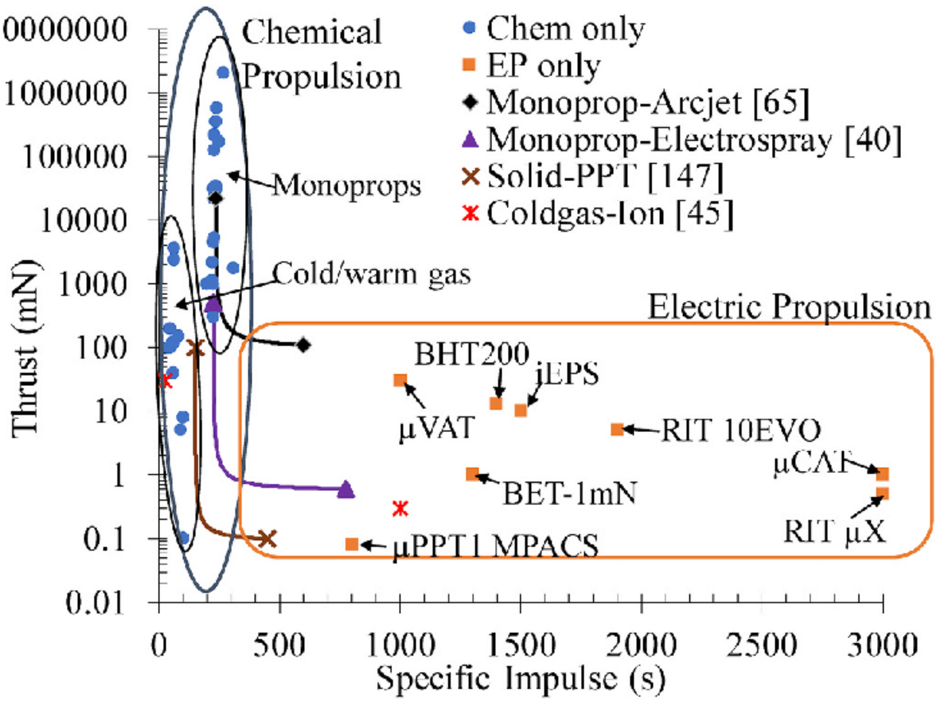

Figure 5. Chemical propulsion systems for small satellites[3.1]

➢ **Solid Propulsion Systems (SPS):** Chemical propulsion systems, such as **SPS** for small satellites, produce thrust using solid propellants. These propellants are useful for monopropellant engines because of their high energy and ability to decompose quickly when exposed to catalysts. Hydrazine (N_2H_4) or one of its derivatives, such as hydrazine hydrate ($N_2H_4 \cdot H_2O$), is one of the most often used monopropellant engines [4].

Because they are straightforward, dependable, and have a lengthy storage life, these systems are frequently utilized in small satellite missions. Additionally, they are lightweight and small, which makes them perfect for small satellites with constrained volume and power [4].

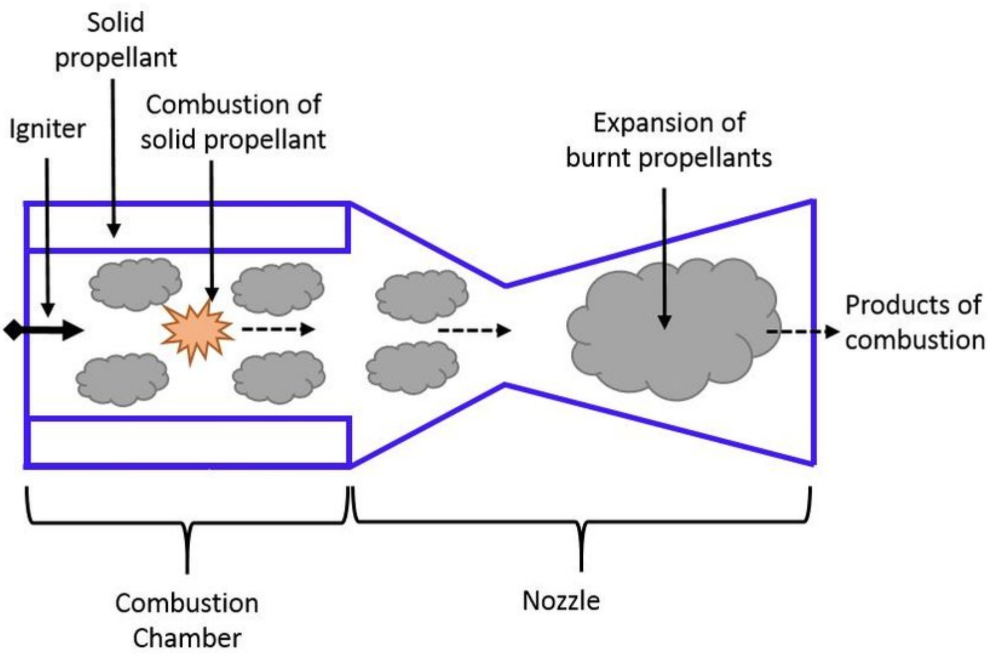

Figure 6. Solid Propulsion System [3.2]

Solid propellants are made up of a binder and a combination of metal powders that are packed into a combustion chamber. The solid propellant burns when ignited, producing hot gasses that are ejected via a nozzle to produce thrust. The propellant combination, nozzle design, and combustion chamber size and shape all affect how much thrust a solid rocket motor can generate [4].

Small satellite attitude control normally does not use solid propulsion systems. Instead, orbit insertion, station holding, and de-orbiting maneuvers are where they are most frequently employed. This is due to the fact that precise attitude control maneuvers need liquid propulsion systems, which are often more controllable than solid rocket engines. Solid propulsion systems may be utilized for attitude control in some particular situations, such as in high-thrust applications where precise control is less important or for attitude control during re-entry or other high-dynamic events, in small satellites. However, solid propulsion technologies are not often employed in small satellites for attitude control [4].

- ➢ **Liquid Propulsion Systems (LPS)**: **LPS** generates hot gasses by the combustion of a liquid fuel and oxidizer that are fed into a combustion chamber, combined, and ignited to provide thrust. Comparatively speaking, **LPS** offers more performance and versatility than solid propulsion systems. Small satellites frequently employ them for orbital insertion, station-keeping, and attitude control[4].

A number of important variables, like specific impulse, thrust-to-weight ratio, and propellant consumption rate, affect how well **CPS** performs. A higher specific impulse translates into stronger mission capability since it is a measure of the propulsion system's fuel efficiency. A higher ratio leads to more acceleration and maneuverability since it measures the force produced by the propulsion system in relation to its mass. Lower propellant consumption rates lead to longer mission durations since they indicate how much fuel the propulsion system uses per unit of time[4].

Overall, chemical propulsion technologies provide small satellites a dependable and tested mode of propulsion. However, they need a lot of propellant, which might cut down the length of their missions. In some chemical propulsion systems, the use of poisonous and dangerous propellants can also raise issues with safety and the environment [4].

TECHNOLOGY	**THRUST RANGE**	**SPECIFIC IMPULSE RANGE (sec)**
Hydrazine Monopropellant	0.25 - 25 N	200 - 285
Alternative Mono- and Bipropellants	10mN - 120 N	160 - 310
Hybrids	1 - 230 N	215 - 300
Cold / Warm Gas	10 µN - 3 N	30 - 110
Solid Motors	0.3 - 260 N	180 - 280
Propellant Management Devices	N/A	N/A

Table 3. Chemical Propulsion Technologies [18].

3.2. Electric propulsion systems

Small satellites are increasingly using electric propulsion systems (**EPS**) for a variety of purposes. These devices ionize and accelerate propellant using electric power to produce thrust[4].

