BACHEROL THESIS

Simulation of space launcher trajectories

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1. Purpose, Tasks, Planning and Motivation

1.1 Purpose

The present project will simulate a space launch vehicle trajectory for given launcher and external conditions. It also will give an optimal solution for this trajectory when trajectory parameters are not fixed.

1.2 Tasks

- To develop a launcher trajectory simulator in MATLAB environment.
- To implement launcher external and vehicle models to have a realistic environment with the accuracy required by the simulator.
- To validate the simulator with a real trajectory mission of the Ariane 5 [1].
- To develop an optimization tool in order to optimize a not defined Low Earth Orbit trajectory for a given launcher.

1.3 Project Planning

1. Firstly information about the launchers trajectory problem was looked for, as well as other similar software[1] that tries to solve the same problem.
2. Secondly the launcher simulator software was developed in MATLAB. This task was carried out together with the third task in the planning.
3. Apply proper performance and environmental models[2] to the simulator.
4. The software is validated with an Ariane 5 mission. Source [1].
5. Optimization problem of a given trajectory is solved using Genetic Algorithms.
6. Results and software architecture is reported.

1.4 Motivation

The project was worked out on this topic due to the interest of the author in space field, in particular in space dynamics. The development of this project was an opportunity to increase the space knowledge of the author and to go deeper in space challenges.

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1 See module 6.2 (Other References) "Existent software: Launcher Trajectory Simulators".
2 See 3.3 (Models section).

2. Introduction

The space has been typically a natural barrier to humanity till the last fifty years. Before space technology was available the capacity to explore and understand the world was mainly limited to those things that could be studied in the Earth.

Since the first satellite put into orbit (Sputnik 1 in 1957) many developments have been made, allowing nowadays to use largely spatial knowledge in many applications, for civil use like GPS, TV satellites and in general many applications in the communications field. It also allowed a huge improvement in the possibilities to know and to understand the Earth as well as the window we have in order to understand the space and the universe from its beginnings.

Many other applications are also important, like military applications, the experimental field that the space represents for new technologies, behavior of human and animal bodies in spatial environments (no gravity, higher radiations than usual…)

Because of those things the space field has been for more than fifty years a strategic area of research and technological development for all countries in the world[3]. Of course in order to do space activities real the first step done was to be able to launch technology and human resources to space (firstly to put it in orbit, and finally to be able to send it to outer space).

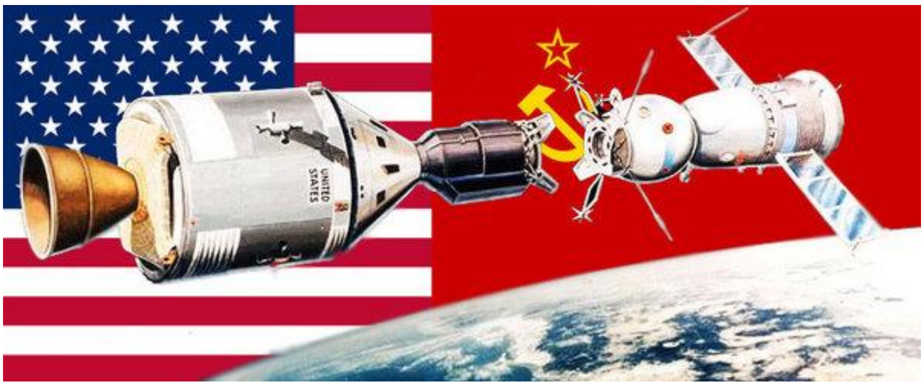

Figure 1. During the Cold War a great development in space technologies was performed. Source: TrinityP3.

[3] Remember the Cold War and the Space Race between the US and the USSR in the sixties and beginnings of the seventies.

This technology has been able to be sent to space by the use of launchers, they are basically the technical means used in order to put some payload out of the gravity attraction force. This payload can be kept into an orbit around the Earth, go to other satellites or planets, or explore other areas of the Solar System or even beyond.

So, thinking about it, we realize the key importance of launchers not only in space developments and challenges but also in many discovers in other fields (medical, biological, physics, materials science, etc) that have been made thanks to the conquest of space.

Launchers, as the reader can imagine, are still one of the opened issues in space developments. The payload a launcher can carry nowadays per the total mass of the launcher is still very low; we are talking of an order of magnitude of 1/50 for LEO or 1/120 for GTO[4]. So the optimization of the launchers and the trajectories those launchers must follow to put material in orbit are very important.

Although there have been many studies related to this topic (launchers trajectory optimization) due to its importance it was thought by the student it could be a very interesting topic from which the student could improve its technical abilities, be familiar and start understanding one of the main activities related with the space field nowadays.

2.1 General Context

Once it was seen the importance of space launchers in the space development it will be seen briefly which are the space areas in which the improvements in the launchers and launchers trajectories are important nowadays.

First it will be seen a bit of history. Initially, in the sixties the space challenges were to be able to develop launchers and to optimize launcher trajectories that allowed in an efficient way to put satellites in orbit. The first objects sent still were not too heavy however the propulsion system improvements and the development of successful trajectories were required.

In following years it was required to send heavier and larger payloads out of gravity attraction, so optimization of launchers (architecture, stages, trajectory, etc) was crucial. Rapidly the idea was not only to send satellites to be put in orbit, but also animals and finally humans inside. Also the missions became more complex requiring not just to keep objects moving around the Earth but to go further developing new trajectory concepts and finding out some interesting ideas to reach very complex projects (as ambitious as the Apollo program, which lead to the landing of humans on the Moon).

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[4] We are talking about kg of payload per total kg launched, where LEO means Low Earth Orbit and GTO means Geostationary Orbit.

