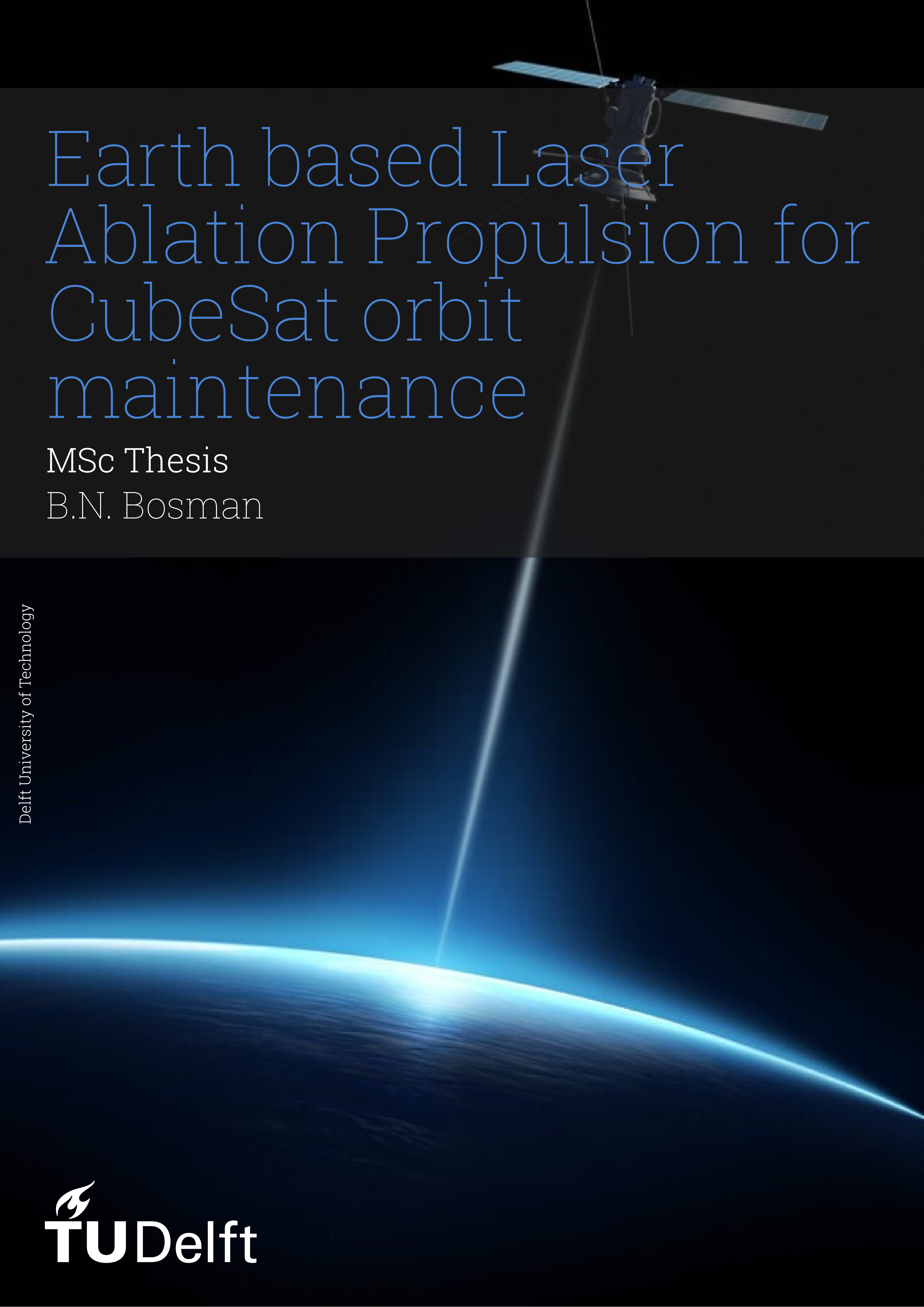

Earth based Laser Ablation Propulsion for CubeSat orbit maintenance

MSc Thesis

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Earth based Laser Ablation Propulsion for CubeSat orbit maintenance

by

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Preface

For the last three years I have been studying for a masters degree of science in the 'Space Flight' track, with a specialisation on planetary exploration and astrodynamics. The last 2 years of this time have been spent on my thesis. This has gone over with ups and downs. The first part of the thesis was during the Covid-19 pandemic, which forced me to work from home, which is not something that works well for me, causing a slight delay. In parallel to the thesis work, I also did project management for the Da Vinci Satellite project at the study society, which ended up costing more time than expected, leading to even more delay. Even though a delay occurred, the experiences that this project gave me are worth a lot and I would not change it if I got to do it again.

The results of this work would not have been possible without the support of many people. Firstly, I would like to thank the Tudat community and specifically Dominic Dirkx for assisting me with any Tudat problems I encountered. Secondly, I would like to thank my friends for keeping me company and encouraging me when my motivation took a dip. Thirdly, I want to speak out my gratitude to my family, and mainly my parents for supporting me though out this journey even though it took longer than initially planned. Fourthly I want to thank my supervisor Joao De Teixeira da Encarnacao for the knowledge support and for allowing me to do the work at my own pace. Lastly I want to thank who, when I started with this thesis, was my girlfriend and currently is my wife. She supported me every day regardless of the progress made.

Bastiaan Bosman
Delft, May 2023

Summary

Current day space technology allows for the creation of smaller and smaller satellites. This makes the possibility of launching constellations of many satellites both financially and technically more attractive. A downside of launching many satellites in to LEO, is that they will slowly lose their orbital altitude due to drag and other perturbing forces. In order to counteract this, an on-board propulsion system is required. The propulsion system mass percentage of a regular low Earth orbit satellite is between 10 and 30 percent [1]. If the propulsion system mass percentage can be reduced, the costs of launching these satellites can be reduced or more satellites can be launched on the same vehicle.

One way to reduce the on-board system mass, is to decrease the size of the system section that is on the satellite itself and moving a large part of it down to Earth. Laser Ablation Propulsion (LAP) can offer this. With a high power, Earth based laser that can ignite a surface on the spacecraft that is covered in propellant, thrust can be generated. This thrust can be used to raise the orbit by small amounts to counteract the altitude loss discussed before. This thesis will research the viability of LAP for cubesats in a Low Earth Orbit (LEO). This will be done by answering the following research question.

How can Earth based Laser Ablation Propulsion be a viable and attractive propulsion alternative for orbit maintenance for low Earth orbit cubesats?

This question will be answered by simulating a spacecraft in an orbit around the Earth with a laser station on the planet. The results of this simulation will show whether LAP can keep an orbit stable and if it is an efficient way to do so.

The propellant for the ablative surface is chosen to be pyroxylin for its realistic flux requirements and its sufficiently high specific impulse. The laser type will be a Chemical Oxygen Iodine Laser (COIL). This is chosen because of its realistic 9m diameter mirror size, with the added benefit of the technological readiness. This laser has an output power of 20kW, which ensures that enough power arrives at the ablative surface. The laser pulse duration and frequency has been set at a burst of 0.01 seconds every 10 seconds, because this is sufficient to sustain a Laser Supported Detonation (LSD). The orbit analysed is inspired by the orbit of Delfi-C3.

The propagation model uses a Runge-Kutta method (RK4) to calculate the results. The Tudat propagator function requires the acceleration model, the system of bodies and the initial state as inputs. The outputs consist of the state of the satellite, the total acceleration and the thrust acceleration.

The laser activation is constrained to ensure that the orbital elements remain similar to the initial conditions and to make sure that the laser can illuminate panel with the ablative material. Another constraint is implemented on the laser pointing angle to reduce the manoeuvrability requirements of the laser mirror.

Multiple analysis are done to determine the input parameters. The first, is an analysis of the timestep. The 30 seconds interval is chosen to the optimal trade-off between run-time and accuracy. During the rest of the parameter estimation, this 30 second timestep is used. For the final model, the 10 seconds timestep is used, as this is more accurate and this simulation only has to be run a few times. Both the longitude and altitude of the laser station are shown to have a negligible impact on the performance. The latitude has to be between 30 and -30 degrees. To keep the orbit circular, a pair of laser stations is required. The chosen locations are 0°N, 111.5°S and 0°N, -68.5°S with an average altitude of 62.5m. The Laser Elevation Activation parameters determine for which angle range above the horizon, the laser can activate. This range is set to be between 0 and 10 degrees above the horizon.

The final model shows that LAP can work for orbits of 400 and 450km. The altitude can be maintained until the end of the simulation at 2000 days. It can be assumed that after these 2000 days, the orbit can continuously be maintained.
Two assumptions are in place to ensure that the laser reaches the ablative surface. The first assumption is that the laser station has a 100% accurate pointing mechanism and satellite positioning knowledge. The second assumption is that the atmosphere only reduces the laser intensity and does not affect its direction. In reality this is not the case, because errors are unavoidable. An offset of only 5cm on the ablative surface means that the arriving power on the ablative surface decreases by 85%. This accuracy is not realistic yet. For that reason, Laser Ablation Propulsion is not a viable alternative to conventional propulsion yet. If in the future, a accuracy better than the mentioned 5cm can be achieved, LAP could be a viable propulsion method.

If a system like this would truly be realised, there will be many regulation related issues that would have to be solved. Regulations on air space occupation and targeting of objects on Earth will have to be made. These are just two of the many regulations that will be necessary for the implementation of LAP.

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Nomenclature

Abbreviations

Abreviation	Definition
ADCS	Attitude Determination and Control System
CO_2	Carbon Dioxide
COIL	Chemical Oxygen Iodine Laser
DAS	Debris Assessment Software
EIA	US Energy Information Administration
ESA	European Space Agency
FOV	Field Of View
GTO	Ground To Orbit
HES	High Elevation Scenario
ISS	International Space Station
LAP	Laser Ablation Propulsion
LEA	Laser Elevation Activation
LEO	Low Earth Orbit
LES	Low Elevation Scenario
LSD	Laser Supported Detonation
PAD	Pointing Angle Direction
PMMA	Polymethyl methacrylate
RK4	Runge Kutta 4
TU Delft	Delft University of Technology
U	Unit
USD	United States Dollar

Symbols

Symbol	Definition	Unit
C_d	Drag coefficient	-
C_m	Coupling moment coefficient	N/W
C_p	Radiation pressure coefficient	-
D	Drag	N
d_{atm}	Distance through the atmosphere	m
E_{tot}	Total energy	J
F_g	Gravitational acceleration	m/s^2
F_t	Thrust force	N
G	Gravitational constant	m^3 kg^{-1} s^{-2}
g_0	Standard gravitation parameter Earth	m/s^2
h	Station altitude	m
I_{sp}	Specific Impulse	s
k	Boltzman constant	J/K
k_n	RK4 constant	-
l	Effective path length	m
m_E	Ion mass	kg
m_n	Mass of body n	kg
$\dot{m}$	Massflow	kg/s
n_p	Number of pulses	-
p	Pressure	Pa
P_l	Laser power	W
Q^*	Specific ablation energy	J
r	Orbit altitude	m
r	Distance	m
r_0	Characteristic thrust radius	m
R_e	Radius Earth	m
$\vec{R_{gs}}$	Radius ground station	m
r_m	Mirror radius	m
R_{max}	Maximum visible range	m
r_R	Range	m
$\vec{R_{sat}}$	Radius satelite	m
R_0	Characteristic range	m
$(r-R)$	Distance satellite-ground station	m
S	Surface area	m^2
T	Temperature	K
t_n	Time step n	-
t_p	pulse duration	s
u	Velocity	m/s
V	Velocity	m/s
$\vec{V}$	Velocity	m/s
v_E	Exhaust velocity	m/s
v_x	Velocity in x direction	m/s
y_n	State at time n	[m,m,m,m/s,m/s,m/s]
$\beta(r)$	Inverse scale height	m^{-1}
δ	Laser angle	rad
ϵ	extinction coefficient	m^{-1}
η_{abs}	Absorbtion efficiency	-
η_{AB}	Ablation efficiency	-
η_{diff}	Diffraction efficiency	-
λ	Wavelength	m
μ	Ablated mass areal density	g/m^2
ρ	Density	kg/m^3
σ	Impulse density	s^{-1}
Φ	Incident laser pulse fluence	W/m^2

1
Introduction

1.1. Motivation

A very popular trend in the current space industry is launching large constellations of both big and small satellites. When launching more than a hundred satellites, the total costs can be very high. The propulsion system mass percentage of a regular low Earth orbit satellite is between 10 and 30 percent [1]. This system is required to perform orbit alterations such as orbit maintenance or an of life deorbit manoeuvre. These manoeuvres are required as the orbit slowly loses altitude due to small amounts of drag and radiation pressure.

If the propulsion system mass percentage can be reduced, either the costs of launching these satellites can be reduced or more satellites can be launched on the same vehicle.

One promising option for reducing the on board propulsion system mass is to leave the largest part of the propulsion system on Earth in the form of a high power laser. This laser will then be used to ignite an ablative surface on the spacecraft, which will result in a small propulsive force on the satellite that will provide the required delta V for proper orbit maintenance. With this type of system the only part that needs to be on the satellite is an ablative surface.

1.2. What is Laser Ablation Propulsion?

Laser Ablation Propulsion (LAP) is a propulsion concept where a laser shines on a surface covered in propellant, which results in a jet of vapour or plasma. The thrust force that a LAP system produces is caused by the reactant force on the satellite surface. This chapter is mainly based on the paper 'A review of laser ablation propulsion' by Phipps et al. [2]. LAP thrusters can vary greatly in power and efficiency. The specific impulse values range between 200s and 3100s with thrust values of 800kN/m^2. The thrust efficiency can be high as 230% with certain ablative materials, because of the contribution of the chemical energy of some exothermic polymers. This can be explained by Equation 1.1 where η_T is the thrust efficiency, η_{eo} is the electrical to optical efficiency and η_{AB} is the exhaust power to input laser power factor. Even with η_{eo} values of around 50%, a more than 100% thrust efficiency can be achieved.

$$\eta_T = \eta_{eo}\eta_{AB} \tag{1.1}$$

1.3. How the high specific impulse is generated

Generally, the specific impulse of a chemical rocket engine is computed with Equation 1.2 which can be rewritten to Equation 1.3 when used for laser ablation applications. Where T_i is the ion temperature, which is a value that can very easily be influenced by the laser.

$$I_{sp} = v_E/g_0 \tag{1.2}$$

$$I_{sp} = \sqrt{\frac{2kT_i}{m_i}}/g_0 \tag{1.3}$$

In theory an I_{sp} of 83000 seconds can be achieved with T_i at 10^8K [3] if there was a practical laser system that could generate this high ion temperature in space.
Next to the fact that the LAP system offers a high efficiency, it also has the benefit that the payload to wet mass fraction is much bigger than for conventional spacecraft as the heaviest component of the propulsion system stays on Earth

1.4. Previous work

This technology has very scarcely been researched in the past. It has seen some experimentation for Ground To Orbit (GTO) systems back in the 1970s, but LAP was not seen as a viable GTO option just yet [2]. The studies done in the past showed that the atmosphere is a large hurdle to cross as the thrust force fell in balance with the gravitational force at 72m altitude in free flight with a 10kW carbon dioxide laser [4]. This is the case because a CO_2 lasers lose intensity quickly in the atmosphere. Phipps theorised in 1986 that a 10Mw CO_2 laser with a 10m diameter laser could send a 13kg payload into a 400km orbit every 10 minutes, but a major issue for this research was that a propellant would have to be developed that is efficient enough while still withstanding the launch environment [5]. Another study by Phipps, required laser intensities of 1.4×10^{14} W/m^2 with a CW laser [6]. This is not realistic for the application studied during this research, because the power requirement would be far to high. Some successful test results were found on a wired flight, where a thrust force of 2N was achieved with air as the propellant. Another previously researched system is The Laser Plasma Thruster (LPT), which was designed for attitude control purposes on microsatellites and it had the laser system on board. A variation with an external laser was also theorised [7]. For his system a high power 920 nm diode laser was used and pulsed with a microsecond duration. The propellant tape was made of polymerised GAP with a kapton layer. The system produced 10 mN of thrust with an input power or 20W. If liquid propellants are used, the thrust can be increased to 6N in ms pulse mode.
Some of the work done, is on how LAP works in theory and on ablative materials. These topics will be elaborated upon in Chapter 2 and specifically Section 2.3 for the materials, because a lot of that work is used for this research.

1.5. Knowledge gap

As discussed above, previous research has mainly been done on ground to orbit systems, but there is no research on using LAP with an Earth based laser for orbit maintenance on cubesats that are already in space. This research will determine what is required to have LAP function as a viable propulsion method that can be used as a LEO maintenance system for cubesats. This will be done with numerical simulations. The results from this analysis could be a baseline for any future research on Laser Ablation Propulsion for orbit maintenance.

1.6. Research questions

In order to properly research how LAP can be a good alternative to conventional propulsion, a research question needs to be formulated. This question has been composed as follows:

How can Earth based Laser Ablation Propulsion be a viable and attractive propulsion alternative for orbit maintenance for low Earth orbit cubesats?