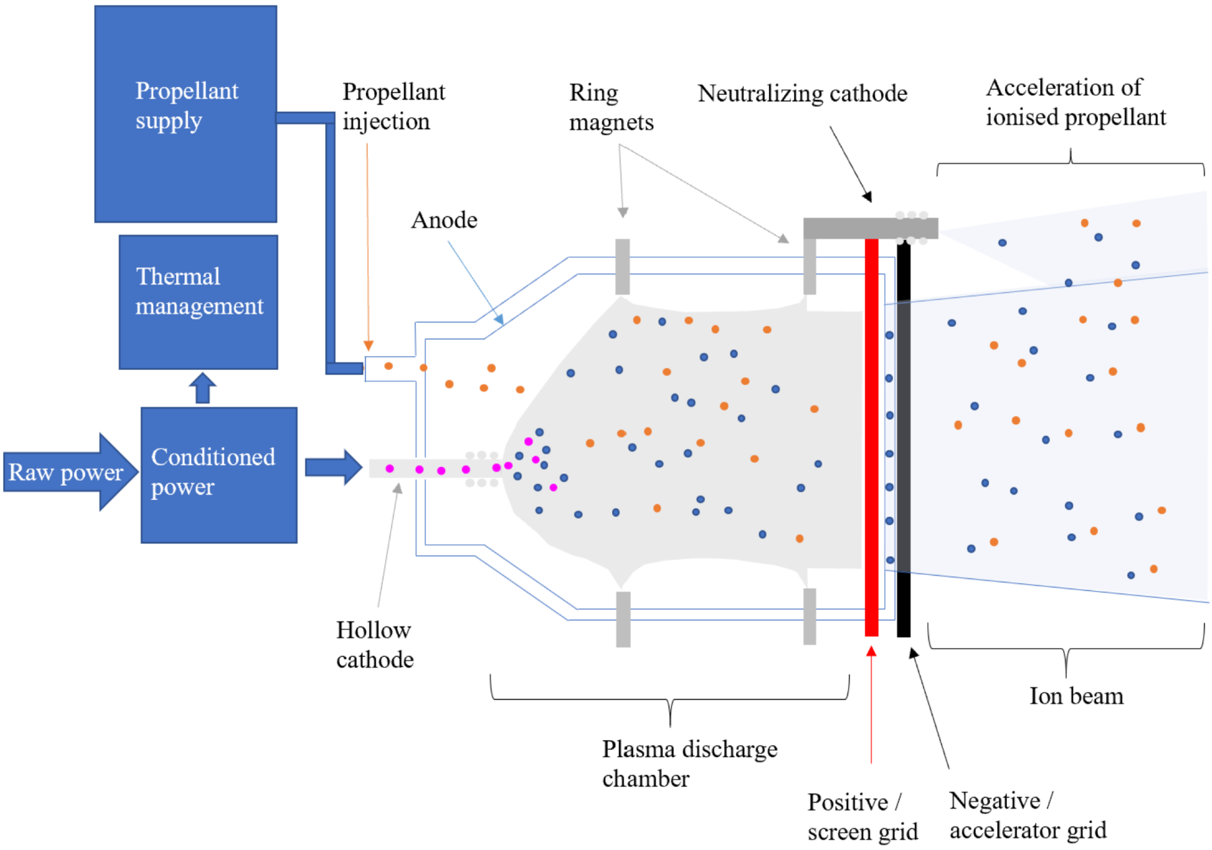

Figure 7. Electric Propulsion Systems for Small Satellites [3.2.4]

Small satellites often have electric propulsion systems that use electromagnetic forces to accelerate ions, neutral particles, or plasma to produce thrust. They provide more specific impulse than traditional chemical propulsion, allowing for longer flights or larger cargo capacities while using less propellant mass. Electrothermal and electromagnetic electric propulsion systems are the two main divisions[4].

Systems that use an electromagnetic field to ionize and accelerate a propellant are known as electrothermal propulsion systems. Resistojets, which ionize a propellant and produce propulsion using a heated resistive element, are the most typical electrothermal systems for small satellites [5].

Electric and magnetic fields are combined in electromagnetic propulsion systems to accelerate a propellant.

Hall effect thrusters, which ionize a propellant using a plasma discharge and utilize a magnetic field to accelerate the generated ions to create thrust, are the most popular electromagnetic systems for small satellites. The pulsed plasma thruster is another form of electromagnetic device that uses electrical pulses to create a plasma discharge in order to accelerate ions and produce thrust[5].

Different energy sources, such as solar cells, batteries, or radioisotope thermoelectric generators, can power **EPS**. Even while electric propulsion has numerous benefits, it often produces less thrust than chemical propulsion, which may restrict its application for specific maneuvers or missions[5].

TECHNOLOGY	THRUST RANGE	SPECIFIC IMPULSE RANGE (sec)
Electrothermal	0.5 - 100 mN	50 – 185
Electrosprays	10 µN – 1 mN	225 – 5,000
Gridded Ion	0.1 – 20 mN	1,000 – 3,500
Hall-Effect	1 – 60 mN	800 – 1,950
Pulsed Plasma and Vacuum Arc Thrusters	1 – 600 µN	500 – 2,400
Ambipolar	0.25 – 10 mN	400 – 1,400

Table 4. Electric Propulsion Technologies [18].

3.3. Cold gas propulsion systems

Small quantities of push are delivered to a satellite via a type of thruster called a cold gas propulsion system (**CGPS**). Pressurized gas is used in this straightforward and dependable technology to provide thrust. When a low cost and low complexity propulsion system is needed, such as in small satellites like CubeSats or nanosatellites, this technology is frequently utilized [4].

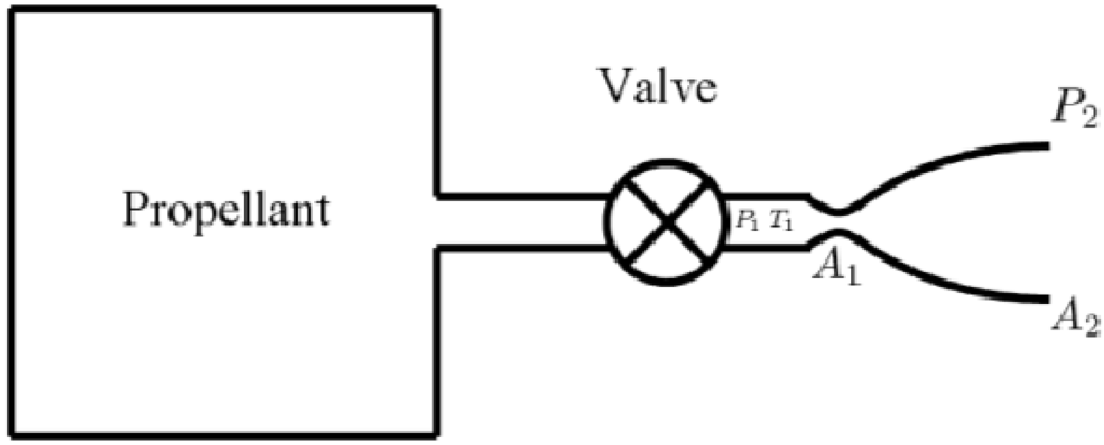

Figure 8. Cold Gas Propulsion System [3.3]

A cold gas propulsion system's fundamental idea is to store gas —typically nitrogen or helium— at a high pressure in a tank. The satellite is propelled in the opposite direction by push created when the gas is let go through a nozzle. The size of the nozzle, the gas pressure, and the length of the release all affect how much thrust is produced [4].

The technology is known as "cold gas" because, unlike in chemical or electric propulsion systems, the gas is not heated or ionized before it is released. This indicates that the system is straightforward, lightweight, and uses little power [4].

Instead of making significant orbital modifications, **CGPS** are frequently employed for attitude control and orbit maintenance. They are able to deliver a modest and steady push, enabling precise control of the satellite's location and orientation. Additionally, they can be utilized to deorbit the satellite once its job is complete [4].

In general, a **CGPS** is an affordable and dependable propulsion option for small satellites. Its performance is constrained in comparison to that of other propulsion systems, and it might not be appropriate for all missions [4].

For small satellites, a number of cold gas propulsion methods are suitable →

- **Nitrogen gas thrusters:** Due to the affordability and accessibility of nitrogen gas, they are frequently utilized for small satellites. To create thrust, the gas is first held in a tank and then released through a nozzle. The system has a low specific impulse but is easy to use and trustworthy [4].

- **Helium gas thrusters:** Another application for helium gas is as a cold gas propellant. Compared to nitrogen, it has a larger specific impulse. In hybrid systems, where it is combined with other propellants to boost performance, helium is frequently used[4].

- **Xenon gas thrusters:** Xenon gas may be utilized as a cold gas propellant in addition to being often employed in electric propulsion systems. Xenon is an effective propellant because of its high specific impulse. Its handling and storage, however, are more expensive and complicated[4].

TECHNOLOGY	THRUST RANGE	SPECIFIC IMPULSE RANGE (sec)
Nitrogen cold gas thrusters	0.1 N - 1 N	50 - 80
Helium cold gas thrusters	0.01 N - 0.5 N	70 - 90
Xenon cold gas thrusters	5 mN - 10 mN	1000 - 5000

Table 5. Cold Gas Propulsion Technologies [18].

4. Advantages and disadvantages of propulsion systems

We will examine the benefits and drawbacks of the three different small satellite propulsion technologies in this lesson: chemical propulsion, electric propulsion and cold gas propulsion. In order to determine if these systems are appropriate for a given mission's needs, it is essential to understand their strengths and weaknesses.

4.1. Advantages and disadvantages of chemical propulsion systems

Advantages of chemical propulsion systems for small satellites [7]:

- High thrust and acceleration capability: Chemical propulsion systems provide tremendous thrust and acceleration capabilities, which let small satellites swiftly and effectively enter their intended orbits.

- Proven technology: Chemical propulsion systems are a tried-and-true technology with a high level of dependability that have been utilized in space missions for decades.

- Flexibility: Chemical propulsion systems can be tailored to satisfy particular mission objectives, such as orbit modification, attitude control maintenance, or satellite deorbiting.

- Cost-effective: Particularly solid propulsion systems are economical and need little upkeep.

Disadvantages of chemical propulsion systems for small satellites[7]:

- ➢ Limited mission duration: Chemical propulsion systems have a mission-limiting propellant need, which shortens their range. For long-duration missions or missions that need regular orbital modifications, this can be a serious drawback.

- ➢ Complexity: Compared to solid propulsion systems, liquid propulsion systems are more complicated and need more parts and subsystems, which raises the possibility of failure.

- ➢ Safety concerns: Some of the chemical propellants used in propulsion systems can be poisonous and dangerous, raising issues with regard to safety and the environment during production, handling, and launch procedures.

- ➢ Limited maneuverability: Small satellites may not be able to undertake sophisticated orbital maneuvers or station-keeping because chemical propulsion systems are less maneuverable than other propulsion systems, such as electric propulsion systems.