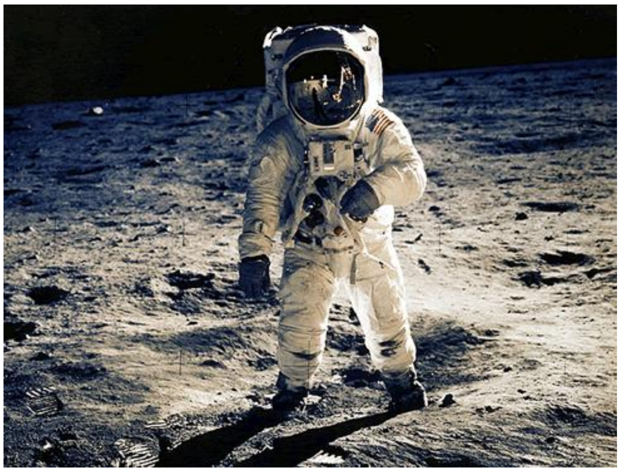

Figure 2 and 3. The Apollo program (and its rockets) allowed one of the greatest humanity achievements. Source: NASA.

The objectives today have in general more commercial purposes; they are in many cases privately financed so the fuel saving aspect is basic. The trajectory launchers problem has not an analytical solution, because all the external changing variables entering in the problem. It has been studied along many years and numerical approaches have been reached. It is important to remember that although optimal trajectories are used the behavior of the models is used can change a lot with reality, for instance atmospheric model.

The general solutions that are used nowadays will be briefly pointed out in section 2.2.3 (Launchers State of the Art) and later when talking about the Launcher Trajectory Definition (Section 3) software developed.

2.2 Launchers

Once it was presented the field in which the launchers are mainly used[5] our attention is focused on the launchers themselves. A brief introduction to its history will be made and latter on the state of the art in this field will be slightly touched.
As it was said in previous section, the space launchers started to be important when the Space Race started in the beginnings of the sixties, however, sometime before the first long range launcher trajectories started to appear also in the military field.

[5] It is important to remark that launchers are also used in other applications, for instance in military applications talking about long range missiles in which the accuracy of the trajectories is one of the most important aspects. However in the present document the student will focus only on space launchers.

However, if it is been considering the rockets as the precursor of space launchers the first rocket known came from China around 1200 A.D., it was the first time the idea of creating a flying object with its own propulsive system inside that basically flies due to the thrust provided and not by other mean.

If we go directly to space launchers it is needed to go much closer in time. Before space launchers appear, there were a few scientifics that actually believe space travels were possible, in this matter some of the pioneers were the American Robert Goddard[6], the German Hermann Oberth[7] and the "father of astronautics" the Soviet Konstantin Tsiolkovsky.


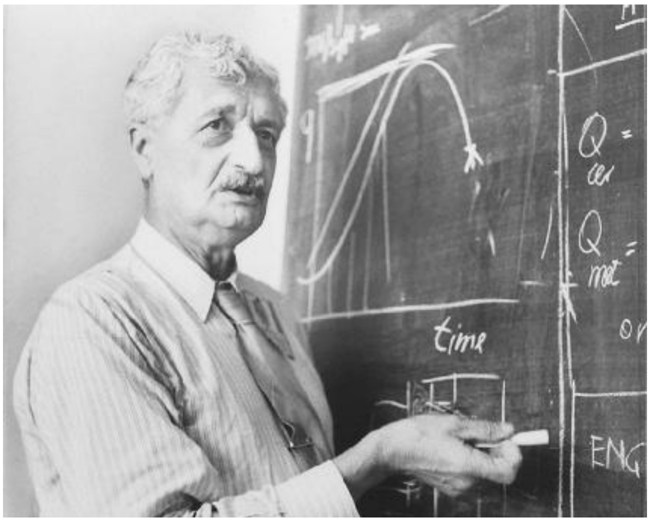

Figure 4 and 5. First pioneers in the study of rockets like Wernher von Braun and German Hermann Oberth made amazing achievements before even rocket vehicles were possible to be built. Source: Smithsonian Air and Space Museum and Urbana High School respectively.

Following the ideas of engineers and physicists advanced to its time the first liquid-propellant rockets were developed[8]. It was a key step, because in this way the rocket could carry both the propellant used as fuel and the oxygen required to burn (allowing future space missions were no oxygen is present in the environment).

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[6] He was ridiculed when he wrote in 1919 that with the help of rockets would be possible to reach the Moon. However he started to build rockets based on the principles later on took human to the Moon.

[7] He was a German physicist that in the beginnings of the nineteenth century started to study the possibility of interplanetary travels.

[8] It is important to notice the fact that the first liquid-fueled rocket was firstly launched in 1926.

Later on, the first rocket reaching the space was developed by Germans in 1942, it was the rocket V-2, from this moment on many experiments were carried out mainly by the Soviet Union and the U.S. but it was not till 1957 when the first successful orbital launch[9] was made by the Soviets, the same year the first animal was sent into space also by the Soviet Union.

Next years were very important in the development of space technologies and particularly launchers, because it was rapidly required to send to space heavier and larger payloads. In fact during next years (in Cold War) incredible advances came on, human in space, landing into the Moon and all those achievements were completed mainly due to the improvement of space launchers. It is important to mention here some launchers that were fundamental at that moment of the history; the Saturn series with which the Americans arrive to the Moon, other important American launchers at the time were the Vanguard, the Thor-Agena and the Atlas, the Delta or the Titan series. Those modern rockets that allowed first contact between human and space were based on the German V series[10].

The German rockets were also the base of the postwar launchers of the Soviet Union, the series called A, B, C, D and G (also called Proton). They carried with the first satellites in orbit.

Years later, when the space exploration was in a peak the idea of doing (partial) reusable rockets came in. It produced the space shuttle program to start. Although the space shuttles are not rockets (they are put into space thanks to a main rocket and two boosters) they are like space vehicles that can "glide" (quite bad gliding performances but after all it glides) to safely launch when they return to Earth. Its development was remarkable to do space flights more costly effective.

Forgetting the world of space vehicles and returning to space launchers, it is a must to mention the existence of launchers from other space agencies (than the NASA and the Soviet/Russian agency). In this field the Ariane rocket series from the ESA agency is probably the most important family of rockets made, although other countries like China, Japan and India have also developed its own launchers.
The Ariane 5 rocket will be the rocket chosen to validate the code developed during this project; it is so because specific data of the European rocket was easier to be found. The Ariane series have developed 5 rockets till Ariane 5 (the only in use nowadays), and the development of the new rocket, Ariane 6 is supposed to finish in 2021 or 2022.