To answer this question, some subquestions need to answered first.
The first question that will be discussed focuses on what makes an accurate model for the simulation. To accurately asses whether LAP is a viable option, the environment has to be modelled properly. In order to do this, the relevant accelerations have to be determined, a proper integrator has to be chosen and the different ground station parameters have to modelled.

1. What is needed to create an accurate model in Tudat?
   (a) Which disturbances will be included in the model?
   (b) Which integrator will be used for the model?
   (c) How can different locations on Earth be modelled for the laser location?

The second subquestion focuses on the laser system itself. Which laser system can provide the optimal solution? There are various different options for laser types and operation parameters. A specific laser type with its corresponding wavelength has to be chosen to ensure that enough power is generated, the pulse duration has to be set, so the ablative surface can reach its required temperature and lastly, the layout of the physical ground station architecture has to be composed.

2. What laser system is optimal for LAP use?
   (a) Which chemical composition and its corresponding wavelength should be chosen for the laser system?
   (b) What is the pulse duration required for proper ablation?
   (c) What does the physical laser ground installation consist of?

Subquestion three discusses the satellite side of the LAP system and how it might have to be adjusted. Currently a cubesat is not capable of functioning with LAP, so some adjustments need to be made. Firstly, a satellite will require a surface covered in an ablative material. Which material this is and how much of the surface should be covered will be answered by this question. The effects of the laser on the rest of the cubesat also has to be analysed. It is possible that there are both beneficial and negative secondary effects from the laser on the spacecraft. It also has to be assessed whether current day technology is ready to accommodate LAP.

3. How should the usual cubesat layout be adjusted to accommodate LAP?
   (a) Which ablative surface yields the most efficient result?
   (b) How much of the cubesat surface has to be covered in ablative material?
   (c) Is the propulsion system causing thermal problems inside the spacecraft?
   (d) Are there any beneficial effects, next to the propulsion element, of the laser on the cubesat?
   (e) Is current day technology ready to accommodate LAP?

The last question focuses on the thresholds for which LAP can be deemed viable. For a technology to be adapted by the industry, it has to be financially interesting to a company. For this reason it has to be assessed whether LAP can offer a cheaper solution compared to conventional propulsion systems. Added to this, it has to be researched if LAP is more reliable, as reliability is very important in satellites that can not be serviced once they are launched. In addition to cost and reliability, the convenience of the system has to be discussed. It is possible that the lack of an internal conventional propulsion system can provide a more optimised subsystem configuration, leading to a more efficient design.

4. How well does the propulsion system have to perform to be deemed viable and attractive?
   (a) Is LAP financially attractive to cubesat providers?
   (b) Can LAP provide a more reliable propulsion system?
   (c) Can LAP allow the cubesat itself to function more efficiently due to fewer space constraints?

1.7. Requirements

The research questions mentioned above lead to the set up of various requirements. They are listed below and follow the SMART method. If the results meet these requirements, LAP will theoretically be a viable option for cubesats in LEO. For that reason, these three requirements will be assessed at the end of the research.
The first requirement is a self explanatory one. For LAP to be a viable alternative to conventional propulsion methods, it needs to be able to keep the satellite in orbit for a long time. The second requirement needs some more explanation as to why these specific margins were chosen. The orbit insertion margins of a launcher were chosen because cubesats are designed to function within this margin of error. If the accuracy of the LAP orbit maintenance is equal or better than the margins of the the chosen launcher, the spacecraft will remain within the altitude range that it was designed for. The Falcon 9 specifically, was chosen because of its easily accessible launcher information. The third requirement is in place to ensure that next to functional viability, LAP is also financially attractive for companies. LAP needs to be cheaper than conventional propulsion for it to be widely adopted by the industry.

1. The system shall be able to keep the spacecraft from deorbiting for the indefinitely.
2. The shape of the orbit shall not be altered by more than the orbit insertion margins of the falcon 9 [8].
3. LAP shall be financially attractive for cubesat providers.

1.8. Structure of this report

Firstly, the methodology is discussed in Chapter 2. This chapter is broken up in to the different models that were created to make up the simulation. The first model, is the environment. Section 2.1 discusses all of the perturbing forces and other natural phenomena that have to be taken into account. The second model is the laser station model. Section 2.2 details how the location of the laser is implemented and how the laser itself will be modelled. Section 2.3 will highlight the propulsion system model. It will discuss how the ablative surface is chosen and how it will be used in the simulation. This section will also explain how the thrust generation works. Section 2.4 will highlight how the full model will be structured. It will first explain how a basic framework model is composed and then how it is adapted to be a more realistic version. Section 2.5 will focus on the propagation methods used. Firstly it gives an overview of the used satellite and its input parameters. After this, it will show which propagation method is used and what the inputs are. Section 2.6 will discuss how the input parameters for the model are found. These inputs consist of the timestep, the ground station location and the laser pointing parameters.

In Chapter 3, the input parameter determination will be reported. Firstly, in the timestep results are presented and a decision is made on the timesteps that will be used for the different analyses. Secondly, the ground station parameters are studied. The results from the latitude, longitude and station altitude analyses will be presented and a ground station location is chosen. Lastly, the laser pointing parameters are discussed. Various different scenarios are used to find the optimal pointing requirements for the laser.

Chapter 4 elaborates upon the method used to verify and validate the model. The verification will be done by performing unit tests on the perturbation effect and on the model constraints. The validation will be done by using the model with inputs from the ISS and comparing the outputs with the known orbital data of the station.

The final results are presented in Chapter 5. It will give the altitude data from the simulation with the previously derived inputs. The data will be analysed and discussed in this chapter. In addition to the altitude profile discussion, the laser activation frequency and accelerations will also be discussed. The analysed data will be used to answer the research questions and to determine whether the requirements are met in Chapter 6. Chapter 7 will give the final conclusions and the report ends with the recommendations for future work in Chapter 8.

2
Methodology

In order to asses how LAP can be viable alternative to conventional propulsion, a simulation is done that represents the universe in an accurate way. The set up of this model is presented below. Firstly, the set up of the environment is be elaborated upon. Section 2.1 highlights how the physical universe can be accurately modelled in a computer simulation. Secondly, the laser system model is be discussed in Section 2.2. Both the general ground system and the laser generator itself are focused upon. Thirdly, Section 2.3 explains the on-board propulsion system model. This elaborates upon the different ablative surfaces and on how thrust is generated on an ablative surface. Fourthly, the laser interaction model is explained in Section 2.4. This details the set up of the laser activation constraints for both the basic and advanced model. Fifthly, the propagation model setup is detailed. Section 2.3 highlights the satellite model and the propagation strategy used with its required inputs. Lastly, in Section 2.6, the input parameter determination is detailed. This section shows the main input parameters that are studied during this research to make the final model as accurate as possible. The first parameter is timestep, the second is the ground station position and the third is the initial orbital altitude.

2.1. Environment Model

The entire model is set up in Tudat, which is a toolbox designed by the Delft University of Technology and houses many features that can be used to model (space)flight. There are many different integrators and environmental models available. Parameters such as the celestial body positioning and their physical parameters are examples of environmental parameters from Tudat that will be used during this research.

2.1.1. Model of the solar system

The solar system model used for this thesis includes the Sun, all of the planets and the Moon. For the celestial bodies other than the Earth, a point mass gravity acceleration is used. This acceleration is based on the assumption that a body exerts a force based on the entire mass of the body towards the centre of the body as if it is a single point.

For the Earth, a spherical harmonic gravity model is implemented. This is done, because the local differences in the Earth's gravitational acceleration are important to take into consideration. Due to the fact that the Earth is not a perfect sphere, the gravitational acceleration above different parts of the planet slightly vary. At close range these differences interfere with the orbital parameters of an orbiting body. The influence of different types of spherical harmonic gravity types are given in Figure A.1 in Appendix A. The other planets were not given this spherical harmonic gravity model, because the impact at a large distance is not noticeable and a point mass gravity approach is computationally cheaper. The difference between the point mass gravity and the spherical harmonic gravity approach for Saturn, Mars, Venus and the moon are shown in Table 2.1.

Next to the gravitational accelerations exerted by the aforementioned bodies, the cannonball radiation pressure is also modelled as an acceleration induced by the Sun. The cannonball approach is chosen, as this gives a first order approximation of the radiation perturbation in a computationally efficient way [9]. The cannonball approach would be less accurate for a spacecraft with a highly complex geometry, as this would have an effect on the torque exerted by the radiation pressure, however this research analyses LAP for a simple 10x10x30 cm cubesat. All of these accelerations can be implemented in a Tudat acceleration model with these perturbations in the acceleration settings.

Table 2.1: Percentage difference between the point mass gravity and the spherical harmonic gravity approach

Body	Difference [%]
Saturn	1.26×10^{-5}
Mars	0.00134
Venus	0.00123
The Moon	0.00103

2.1.2. Model of the atmosphere

The Earth's atmosphere has to be modelled for two different purposes. The first effect that the atmosphere has on the spacecraft, is drag induced acceleration. A satellite in LEO is affected by drag, so the aerodynamic acceleration is introduced into the environmental model. Similarly to the previously mentioned solar system perturbations, the atmospheric drag is introduced through the acceleration model of Tudat and it uses Equation 2.1 to determine the magnitude. Lift does not act on the spacecraft, as the spacecraft is assumed to always point in to velocity direction. If the spacecraft is in line with the velocity and has a cube shape, the angle of attack of zero leads to a zero lift scenario.

$$D = \frac{1}{2} C_d \rho V^2 S \tag{2.1}$$

The second attribute that is influenced by the atmosphere, is the laser power arriving at the satellite. The fluence of the laser is reduced by extinction and the beam width is increased by diffraction. Both of these phenomena are described in Subsection 2.2.2.

2.2. Laser System Model

The Laser system model is divided up into two different sections. The first is the physical laser system on Earth. This system has multiple different attributes that will be used as inputs into the model. These inputs are the physical position of the station, the laser type and the laser pointing limitations. The second section will focus on the lasers progression through the atmosphere, as there are various phenomena that limit the laser performance as it passes through the air.

2.2.1. Ground station selection

The physical location of the ground station will be analysed during this research. The latitude, longitude and altitude will be varied throughout to analyse which location is optimal for LAP.

One of the major problems of using LAP with a single laser station, is that activating the propulsion system on one side of the orbit, will eventually lead to boosting only at the pericenter side of the orbit. When continuously raising the apocenter, the eccentricity keeps increasing, but the pericenter keeps losing altitude due to the perturbing forces that are acting on the spacecraft. This eventually still leads to orbit degradation. To counteract this, another laser system is placed on the exact opposite side of the Earth. If the laser can accelerate the spacecraft at both the apocenter and pericenter, the eccentricity can remain small and the satellite can stay in space longer. This function does not take into account the physical parameters on that side of the planet. It considers the possibility that there could be a laser station in the middle of the ocean at 8000 meters altitude. This is only the case during the initial parameter determination, as a physical location will be chosen for the final model.

For this research, there are two main laser types that are being considered. The first is a custom CO_2 laser. A recent development in CO_2 laser design is a slab-discharge sealed-tube lasers by Coherent Inc. (Santa Clara, CA), the output power is dependant on the area of the electrode. Systems like this can have an output up to 1W/cm^2 [10]. For the model, the size of the electrodes is a variable input that can be experimented with to attain an output power that is high enough for LAP. A CO_2 laser emits light at a wavelength of 10-11 μm. The second laser type is a Chemical Oxygen Iodine Laser (COIL) and specifically the system used on the BOEING YAL-1 aircraft [11]. The YAL-1 aircraft is also known as *the Airborne Laser*. It was a military BOEING 747-400F with a 20kW COIL on board. This laser was designed to intercept and destroy incoming missiles. A COIL has a wavelength of 1315 nm.

The final parameters that needs to be addressed for the ground system, are the pulse parameters. These include the pulse duration, pulse frequency and the laser direction. Firstly, for the pulse duration, a time of 0.01s is chosen as this is the time required for the ablative surface to get to a temperature high enough for plasma formation [12]. Secondly, the pulse frequency is a parameter that can be varied in order to analyse what a beneficial frequency would be. Lastly, there are constraints for the angle to the horizon that the laser can activate for. The limits are in place to reduce the manoeuvrability requirements of the mirror. These angle constraints will be optimised during the input parameter determination.
For this research, it is assumed that both the pointing accuracy of the laser and position determination of the spacecraft are 100% accurate. This assumption is essential for this numerical experiment to ensure that the laser can illuminate the surface.

2.2.2. Laser model

Over the path of the laser through the atmosphere, there are two main phenomenon that affect the laser power that arrives at the satellite. The first effect is absorption. Some of the light that is emitted, is absorbed by the molecules in the atmosphere, which significantly reduces the laser power at arrival. In order to accurately determine how much light is absorbed, Equation 2.2 is used, where the extinction coefficient ϵ is set at 1.25$\times$ 10^{-5}m^{-1}[13]. The $d_{atm}/100$ parameter is added in order to compensate for the angle of the laser as the base equation is only for vertical use. It has the 1/100 term as the vertical distance to the edge of space is 100 km. The $(r - R)$ term is the orbital radius of the satellite and $\beta(r)$ is the inverse scale height. If the distance to be traversed through the atmosphere is 250km, the power term becomes 2.5 to compensate for this longer path.

$$\eta_{abs} = (e^{-\epsilon l})^{d_{atm}/100} \tag{2.2}$$

where the effective path length l is defined as

$$l = \frac{1}{\beta(r)}[1 - e^{-\beta(r)(r-R)}] \tag{2.3}$$

The second phenomenon the affects the laser, is diffraction. When the photons pass through the air, they can be redirected slightly. This causes a spread of the beam and a redirection of the centre of the beam. Diffraction is impossible to predict perfectly, but an approximation can be made with Equation 2.4 [14].

$$\eta_{diff} = 1 - 4\left(\frac{r - R}{R_0}\right)^2 \tag{2.4}$$

where the characteristic range R_0 is defined as

$$R_0 = \frac{2\pi r_m r_0}{\lambda} \tag{2.5}$$

r_0 is the characteristic thrust radius, which is assumed to be the same as the hotspot radius on the ablative surface. This assumption can be made as the hotspot radius and r_0 are the same when the surface is illuminated with the minimum power required to ignite and maintain proper combustion of the ablative material. This combustion is called a Laser Supported Detonation (LSD). The hotspot is the

focus of the laser beam. It is the part of the illuminated area with the most energy. r_m represents the laser mirror radius and λ is the wavelength.
η_{diff} and η_{abs} are combined to determine the total pass through efficiency for a given distance that has to be traversed. Figure 2.1 shows the results of the losses for both laser types. The first parameter that was experimented with was the mirror radius of the COIL system. This radius was set such that the efficiency would reach 0 at a distance larger that 520km, as that would be the maximum distance that the laser would have to traverse through the atmosphere. After this, the mirror radius for the CO_2 laser was determined to have a similar trend to the the efficiencies of the COIL. In the end, a 4.5m radius for the COIL and a 34m radius for the CO_2 mirror were found. From this calculation, the COIL was determined to be optimal LAP solution for practical reasons. A 68m diameter mirror would be far to impractical and expensive. This reason goes paired with the high Technology Readyness Level (TRL) of the COIL, because it was used for the YAL-1 aircraft at the output power of 20kW that is also used for this research.

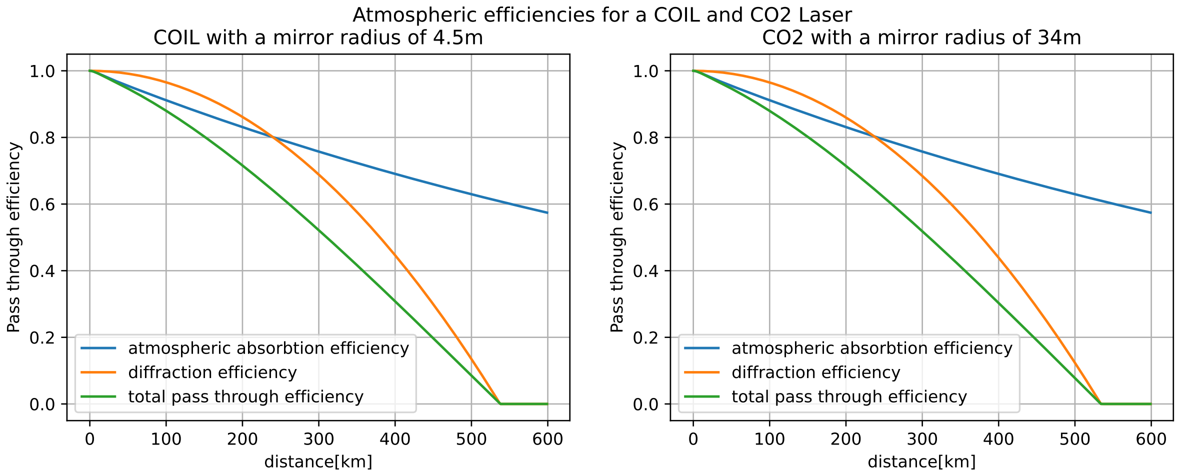

Figure 2.1: Atmospheric efficiencies for both laser types as a function of distance

2.3. Propulsion system Model

2.3.1. Ablative surface

The ablative surface is placed on one of the small exterior panels of the cubesat. These surfaces have an area of 100cm^2. In this area, the propellant will be attached in a circle with a 5cm radius. For this research, three different propellants were considered, as shown in Figure 2.2 [15]. The figure shows data of the specific impulse of three propellant options as a function of the laser intensity. The three studied propellants all have a specific benefit and a downside. 6061 Aluminium has a very high specific impulse (I_{sp}), but it also has a very high required laser intensity. The Pyroxylin has a very low requirement for the laser intensity, but this is paired with a lower I_{sp}. PMMA has a very wide range of operable laser intensities with a wide range of I_{sp} values. This broad operability does come at the cost of efficiency. At high laser intensities, it performs worse than aluminium. The same counts for the low laser intensities in comparison to pyroxylin. The required power intensity for aluminium is to high as it is between 3 and 4 orders of magnitude higher than pyroxylin. One of the main constraints to LAP will be the laser power that reaches space, so a lower laser intensity requirement is beneficial. For this reason, the research will be done with pyroxylin. The analysis was also done without propellant. In this case the pure photon impact would provide the required impulse. It was found that this force was 5 to 6 orders of magnitude too small to provide a visible difference in the results.