LIQUID PROPULSION SYSTEM	**TYPICAL PROPELLANTS**	**ADVANTAGES**	**DISADVANTAGES**
Monopropellants	Hydrazine; Green Propellants	Relatively simple	Require heavy catalyst systems to operate
Hypergolic (bi-propellant)	Hydrazine; Nitrogen Tetroxide	Long term, in-space storable. Don’t require an ignition source	Toxic; Corrosive Lower performing than other propellants
Cryogenic (bi-propellant)	Hydrogen; Oxygen; Methane	High performance; Relatively benign	Need to be kept very cold; can have very large tanks
Nuclear Thermal	Hydrogen	Very High Performance	Requires nuclear reactor; heavy

Table 6. Advantages and disadvantages of liquid propulsion systems [10].

Generally speaking, chemical propulsion systems are a trusted and established method of propulsion for small satellites, but they have constraints in terms of mission duration, complexity, safety, and maneuverability.

When choosing a propulsion system for a particular small satellite mission, it is important to take these restrictions into serious consideration[7].

4.2. Advantages and disadvantages of electric propulsion systems

For small satellites, electric propulsion technologies have both advantages and downsides. Some of the more significant ones are listed below:

Advantages [7]:

- ➢ Efficiency: Because electric propulsion systems are more effective than conventional chemical propulsion systems, they may produce more thrust with a less amount of fuel. They are therefore perfect for small satellites with constrained propellant capacities.

- ➢ Specific impulse: In comparison to chemical propulsion systems, electric propulsion systems have a higher specific impulse, which allows them to produce more thrust per mass of fuel. As a result, missions last longer and orbital control is more exact.

- ➢ Longevity: Electric propulsion technologies are more suited for long-duration missions since they can run for longer periods of time than chemical propulsion systems.

- ➢ Precision: Small satellites that require fine orbit maintenance or frequent orbital modifications are best served by electric propulsion systems because they offer more exact orbital control than chemical propulsion systems.

- ➢ Flexibility: Electric propulsion systems are versatile and flexible to a variety of missions because they may be tuned for specific mission needs.

Disadvantages[7]:

- ➢ Low thrust: Low amounts of thrust produced by electric propulsion systems make it more difficult to enter or modify orbits quickly.

- ➢ Complexity: It may be more challenging to design, construct, and run electric propulsion systems since they are more complicated than chemical propulsion systems.

- ➢ Power consumption: Large amounts of electrical power are needed for electric propulsion systems, which presents a problem for small satellites with constrained power generating capabilities.

- ➢ Cost: Because they are often more costly than chemical propulsion systems, electric propulsion technologies may not be as appealing for some small satellite missions.

- ➢ Limited performance: When a mission calls for strong thrust or quick movements, electric propulsion systems might not be the best option.

4.3. Advantages and disadvantages of cold gas propulsion systems

For small satellites, cold gas propulsion systems have the following benefits and drawbacks:

Advantages[9]:

- ➢ Simplicity: Cold gas propulsion systems are an economical choice for small satellites since they are straightforward and have a low degree of complexity.
- ➢ Reliability: Fewer moving components reduce the likelihood of system failure, making the system more dependable.
- ➢ Low Power Consumption: The method is appropriate for small satellites with restricted power supply since it utilizes comparatively less power in comparison to other propulsion systems.
- ➢ Low Toxicity: Since the system's gas, such as nitrogen or helium, is non-toxic, both the environment and the satellite are made safer.
- ➢ Safe Operation: Due to the absence of explosive substances or high temperatures, the system is safe to use.

Disadvantages[9]:

- ➢ Limited Performance: When compared to other propulsion systems, cold gas propulsion systems perform poorly and have a low thrust capacity. They are therefore inappropriate for more complex orbital movements.
- ➢ Limited Fuel Capacity: The system can only operate for a certain length of time since the amount of gas that can be stored in a tank is restricted.
- ➢ Inefficient: Compared to other propulsion systems, the system is somewhat inefficient in terms of the quantity of gas needed to produce a given level of thrust.
- ➢ Difficult to Control: Accurately regulating the thrust's length and direction is difficult. This makes accurate orbit movements more difficult to execute.
- ➢ Large Propellant Tank: The tank capacity needed to hold the gas for extended operations may be fairly considerable, which might increase the satellite's total mass.

However, compared to other propulsion systems, cold gas propulsion systems have certain drawbacks in terms of performance, economy, and control. Nonetheless, they are a dependable and affordable option for small satellite propulsion demands.

5. Examples of propulsion systems for Small Satellites

5.1. Examples of chemical propulsion systems for small satellites

Here are a few small satellite chemical propulsion system examples that have been utilized or are being considered [10]:

- ➢ Monopropellant thruster: Thruster that only employs hydrazine as its propellant. They are often employed on small satellites for deorbiting, attitude control, and orbit modifications. A few examples include the **XACT** hydrazine thruster, which was created especially for small satellites, and the Hydrazine Thrusters, R-4D-11 thruster, both of which have been deployed on several small satellite missions.

Figure 9. Hydrazine Thrusters [5.1.1]

THRUST	100 - 1500 mN
SPECIFIC IMPULSE	140 - 180 s
DELTA - V	50 - 300 ms^{-1}
MASS FLOW	0.055 - 0.9 gs^{-1}
LIFETIME GOAL	-16 hours

Table 7. Performance Parameters of the Monopropellant Thruster System [22]

➢ Bi-Propellant Thrusters: These are thrusters that combine two different propellants to produce a chemical reaction that produces thrust. Examples include the 50N Bi-Propellant Thruster, which was created especially for small satellites, and the LEROS 1B and 1C thrusters, which have been deployed on several small satellite missions.

THRUST	1-2 N
SPECIFIC IMPULSE	320 s
DELTA - V	500 ms^{-1}
MAXIMUM MASS	400 g
MAXIMUM VOLUME	0.8 l
SATELLITE CLASSES	10 - 100 kg
ELECTRICAL POWER	6 W

Table 8. Performance Parameters of the Bipropellant Thruster System [22]

➢ Solid Rocket Motors: These rocket engines burn pre-mixed solid propellants that are kept in solid form until they are ignited to provide thrust. They have been employed for a variety of small satellite missions, including as orbit insertion, launch vehicle separation, and deorbiting.

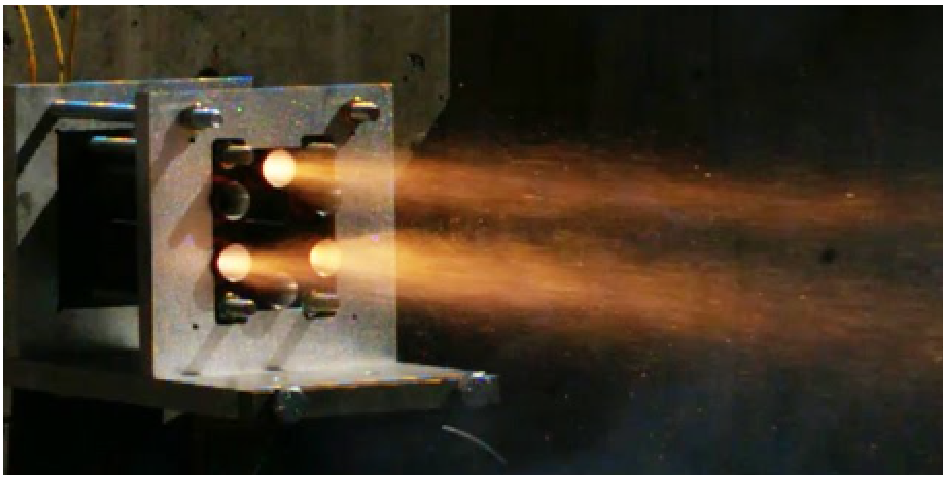

Figure 10. Solid Rocket Motor [5.1.2]

PRODUCT	MANUFACTURER	TOTAL MASS	AVERAGE THRUST	SPECIFIC IMPULSE
ISP 30 sec motor	Industrial Solid	0.95 kg	37 N	187 s
STAR 4G	Propulsion Orbital ATK	1.5 kg	258 N	277 s
CAPS-3	DSSP	2.33 kg	0.3 N	Up to 900 s

Table 9. Solid Rocket Motors [4].

➢ Green Propulsion Systems: These are a new generation of chemical propulsion systems that lessen the environmental effect of space missions by using ecologically benign propellants like hydroxyl ammonium nitrate (**HAN**) or LMP-103S. Examples include the LMP-103S thruster produced by Busek Co. Inc. and the HAN-based rocket motor created by Accion Systems, both of which have been proposed for use on small satellites.

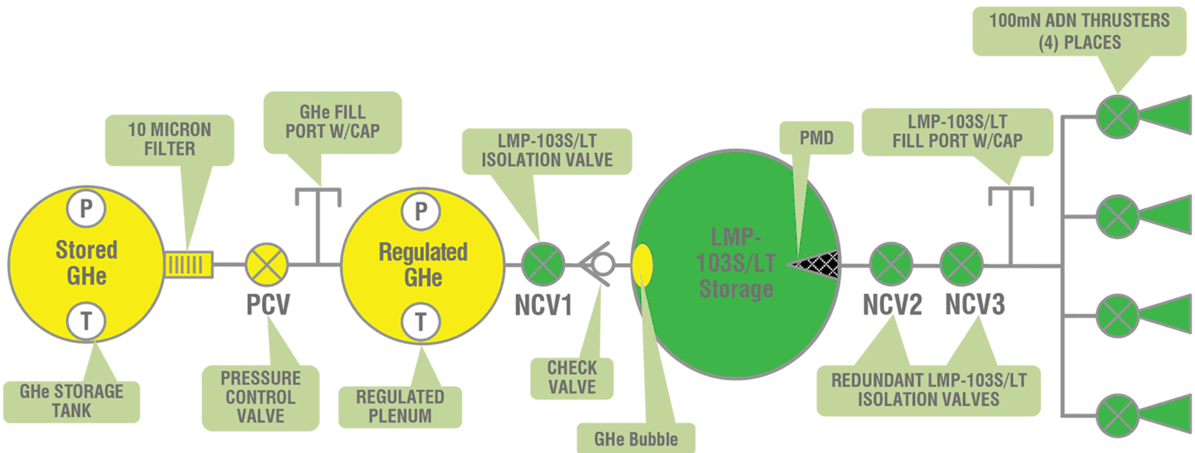

Figure 11. Green Propulsion System [5.1.4]

PRODUCT	MANUFACTURER	THRUST	SPECIFIC IMPULSE
GR-1	Aerojet Rocketdyne	0.26 - 1.42 N	231 s
GR-22	Aerojet Rocketdyne	5.7 - 26.9 N	248 s
1 N HPGP	ECAPS	0.25 - 1.00 N	204 -235 s
HYDROS	Tethers	0.2 - 0.6 N	258 s
BGT-X5	Unlimited Inc. Busek	0.5 N	220 s

Table 10. Green Propellant Propulsion Systems [4].