9 The rocket R-7 carried the satellite Sputnik 1 which orbited the Earth at a height about 250km.
10 It is compulsory to mention here the immeasurable work of Wernher von Braun in the development of the first rockets (as missiles) in the WWII.

2.2.1 Launchers Context Nowadays

Today there is a changing tendency in the development of rockets because it is starting to be not only a matter of governments or governmental associations, but also private companies are starting to develop its own launchers. In fact the first private launch of a capsule orbiting the Earth was made on 2010 by the company SpaceX, which launched the Falcon 9 rocket.

Moreover the national agencies are thinking about changing the typical model of rocket to a full reusable one. In fact, since the space shuttles became retired the NASA is looking for the next generation of both launchers and space vehicles it will use.

2.2.2 Space Legal Framework

The legal framework in charge of space cases is still not well defined due to it is relatively new. The basis of the international space law is collected in the so called Outer Space Treaty, although there are many countries that still not signed it.

In the Treaty some principles are stated, between them the use and consideration of space activities as pacific activities, the fact that any country can claim celestial body or space area rights and for the case of interest for us, launcher case, some points are considered in the Treaty. Mainly they are safety considerations during launch and reentry, limitation of dangerous activities and restrictions to perform launches and spatial activities under particular conditions far from populated areas.

In the following years the space law will start to be important if the amount of launches and space activities continue increasing as expected.

2.2.3 Launchers State of the Art

Launchers state of the art? Maybe the reader can think no more research on launchers can be going on, however in the last years some interesting and important improvements are been carried out, the main idea for future launchers is to get fully reusable rockets, for doing that it is not only important the trajectory it describes during take-off, but also the trajectory and the control system to safely land all the different parts and stages of the rocket[11].

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[11] Interesting video of some tests carried out by the company SpaceX while developing a fully reusable rocket, the Grasshopper which is a Vertical Takeoff Vertical Landing (VTVL) vehicle designed not only to support reentry but also to return and land safely in the launch pad. https://www.youtube.com/watch?v=eGimzB5QM1M

It will be probably the future of space launchers due to the saving in costs need to accomplish the next step in space exploitation and to make space flights not only for governments investing billions of dollars but also to private companies in order to take advantage of the huge bunch of possibilities the space gives humanity.
In this way, maybe the recent future will be to improve reentry trajectories and reentry control of the different stages of the rockets.

Figure 6. Falcon 9, first private funded spacecraft in launch, orbit and be safely recovered. Source: SpaceX.

It is important also to remark that in next centuries it is not only expected the exploitation of Earth orbits, but it is thought in more ambitious space flights to get permanent bases on the Moon and even on Mars. Those larger and more complex trips imply other problems in trajectories and optimization developments and also in many other areas as biological issues. However and because those future issues are still not real, it will not be gone further on them.

3. Launcher Trajectory Definition: Architecture and Implementation

In this section the working principles of the simulation program will be explained, also the basic physics the code simulates will be covered. This section tries to clarify the way both the simulation and the implementation in MATLAB was done and why the decisions took in each step were made.

3.1 Introduction

This introduction covers the way in which the trajectory of a launcher is defined given a closed problem with all the launcher characteristics given. So the task in this part is to solve the equations that define the motion of the launcher as well to simulate properly the environmental characteristics that affect the launcher behavior.

3.1.1 Objectives

The objective of this subsection is to define and simulate the trajectory of a launcher once the parameters of the launcher are given. In order to do that the aerodynamic characteristics, the weight of the launcher, the thrust the different rocket engines provided are given. It is also required to take into account the environmental conditions that will be around the launch, gravity field, atmospheric conditions (density variations, maybe wind is present).

In this phase of the project the control conditions of the rocket are imposed. It means all the staging of the launcher will be fixed; the different stages will not be optimized, so they are imposed. The thrust applied on the launcher is given externally as well and the motion of the control surfaces is not optimized.

So, the definition of the trajectory without unknown variables is required. It will allow us in further steps to optimize the trajectory that will be computed with the code developed in this module 3 (Launcher Trajectory Definition).

Three tasks are important in order to determine the trajectory:

- The determination of environmental models; in particular the field gravity model and the atmosphere model.
- The definition of the dynamics of the launcher and the development of a code that solves the state the space launcher.
- The use of control parameters from a real case data.

They will be explained one by one:

Environmental models

As it was said, environmental models have to be defined, in particular, the gravity field model, whose variation will be initially defined by the square of the launcher distance to Earth's surface. Later on finer models will be directly used in order to study the impact on trajectory accuracy. It will allow analyzing which will be the optimal model required to be used in terms of accuracy and needs in the project (also in the further optimization development).

The other ambient model required was the atmosphere model (our particular interest is the density variation) will be taken from different sources and the student will determine which model fits better with the given needs of the project.

Launcher dynamics

The dynamics of the launcher vehicle are defined by the state of the launcher at each point. In order to get a state that defines completely how the model is behaving it is needed to have velocities in two different directions and positions in those directions (or other two different). It is true because it has been assuming the launcher moves in a plane (2D motion), because the ideal trajectory is expected to be in 2D.

However, not only the velocity and position parameters are required to define the state of the model, it is also needed the mass of the model at each time. For solving the state of the launcher the equations of motion of the model has been set and solved. It will be explained later on in chapter 3.2 where the implementation of the models in MATLAB is explained.

Control Parameters Data

The control parameters of the launcher will be more important in module 4 (Launcher Trajectory Optimization) of the work, however, in this part, they are just given parameters.
It is important to distinguish between the thrust control parameters and the aerodynamic control parameters.

The thrust control parameter determines not only the thrust the rocket produces at each time, but also the duration of each stage. So, how much time this amount of thrust is acting on the launcher and the direction in which this thrust is acting, it is defined by the angle v between the velocity and the thrust vectors. For the trajectory definition case, this data will be taken from the Ariane 5 User's manual [1], so it is determined and we simply define the given trajectory.