To determine the required mass of the ablative surface, the mass flow has to be computed. This is done with Equation 2.6. Because of the very low thrust, the result is that the massflow is around 0.001 g/s. A single pulse takes 0.01 seconds, leading to a mass loss of 10^{-5} gram per pulse. If the spacecraft would get a boost twice every orbit, one for each station, the surface would lose about one gram of propellant after 3000 days. For this reason, the assumption is made that the spacecraft has a constant

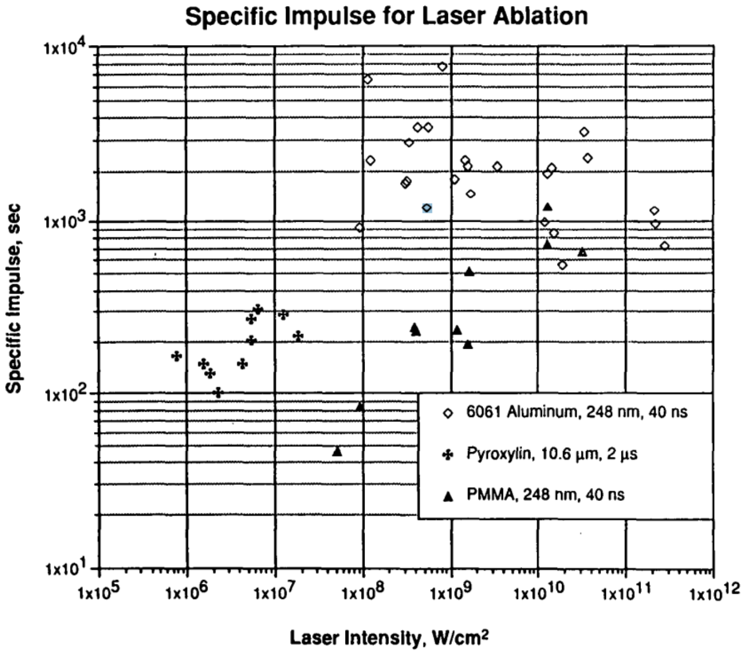

Figure 2.2: Specific impulse for given laser intensities for the three propellants[15]

mass. At the end of the research in Section 5.3 the fairness of this assumption will be discussed.

$$\dot{m} = \frac{F_t g_0}{I_{sp}} \tag{2.6}$$

2.3.2. Momentum coupling coefficient

The momentum coupling coefficient C_m is the ratio between the impulse density σ (the amount of pulses per unit time) and the incident laser pulse fluence Φ (the intensity of the pulse per unit area), where exhaust velocity $v_E =< v_x >$ is the first moment of the velocity distribution $f(v_x)$ along the thrust axis x [16].

$$C_m = \frac{\sigma}{\Phi} = \frac{\mu v_E}{\Phi} \tag{2.7}$$

Q* is the specific ablation energy defined as the ratio between the laser fluence and the target areal mass density μ.

$$Q^* = \frac{\Phi}{\mu} \tag{2.8}$$

This leads to:

$$v_E = C_m Q^* \tag{2.9}$$

The ablation efficiency is:

$$\eta_{AB} = \frac{\mu \psi v_E^2}{2\Phi} = \frac{\psi C_m v_E}{2} \tag{2.10}$$

where ψ is defined as:[17]

$$\psi = \frac{< v_x^2 >}{(< v_x >)^2} = \frac{u^2 + \frac{kT}{m_E}}{u^2} \tag{2.11}$$

where u is the velocity, k is the Boltzmann constant, T is the temperature and m_E is the ion mass. C_m and I_{sp} form a constant product

$$C_m I_{sp} = \frac{2\eta_{AB}}{\psi g_0} \tag{2.12}$$

From literature, a maximum C_m of 950$\mu N/W$ for pyroxylin is found [18]. Next to this, the assumption is made that the constant absorption efficiency of the surface is 40% [19].

2.4. Two interaction models

Throughout the process of this thesis, two variations of the model were composed. The first was a oversimplified baseline model that was used to check whether the physics of the simulation functioned as desired. The second was the evolution of the baseline model. This simulation incorporated more realistic attributes. This section will first detail the baseline model in order to show how the core of the model functions. After this, the more elaborate additions to the simulation will be explained.

2.4.1. The basic version

The basic version of the model only includes basic constraints for laser activation. If the satellite is above the horizon, the propulsion system is active. There is also no compensation for the velocity-laser angle δ, which is illustrated in Figure 2.3. This means that all of the power from the laser is

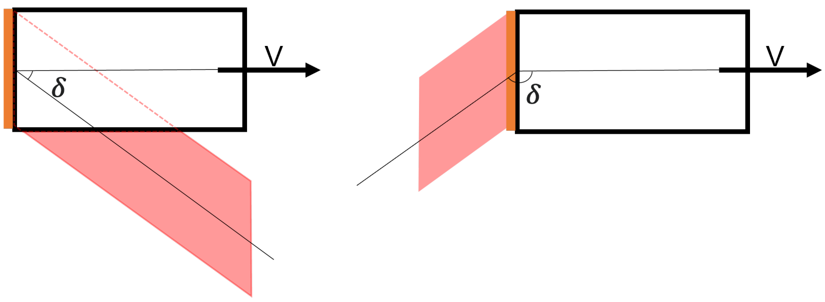

Figure 2.3: Illustration of the angle between the velocity direction and the incoming laser.

assumed to cause a thrust force opposite to the velocity vector. This is not a fair assumption to make, as this means that the laser would produce thrust when the ablative surface is not visible to the laser, as shown on the left side of Figure 2.3.
The basic model does have some constraints on the laser ignition however. These relevant constraints are listed below.

1. The satellite has to be above the horizon
2. The orbital radius can not be more than 1.02 times the original orbital radius
3. The eccentricity can not exceed 0.002

The first constraint is an obvious one. The satellite has to be in view in order for the laser to reach the spacecraft. This is achieved by finding the distance between the laser station and the satellite when the spacecraft is at the horizon. That parameter is set as the maximum range for which the laser can be active. Figure 2.4 shows this in practice. When the satellite is in the blue segment of the orbit, the range is smaller than the maximum range at the horizon. In the red orbit segment, this distance is larger than the maximum allowed, so the propulsion system is idle. Because the angle between the spacecraft and the horizon θ is 0 at the maximum range, the maximum range can be calculated using Equation 2.13, where r represents the satellite altitude and h the laser station altitude. The second constraint is there to ensure that the orbit does not get altered too much. The 2% was chosen to have some flexibility in radius to ensure that the altitude will fluctuate around the initial value instead of constantly staying below the intended height. The third constraint has a similar reason as the second with the addition that, if the eccentricity becomes to high, one of the laser stations can not reach the spacecraft anymore. This means that the the pericenter can not be raised anymore, which leads to the eventual de-orbiting of the satellite.

$$(r - R)_{\theta=0} = R_{max} = \sqrt{(R_e + r)^2 - (R_e + h)^2} \tag{2.13}$$

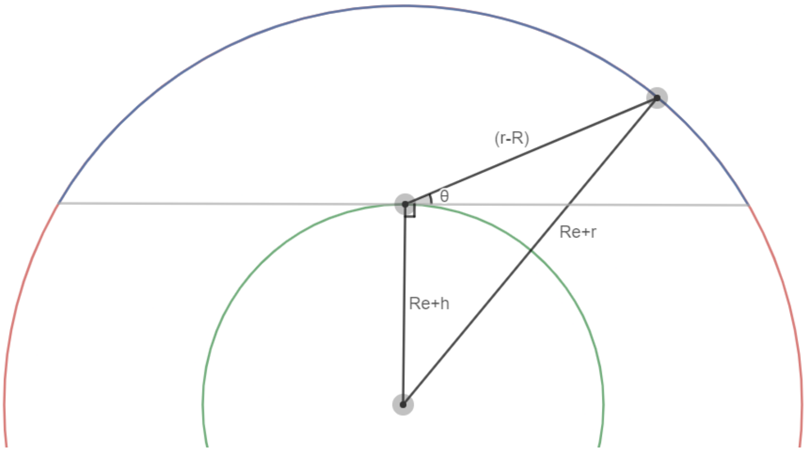

Figure 2.4: A schematic representation of the horizon constraint for the basic model

2.4.2. The advanced version

The advanced version of the model has various additional constraints built in to the model to represent a situation that is more realistic. The used constraints are listed below. The order of the constraints is not relevant.

1. The orbital radius can not be larger than the original orbital radius.
2. The orbital radius has to be larger than the semi major axis.
3. The angle between the velocity and the laser has to be more than 90 degrees.
4. The elevation angle has to be between the predetermined limits dependent on the study case.

Constraint one is slightly altered from the 1.02 times the original radius in the basic model to 1.00 times the original radius in the advanced model. In the advanced model there are more limitations, which means that the thrust is lower. Because of this lower force, the jumps in velocity are smaller, which results in a smoother altitude transition, as demonstrated in Chapter 5. With the smoother transitions, the fluctuations in orbital parameters are smaller, which in turn means that the 2% given before is no longer needed.

The second constraint makes sure that the propulsion system is active at the apocenter side of the orbit. This limitation enforces that the problem of the run-away eccentricity described in subsection 2.4.1 is never possible.

Constraint three makes sure that the laser is able to illuminate the ablative surface of the spacecraft. Figure 2.3 is an illustration of the velocity-laser angle δ. If the angle is smaller than 90 degrees, the laser is not able to reach the ablative surface as shown on the left side of the figure. The right side shows an angle greater than 90 degrees, in which case the laser is able to heat up the propellant. This constraint does not have an upper limit as the angle can never be greater than 180 degrees in any location in an orbit. This claim can be backed up with the results shown in Figure 2.5. It is assumed that the laser system mirror is able to focus the beam to fit on the ablative surface. The value for the laser-velocity angle is found by taking the inverse cosine of the dot product of the velocity and relative position vector as shown in Equation 2.14.

$$\delta = \arccos(\vec{V} \cdot (r \vec{-} R)) \tag{2.14}$$

where:

$$(r \vec{-} R) = \vec{R_{sat}} - \vec{R_{gs}} \tag{2.15}$$

The fourth constraint is in place to restrict the angle of the laser to a specific value for which the arrival power and arrival angle are optimal. When looking at Figure 2.4, it can be seen that the impact angle is optimal at the horizon, as this angle is 90 degrees plus the angle between the orbital radius vector

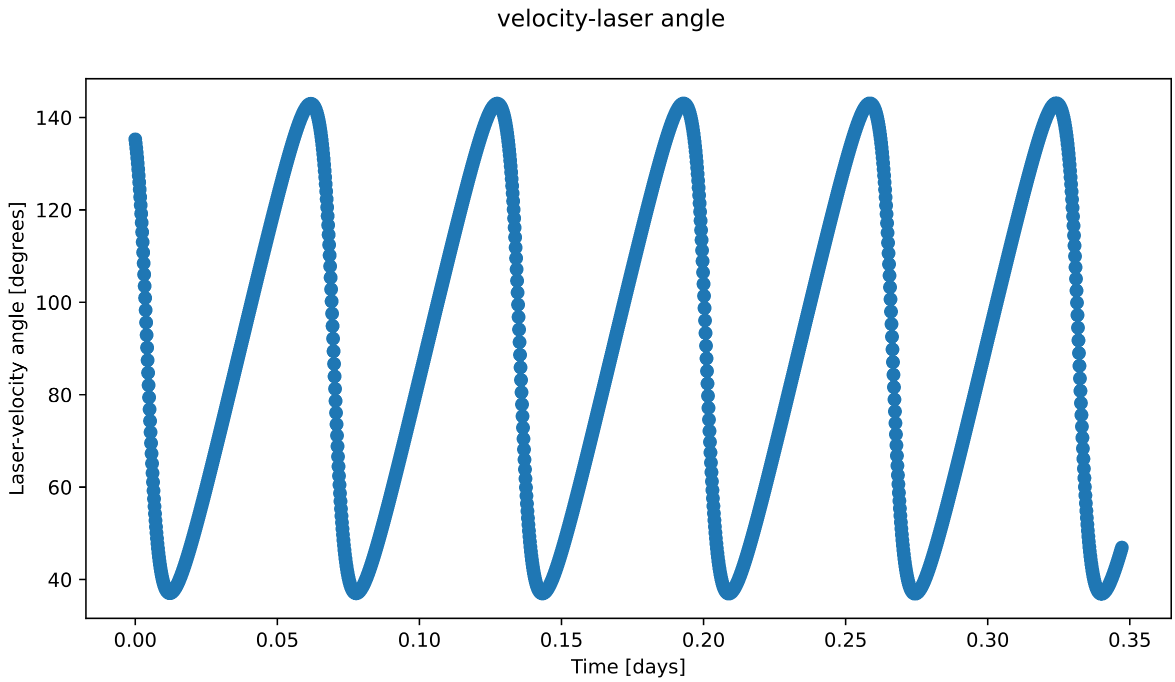

Figure 2.5: Velocity-laser angle at the beginning of the simulation

and the range vector (r_R). The downside to this angle range is that the laser has the longest possible path length through the atmosphere, leading to a reduced arrival power. The opposite of this is also true. When the satellite is directly above the laser station, the arriving power is optimal, as the shortest distance is traversed through the atmosphere. If the impact angle is 90 degrees however, it means that there is no absorption and thus no thrust. In order to determine an optimal elevation range, the model has the various ranges studied.

2.5. The numerical model

This section will firstly go in to the satellite model. Both the input parameters to the physical satellite and its rotation model will be discussed. After this, the propagator settings will be highlighted.

2.5.1. Satellite model

For this research, the physical model is inspired by the Delfi-C3 satellite seen in Figure 2.6 [20]. This spacecraft is a 3U cubesat developed by the TU Delft with various experiments on board, for example, thin film solar cells and autonomous wireless sun sensors. The mission of Delfi-C3 is not relevant for this research. Only the basic physical and orbital parameters were used to represent a realistic case. The spacecraft characteristics are as follows:

- Mass = 3kg
- Drag area = 0.05m^2
- C_d = 1.2
- Radiation area = 0.05m^2
- C_p = 1.2

Next to the satellite specifications, the initial orbital parameters were also inspired by Delfi-C3. They are listed below:

- Eccentricity = 0
- Inclination = 85.3°
- Argument of periapsis = 235.7°.

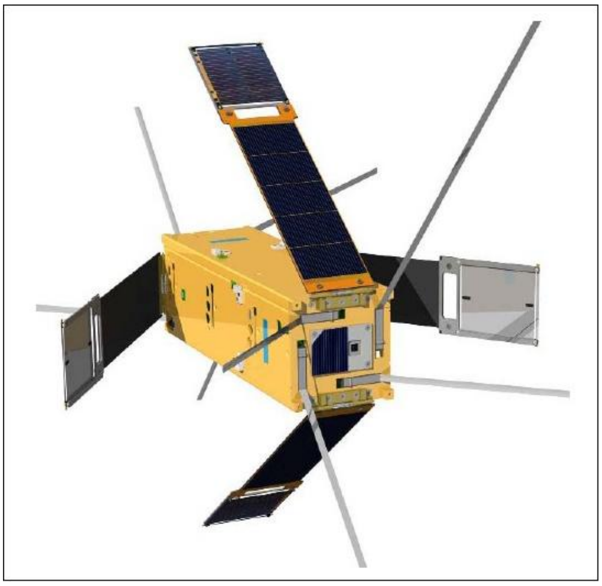

Figure 2.6: Delfi-C3 image from TU Delft [20]

- Longitude of the ascending node = 23.4°
- True anomaly = 137.87°

The initial orbital altitude of Delfi-C3 was not used as this parameter is one that will be studied during the research.