5.2. Examples of electric propulsion systems for small satellites

Small satellites can be propelled by a variety of electric propulsion methods. Here are a few instances:

➢ Hall Effect Thrusters (**HETs**): These electric propulsion systems are the most prevalent kind utilized in small satellites. They ionize and accelerate propellant by means of a magnetic field. Typically, xenon gas serves as the propellant. It is heated and ionized in a discharge chamber before being pushed out of the thruster to produce thrust[4].

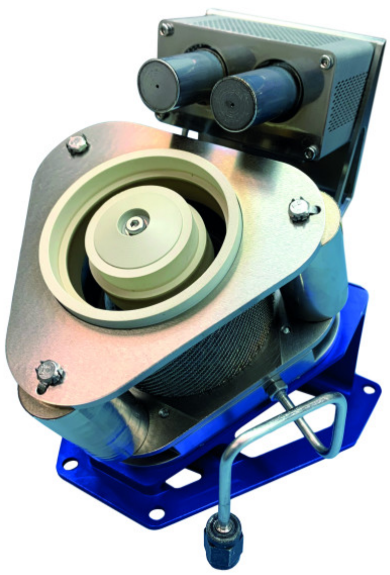

Figure 12. Hall-effect thruster [3.2.1]

PRODUCT	MANUFACTURER	THRUST	POWER	SPECIFIC IMPULSE
BHT - 200	Busek	13 mN	200 W	1390 s
HT 100	SITAEL	5-15 mN	175 W	up to 1350 s
CHT	UTIAS SFL	6.2 mN	200 W	1139 s

Table 11. Hall Effect Propulsion Systems and thrusters [4].

➢ Pulsed Plasma Thrusters (**PPTs**): **PPTs** are small and straightforward electric propulsion devices that generate thrust from plasma pulses with high energy. These systems ionize and accelerate propellant using a high-voltage discharge. Although they are often easier and less expensive to produce than Hall Effect Thrusters, they are typically smaller and less powerful[11].

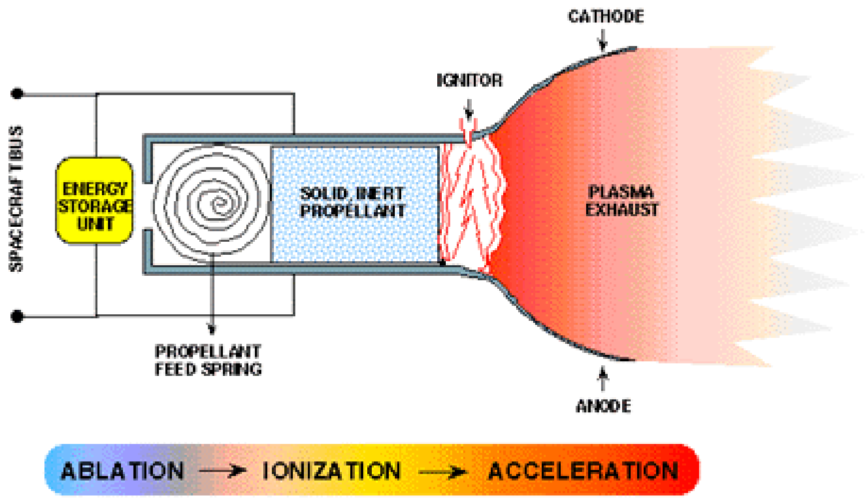

Figure 13. Pulsed Plasma Thrusters [3.2.2]

PRODUCT	MANUFACTURER	THRUST	POWER	SPECIFIC IMPULSE
PPTCUP	Mars Space and Clyde Space	40 µN	2 W	655 s
NanoSat PPT	Mars Space and Clyde Space	90 µN	5 W	640 s
µCAT	GWU and USNA	1 to 50 µN	2 to 14 W	2500 - 3000 s
BmP-220	Busek	20 µN-s Impulse bit	1.5 W	536 s
MPACS	Busek	80 µN-s Impulse bit	10 W	827 s

Table 12. Pulsed Plasma and Vacuum Arc Propulsion Systems [4].

➢ Field Emission Electric Propulsion (**FEEP**): **FEEP** devices create very accurate and reliable propulsion by accelerating and ionizing liquid metals using electric fields. Propeller is ionized in these systems via a field emission cathode. They are comparable to Hall Effect Thrusters in terms of size and power, but they are less effective[11].

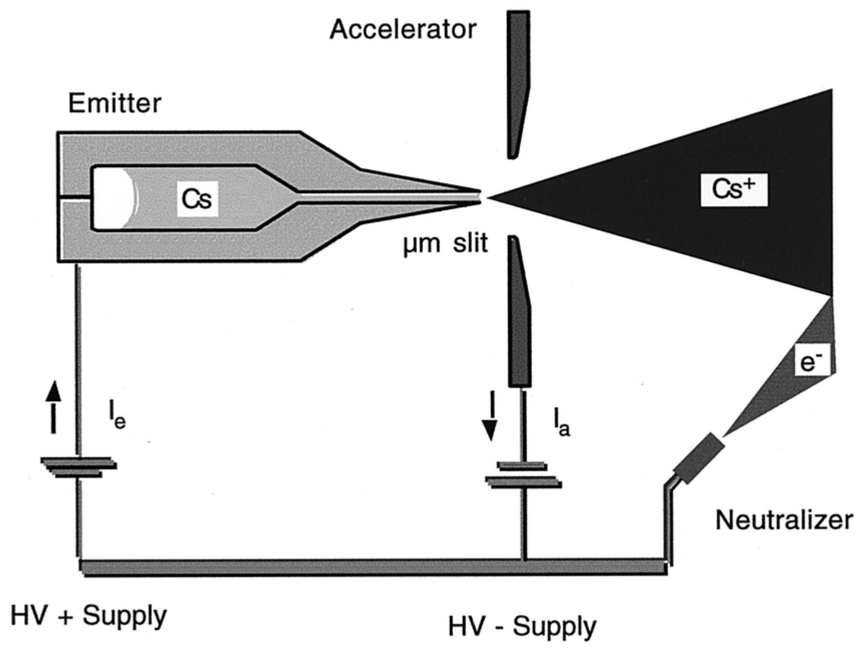

Figure 14. Field Emission Electric Propulsion [3.2.3]

➢ Ion Thrusters: Electrostatic forces are used by ion thrusters to accelerate ions and generate thrust. Although they can be utilized in smaller satellites with bulk and power limitations, they are typically employed in bigger satellites[4].

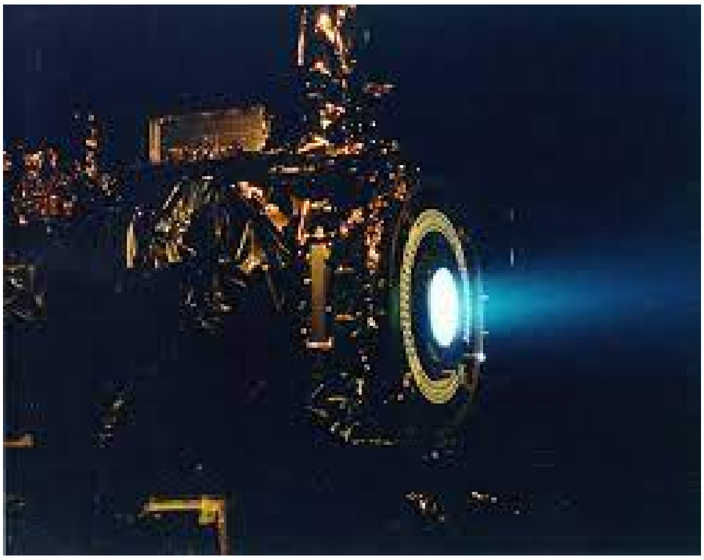

Figure 15. Ion Thrusters [5.1]

PRODUCT	MANUFACTURER	THRUST	POWER	SPECIFIC IMPULSE
BIT - 3	Busek	1.4 mN	60 W	3500 s
BIT - 1	Busek	0.1 mN	10 W	2250 s
I - COUPS	University of Tokyo	0.3 mN	N/A	1000 s
RIT µX	Airbus	50-500 µN	50 W	300 - 3000 s

Table 13. Ion Propulsion Systems and thrusters [4].

➢ Electrospray Propulsion: Electrostatic forces are used by ion thrusters to accelerate ions and generate thrust[4].