The aerodynamic control parameters have to be taken into account. They basically are the deflection of the control surfaces to have aerodynamic forces[12]. However, in this project they would not be taken into account because the data that could be found about them where to rough, so it was preferred to fully control the launcher model with the thrust model. In this way mainly the module 4 of the trajectory optimization will be much easier to solve because it is only needed to apply optimization techniques to the thrust parameters.

3.2 Dynamics Implementation

In this section the way each part of the software was developed will be described, also the physics behind the software will be briefly pointed out along this part of the report.

The most important part of this project is the correct dynamics definition of the launcher. The problem will be faced with some references that can be found on section 6.1 of the report (Main References).

3.2.1 Assumptions

The different assumptions taken to model the launcher will be pointed out and explained below:

- Inertial Forces are neglected

It is important to notice at this point that the inertial forces due to the rotation of the Earth will not be considered in the model. It is because they can be neglected in an initial approximation of the model[13]. However in order to compute the “ground position” (position of the satellite with respect to the Earth) the rotation of the Earth will be accounted in the position calculation (not in the forces model).

- 2D motion of the body

The launcher is supposed to move in a 2D plane. It has been done in this way because the trajectory of a launcher is mostly defined in a 2D plane, unless the launcher has to go over a populated area (in those cases a maneuver to avoid such places is made).

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[12] In the case of launchers what it is basically done is to control the angle of attack of the body.

[13] The launcher is modeled in this way because the optimization approach that will be performed in the second part (using genetic algorithms) would be an approximation for an early stage of the design, so no too accurate results are required. Moreover the fact that the inertial forces can be neglected for a first approach is justified in Chapter 1 of [7].

It is because of that the launcher is only defined in 2D assuming the body does not move in the third direction, to avoid undesired motion in other planes slight thrust and aerodynamic corrections are made (those corrections are assumed and they are not going to be considered, not in the model nor in the optimization).

- Attitude parallel to velocity vector

This assumption will be made at least during low atmosphere phases, because if it is not true aerodynamic forces become quite complex, unsteady and stability problems can appear. In fact this assumption is pretty realistic because in real missions during those phases where density is still significant for launcher performance (below 70km approximately) one of the main rocket enemies is drag (together with gravity) and it is tried to be reduced as much as possible using a rocket aerodynamic shape and pointing it in launcher velocity direction.

3.2.2 Launcher State Definition

Once those assumptions have been explained, the way in which the state of the body is expressed will be defined. Initially the problem is stated by defining the launchers position and forces that will be acting on it.

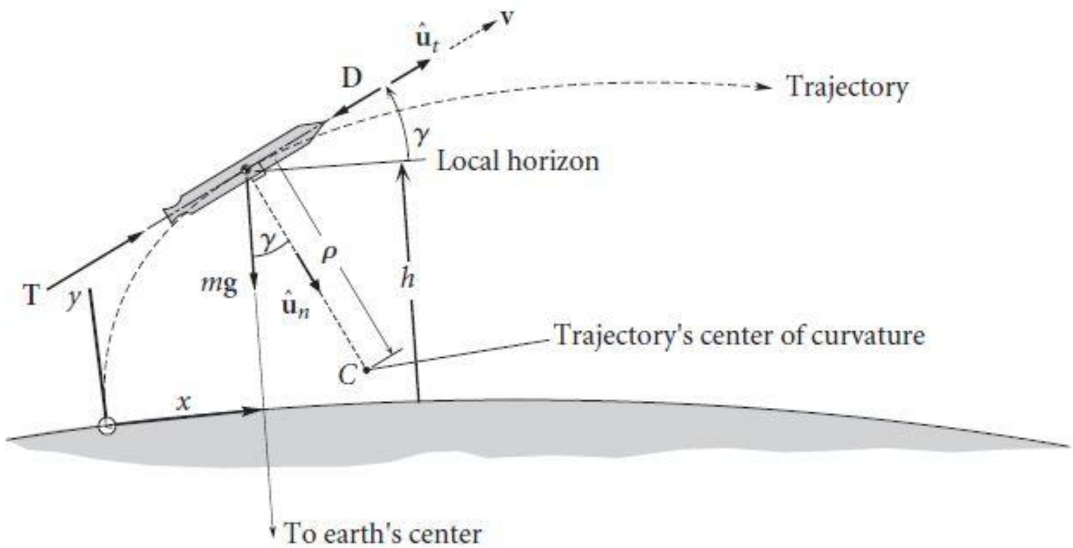

Figure 7. Launcher state parameters and forces. Source: [2].

The above figure 7 will be used to show the variables that will be used to define the state of the body; the launcher will be fully defined by 5 parameters, the two positions in the directions of the 2D plane, and two more variables that fully defined the velocity vector of the launcher. As well the mass of the launcher at each time is required to define properly the forces acting on the launcher. Below they are explained:

- X position, it defines the horizontal position of the launcher with respect to ground horizontal x axis, as it is shown in the figure 7. It will be around a 10% the of the height (y position) during the initial phases of the launch (before orbit insertion).

- H height, it determines the y position of the figure 7, so y position with respect to ground.

- V velocity, the velocity of the launcher will not be split into components but the modulus of the velocity will be expressed as a parameter (v) and the direction of this vector would be expressed with an angle gamma explained below.

- ɣ angle gamma, it provides the direction of the velocity vector of the launcher, as it is shown in the figure 7. It is important to remark that ɣ is defined in a way that whenever the launcher is pointing up (before launching) the angle gamma is π/2 and while the body is orbiting the ɣ is zero. Do not mistake between direction of the velocity vector and attitude of the launcher[14].

3.2.3 Launcher Equations of Motion

In this section the basic physics that are applied to solve the problem are described.

In previous section the state variables were defined, now it will be seen how those variables change in time. At this moment the equations of motion of the vehicle have to be defined, so the forces and accelerations acting on the vehicle at each moment or time are set.

Accelerations on each of the vehicle directions:

- Acceleration tangential to the velocity of the launcher, it will be called a_t and it is simply the derivative o f velocity with respect to time.

$$a_t = \frac{dv}{dt} \tag{1}$$

- Acceleration normal to the velocity of the launcher, it will be called a_n and it is defined using the angle ɣ defined in figure 7. It will be much smaller than the tangential acceleration, so it can be defined as follows after the change of ɣ with respect to time is considered small.