The rotation model for the satellite is a very basic one. The satellite will always be oriented in such a way what the ablative surface is pointed away from the velocity direction. This way, the thrust will always have the most efficient direction for orbit raising. It is assumed that the given spacecraft is able to keep this attitude with its own ADCS. The LAP system will not be used for attitude corrections. This is a fair assumption as a satellite with a conventional propulsion system would also need to control its attitude in a similar way.

2.5.2. The propagator settings

For this research, the decision was made to use a Runge-Kutta method (RK4) seen in Equation 2.16.

$$y_{n+1} = y_n + \frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right) h \tag{2.16}$$

where $\frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right)$= weighted average slope with:

$$\begin{aligned} k_1 &= f\left(t_n, y_n\right) \\ k_2 &= f\left(t_n + \tfrac{h}{2}, y_n + \tfrac{h}{2}k_1\right) \\ k_3 &= f\left(t_n + \tfrac{h}{2}, y_n + \tfrac{h}{2}k_2\right) \\ k_4 &= hf\left(t_n + h, y_n + hk_3\right) \end{aligned} \tag{2.17}$$

This choice is based on multiple factors. The first factor is computational time. At the end of the research, when dealing with a propagation duration of 2000 days and a timestep of 10 seconds, the simulations could take over 16 hours to run, which is not desirable as many runs have to be performed separately for the sensitivity analysis. Next to the time issue, the simulation will terminate halfway due to memory issues, so the propagation can not be completed. From literature it is also known that the RK4 method is an often used method due to the high accuracy and the complicated nature of higher order methods. [21] The model could also have been propagated with a lower order method such as the forward Euler method from Equation 2.18.

$$y_{n+1} = y\left(t_n\right) + h\left.\frac{dy}{dt}\right|_{t_n} \tag{2.18}$$

The forward Euler method is computationally lighter, so it could have improved the speed of the simulations. The decision to not use the forward Euler method was made as this method is generally unstable for oscillating situations and in general, the error for the Euler method is higher than for the RK4 method [21]. This is to be expected as it only uses the previous data point and the first derivative times the timestep. The dynamics simulator function in Tudat performs the propagation with the inputs given in Table 2.2.

Table 2.2: Input and output parameters for the RK4 propagation

Input	**Contents**
Central body	Earth
Acceleration models	1.Point mass gravity accelerations from the Sun, the Moon and the non Earth planets 2.Cannonball radiation pressure acceleration from the Sun 3.Spherical harmonic gravity (5,5) acceleration from Earth 4.Aerodynamic acceleration from Earths atmosphere 5.Thrust acceleration from the main LAP engine
Bodies to propagate	The Satellite
Initial state	Keplerian to Cartesian translation from the parameters given in subsection 2.5.1
Termination conditions	Final timestep (varies per analysis)
Output variables	Total acceleration Keplerian state Spacecraft latitude and longitude Spacecraft body fixed Cartesian position Thrust acceleration

2.6. Input parameter determination strategy

This section will discuss the two main parameters that will be analysed during this part of the research. The first parameter is the ground station location and the second is the initial orbital altitude.

2.6.1. The ground station location

There are three parameters of the ground station that influence the performance of the system. These are the latitude, the longitude and the altitude. The impact of the latitude is heavily dependent on the orbital parameters of the spacecraft. A perfectly polar orbit will always pass over both poles. This means that a ground station at the poles have the spacecraft above the horizon on every pass. The opposite is true for a perfectly equatorial orbit. In that case, the satellite will never be in view for a polar station. Delfi-C3 has a near-polar orbit, so the effects of more northern, and thus also more southern for the opposite station, latitudes will be researched. It would be beneficial if the laser station is able to function for both polar and equatorial orbits. For this reason, the latitude impact on a perfectly equatorial orbit will also be studied. In the end, a combined best solution will be chosen.
For the latitude, the analysis will be done by running the simulation with the latitude input increasing from 0 degrees to 90 degrees with increments of 10 degrees. The same counts for the longitude, but this input increases till 50 degrees, because this smaller range can already indicate whether the shifting longitude has a major influence on the performance of LAP. The results of this analysis will be shown and discussed in chapter 3.
In most cases, the altitude has an effect independent of the latitude or longitude of the ground station. The change in altitude will have both a positive and a negative influence on the efficiency of LAP. The positive effect is that the laser is closer to the satellite, which means that the extinction and diffraction have a smaller impact. The influence of this phenomenon will be researched during this thesis. The negative implication is that a shorter arc of the orbit will be above the horizon. This is the case because the laser can never point below its local horizon for this research. From Equation 2.13, it can be noted that the maximum range R_{max} becomes smaller when the station altitude h gets larger. During the analysis of the effect of the station altitude, the altitude will increase from 0 to 9 km with increments of 1 km, after which the results will be compared. The decision to go up to 9km was made as this is

close to the highest mountain on Earth. The assumption is made that the location of the laser station is not influenced by the physical layout of the planet's surface or other interfering influences. Influences such as support infrastructure, disturbance to populated areas and resource supply are not taken into account. The results for the station altitude analysis can also be found in chapter 3

3

Input parameter determination

3.1. Sensitivity analysis

To determine the optimal input parameters for the model, various analyses were conducted. This assessment was done for three different inputs. The first assessment will be on the integration timestep. The second analysis is done on the ground station location, which contains the ground station latitude, longitude and altitude. The final parameter determination will focus on the Laser Elevation Activation (LEA). The LEA parameters determine for which angles above the horizon, the laser system can activate. This group contains an analysis on the High Elevation Scenario (HES), the Low Elevation Scenario (LES) and the Pointing Angle Direction (PAD). What each of these scenarios mean, is explained in Subsection 3.1.3.

3.1.1. Timestep analysis

The assumption can be made that a smaller timestep is usually better. A smaller timestep does come at the cost of computational time. This analysis will determine for which timesteps the results still follow the results with the most accurate timestep close enough to be deemed accurate.
The results for the timesteps from 10 to 50 seconds with 10 second intervals can be seen in Figure 3.1.

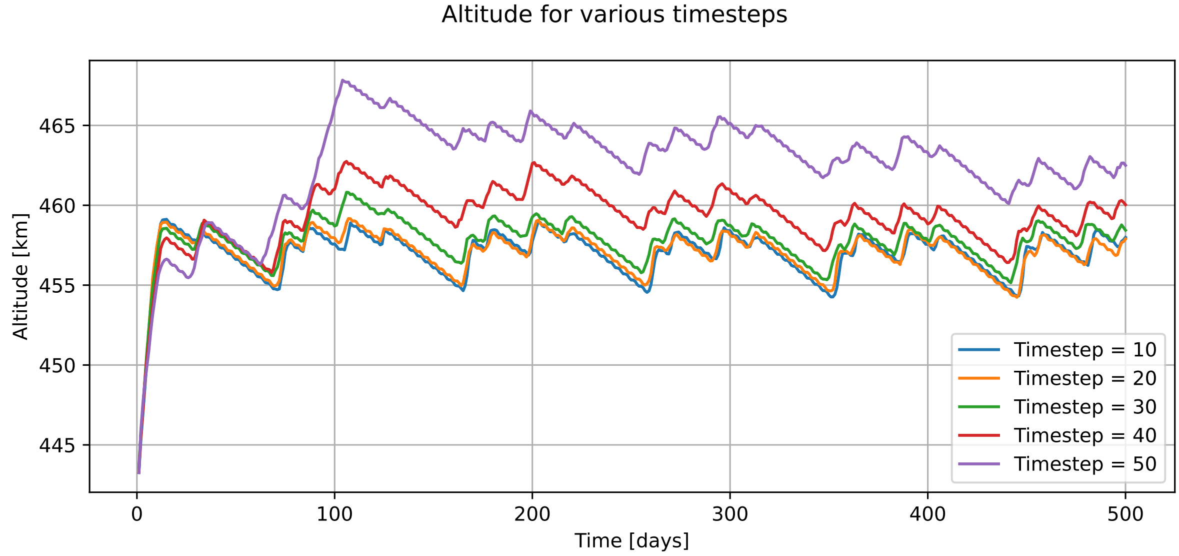

Figure 3.1: Altitude for the analysed timesteps

This figure shows the daily average altitude of the spacecraft for different integration timesteps. The daily average is plotted, because the raw data has large oscillations that make it hard to accurately study the results. The figure shows that the orbit can be kept stable for all five cases. As expected, the larger timesteps have a larger offset from the baseline of 10 seconds. Quantifying how big the offset actually is, is hard to do by only looking at the lines in Figure 3.1. In order to more accurately determine how large the difference is, the data will be processed further. The average over the entire time span will be computed and compared to a baseline. A similar analysis will be done for all of the other input parameters. In this case, the baseline is the 10 second case as this is assumed to be the most accurate. The results from this analysis can be found in Figure 3.2.

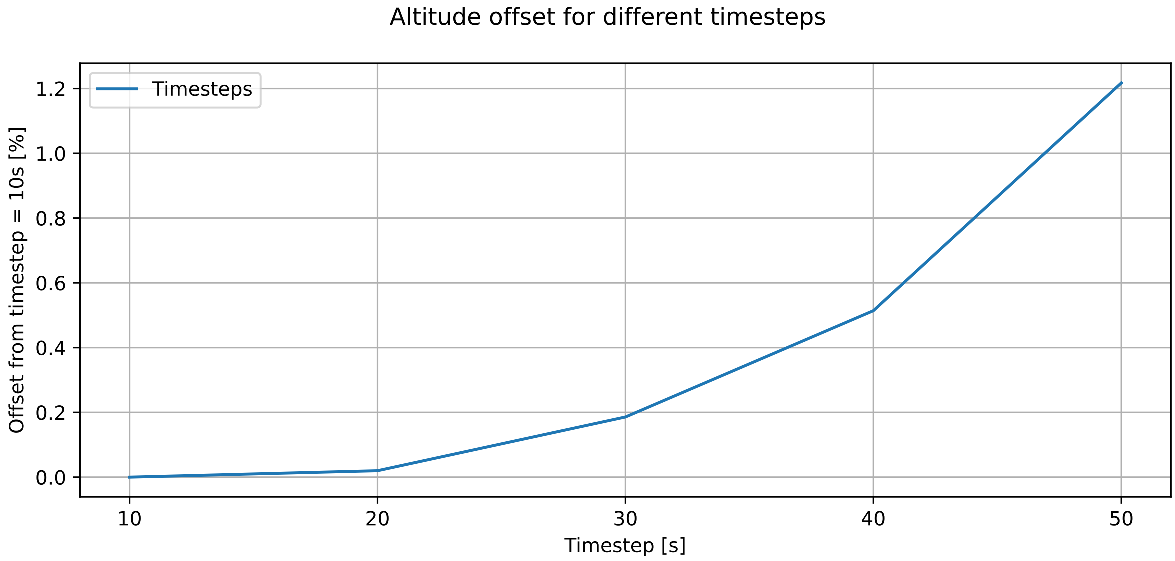

Figure 3.2: Altitude offset for all analysed timesteps

This figure shows that the offset drastically increases for each 10s jump in timestep. The 10 seconds option would be the most accurate, but the 50 second option would be the best with respect to run time and memory management. The 30 second time step is chosen to be optimal. It only has an offset of 0.2% in average altitude, while reducing the computational load and lowering the data size by a factor of three. This 30 second timestep will be used for the remainder of the input parameter determination, because this part of the research requires many simulations. The final run with all of the inputs fixed, will use the more accurate 10 second timestep as this simulation will only need to be done a few times, so time is less of a constraint.

3.1.2. Ground station parameters

The ground station model has three parameters that have to be analysed. All three are about the location of the station. The three parameters are the latitude, the longitude and the station altitude. For the latitude, the analysis was done twice. Once with an equatorial orbit and once with a polar orbit. This is done because a ground station on the pole of the Earth is able to reach a spacecraft in a polar orbit, but it is unable to illuminate a spacecraft in an equatorial orbit. In order to fairly asses the optimal latitude, both inclination cases have to be evaluated.

For clarity, the actual data as previously shown for the timestep in Figure 3.1 will not be shown here. This analysis will draw its conclusions from the offset of the average altitude compared to the initial orbital altitude for each input. The data was processed similarly to the timestep data. The actual altitude data can be found in Figure A.6, Figure A.7 and Figure A.8 in Appendix A.

Figure 3.3 shows the altitude offset from the initial orbital altitude on the y-axis. If the offset is positive, it means that the final stable orbital altitude found, is higher than the initial condition. A positive percentage also means that the orbit can be maintained, so the chosen input parameters are viable options for the final model. If the offset is around zero percent, it means that the final stable orbital altitude reached, is around the initial condition and it can be assumed that the orbit can be maintained. This

also means that the chosen input parameters are viable options for the final model. If the offset is far below zero percent, it means that that the orbit can not be stabilised for the given input parameters, so those parameters are not suitable for the final model. If a line in Figure 3.3 is horizontal, it means that the effect of the studied impact parameter is negligible. This is the case because any value on the x-axis will have the same value on the y-axis. This means that any decision on the studied parameter is equally viable.
In Figure 3.3 it can be seen that both the longitude, the orange line, and altitude, the green line, have a fairly stable behaviour. This means that the value of both parameters have a negligible effect on the performance of LAP. The difference between the offset value can be explained by the final orbital altitude found. Each different parameter analysis finds a different stable orbital altitude, so the final orbital altitudes for the station altitude analyses are slightly higher than for the longitude analyses. This is not an issue for the parameter selection, because the objective of this analysis is to determine which input parameters can produce a stable orbit.

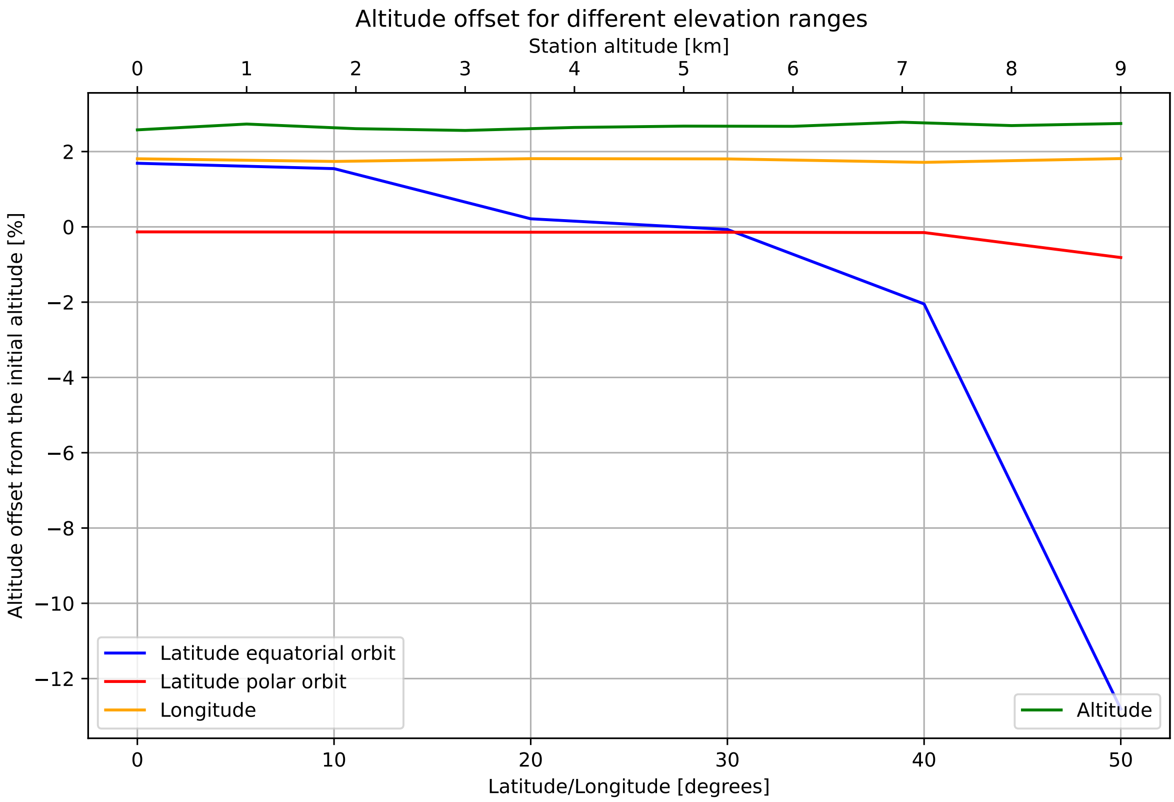

Figure 3.3: Altitude offset for various input parameters

The latitude has two lines in the graph. The first is the analysis with the orbital inclination set at 0 degrees, this is represented by the blue line. The second is with the inclination set to 90 degrees, this is shown with the red line. Both inclination cases were studied to make sure that satellites in both equatorial and polar orbits can be serviced by the laser station to increase the applicability of LAP to as many cubesats as possible. Firstly, the laser station latitude impact on an equatorial orbit, the blue line, is studied. As expected, this case shows that the 0 degrees latitude case keeps the orbit the highest within in the given constraints. Also as expected, there is a latitude for which the station can not reach the spacecraft often or long enough anymore as it does not enter the field of view long enough. The effect of this phenomenon can be seen by the reduction in offset percentage as the latitude increases. As soon as the offset percentage is clearly lower than 0%, it means that the orbit can not be maintained indefinitely. This is clearly the case for 40 degrees and above. At 30 degrees, the percentage is very slightly below 0. This means that the final stable orbital altitude for this case, is approximately the same as the initial orbital altitude. For the ground station latitude with an equatorial orbit, a value of 0, 10, 20 or 30 degrees can keep the orbit stable. The latitude analysis for the polar orbit, the red line, only has to be looked at for the previously found 4 latitudes. For all still available latitudes, the graph shows very similar results. This means that all four of these latitudes can work for LAP for polar orbits.