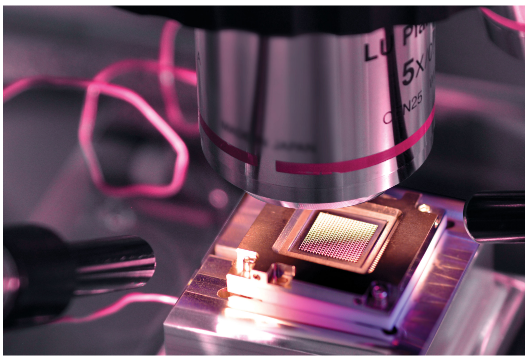

Figure 16. Electrospray Propulsion [5.2]

PRODUCT	MANUFACTURER	THRUST	POWER	SPECIFIC IMPULSE
S-iEPS	MIT	74 µN	1.5 W	1160 s
IMPACT	Accion Systems Inc.	60 µN per axis	0.75 W per axis	1200 s
MAX-1	Accion Systems Inc.	120 µN	1.6 W	2000 s
1 mN Electrospray	Busek	0.7 mN	15 W	800 s
100µ	Busek	0.1 mN	5 W	2300 s

Table 14. Electrospray Propulsion Systems [4].

There are many more types and variants of electric propulsion systems that may be employed based on the particular mission requirements. These are just a few examples of electric propulsion systems that can be utilized in small satellites.

NAME	**Type**	**Specific Impulse (s)**	**Thrust (N)**	**Power (W)**	**Propellant**
MR-512	Arcjet	502	254 m	1.8 kW	N_2H_4
MR-502	Resistojet	304	0.5	840	N_2H_4
ATOS	Arcjet	400	0.1	750	NH_3
VELARC	Arcjet	865	22.5	365	H_2
FMMR	Resistojet	65	1.2	<6	H_2O
AQUARIUS	Resistojet	70	4 m	<20	H_2O
STAR	Resistojet	79.42	29.8	28.55	Ar
Sagami 3	Arcjet	480	<50 m	300	$N\ H_3$

Table 15. Examples of electrothermal thruster parameters [17].

Name	Type	Specific Impulse (s)	Thrust (N)	Power (W)	Propellant
APPT-250	APPT	1900	1.2 m	60-120	Teflon
ADD-SIMP LEX	iMPD	2761	1.375	<100	PTFE
PETRUS	iMPD	1567	41.46 μ	5-8	PTFE
BmP 220	PPT	536	0.14 m	<3	PTFE
MPACS	PPT	827	0.144 m	<10	PTFE

Table 16. Examples of electromagnetic thruster parameters [17].

5.3. Examples of cold gas propulsion systems for small satellites

Small satellite cold gas propulsion systems come in a variety of forms. To name a few:

- NanoAvionics Cold Gas Thruster System: Cold gas thrusters are among the small satellite propulsion technologies that the NanoAvionics firm manufactures. They can produce up to 1 N of thrust with either nitrogen or helium gas in their thrusters. The system has a nozzle, flow control valve, and pressure regulator, and it may be managed via a straightforward electrical interface. The NanoAvionics thrusters may be used for attitude control, orbit maintenance, and other maneuvers on CubeSats and other small satellites[8].

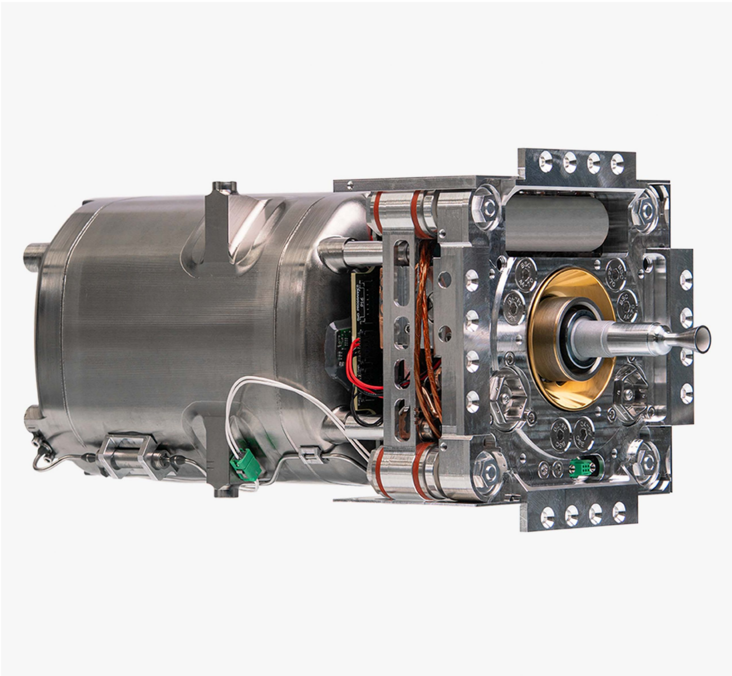

Figure 17. NanoAvionic Thruster [5.3.2]

➢ Bradford Cold Gas Thruster System: A compact, light-weight propulsion system called the Bradford Cold Gas Thruster is created specifically for CubeSats and other small satellites. It can produce a thrust of up to 0.5 N and uses compressed nitrogen gas as its propellant. The system has a nozzle, flow control valve, and pressure regulator, and it may be managed via a straightforward electrical interface. The Bradford thruster is intended to be used in missions like Earth observation and remote sensing that need for accurate attitude control[9].

Figure 18. Bradford Cold Gas Thruster System [5.3.3]

These are but a few instances of cold gas propulsion systems for small satellites. There are several more systems out there, each with distinct features and capabilities.

PRODUCT	MANUFACTURER	THRUST	SPECIFIC IMPULSE
Micro-Thruster	Marotta	0.05 - 2.36 N	65 s
Butane Propulsion System	SSTL	0.5 N	80 s
MEMS	NanoSpace	0.01 - 1mN	50 -75 s
POPSAT-HIP1	Micro Space	0.083 - 1.1 mN	32 - 43 s
CNAPS	UTIAS/SFL	12.5 - 40 mN	40 s
CPOD	VACCO	25 mN	40 s

Table 17. Cold Gas Propulsion Systems [4]

6. Performance Comparison of Small Satellite Propulsion Systems

6.1. Evaluation of propulsion systems based on key parameters and performance metrics

Here is an evaluation of the different propulsion systems [19]:

1. **Chemical Propulsion Systems:**

KEY PARAMETERS →

SPECIFIC IMPULSE (ISP)	THRUST	PROPELLANT MASS FRACTION

PERFORMANCE METRICS →

TOTAL DELTA-V	PROPELLANT CONSUMPTION	SYSTEM MASS

Though they require large amounts of fuel, chemical propulsion technologies offer tremendous thrust and specific impulse. Although the overall delta-v achieved is considerable, compared to other propulsion systems, the system mass is usually higher.

2. **Electric Propulsion Systems:**

KEY PARAMETERS →

SPECIFIC IMPULSE (ISP)	THRUST	POWER	EFFICIENCY

PERFORMANCE METRICS →

TOTAL DELTA-V	POWER CONSUMPTION	SYSTEM MASS

Electric propulsion systems are being scrutinized since they have a high specific impulse but little thrust and consume a lot of electricity. Although the overall delta-v achieved is considerable, power consumption and system mass are often higher than in chemical systems.

3. **Cold Gas Propulsion Systems:**

KEY PARAMETERS →

SPECIFIC IMPULSE (ISP)	THRUST	PROPELLANT MASS FRACTION

PERFORMANCE METRICS →

TOTAL DELTA-V	PROPELLANT CONSUMPTION	SYSTEM MASS

Cold gas propulsion systems are straightforward and simple to use, but their particular impulse is not very high. This system is less effective because of the low overall delta-v achievable and the high average propellant consumption.

Now we are going to see the graphs of power and thrust →

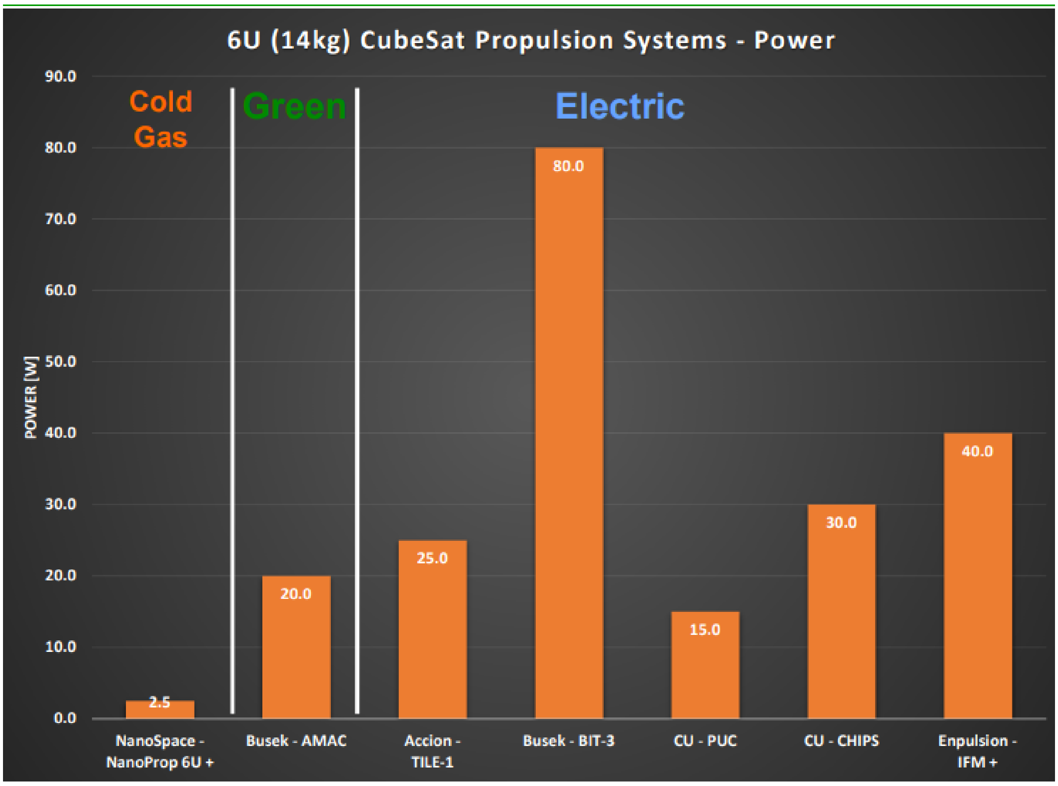

Figure 19. Graph of power [14]