[14] Velocity vector indicates where the vehicle is moving to while the attitude indicates where the spacecraft is pointing to. They are usually different in outer space, while in the dense atmosphere they are kept almost equal to reduce as possible aerodynamic drag.

$$a_n = -v\frac{d\gamma}{dt}$$
(2)

However, once the curvature of the Earth is taken into consideration an additional term has to be added[15] giving finally the next expression:

$$a_n = -v\frac{d\gamma}{dt} + \frac{v^2}{\Re + h}cos\gamma$$
(3)

Once the accelerations in the two directions in which the launcher will move are defined, it is helpful to develop a forces diagram in order to obtain the equations of motion of the launcher, both together with the above describe accelerations and with the forces analysis performed below.

$$ma_t = T - D - mgsin\gamma$$
(4)

$$ma_n = mgcos\gamma$$
(5)

As it can be seen here the controls are not taken into account, in case they were accounted in the analysis they should be included both thrust control (v angle) and aerodynamic control which would be defined by the lift produced due to some angle of attack of the launcher and the lateral forces that the aerodynamic surfaces can produce on the launcher.

$$\frac{dv}{dt} = \frac{T}{m} - \frac{D}{m} - gsin\gamma$$
(6)

$$v\frac{d\gamma}{dt} = -\left(g - \frac{v^2}{\Re + h}\right)cos\gamma$$
(7)

Below, the equations to account for the launcher controls are shown. Although they will not be used directly in this project, they allow generalizing the problem and in the future launcher controls can be applied using the same MATLAB code.

$$\frac{dv}{dt} = \frac{Tcos(\mathrm{v})}{m} - \frac{D}{m} - gsin\gamma$$
(8)

[15] See Section 1.6 of [2].

$$v\frac{d\gamma}{dt} = -\left(g - \frac{v^2}{\Re + h}\right)cos\gamma - L - Tsin(\nu)$$
(9)

Where the lift would be:

$$L = qA_{front}C_L$$
(10)

Being q the dynamic pressure A_{front} the front area of the launcher (the area accounted if the launcher is seen from the top) and the lift coefficient been defined by using a coefficient to account for the change in angle of attack:

$$C_L = C_{L\alpha}\alpha$$
(11)

Of course the parameter and the effect more difficult to estimate is the angle of attack effect due to the difficulty to take an estimation of$C_{L\alpha}$.

Here it is important to remark the launchers trajectory problem can have many improvements to do it more realistic and accurate. The project is intended to be a first approach of the problem, because it is a general approach it was intended to solve the problem and implement the software code as general as possible in order to allow future improvements.

One of the most interesting cases to simulate that will not be covered is to set the control parameters required to control the launcher trajectory as desired. It was not covered in this report because no enough information about the control characteristics, aerodynamic surfaces and thrust control dependence was available. However in the future the launcher simulator could be improved by adding those characteristics, because the equations and the motion of the launcher already take into account controls (although they are not used).

Using the equations of motion, (6) and (7) together with the kinematic relations for the height and the horizontal position (the variables that determine the position of the vehicle at each time) is possible to close and solve the problem of state of the vehicle. In this way the system of differential equations is solved using ode45 in MATLAB (because no stiff function problems appeared). To completely define state of the rocket the mass has to be considered, in fact it will enter in the equations of motion inside the weight.

The two coordinates of the position with respect to the Earth are simply solved by using the kinematic relationships; see equations (12) and (13).

$$\frac{dx}{dt} = \frac{\Re}{\Re + h} v cos ɣ \tag{12}$$

$$\frac{dh}{dt} = v sin ɣ \tag{13}$$

While mass equation is simply defined as the thrust over the specific impulse, specific impulse will be expressed in meters per seconds to be consistent with the units. The rocket performance characteristics of the launcher in order to validate the model with the Ariane 5 rocket are taken from [1].

$$\frac{dm}{dt} = -T/C \tag{14}$$

At this point it is important to notice the difference between liquid and solid propellant rockets despite it will not be applicable for the software developed, in further optimization it should be distinguished between solid and liquid propellant rockets, because the liquid ignition can be stopped, or at least controlled, while the solid ignition once started cannot (or it is very difficult to) be controlled.

Using this idea of the different propulsion systems used depending on the different stages of the launcher it will be linked with the next section (3.2.4 Phases and Stages) in which the different stages and phases of the launches are explained. Also the performance of the launcher and the types of mission that will be simulated in this project will be explained.

3.2.4 Launch Performance: Phases and Stages

In this section the basic phases and stages allowable by the simulation code developed will be shown. The example case of the Ariane 5 mission used to validate the code will help to explain the way in which the different stages and phases are defined:

Launcher stages

In the following figure 9 they are shown the different basic common stages of an Ariane 5 mission:

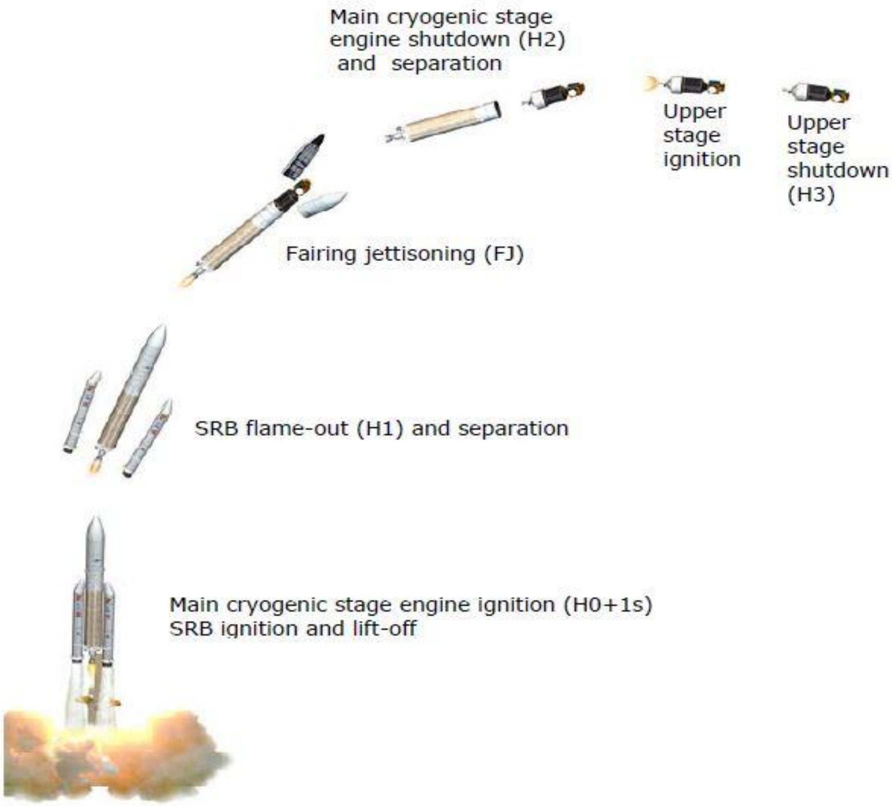

Figure 9.Launcher stages of an Ariane 5 Mission. Source: Ariane 5 User Manual [1].

Just to notice, fairing jettisoning[16] stage has not been considered due to the lack of data about how it would change launcher characteristics in the Ariane 5 case that was cover in this project.

The software developed allows us to simulate a launch system with the stages desired, just by setting the aerodynamic configuration of each stage, the thrust the launcher system provides, weight characteristics and fuel consumption of each stage and the time the stage needs to burn out.

In order to validate the code the stages of an Ariane 5 mission have been simulated. The Ariane 5 is a rocket with two stages[17], for easier stage identification in the code developed, because the conditions change it will be said the rocket has three stages:

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[16] The fairing jettisoning is the process by which the fairing (nose cone) that protects the launcher payload is removed to reduce the weight of the remaining body. The fairing protects the payload from the environmental conditions, temperature, wind, etc It also improves the aerodynamics of the launcher.

[17] Although the Ariane 5 rocket only has two stages, it has to boosters that are burned out before the first stage is finished. It is why from now on it will be said the rocket has three stages (the first "boosters + main stage" stage and the two actual stages).

1. Boosters + Main stage. The first stage starts at time zero (H0 in figure 9), when the launcher leaves the ground. In this stage two boosters P238 carrying solid propellant provide the main part of the acceleration of this stage. They are fixed to the main stage.

   The main stage (cryogenic H158) carries liquid propellant and the engine it uses provides a twelfth of the force the two boosters provide together (see table 8).

2. The second stage of the rocket has been defined as the part of the launch in which the only propulsive system active is the main stage engine. It starts once the two boosters are discarded, H1 in figure 9.

3. The third and in the case of the Ariane 5 the last stage starts once the main stage burns out and it has been discarded, H2 in figure 9. Then, the engine of the upper stage, an Aestus engine, provides the propulsion required. Both the thrust it provides and the fuel this stage carries are much less than for the other stage as it can be seen in table 8.

	Thrust [kN]	Burn time (s)	Total mass (tons)	Empty mass (tons)
2x P238 Boosters	12100	129	562	8
Main (H158) Stage	1118	589	170	15
Upper Stage	27.54	1100	9.06	0.15

Table 8. Main characteristics of the stages and boosters of the Ariane 5 rocket. Source: Ariane 5 User Manual [1].

Launcher phases

In this subsection the different phases during a launch will be explained. These phases are defined as each interval of time in which the control law applied to the body is different.

So, it is actually how to manage the trajectory of our launcher. In order to solve this problem the typically applied approach has been used. It has been taken from [4] and [5].

Following this typical approach, the launch can be divided in the following phases:

1. Vertical ascent, it is a short amount of time (of the order of 10 seconds) in which the rocket velocity direction is vertical, without applying any rotation to it. It is done to allow rocket initial acceleration from zero velocity.

2. Pitch-push maneuver, during this maneuver the rocket direction starts to be deflected, and the angle ɣ (defined in figure 7) decreases, to point the rocket slightly to East[18]. In this way, during the following phases the rocket will continue rotating due to the action of gravity, while thrust starts to point to the East. Due to this the vehicle will enter in orbit with a ɣ angle close to zero.

3. Gravity turn maneuver, it is performed only by action of gravity acceleration, the direction of the space vehicle will change because the forces present; gravity with thrust and drag are not more aligned. It is shown in figure 10 below.

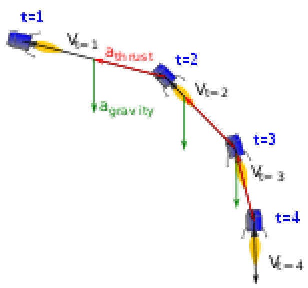

Figure 10. The gravity turn maneuver is the same as landing maneuver, where the forces are not aligned. Source: Wikipedia.org

4. Bilinear tangent maneuver for orbit insertion, a transition phase is required to achieve successful orbit insertion. The vehicle not only has to reach the given orbit height, it should be inserted with a smooth angle ɣ and with the proper orbital velocity to keep the orbit stable (to compensate gravity with centrifugal force).

Those phases are the typical applied for a rocket to insert its payload in orbit, so the simulator developed has been designed in particular those kind of missions, although it can simulate also long range ballistic trajectories, and escape trajectories, the only difference with this kind of trajectories are the conditions and the requirements each phase has to fulfill.

One of the most important parts in the simulator development was to decide the control laws the vehicle will follow at each of the launch phases, below they will be explained the control applied and a brief justification of why they were used:

1. Vertical ascent, the control law is simply to keep the rocket pointing upwards, in real life it would be achieved both by the propulsion system and the thrust vector.

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[18] During launchs the rocket are always directed towards the East in order to take advantage on the additional velocity the Earthh rotation provides to the launcher vehicle. It is also why the launch sites are usually placed near the equator, to provide the highest linear velocity to the rocket as possible.

2. Pitch push maneuver, in this phase a change in ɣ is imposed, because this change is performed in a short amount of time (the order of 20 seconds) it is assumed, see [5], the change in ɣ will be linear, so if the final angle of the maneuver and the time required for the maneuver are imposed the change in angle ɣ is fixed, following the next relation.

$$\frac{d\gamma}{dt} = \left[\frac{\gamma_{pp} - \pi/2}{t_{final} - t_{init}}\right] \tag{15}$$

Where γ_{pp} is the angle after the pitch push maneuver is completed and t_{final} and t_{init} are the final and initial times of the maneuver respectively.