3.1.3. LEA parameters

The Laser Elevation Activation parameters determine for which elevation angles the laser can activate. For the LEA, there are two main parameters that need to be assessed. The first is the width of the angular range and the second is the elevation of its mid-point.
Firstly, the width of the field of view is analysed. Preferably, the width would be as small as possible so the need for movement of the mirror is limited. This width is analysed by starting with a range between 0 and 10 degrees and increasing the upper limit with intervals of 10 degrees until the window between 0 and 90 degrees is done. This scenario is called the Low Elevation Scenario(LES) and is shown in blue in Figure 3.4. After this, the inverse happens. The elevation range is analysed at 90 to 80 degrees with a decreasing lower limit until 90-0 is reached. This scenario is called the High Elevation Scenario(HES). This scenario is shown in orange in Figure 3.4.

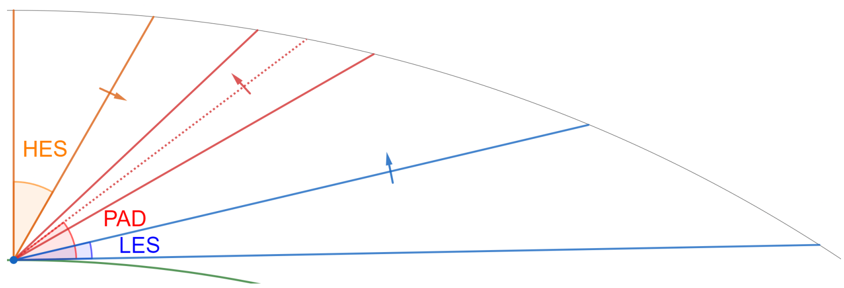

Figure 3.4: Graphical representation of the LEA cases

Both scenarios have their advantages. The LES covers a wider range of ascending nodes. This means that there are more points in time when the orbit can be raised, leading to a possible lower deorbit risk. This is the case because the ascending node of an orbit shifts over time. If a wider range of ascending nodes can be covered, there are more possible moments to raise the orbit.
The HES has a smaller area of airspace interference. This reduced airspace used, is beneficial for keeping the airspace free for air travel, but also for natural events such as bird migration.
Secondly, the Pointing Angle Direction (PAD) is studied. This is done by assessing the viability of 10 degree windows from 0-10 degrees up to 80-90 degrees and in shown in red in Figure 3.4. The dotted line is the elevation of the mid point of the ten degree range. This is done to analyse whether a elevation scenario that does not start at 0 or 90 degrees can outperform the LES and HES.
For all cases, the spacecraft will have passed the point of highest elevation, so the laser-velocity angle mentioned in subsection 2.4.2 is larger than 90 degrees.

The results for this analysis can be found in Figure 3.5. Firstly, the LES and HES will be observed. The orange line gives the results for the HES and the blue line shows the LES. As expected, the results of 90 degrees HES and LES are the same. For the HES, there is one major offset for the HES between 90 and 80 degrees. For this scenario, LAP can not be used, because the offset lower than -5% indicates that no stable altitude can be reached. This is to be expected, as the laser-velocity angle in very inefficient on these high elevations as shown in Subsection 2.4.2. All of the other scenarios show that they can sustain a stable orbit as the offset of the initial altitude is minimal.
To determine in which direction am angle range is a viable option, the red line has to be observed. This line represents the offset as a function of the elevation mid-angle represented on the top x-axis, showing the PAD. As both of the previously studied scenarios start with a 10 degree window, their first data point matches with the first and last data points of the PAD data. The conclusion that can be drawn from this graph is that any 10 degree window except for the 80 to 90 degrees window is a viable option for the current laser station.

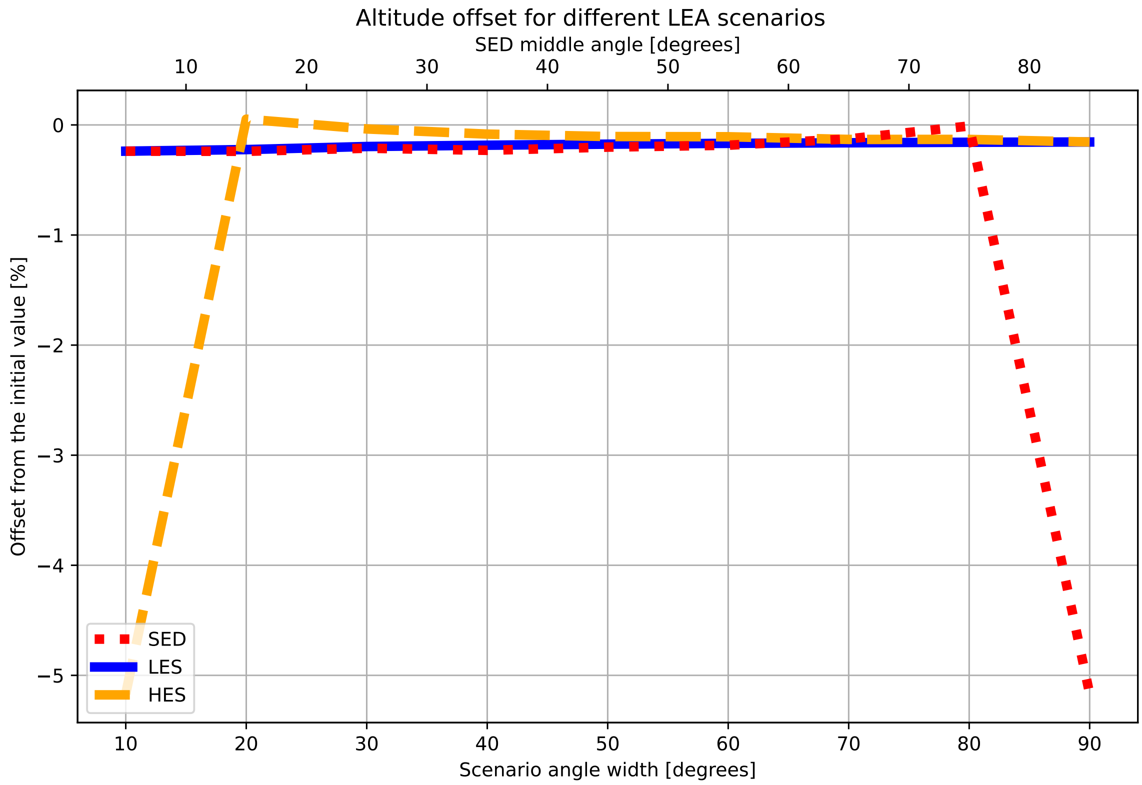

Figure 3.5: Altitude offset for the elevation scenarios

Figure 3.5 shows that multiple scenarios can work, but it is hard to determine which scenario is the best. When reducing the initial orbital altitude it can be determined which PAD is more versatile, as a lower altitude requires a more capable system. The results from Figure 3.6 show that the 10 degree PAD scenario around 5 degrees, meaning the 0 to 10 degree elevation range, can maintain the 325km orbit the longest and thus is optimal for LAP.

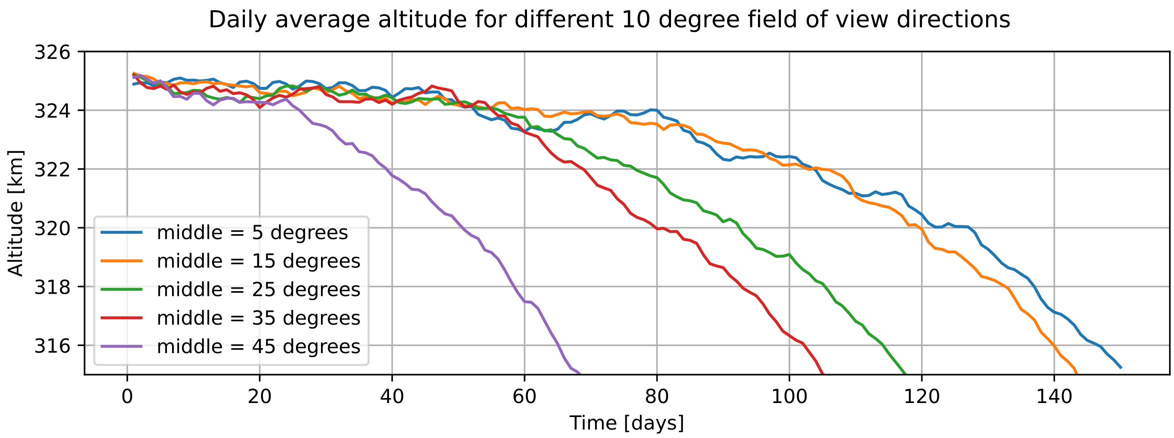

Figure 3.6: Daily average altitude for different 10 degree field of view directions

If the initial orbital altitude is lower, a wider angle range is required to maintain the orbit.
For general cubesat use, a 10 degree scenario will suffice as most cubesats are in an orbit at around 400 to 500km altitude. To research the limits of LAP, an analysis is done on the capabilities of the widest scenario of 90 degrees. For this case it is found that the lowest stable altitude is 255km. Any satellites in orbits lower than this, encounter perturbing forces larger than what can be counteracted by the LAP system. The data can be found in Figure A.5 in Appendix A.

3.2. Final input parameters

This section summarises the results that were gathered in this chapter. The chosen input parameters will provide the optimal situation for LAP to be a viable alternative to conventional propulsion.

Timestep

The timestep chosen is to be 30 seconds for all of the parameter determinations, but it is reduced to 10 seconds for the final propagation.

Laser station locations

The ground station location can be placed at any location between 30 and -30 degrees latitude around the Earth. Figure 3.7 shows the Earths antipodes. An antipode is a location on land that also has land on the exact opposite side of the planet. Because of the requirement of the second laser station, an antipode is an ideal location for a laser station. As the station has to be between 30 and -30 degrees latitude, the Indonesia and northern South-America antipodes are great candidates for the laser stations. The locations at 0°N, 111.5°S and its antipode at 0°N, -68.5°S are both on land with elevations close to 0m.[1] The average altitude of the the locations is 62.5m, which will be used as the input to the model.

Elevation parameters

The LEA range will have a width of 10 degrees, as this is sufficient for orbit maintenance as shown in Figure 3.5. The angle limits will be from 0 to 10 degrees above the horizon.

Figure 3.7: Antipodes of the Earth [22]

[1]calculated by `https://www.freemaptools.com/elevation-finder.htm`

4 Verification and validation

For any model, it is of critical importance to ensure that it is correct. This is done by verifying and validating the model. 'Verification is performed to ensure the product complies with requirements. Validation is performed to ensure that the product is ready for a particular use, function, or mission.' [23] Verification can be done by testing separate parts of the model to see if the results are as required. Validation is done by applying the model to another case for which the input and output parameters are known. If the model produces the same outputs with the given inputs, the model has been validated.

4.1. Verification

The first unit test performed for model verification is the perturbation test. This turns off any propulsion to see if the deorbiting or the spacecraft happens over time. This test uses the aforementioned 3U Delfi-C3 cubesat layout and orbital parameters with an initial orbital altitude of 450km. The European Space Agency (ESA) Debris Assessment Software (DAS) tool predicts between one and two years of orbit life time dependent on various parameters such as the solar activity. Figure 4.1 shows the results from this simulation. As can be observed, the spacecraft initially loses its altitude slowly, but the lower it gets, the faster it decreases in altitude. The model shows that the spacecraft reaches the Earths surface around 490 days, which is 1.34 years. This falls in the window provided by the DAS tool, so the perturbation section of the model is in line with expectations.

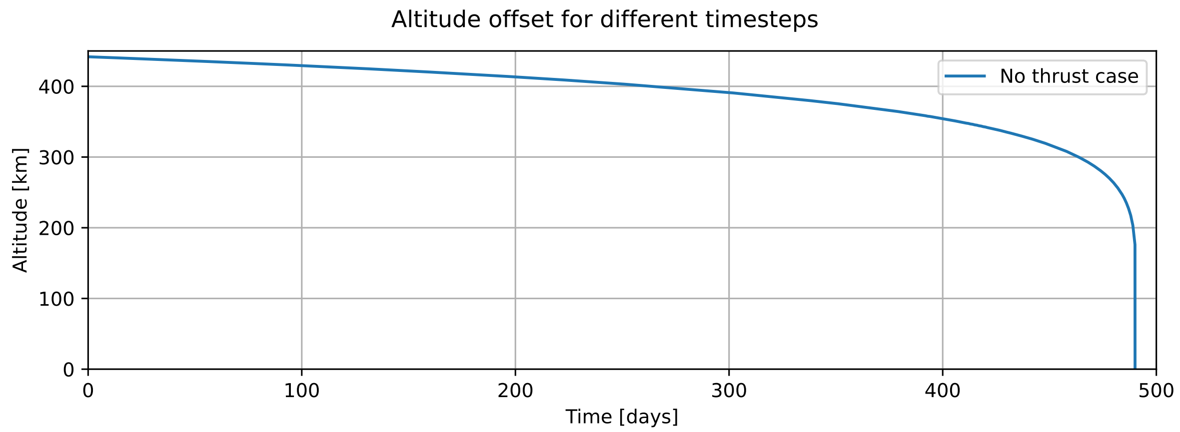

Figure 4.1: Altitude for the no thrust case

The laser activation constraints discussed in Subsection 2.4.2 robustness was also tested. To determine whether the constraints were enough to ensure that the results would not get out of control, a sensitivity analysis was done on the laser power. The output power was increase by a factor 10, which resulted in the trends shown in Figure 4.2. The 200kW altitude profile does have a slightly higher average altitude, but the orbit is stable. The higher average altitude is caused by the higher generated thrust. A higher thrust means that less passes are needed to raise the orbit, so the spacecraft is above the threshold altitude for longer and thus has a higher average altitude. This higher average altitude is not caused by the laser activation constraints themselves, so they function as desired.

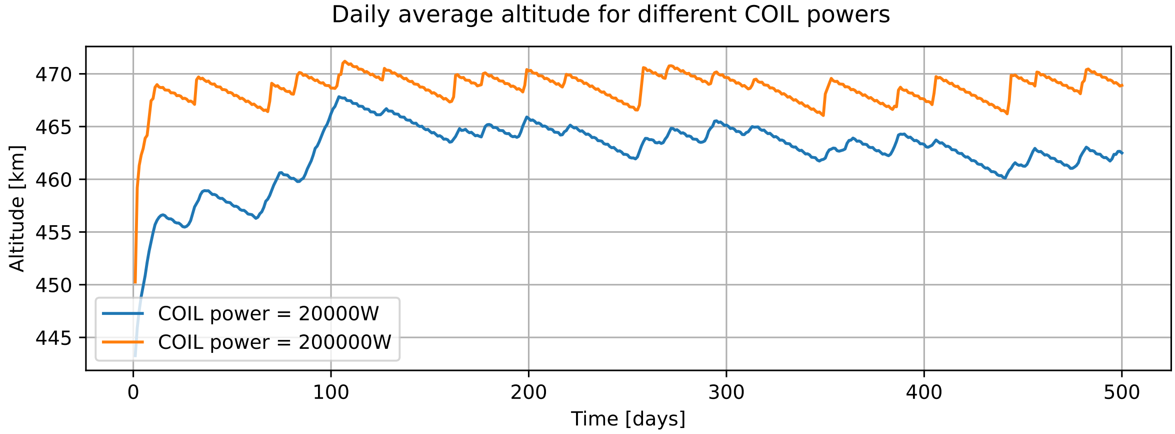

Figure 4.2: Daily average altitude for different COIL powers

4.2. Validation

The validation process has been done by replacing the cubesat that was initially the modelled spacecraft by the International Space Station (ISS). A lot is known about the orbital parameters of the space station, so it is a great candidate for the validation of the system. There are two methods that were used for the validation of the model. Both are based on different data sources. The first was finding actual data on the delta-v requirement of the ISS and comparing this to the produced delta-v from the model. The second method is by theoretically determining the energy loss per revolution of the ISS for two initial altitudes. With this energy loss, the delta-v requirement can be computed. A high and low initial altitude were chosen to validate the model for a high and low density situation.