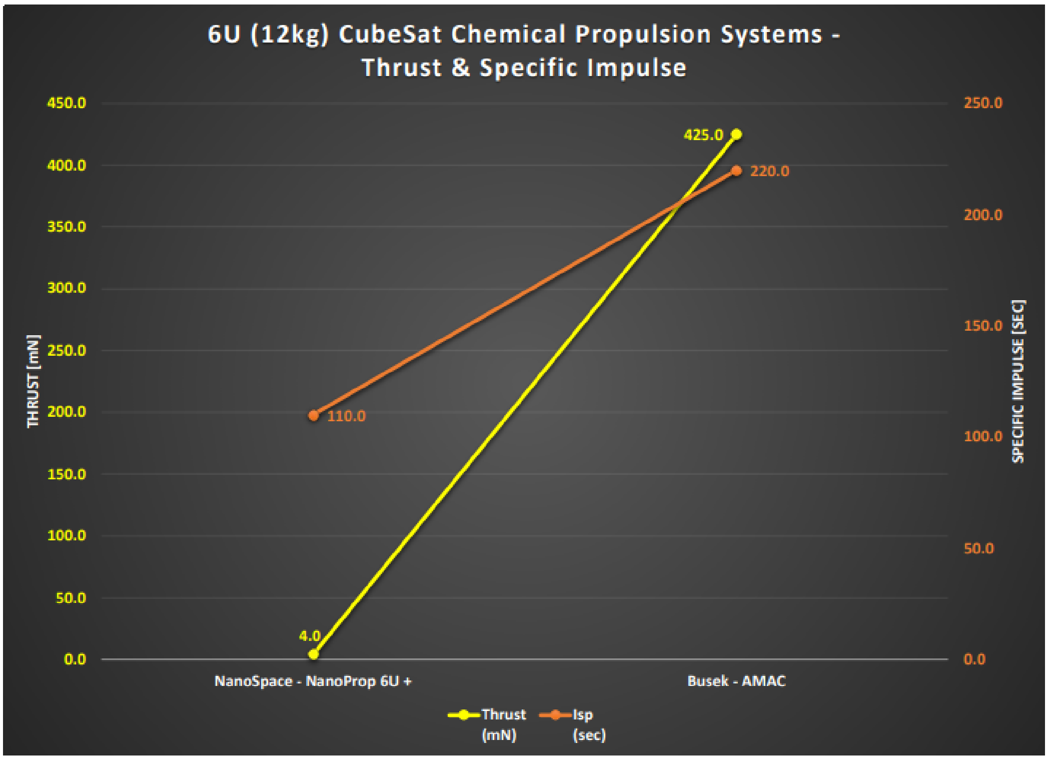

Figure 20. Graph of Thrust of Chemical Propulsion Systems [14]

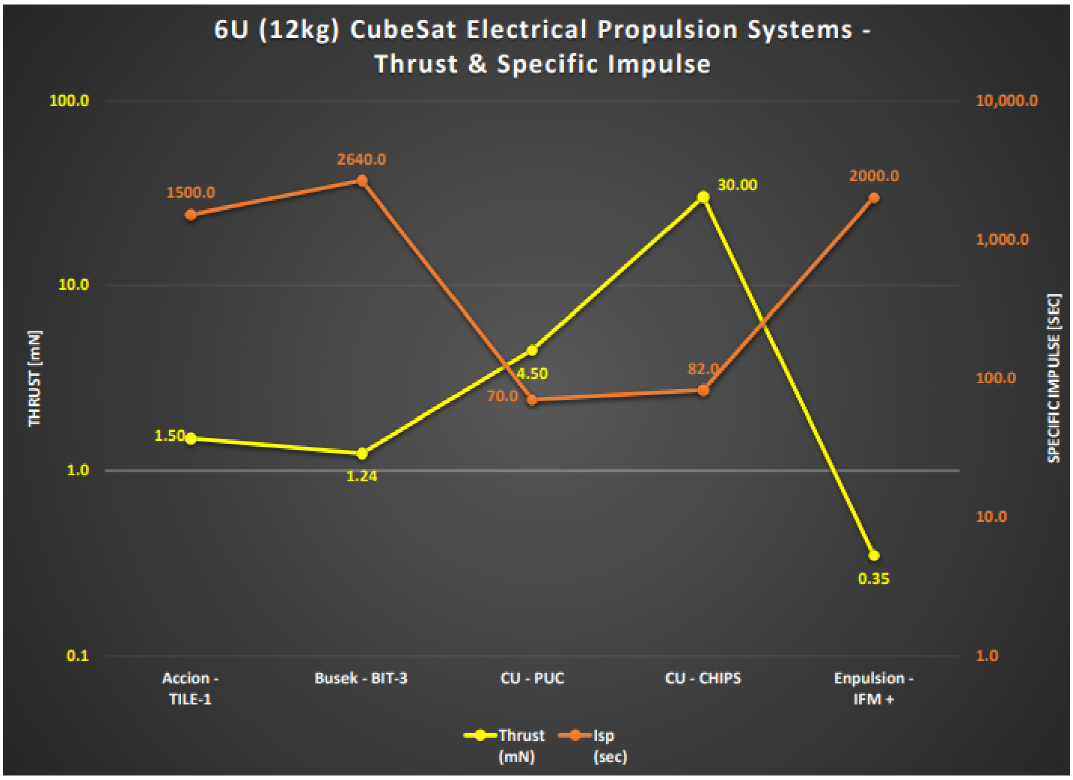

Figure 21. Graph of Thrust of Electric Propulsion System [14]

6.2. Comparison of the advantages and disadvantages of different propulsion systems

The benefits and drawbacks of the various propulsion technologies are contrasted as follows:

	ADVANTAGES	DISADVANTAGES
CHEMICAL PROPULSION SYSTEMS	High thrust, high specific impulse, well-established technology	High propellant consumption, large system mass, complex propellant handling.
ELECTRIC PROPULSION SYSTEMS	High specific impulse, low propellant consumption, smaller system mass than chemical systems, precise control	Low thrust, high power consumption, complex design and operation, expensive.

COLD GAS PROPULSION SYSTEMS	Simple design and operation, low cost, easy to use and maintain.	Low specific impulse, low thrust, low delta-v achievable, inefficient.

Table 18. Comparison of the advantages and disadvantages of different propulsion systems [19].

Overall, every propulsion system has pros and downsides, and the best system for a given mission relies on its particular requirements and limitations. While electric propulsion systems are more efficient but more complicated and require a power source, chemical propulsion technologies are well-established but require a substantial amount of propellant. Cold gas systems are straightforward and inexpensive, but they have poorer efficiency and lower possible delta-v.

6.3. Discussion of trade-offs between propulsion systems for specific mission requirements

The needs and limitations of the task will determine which propulsion system is best for that mission. For particular missions, the following propulsion system trade-offs may be relevant:

1. Low Earth Orbit Missions (**LEO**): The region of space within 2,000 kilometers (1,200 miles) of the Earth's surface is referred to as Low Earth Orbit (**LEO**).The region of observation and the distance from Low Earth Orbit (**LEO**) to the Moon might change based on the precise orbital height. [15] Due to their high specific impulse and little fuel consumption, electric propulsion systems are advantageous for missions to low Earth orbit. However, the high power requirements of electric propulsion systems might be a problem for small satellites with constrained power supplies. A fair balance between specific impulse and propellant may be found in hybrid propulsion systems[29].

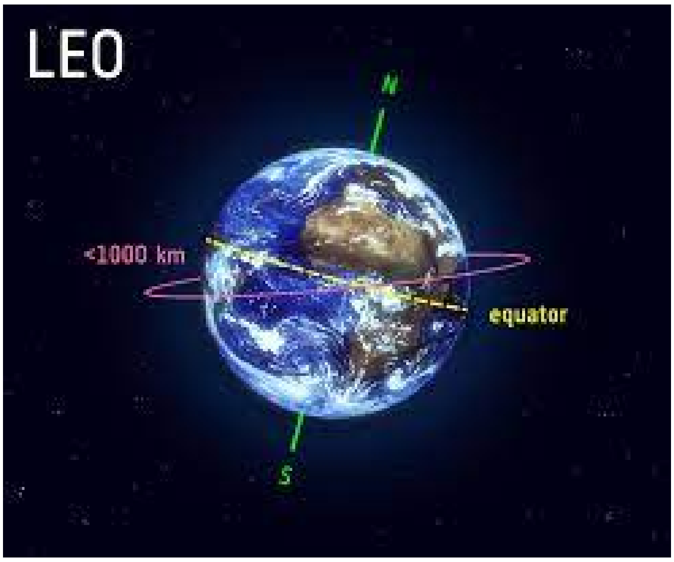

Figure 22. Low Earth Orbit Missions [6.3.1]

2. Geostationary Orbit Missions (**GEO**): Chemical propulsion systems are preferred for geostationary orbit missions because of their high thrust and high specific impulse. Chemical propulsion systems, on the other hand, need a substantial volume of fuel, which might be a problem for small satellites. Due to their high specific impulse and little propellant use, electric propulsion systems may be a suitable option, although they consume a lot of electricity. Although hybrid propulsion systems can be more complicated than electric propulsion systems and require a power source, they may be a suitable balance between specific impulse and propellant consumption[30].