1. During the gravity turn maneuver no control actions are taken. In real life corrections due to weather conditions and other unexpected changes in vehicle motion are corrected mainly using the aerodynamic surfaces of the launcher vehicle.

2. The bilinear tangent maneuver is the complex one in terms of control because its task is to leave the payload in the final orbit with the proper velocity and direction. Because in this project it is not the task to show how the controls behave, it has been assumed the changes the controls should apply are achievable, and the evolution of the ɣ angle will be defined with an optimal guidance law (16), below, which requires an uniform (or almost uniform) gravitational field to be true[19]. The idea of using this optimal guidance law was taken from [5] and [4].

$$\tan\gamma = (\tan\gamma_f - \tan\gamma_o)\frac{t}{t_f} + \tan\gamma_o \tag{16}$$

So, basically what the simulator does is to solve the state problem of the launcher vehicle for a given phase and stage of the launcher in a given amount of time. Moreover the simulator uses some models to show as real as possible external and launcher conditions.
In the next chapter the models used will be described.

[19] At this maneuver the height of the launcher is so high and the angle ɣ is of the order of less than 10 degrees. So the assumption of a nearly uniform gravitational field is reasonable.

3.3 Models

In this section the models used both, vehicle models (thrust profiles and aerodynamic model) and external models (gravity and atmospheric models) will be explained.

The advantage of the simulator developed is you can change the model you want and its accuracy with no changes in the code, just by adding the call to the new model and changing the parameter that tells the simulator which model has to change. It was done to try to have the launcher simulator as general as possible, to be used in the future for other purposes different for the ones of the project[20].

3.3.1 Rocket Models and Performances

Thrust Model

The thrust model of the launcher is basically the data required to know the following parameters at each of the stages of the launcher:

- Thrust profile at each stage
- Specific Fuel consumption of each stage
- Burn time of the stage
- Mass of the empty stage
- Total mass of the stage
- Way in which the stages are used (Maybe at the beginning the boosters are burnt together with the main stage, or not…)

In order to get real data about the thrust profile of the Ariane 5 rocket. It was needed to get it from the User Manual. In case it was desired to simulate the trajectory of other kind of rocket at least a first approach of these values has to be handled, because the trajectory will be completely different with small changes in those parameters[21].

Even for the different configurations of the same rocket (like the Ariane 5 in this case) the differences in thrust parameters lead to very different trajectories.

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[20] Maybe in the future it will be desired to use this simulator as a low height ballistic simulator. Probably in this case the aerodynamic model will be changed because aerodynamic effects are more important along the whole trajectory.

[21] The reader has to think that a small change in the first phases of the launch will have an important relevance in following phases.

Figure 11. In this figure the three propulsive systems of the Ariane 5 are shown. Source: Airbus Space and Defence (former Astrium) website.

In figure 11 the propulsive systems (engines and tanks) of the several types of Ariane 5 rockets are clearly distinguish. On the sides the two boosters clamped to the main stage and on the upper part the different available configurations for the upper stage of the rocket.

Launcher Aerodynamic Model

The aerodynamic model of the launcher is maybe the model with the highest error of the four. It will return the drag force the launcher will support, when you provide atmospheric conditions (density parameter) and vehicle characteristics, velocity and aerodynamic parameters (drag coefficient and frontal area of the launcher).

The value of the drag coefficient is very difficult to estimate, so it is usually obtained with models and experiments and later refined with missions of previous launches. Because of those reasons, in this project it will be used directly the value of the effective area, an estimation of the frontal area (see figure 12 below) times the drag coefficient. The effective area of the Ariane 5 at each stage has been taken from [1].

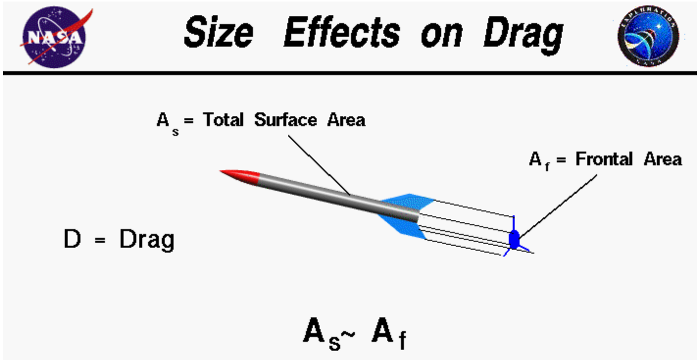

Figure 12. Frontal area22 of a rocket, measured in meters. Source: NASA website.

Finally the aerodynamic forces are computed as follows:

$$D = A_{eff} Q \tag{17}$$

In (17) Q stands for dynamic pressure. The lift is considered to be zero because the aerodynamic controls deflections are assumed to be zero and the attitude of the launcher is considered parallel to the velocity vector at all times.

3.3.2 External Models Used

Below and initial approach of the external models that affect the rocket will be proposed.

Atmosphere Model

The atmospheric model will be more important for the initial phases of the launch, where still density, so drag, is important terms in the equation.

The atmospheric model finally implemented is the typical approach used in aeronautical applications. So it is assume it is valid for our case in which atmospheric conditions are less (although still important) than for aircraft analysis.

[22] It simply measures the area the air in front of the rocket "is seeing", if the angle of attack of the rocket is not zero, the frontal area will increase.