The actual delta-v data is very hard to compare to as this fluctuates greatly. Changes in solar activity can easily influence the density at 400km by an order of magnitude. On average however, the delta-v requirement of the ISS is around 30 to 40 m/s per year with ESA giving 0.09m/s per day in an educational example [24], leading to 32.85 m/s per year. Depending on parameters such as solar activity, the model produces delta-v results in the range of 30 to 50 m/s per year. This was done by finding the thrust acceleration output of the model and multiplying this by the time for which thrust was active. The 32.85 m/s being in the range found by the model, and the results being of the same order of magnitude already provides some reliability to the model.
The theoretical assessment can confirm this reliability. Using the input data from Table 4.1 and 2 initial orbital altitudes of 415.7km and 350km, the delta-v values were computed.

Table 4.1: Input parameters for the ISS delta-v computation [25]

Mass	417289 kg
Drag area	2500 m2
Cd	2.07
eccentricity	0.00058
argument of periapsis	136.6906 deg
longitude of the ascending node	23.4 deg
true anomaly	0 deg
inclination	51.8 deg

The delta-v outcomes can be seen in Table 4.2. The decision for two altitudes was made to assess a high and low density situation for optimal validation. With the difference for both cases smaller than one percent, the model has been validated.

Table 4.2: ISS delta-v calculation results

Initial orbital altitude	Model	ISS calculation	Percentage difference
415.7 km	25.92 m/s	26.17 m/s	0.94%
350 km	96.28 m/s	95.74 m/s	0.57%

5
Results

5.1. Presentation of the results

The input parameters have been established as discussed in chapter 3, so the final run of the model can be performed. This run will be done with the physical and orbital parameters of Delfi-C3 as mentioned in subsection 2.5.1. The initial orbital altitude is set at 450 and 400km, because these are very common values for cubesats. Lower altitudes are not considered for this analysis as 350km can not be kept stable for the current input parameters. All of the other input parameters are summarised in Table 5.1.

Table 5.1: Input parameters to the final propagation

Parameter	Value
Max time	2000 days
Pulse duration	0.01 s
Pulse frequency	1/10 s^{-1}
Mirror diameter	9 m
COIL power	20 kW
Timestep	10 s
Station latitude	0°

Parameter	Value
Station longitude	111.5°
Station altitude	62.5 m
C_m	950 μN /W
Altitude	450 & 400 km
Activation angle lower limit	0°
Activation angle upper limit	10°
Laser wavelength	1315 nm

Because of the long simulated period, the oscillations in the daily average make the results hard to read. For this reason, the weekly and monthly (30 days) averages are computed and added to the graph. For the 450km case, the raw altitude data is included to show different processing outcomes of the data and to show that it is hard to analyse due to its large oscillations. The 400km case does not include this raw data to make the analysis clearer. Figure 5.1 shows the altitude profiles for both of the initial altitude cases.

5.2. Altitude profiles

5.2.1. Common behaviour analysis

For both cases, there is some very clear unexpected behaviour just after the beginning of the simulation. The altitude jumps up rapidly and falls back to below the initial altitude, after which it climbs back to peak height. This behaviour can be explained with the help of the constraints defined in subsection 2.4.2. The first 2 constraints dictate that the orbital radius can not be larger than the initial orbital radius and has to be larger than the semi major axis. Because of the oscillatory behaviour of the altitude that can be observed in the raw data, the orbital radius dips below the initial altitude for every oscillation. The lowest point of the oscillation has to be above the threshold for the laser system not to activate. This is what causes the altitude to jump up initially and it also explains that the stable altitude that is found after the initial unexpected behaviour is slightly higher than the initial orbital altitude.
This reason does not explain why after the initial peak, a dip is observed. This dip is also caused by the two constraints mentioned before, but it has a different explanation. After the initial altitude jump, the eccentricity has been altered to such an extent that the laser system will not activate at the arc close to

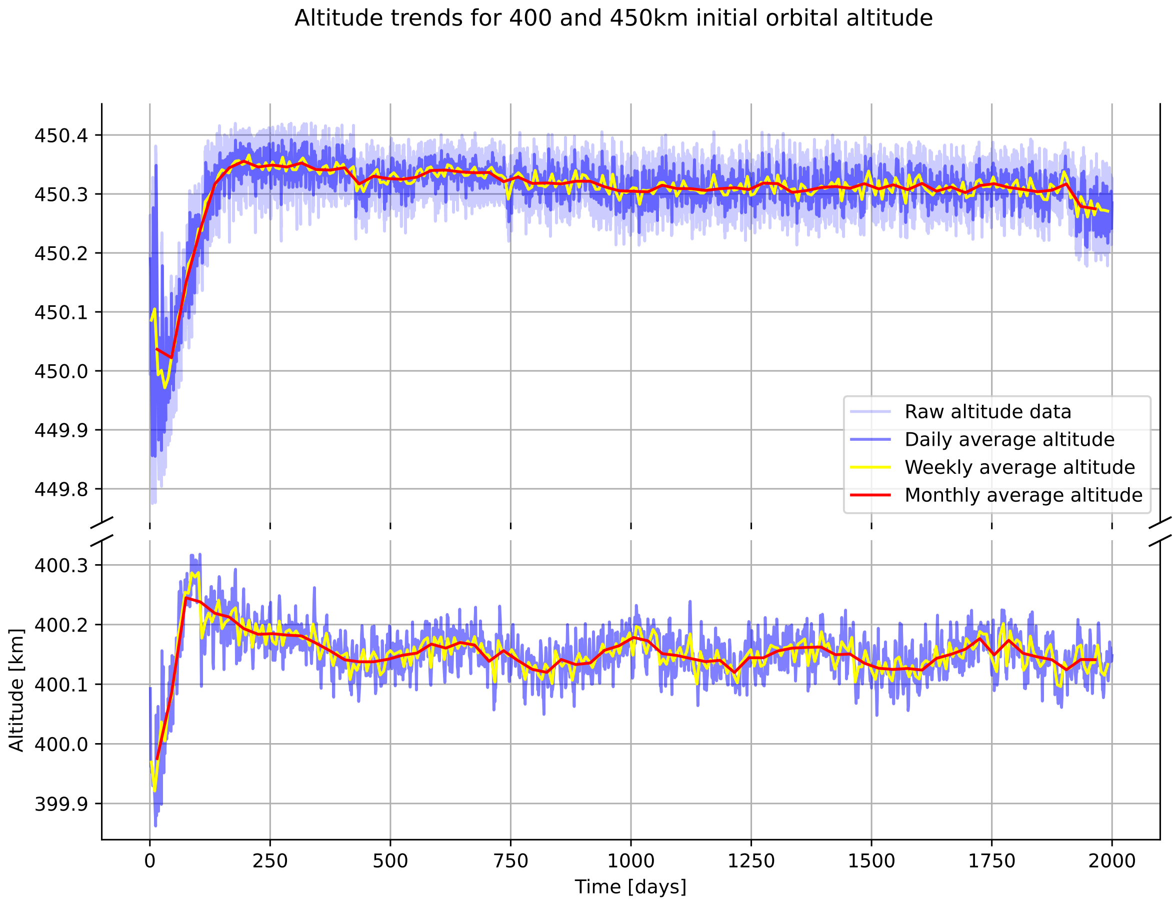

Figure 5.1: Altitude data for the 400 and 450km initial altitude simulations

the perigee due to the semi major axis constraint and the laser system will not activate on the arc close to the apogee because of the initial orbital altitude constraint. The orbital altitude first has to naturally be lowered, before the laser can activate again. Once this happens and the orbital altitude is raised again, both constraints are in balance and the altitude can be kept stable.

5.2.2. Difference between the cases

Next to the similarities in behaviour, there are also some clear differences between both altitude cases. The initial jump after the initiation of the simulation for the 400km situation is smaller. This means that the initial constraint instability that is present in the 450km case is less influential for the 400km case. The effect of the overshoot that causes the initial peak in the 450km case, does still affect the 400km scenario altitude. The overshoot after the dip is more present for the lower altitude simulation. This is the case, because both constraints still need to find the balance that occurred sooner for the high altitude scenario.

A second difference is the spread of the data points. The 450km case has a standard deviation of 31 meters, while the 400km situation has a 43 meters standard deviation during the stable period. The monthly average also has a less stable behaviour for the 400km analysis. This behaviour appears because of the bigger perturbing forces. The aerodynamic drag greatly increases at lower altitudes. As shown in Figure 4.1, the effect of the lower altitude clearly influences the speed at which the deorbiting occurs. This faster rate of altitude loss, means that there are lower dips in altitude that will then be boosted back up to the top of the allowed limit by the constraints. This causes the bigger spread in altitude.

5.3. Laser activation

5.3.1. Activation frequency

As can be expected, a lower orbit requires more thrust to stay in orbit because of the higher drag. This phenomena is studied for the results presented above. For efficient data processing reasons, this analysis is done for the period between 250 and 500 days. This range is chosen because it represents the first stable period while still being a short enough range for manageable data processing. The laser activation frequency will then be extrapolated to a per orbit, daily and yearly number of activations for each initial orbital altitude. The results are shown in Table 5.2.

Table 5.2: Laser activation frequency for multiple periods

Altitude	**250 days**	**1 orbit**	**1 day**	**1 year**
400 km	2206 pulses	0.57 pulses	8.82 pulses	3221 pulses
450 km	969 pulses	0.18 pulses	3.88 pulses	1415 pulses

Table 5.2 shows that the expected higher frequency for lower orbits is true. The pulses per orbit show that for a 400km initial altitude, about one laser pulse per 2 orbits is required, which means one pulse in about three hours. This indicates that the laser system, which can activate every ten seconds, can handle a large number of different satellites simultaneously. For the 450km case, this time increases to about one pulse per 8.5 hours. This analysis also shows that the constant mass assumption from Section 2.3.1 is a fair assumption to make, which means that the orbit can be maintained indefinitely.

5.3.2. Maximum acceleration

During all of these pulses, the spacecraft undergoes an acceleration. The magnitude of this acceleration depends on the arriving laser power. The maximum acceleration encountered is around 14.5 m/s^2 for both initial altitude cases. The 450km case has a slightly lower acceleration at 15.48m/s^2, while the 400km case has a maximum acceleration of 14.55 m/s^2. As with the orbital parameters, the accelerations encountered here will have to be smaller than the accelerations encountered during the launch with a Falcon 9. The Falcon 9 has design load factors between -2G and +6G in both the lateral and axial direction [8]. Because the acceleration by LAP is in the positive axial direction, the +6G requirement has to be complied with, and this is clearly the case. 14.55m/s^2 is less than 1.5G, which is far below the 6G.

6 Research questions and requirements

Before a conclusion can be drawn, the research question and its corresponding subquestions and requirements have to be revisited. This is done below.

6.1. Subquestion recap

The subquestions introduced in Chapter 1 will be answered below.

6.1.1. Question one

1. What is needed to create an accurate model in Tudat?
   (a) Which disturbances will be included in the model?
   (b) Which integrator will be used for the model?
   (c) How can different locations on Earth be modelled for the laser location?

Question 1a has been answered in section 2.1. This section gives the implemented disturbing accelerations and the disturbing phenomenon with respect to the laser progression.
The perturbing accelerations are the point mass gravity accelerations of the Sun, the Moon, the non Earth planets, a spherical harmonic gravity (5,5) acceleration from the Earth, cannonball radiation pressure from the Sun and the aerodynamic drag induced by the atmosphere. The disturbing phenomena with respect to laser progression included are the absorption and diffraction of the laser beam.
Question 1b was answered in subsection 2.5.2. The result is that the RK4 integrator provides a good balance between run time and accuracy.
Question 1c was partly answered in section 2.2. The general answer is that the different locations are modelled freely. They are not bound to the geological layout of the surface of the planet during the parameters determination.

6.1.2. Question two

2. What laser system is optimal for LAP use?
   (a) Which chemical composition and its corresponding wavelength should be chosen for the laser system?
   (b) What is the pulse duration required for proper ablation?
   (c) What does the physical laser ground installation consist of?
   (d) What is the optimal location for the laser stations?

Question 2a was answered in subsection 2.2.1 where the decision was made to go with a Chemical Oxygen Iodine Laser (COIL). Specifically the system used on the YAL-1 aircraft. This laser type has an output wavelength of 1315nm. This decision was made to ensure that the Earth based mirror size would not get too large. An additional benefit to the COIL is its technological readiness. Its TRL is high, because of the use on the YAL-1.

Question 2b was answered in subsection 2.2.1. The pulse duration is chosen to be 0.01 sec as this is the time required to generate enough heat to activate the propellant.
Question 2c was partly answered in subsection 2.2.1. The mirror will have a diameter of nine meters as this is the required size for the laser to be able to progress through the atmosphere for long enough to reach the spacecraft. This was shown in subsection 2.2.2. The other parts of the physical ground station were not researched during this thesis, but it would contain various infrastructural, structural en safety features. Some of the main features would be the large chemical storage tanks, the reaction chamber, the mechanical laser pointing system and the control room. In order to specify the exact layout, more research has to be done in to the daily operations that a system like this requires.
Question 2d was answered in chapter 3. The location latitude has to be between 30 and -30 degrees, while the longitude and altitude have a negligible impact. The chosen locations are the antipiodes at 0°N, 111.5°S and 0°N, -68.5°S. The average altitude of the two locations is 62.5 meters.

6.1.3. Question three

3. How should the usual cubesat layout be adjusted to accommodate LAP?
    (a) Which ablative surface yields the most efficient result?
    (b) How much of the cubesat surface has to be covered in ablative material?
    (c) Is the propulsion system causing thermal problems inside the spacecraft?
    (d) Are there any beneficial effects, next to the propulsion element, of the laser on the cubesat?
    (e) Is current day technology ready to accommodate LAP?

Question 3a was answered in subsection 2.3.1. The decision was made to use pyroxylin, as this has both a realistic arrival power requirement and a sufficiently high specific impulse.
Question 3b was lightly discussed in subsection 2.2.2 where r_0 was explained. In order to have the optimal arriving power, the biggest possible r_0 on the surface away from the velocity vector should be chosen. For Delfi-C3, where this surface is a 10x10cm square, an r_0 of 5cm was chosen.
Question 3c was not part of this feasibility study, so it was not answered during this research. It would be a reasonable assumption to assume that a laser heating an ablative surface to a very high temperature, will cause heating problems for the spacecraft. Even if the ablative surface itself has a very efficient insulation layer underneath, the pointing inaccuracies and diffraction errors cause some of the laser light to hit other non insulated surfaces of the spacecraft. In order to accurately answer this question, some experiments should be done that include the more accurate effects of diffraction.
Question 3d was, similar to 3c, not part of the study, so it was not answered during the course of the study. One possible benefit that the laser can have on the spacecraft is that is a part of the diffracted or misaligned beam can illuminate a part of the solar panels. This can generate extra power through these solar panels. This is true as long as the heat does not pose an issue. Another positive influence from the laser on the satellite could be related to question 3c. The heat generated by the laser can be used for temperature management inside of the spacecraft. If the equilibrium temperature appears to be too low for the subsystems, the heat generated by the laser could get the temperature in the desired range.

Question 3e is also not part of this study. The chosen laser system had been produced and tested before, so this technology is ready for more extensive testing. The ablative surfaces researched were chosen because they were experimented with for the exact purpose of laser ablation propulsion, so that technology is also ready. The point where technology might not be ready is in term of the pointing accuracy. As discussed in subsection 2.2.1, the assumption was made that the pointing and position determination accuracy were 100% accurate. In practice, this is not the case. Because the ablative surface is very small at 10cm diameter, an offset of only 5cm already means that the arrived power on the ablative surface decreases by 85%. This 5cm offset already appears if the pointing angle is misaligned by 5×10^{-6} degrees at a range of 500km. Accuracies in this range are not possible yet [26]. For this reason, the answer to this question has to be no.

6.1.4. Question four

4. How well does the propulsion system have to perform to be deemed viable and efficient?
   (a) Is LAP financially attractive to cubesat providers?
   (b) Can LAP provide a more reliable propulsion system?
   (c) Can LAP allow the cubesat to function more efficiently due to less space constraints?

For question 4a, the prices for both systems need to be found. For the conventional system, there are the following costs that need to be considered. The first is the costs of the propulsion system itself. This is very hard to find, as most systems are custom made for a specific spacecraft. An indication can be found for very simple cold gas systems that start at around 100,000 euros [27], but can get vastly more expensive for bipropellant or ion thrusters. Next to the system costs, the spacecraft itself needs to be launched in to orbit. This usually has a price per unit mass or volume. Generally a price around 80.000 euros per U is common. Depending on the size and mass of the propulsion module, the costs will increase greatly. If a 1U simple cold gas system was available, the combination of these two costs would be 180.000 euros excluding any staff costs or other expenses made to integrate the propulsion system in to the spacecraft. A more realistic assumption would be that the addition of a bipropellant system would cost closer to 500.000 or one million euros. The costs for the LAP solutions are also twofold. The first part is the ablative surface. This ablative surface is a very simple part, as is does no require any complicated movable parts or electronics that require redundancy and extensive testing. This makes the assumption that it is a cheaper subsystem compared to conventional propulsion systems an acceptable one. The second cost parameter is the laser system. The YAL-1 aircraft had an estimated price of 700 million USD [28]. The expected costs of the LAP ground station will probably be less than the YAL-1 costs, as this station does not have to be on an aircraft. A Boeing 747-400 costs about 230 million USD[1]. One part that will be more expensive is the mirror. The YAL-1 mirror has a 1.5m diameter, while the LAP system needs a diameter of 9m. If the laser system cost is set at 500 million and an expected conventional system price of 500.000 euros is chosen, the LAP solution will become more affordable after it has serviced 1000 satellites. As determined in Section 5.3, the 400km case requires about one pulse per 3 hours and a single pulse takes 10 seconds. If a perfect schedule can be made, the laser system can in theory handle 1080 satellites in a 400km orbit simultaneously. This is a rough estimation, as this calculation does not involve prices such as: the staff wages, the laser chemicals price, the ablative surface costs and the price for the infrastructure around the station, but this is the case for both propulsion types.