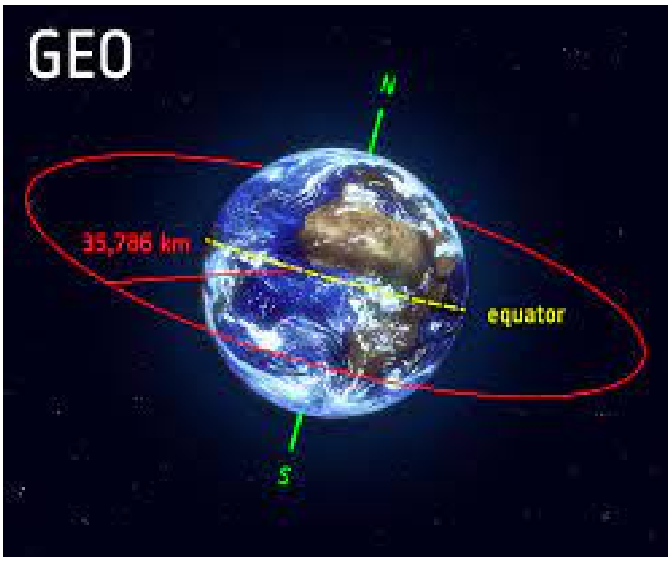

Figure 23. Geostationary Orbit Missions [6.3.2]

NAME	UNITS OR MASS
ASCENT	12 U
GS-1	16 U
SunRISE 1	6 U
SunRISE 2	6 U
SunRISE 3	6 U
SunRISE 4	6 U
SunRISE 5	6 U
SunRISE 6	6 U
HERO-1	6 U

Table 19. CubeSats for Geo [23]

3. Interplanetary Missions[24]:

Electric propulsion systems are preferred for interplanetary missions because of their high specific impulse and low fuel consumption. Interplanetary missions require a significant delta-v attainable and a lengthy working life. Due to their high specific impulse and low propellant consumption, hybrid propulsion systems may potentially be useful, although they need a power source and can be more complicated than electric propulsion systems. Chemical propulsion systems may be acceptable for brief interplanetary voyages, but longer missions may be limited by their high fuel consumption and increased system mass.

Small satellites and CubeSats can be used for interplanetary missions. Due to their small size, reduced price, and technical developments, small satellites like CubeSats are becoming more and more desirable for interplanetary missions.

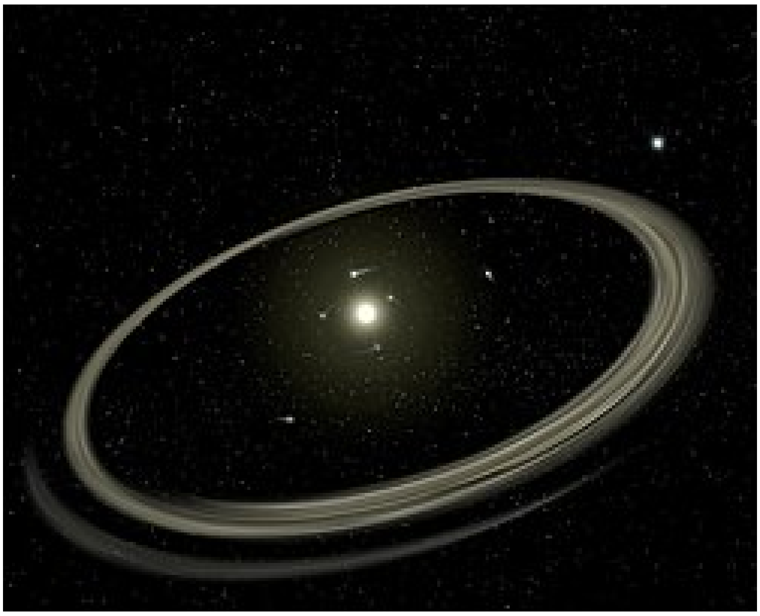

Figure 24. Planetary system [6.3.3]

In general, the selection of a propulsion system for a particular mission relies on the needs, restrictions, and resources that are available. To choose the best propulsion system, trade-offs between particular impulse, propellant consumption, power consumption, and system mass must be carefully evaluated.

7. Selection of Suitable Propulsion System for Low Earth Orbit Deorbiting

Demonstrating a low-cost deorbiting technique for small satellites is the goal of deorbiting. By creating a deployable sail that increases the drag of the satellite and hastens its descent into Earth's atmosphere at the end of its operational life, the aim is to solve the problem of space trash. This device encourages sustainable space operations and lowers the quantity of space junk in orbit [16].

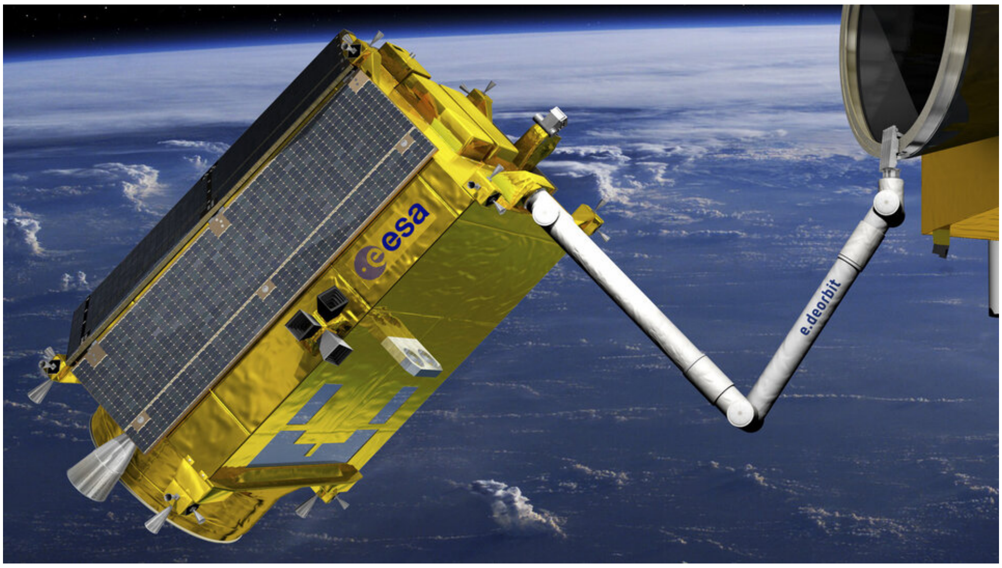

Figure 25. Deorbiting [7.1]

7.1. Criteria for selecting a suitable propulsion system

The following are some broad standards for choosing an appropriate propulsion system for small satellite missions [20][21]:

➢ Mission Requirements: The propulsion system should be chosen in accordance with the particulars of the mission, such as the necessary delta-v, thrust, and duration. Additionally, the propulsion system needs to work with the satellite's required orbit and height.

➢ Propellant Efficiency: High propellant efficiency means that the propulsion system should be able to provide the required delta-v with a low fuel usage. This is crucial for small satellites since they have less power and fuel resources.

➢ System Complexity: The propulsion system needs to be straightforward and dependable, with few moving components and low upkeep requirements. This is crucial for small satellites, which lack the money and available space for sophisticated propulsion systems.

➢ System Cost: In terms of both initial development and manufacturing expenses as well as ongoing operational costs, the propulsion system should be cost-effective. For small satellite missions with tight costs, this is crucial.

➢ Technology Maturity: To reduce the chance of mission failure or performance deterioration, the propulsion system should be built using established, well-tested technology. This is crucial for critical missions, including those requiring communications or Earth observation.

- ➢ Regulatory Compliance: The propulsion system must abide by all applicable laws, rules, and directives, including those pertaining to radio frequency interference, orbital debris mitigation, and launch safety.

The most appropriate propulsion system for a small satellite mission may be chosen using these criteria after being evaluated and compared against the mission's unique needs and limits.

7.2. Evaluation of the performance and requirements of different propulsion systems for deorbiting

The performance and specifications of four distinct propulsion systems—cold gas, monopropellant, bipropellant, and electric—for deorbiting small satellites were assessed by the authors in the study *"Evaluation of Propulsion Systems for Satellite End-Of-Life Deorbiting"* [20]. Due to their high specific impulse and little propellant consumption, the scientists discovered that electric propulsion systems offer the best chance of successfully deorbiting small satellites. They said that the mass and form of the satellite, as well as the intended disposal period, affect the precise specifications for deorbiting, such as the necessary delta-v and the height of the final orbit.

The performance and requirements of three distinct propulsion systems—cold gas, monopropellant, and electrodynamic tether (**EDT**)—for deorbiting very low Earth orbit (**VLEO**) microsatellites were assessed in the study *"Propulsion Options for Very Low Earth Orbit Microsatellites"*[21] by the authors. Cold gas and monopropellant systems are ideal for deorbiting **VLEO**s, according to the scientists, while **EDT** systems may be a more effective choice for deorbiting several microsatellites in a constellation. They stated that depending on the particular microsatellite mission and the intended disposal time, the exact requirements for **VLEO** deorbiting, such as the necessary delta-v and the final orbit height, vary.