Question 4b can be answered under the assumptions made during this research. A conventional propulsion system has a lot of moving parts, while the on board section of the LAP system is very simple without any movement. This makes the LAP system far more reliable as long as the laser system is able to illuminate the ablative surface perfectly. The reliability of the laser system itself might come in to play, as there are many moving parts as well. The main benefit to these problems compared to the conventional propulsion system problems, is that maintenance is possible for an Earth based laser station, while this is impossible for in orbit systems.

Question 4c is also has a straight forward answer under some given assumptions. If the heat generation from the laser has no negative effect on the spacecraft, the cubesat system configuration can be made more efficient and more convenient. A conventional propulsion system has to be on the edge of the satellite and the force vector has to pass through the centre of mass of the spacecraft. These positional constraints fall away when LAP is used, so other systems can be placed more freely throughout the structure.

[1] https://aerocorner.com/aircraft/boeing-747-400

6.2. Requirements recap

With the results from Chapter 5 and the answered subquestions above, the requirements mentioned in section 1.7 can be evaluated.

1. The system shall be able to keep the spacecraft from deorbiting indefinitely.
2. The shape of the orbit shall not be altered by more than the orbit insertion margins of the falcon 9 [8].
3. LAP shall be financially attractive for cubesat providers.

As the results show, the spacecraft can be kept in orbit for the entire simulated duration of 2000 days. The stability shown after the initial dip, indicate that it is safe to assume that this stable behaviour will continue after the 2000 days. This, paired with the negligible fuel usage assumption, means that requirement one has been met.
The second requirement can also be assessed with the results from chapter 5. As indicated by the Falcon 9 Launch Vehicle Payload User's Guide [8], the margins for orbit insertion are ± 10 kilometres for the apogee and perigee. The discussion of the results highlighted that the worst case standard deviation is 43 m. This is far better than required.
The third requirement was discussed for subquestion 4a with a rough calculation. If the station is able to service more than 1000 satellites in its lifetime, LAP is financially attractive for cubesat providers. The calculation in the answer for subquestion 4a shows that for a perfect schedule, 1080 satellites can be maintained simultaniously for the most demanding initial altitude of 400km. This alone would mean that this requirement is met, but the laser system should be able to maintain several generations of satellites, leading to a much larger total number of serviced spacecraft orbits.

6.3. The main research question

Now that all of the subquestions have been answered and the analyses of the LAP interactions are done, the main research question can be answered. The question was composed as shown below.

How can Earth based Laser Ablation Propulsion be a viable and attractive propulsion alternative for orbit maintenance for low Earth orbit cubesats?

To be able to answer how LAP can be a viable option, it first needs to be determined if LAP can work at all. As shown in the simulations, LAP can, in theory, work for orbit maintenance, but these simulations are not a 100% accurate representation of the real world due to two of the assumptions made. These assumptions are that there is a 100% accurate pointing mechanism and satellite positioning and that the atmospheric effects only reduce the arriving power and do not redirect the entire beam. As subquestion 3e showed, modern day technology is not yet able to meet the required pointing accuracies to make LAP work. Next to this mechanical limitation, there is a major safety issue paired with LAP. A 20kW laser, initially designed to disintegrate missiles, is not safe for planes passing over. In order for LAP to function, the airspace should be completely clear. For now these limitations mean that Laser Ablation Propulsion is not a viable and attractive propulsion alternative for orbit maintenance for low Earth orbit cubesats.
If these physical limitations can be overcome, the research question can be answered differently. For LAP to work, there are two main systems that are required. The first is the ablative surface. When using pyroxylin in the 5cm diameter circle on the small panel of the cubesat that can maintain an attitude as described in this research, LAP can work. The second system is the laser station pair. Both stations need to be large Chemical Oxygen Iodine Lasers with a 9 m diameter mirror, a 0 to 10 degree manoeuvrability range above the horizon. The stations will be placed on the antipodes at 0°N, 111.5°S and 0°N, -68.5°S. at an average altitude of 62.5m. When all of these conditions are met, LAP could be used for orbit maintenance.
All of the aforementioned parameters are in relation to the physical system. If a system like this would truly be realised, there will be many regulation related issues that would have to be solved. These regulations will include limits on the occupation of airspace for air travel or animal migration. Another regulation will be about targeting. The laser should never be able to harm anything or anyone on Earth, so the laser can never be pointed towards a building or other ground locations on the planet. This regulation could limit the current optimal elevation scenario of 0-10 degrees. These are just two of the many regulations that will be made for the implementation of LAP.

6.4. Implementation of LAP for real world applications

Now that Laser Ablation propulsion has theoretically been determined viable, some real world applications of LAP can be discussed. As mentioned in Chapter 1, a current trend in the space industry is the launching of many satellites into a constellation. Two examples of these constellations are Starlink by Space-X with a planned 12000 satellites, weighing about 300kg, with the possibility to expand by 42000 more [29] and Oneweb, which is aims to launch 600 satellites of just above 100kg in to a constellation in LEO. Both constellations aim to put their satellites at 450km altitude.

Constellations like these would require endless relaunching of spacecraft if they would not be equipped with a propulsion system. LAP could be the perfect solution for these types of constellations. As mentioned before, the LAP option will become financially attractive for 1000 or more satellites serviced. If a company like Space-X were to accept this propulsion method for their Starlink constellation, this could prove to be a very affordable alternative.

7
Conclusions

The goal of this thesis was to find how Earth based Laser Ablation Propulsion could function as a viable and attractive alternative to conventional propulsion methods. In order to answer this question, a simulation was made in the Tudat environment. This model had a wide range of inputs that could be varied to study a wide range of different parameters such as the laser station position and the orbital parameters.

7.1. Initial parameter selection

Before the first main simulations were run, the initial input parameters were chosen. The propellant for the ablative surface was chosen to be Pyroxylin for its realistic requirements and its sufficiently high specific impulse. After this, the laser type was determined to be a Chemical Oxygen Iodine Laser. This was decided upon because of its realistic mirror size requirement with the added benefit of the technological readiness level. A COIL has a wavelength of 1315 nm and requires a mirror radius of 4.5m in order to progress through the atmosphere for all elevation angles. The laser pulse duration and frequency was set at a burst of 0.01 seconds per 10 seconds to ignite the ablative material. The orbit analysed was the orbit of Delfi-C3 for most of the analyses.

7.2. Propagation model

The propagation model used a Runge-Kutta method (RK4) to calculate the results with timesteps of 30 and 10 seconds and a maximum time of 2000 days. Which time step used, depends on the analysis. For the input parameter determination, 30 seconds is used. The final simulation uses the 10 seconds timestep. The RK4 integrator was chosen as it has good ratio between accuracy and computational time. The Tudat dynamics simulator used, required the inputs shown in Table 2.2 to generate the desired outputs.

7.3. Model constraints

For the LAP system to keep the orbit maintained, some constraints were established. These constraints make sure that the orbital altitude does not get out of control or that the shape of the orbit changes drastically. They are listed below.

1. The orbital radius can not be larger than the original orbital radius.
2. The orbital radius has to be larger than the semi major axis.
3. The angle between the velocity and the laser has to be more than 90 degrees.
4. The elevation angle has to be between the predetermined limits dependent on the study case.

7.4. Input parameter determination

7.4.1. Timestep

To establish the input parameters for the final model. Multiple analysis were done. The first was an analysis of the timestep. The 30 seconds interval was chosen to be optimal as it has a lower computational load compared to the 10 seconds option, while only deviating by 0,2% in the altitude. During the rest of the parameter estimation, this 30 second timestep was used as these determinations required many runs of the code. For the final model, the 10 seconds timestep was used, because this is more accurate and only had to be run a few times.

7.4.2. Ground station parameters

The laser location consists of the latitude, the longitude and the station altitude. Both the longitude and altitude were shown to have a negligible impact on the performance, so those could be chosen freely. The latitude has to be between 30 and -30 degrees. Any latitude outside of the range would mean that equatorial orbits can no longer be serviced. The laser station pair would operate the best if the lasers are located on each others antipode. An antipode that fits inside of the limits given before is the Indonesia and northern South-America antipode. The exact coordinates are 0°N, 111.5°S and 0°N, -68.5°S with an average altitude of 62.5m.

7.4.3. Laser elevation activation parameters

The LEA parameters determine for which angle range above the horizon, the laser can activate. This range was set to be between 0 and 10 degrees above the horizon. At this angle range, satellites in orbits down to 400km can be kept stable. The minimal orbit that can be maintained if this angle range is bigger is 255km for the 0 to 90 degree elevation range. In the end, the 0 to 10 degree range was chosen, as this is sufficient for most cubesats in LEO.

7.5. Final model

With all of the predetermined input parameters introduced in to the model, the final simulations can be started. These simulations have a 10 second timestep and a 2000 days duration. The results for both the 400 and 450km case show that after a period of instability due to the constraints, a stable altitude is found. This means that for the given input parameters, LAP can maintain the orbit of the spacecraft.

7.6. Final conclusions

As shown by the results for the final model, LAP would be a good propulsion method in theory, but in practice this is not the case. Two assumptions that were made for this research to be possible, were in place to ensure that the laser reaches the ablative surface exactly. The first of these assumptions is that the laser station has a 100% accurate pointing mechanism and exact satellite positioning knowledge. This, combined with the second assumption that the atmosphere only reduces the laser intensity and does not affect its direction, means that the laser beam reaching the ablative surface with a 5cm radius in orbit is guaranteed. In reality this is not the case, because satellite positioning and laser system angle errors are unavoidable. This combined with the redirection of light by different air density layers means that misalignments are not negligible. An offset of only 5cm means that the arrived power on the ablative surface decreases by 85%. This 5cm offset already appears if the pointing angle is misaligned by 5×10^{-6} degrees at a range of 500km. Accuracies in this range are not possible yet [26]. For that reason, Laser Ablation Propulsion is not a viable alternative to conventional propulsion yet. If in the future, a mechanical pointing accuracy equal or better than the mentioned 5×10^{-6} degrees can be created and a more accurate model of the atmosphere can be made, LAP might be an effective propulsion alternative to conventional propulsion methods.
If these physical limitations can somehow be overcome, the research question can be answered. Two systems are required for LAP to be a viable and attractive propulsion alternative to conventional propulsion. The first is the ablative surface. Pyroxylin in a 5cm diameter circular patch on the small exterior panel of the cubesat that is facing away from the velocity direction is required to provide the thrust needed for orbit maintenance. The assumption is made that the loss of mass is negligible, so the spacecraft has constant mass. The second system is the laser station pair itself. For enough power

to reach the ablative surface, two powerful Chemical Oxygen Iodine Lasers are required. The lasers have an output power of 20.000W with a mirror diameter of 9m. Both stations have a manoeuvrability requirement of 0 to 10 degrees above the horizon. To keep the eccentricity as small as possible, the laser stations need to be positioned on an antipode. The chosen locations are 0°N, 111.5°S and 0°N, -68.5°S with an average altitude of 62.5m. If all of these specifications can be achieved, LAP could be a viable and attractive alternative to conventional propulsion methods.

The previously theorised set-up was only related to the physical characteristics of the system. If LAP would really be introduced for orbit maintenance, there will be several regulatory issues that will have to be dealt with. One of these regulations will be on the dangers of the laser. A high power laser capable of disintegrating missiles should never be allowed to harm anything on Earth or in space. This means that the occupation of airspace will be limited. Air travel or natural phenomena such as bird migrations or wind supported spreading of organisms will require the laser to be turned off. It also means that the laser should never be able to point to any location on the surface of the Earth. This could mean that the chosen elevation range of 0 to 10 degrees could be limited. These are just some of the many regulatory issues that can come in to play when dealing with LAP.

8 Recommendations for future work

The designed model is capable of showing that the concept of Earth based Laser Ablation Propulsion is a theoretically realistic alternative to conventional propulsion methods. There are however some assumptions made that do influence the accuracy of the model. In order to further the research on LAP, those assumptions would need to be analysed further or need to be avoided entirely.

The first recommendation is to use a more accurate atmosphere model for the extinction and diffraction. Currently, these effects are represented by a singular equation based on a single constant value for the scale height. The atmosphere is very complex to study and it varies drastically over time. If an accurate real time model could be made, the simulations will generate more realistic results. Models like these do exist as daily weather data is gathered with weather stations and balloons.

The second recommendation is to model the ablative surface in more detail. Currently, there is no model for heating of the propellant or degradation of the quality of the surface. Introducing a study on the behaviour of the ablative materials used can provide a more accurate result. This in combination with a thermodynamically accurate surface interaction, will increase the reliability of the results.

A third improvement could come from a more realistic ground station placement. As spoken about before, this model does not take in to account what the environment looks like. A laser station can be placed anywhere at any height. In a real situation, a station has to be placed on the ground with an infrastructure capable of providing the resources needed. This also includes power and emergency services. If the constraint that both stations are perfectly opposite of each other is still in place, that would also limit the possible locations greatly.

Laser systems keep increasing in power and performance, so another recommendation is to further research possible laser types and laser systems. This could decrease the required system size and complexity or it could increase the power that reaches the satellite. If a very large increase in arrival power is achievable, the use of aluminium as a propellant can be experimented with.

In order to reduce modelling errors, a recommendation would be to use a higher power computer system than the system used for this research. The results will become more accurate if smaller time steps are used. A higher power computer will also be able to run the simulation over longer periods of time to analyse whether other issues might come up after more than 10 years.

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A
Sensitivity analysis data

A.1. Perturbations

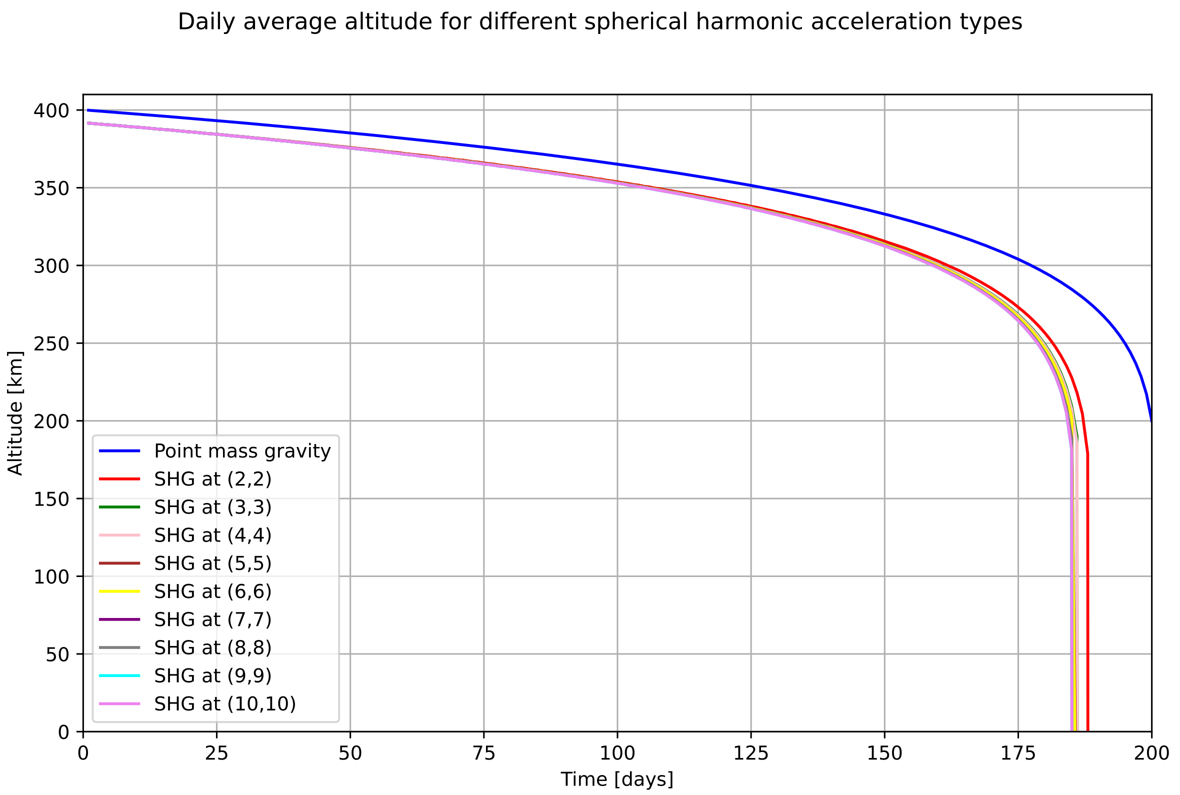

Figure A.1: Daily average altitude for different spherical harmonic gravity types of the Earth

Figure A.1 shows the altitude profile for the version of the model where the laser is not active for different orders of the Earths the spherical harmonic gravity types and the point mass gravity. Clearly, the Point Mass Gravity (PMG) approach oversimplifies the situation and extends the orbital lifetime of the satellite. It is assumed that the higher the order, the more accurate the perturbation is, but this comes at the cost of computational load. The (5,5) approach is almost indistinguishable from the higher order terms, so it is found to be accurate for this model.

A.2. Laser elevation activation parameters

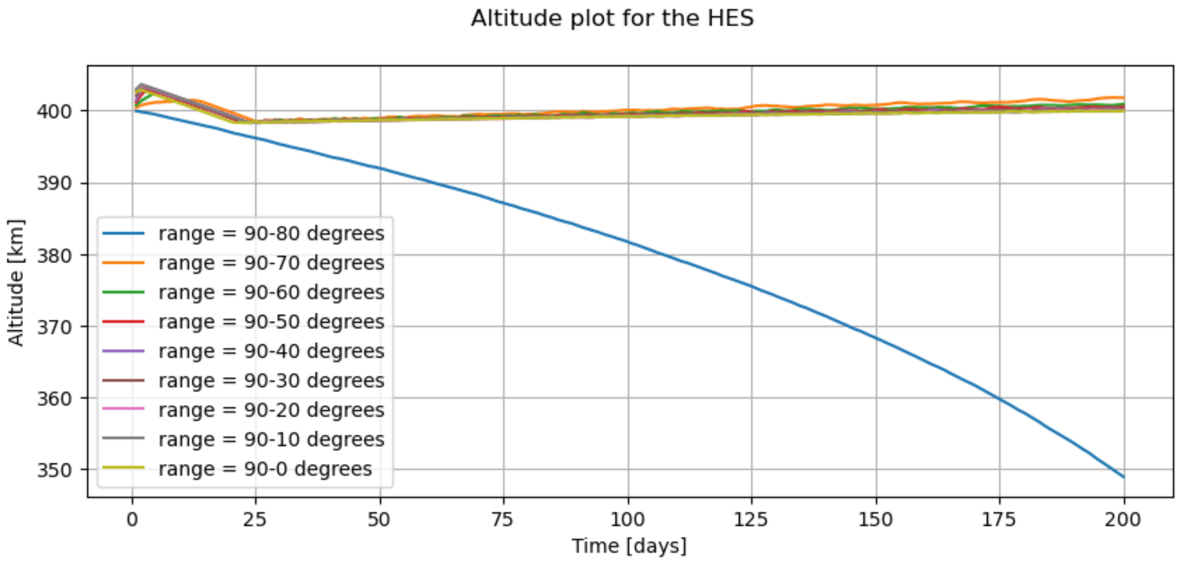

Figure A.2: Altitude data for HES

Figure A.2 shows the daily averages of the data gathered for the different HES ranges. The 80-90 degrees range clearly is not able to maintain a stable orbit. The other ranges can keep the orbital altitude stable.

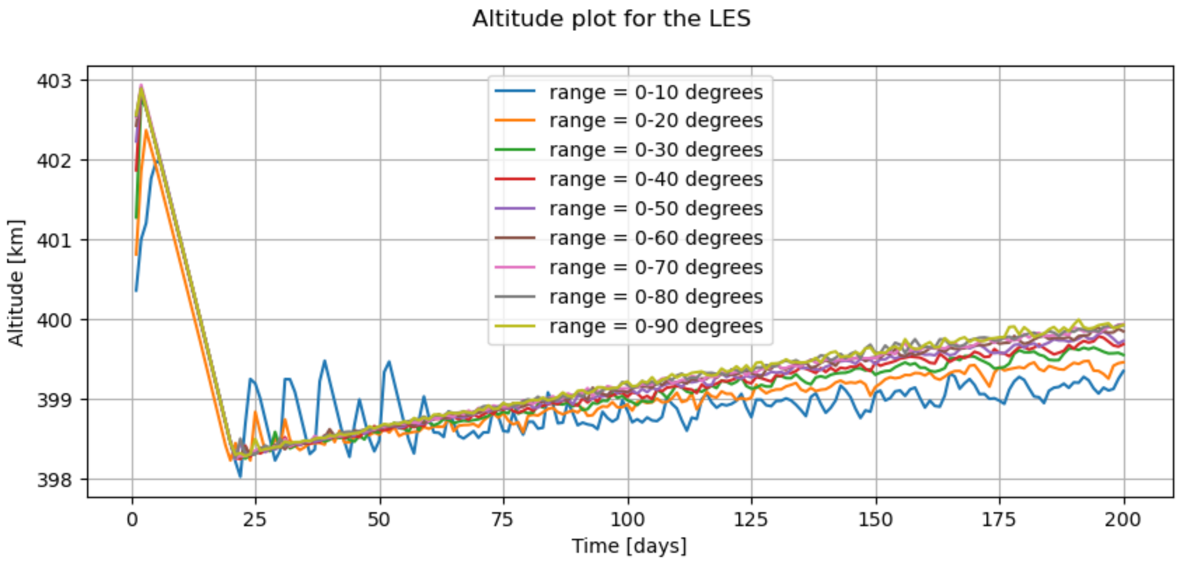

Figure A.3: Altitude data for LES

Figure A.3 presents the results for all of the LES ranges. as can clearly been seen, all ranges can support the orbit after an initial period of instability.

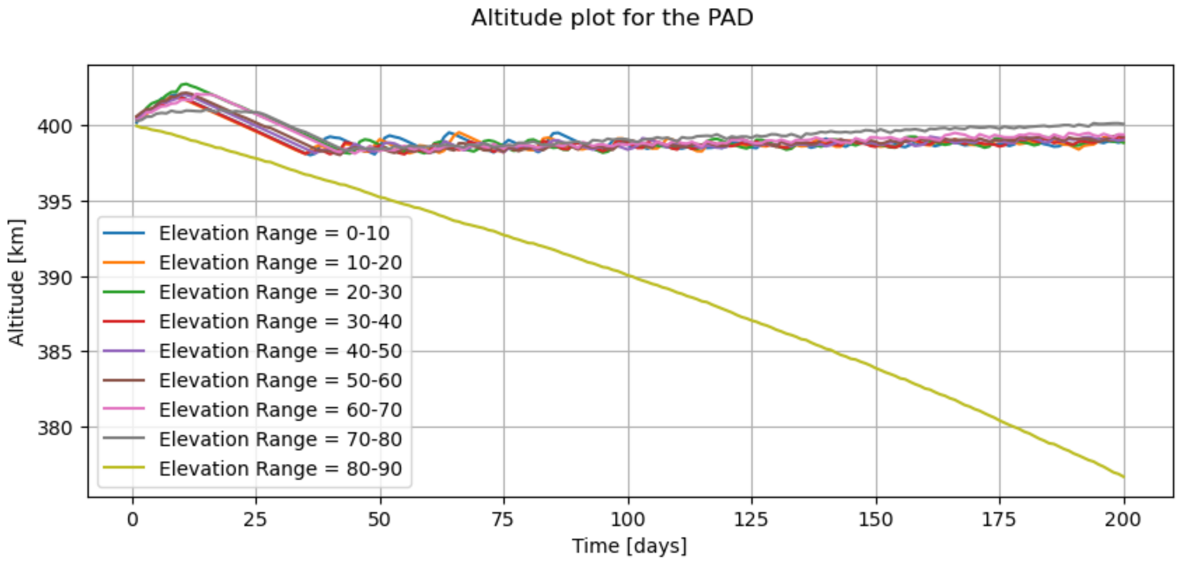

Figure A.4: Altitude data for PAD

Figure A.4 shows the altitude data for all of the PAD ranges. similarly to the HES case, this figure shows that the 80-90 degrees range can not maintain the orbit. All of the other 10 degree ranges work for the analysed orbit.

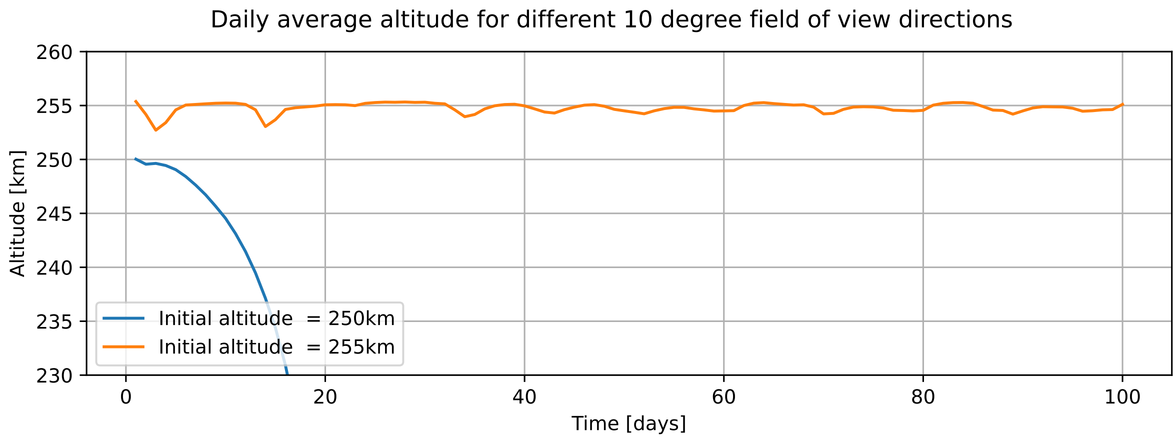

Figure A.5: Altitude data for 0-90 degrees elevation range

Figure A.5 shows the ultimate limit of the LAP system when the entire elevation range is available. This version of the system is capable of maintaining an orbit at 255km.

A.3. Ground station parameters

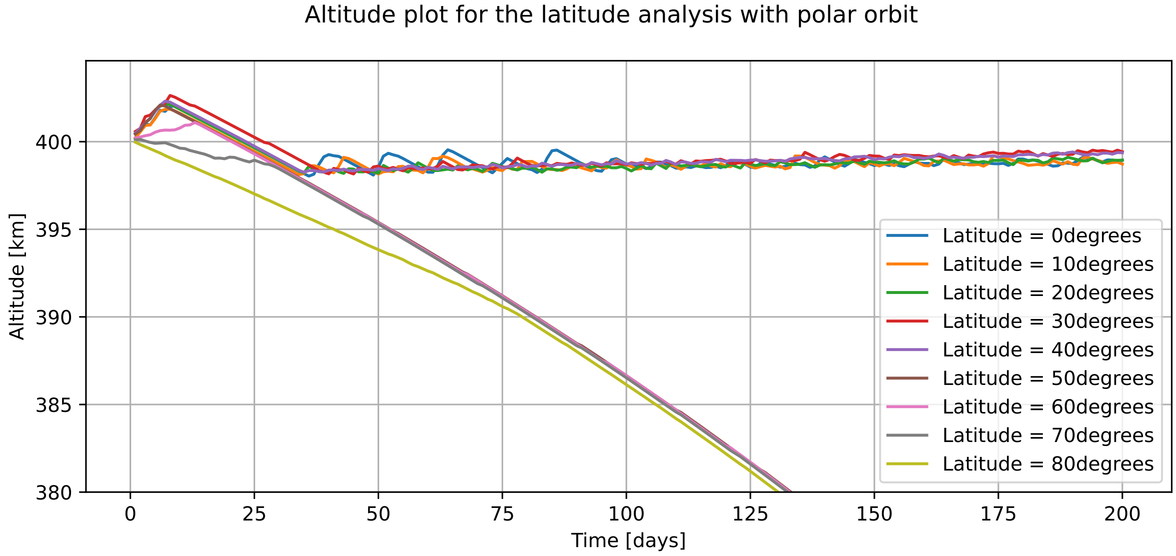

Figure A.6: Altitude data for the latitude analysis

Figure A.6 shows the altitude trends for different ground station latitudes, with the longitude at 0. For latitudes of 40 degrees and higher, the orbit deteriorates after a while, so these values are not suitable for LAP.

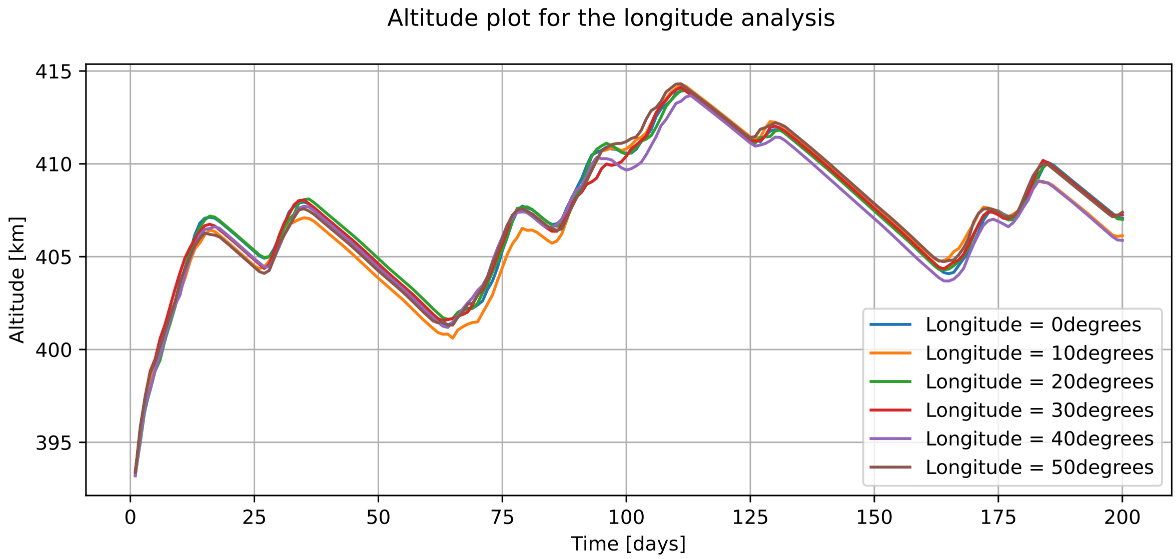

Figure A.7: Altitude data for the longitude analysis

Figure A.7 shows the altitude data for the different longitudes. Because all of the options show a maintainable altitude, all longitudes can be used for the laser station.

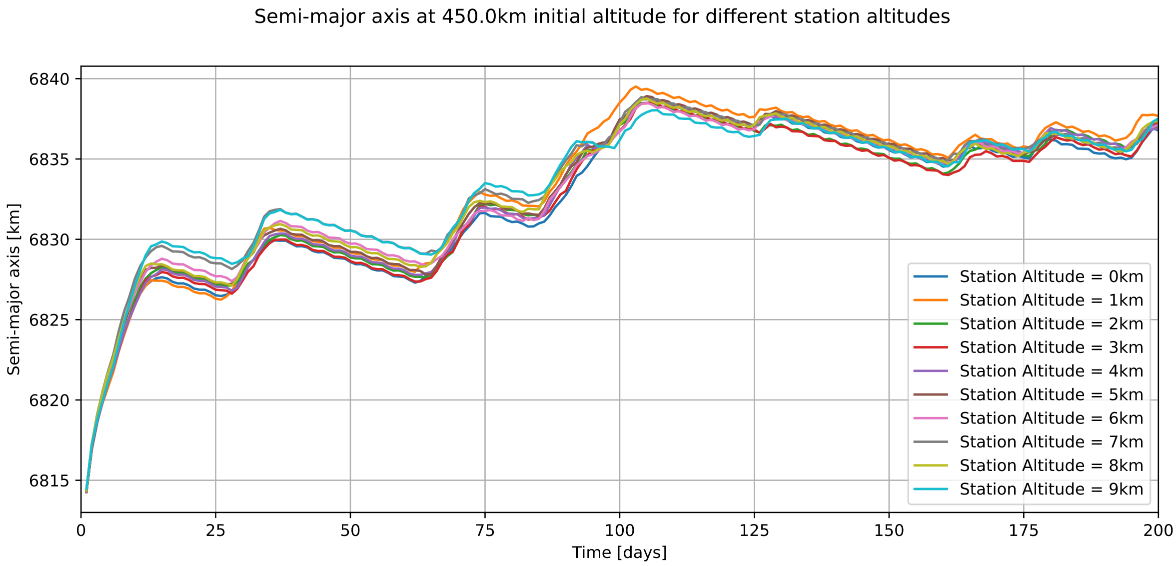

Figure A.8: Semi-major axis data for the station altitude analysis

Figure A.8 gives the semi-major axis output for different laser station altitudes. Similarly to the longitude analysis, all of the researched options are viable altitudes for the station.