Overall, the comparison of several propulsion systems for deorbiting small satellites emphasizes how crucial it is to pick a system that is consistent with the unique mission criteria and restrictions, such as the intended disposal time, orbit height, and propellant efficiency. Although monopropellant and cold gas propulsion systems may be more appropriate for some missions, electric propulsion technologies are widely regarded as a potential alternative for deorbiting small satellites. **EDT** systems could also be a good choice for deorbiting a constellation's worth of microsatellites.

7.3. Discussion of trade-offs between propulsion systems for deorbiting

The ultimate decision on a viable propulsion system for low Earth orbit deorbiting is based on a number of variables, including the mission requirements, the efficiency of the propellant, the complexity of the system, the cost, and the level of technological preparedness.

Our specific needs and goals of the mission are the following →

- Deorbit Time = 5 years
- The satellite needs to decrease its velocity from 160 m/s to 170 m/s
- Transitioning from an initial orbit of 1000 km to a final orbit of 500 km

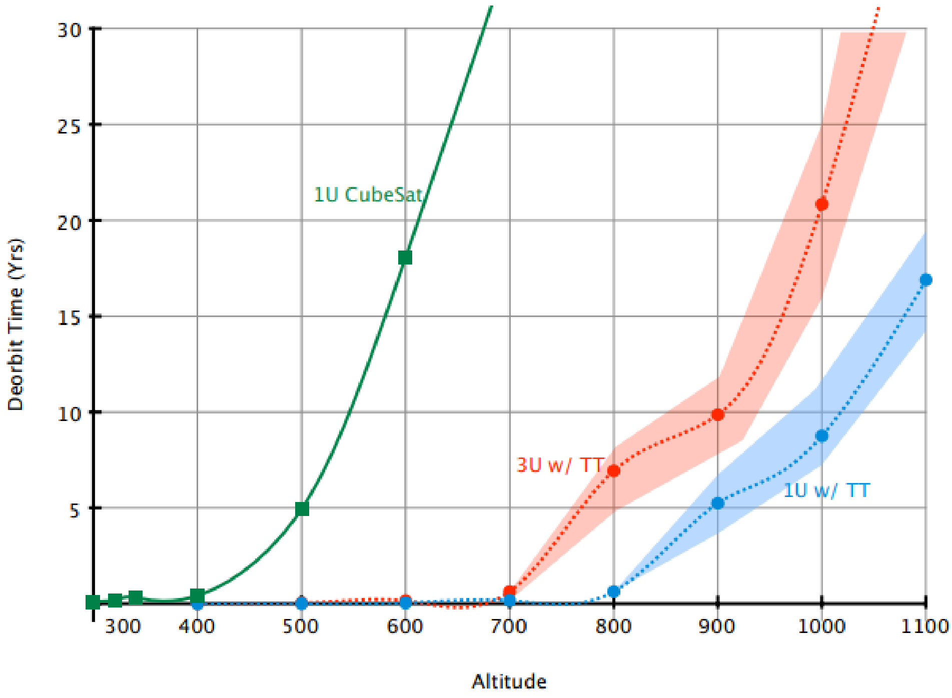

Figure 26. Deorbit Time vs. Altitude [27]

With this parameters we can calculate the altitude change[28]:

$$\Delta v = \left|V_0 - V_1\right|$$

Where:

- V_0 is the velocity of the spacecraft at the initial orbit
- V_1 is the velocity of the spacecraft at the final orbit

so,

$$\Delta v = |160 - 170| = 10 \text{ m}$$

The most important parameter for selecting a propulsion system would be the delta-V capability. The chosen propulsion system must be capable of producing the required delta-V to complete this deorbit maneuver within the allotted five-year time frame.

Using the laws of orbital mechanics, it is possible to determine the delta-V necessary for deorbiting, which will be influenced by the mass of the satellite and the effectiveness of its propulsion system [28].

$$\Delta V = I_{sp}\, g_0\, ln\left(\frac{m_0}{m_f}\right)$$

Where:

- I_{sp} is the specific impulse (s)
- m_0 is the initial mass (kg)
- m_f is the final mass (kg)
- g_o is the standard gravity (m/s^2)

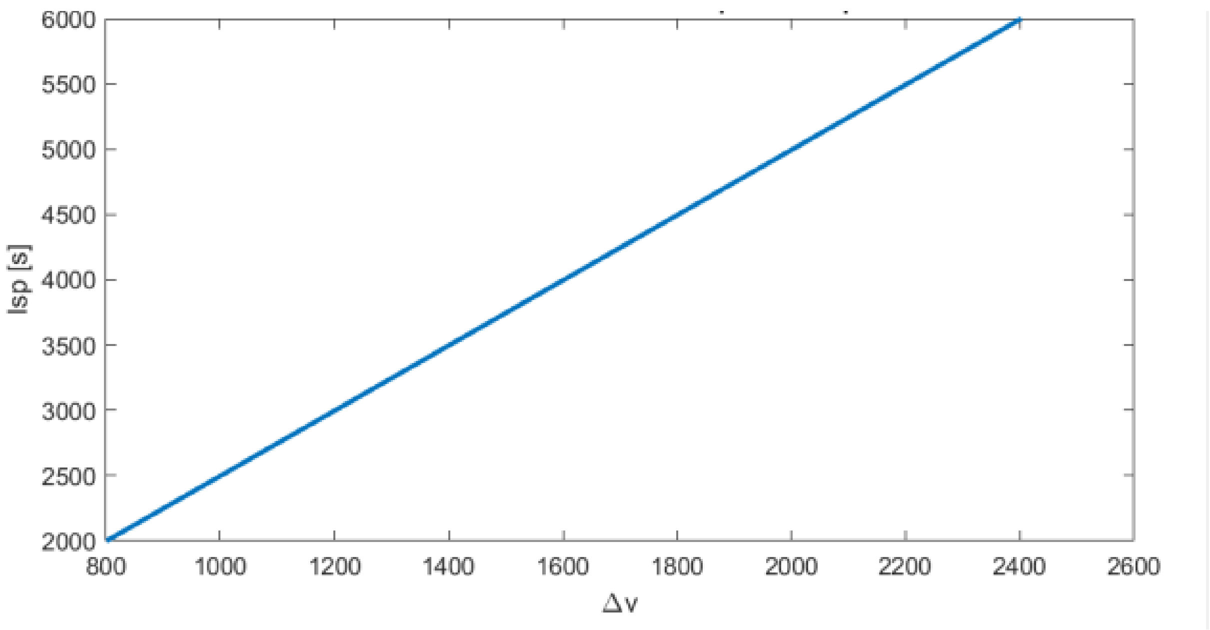

Figure 27. Maximum ΔV as a function of specific impulse [28]

We are going to assume that the initial mass (m_0) = 500 kg and the final mass (m_f) = 96% m_0 = 480 kg

So,

$$\Delta V = 4000 \cdot 9,81 \cdot ln\left(\frac{500}{480}\right) = 1601,85$$

By taking into account the delta-V capacity, the propulsion system is guaranteed to have enough thrust and efficiency to complete the intended deorbit maneuver within the mission's time restrictions[28].

We can also calculate the inclination change with the following equation[28]:

$$\Delta v = V_0 \Delta i \frac{\pi}{2}$$

Where:

- Δv is delta-V capability
- V_0 is the velocity of the spacecraft at the initial orbit

So,

$$1601,85 = 160 \cdot \Delta i \frac{\pi}{2}$$

$$\Delta i = 6,37^{o}$$

A propulsion system is required to deorbit a small satellite from an initial orbit of 1000 km to a final orbit of 500 km during a 5-year period, which requires a greater specific impulse (interval from 2000 s to 6000 s [28]), based on the stated mission objectives and restrictions. So, **the most suitable propulsion system would be an electric propulsion system,** for example an ion thruster [27].

8. Conclusion

In conclusion, a thorough analysis of small satellite propulsion technologies for low Earth orbit missions has been offered in this thesis. The analysis of several propulsion system types, such as chemical, electric, and cold gas systems, has clarified their benefits, constraints, and suitability for use in accordance with specific mission criteria. For instance, a comparison of propulsion systems has shown that electric propulsion systems have higher efficiency but lower thrust whereas chemical propulsion systems have more thrust but lower efficiency.

The performance and needs of existing propulsion systems have been highlighted in this thesis through a comparative comparison of options that are currently on the market. The decision-making procedures for choosing a viable propulsion system for low Earth orbit deorbitation have benefited greatly from this study.

The choice of an appropriate propulsion system for low Earth orbit deorbiting has been discussed, highlighting the significance of taking deorbit duration, beginning and end velocities, and delta-V capacity into account. Therefore, an electric propulsion system would be the most appropriate.

This research adds to our understanding of small satellite propulsion systems by addressing the goals stated in the thesis. It acts as a starting point for additional study and development, promoting improvements in small satellite propulsion technology and allowing more effective and sustainable operations in low Earth orbit missions.

Looking towards the future, it is anticipated that continued research and development will lead to improvements in small satellite propulsion systems. Interests include the creation of hybrid propulsion systems, improved electric propulsion systems, and the investigation of novel ideas like solar sail technology. But there are obstacles to be addressed, including system complexity, power constraints, and regulatory concerns.

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