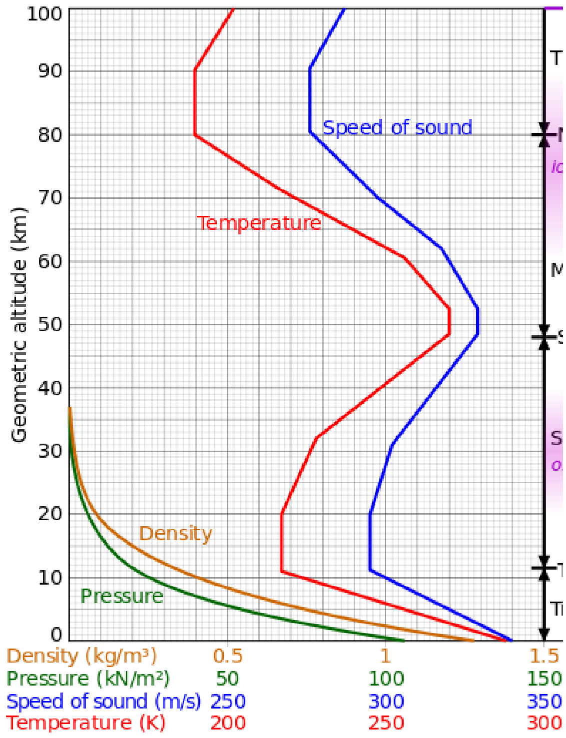

Figure 13. Standard atmosphere model. Source: Centennial of Flight Commission.

In figure 13 it is shown the approach used in the simulator. Initially only the density parameter was required however for more accurate simulations other atmosphere characteristics could be considered.

Gravitational Field Model

The model to simulate the gravitational field of the Earth has been taken from a model of other student of this university (See References). However although the model was used, it required the longitude and latitude position of the launcher (which still have not been validated). Because of that, a simpler model has been implemented.

It is intended to be changed by a more precise model (but longitude and latitude of the launcher are still not validated) so the model used for gravity acceleration increases this one with the square of the velocity as it is expressed below in equation (18).

$$g = g_0\left(\frac{r_E}{r_E + h}\right)^2 \tag{18}$$

3.4 Results

In this section the results of the given launcher trajectory simulator are shown. Because the results of the simulator are the simulator tool itself, the way the simulator results are shown is by proposing two launch cases and analyze them.

Later on, the validation of the software will be performed by comparing the actual trajectory with the same trajectory given in [5], also [1] will be used to validate the model comparing this LEO trajectory.

3.4.1 Results of a Low Earth Orbit Trajectory

The plots below show a trajectory calculated for the Ariane 5 model. Same thrust and aerodynamics characteristics, weight per stages, burn time of the tanks. The only difference of this mission with the mission shown in section 4.3.1 (Comparison with an Ariane 5 Mission) is the duration of the phases of launch.

It will be explained later in module 4 (Launcher Trajectory Optimization) but the way in which the trajectory of the launcher is defined is by controlling the duration of the two first phases (ascent and pitch push maneuver) and the final angle ɣ after the pitch push maneuver.

Once those three parameters are defined the launcher only has to keep the expected trajectory (given by gravity acceleration) and finally in the last phase the launcher is inserted into orbit. So the parameters controlling launcher path are these three:

- Ascent maneuver time (t_{asc})
- Pitch Push Maneuver time (t_{pp})
- Pitch Push Maneuver final angle (γ_{pp})

In this particular case given the value of the three parameters is:

t_{asc}	t_{pp}	γ_{pp}
20 s	35 s	1.3 rad

Figure 14. Value of the control launcher trajectory parameters for a given LEO trajectory.

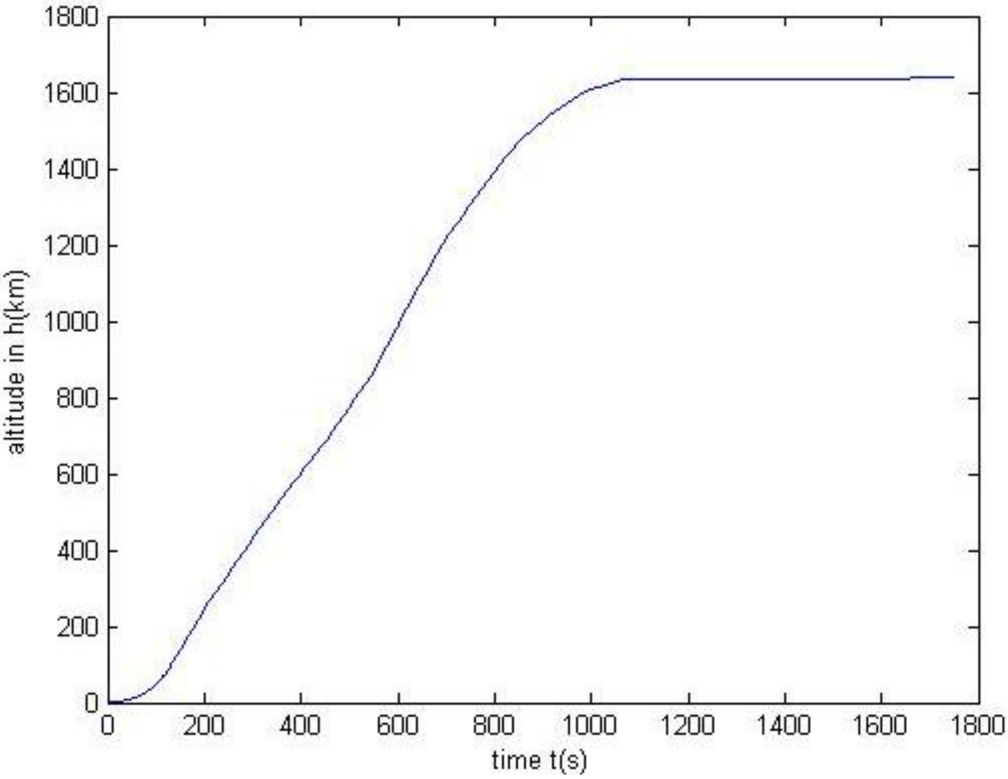

Figure 15. Height vs time (LEO launcher trajectory)

As it can be seen in figure 15 the trajectory reaches a stable orbit at a height larger than 1600 km (it reaches 1637 km). Although the orbit is stable in the short term, for larger times control maneuvers will have to be performed, but it is not the purpose of this project.

The different stages of the launcher can be distinguished in the plot, times at which different stages occurred are shown in table 8 (section 3.2.4). Boosters are discarded at 129 seconds, the main stage is removed at 589 seconds and the final orbit is reached at 1100 seconds.

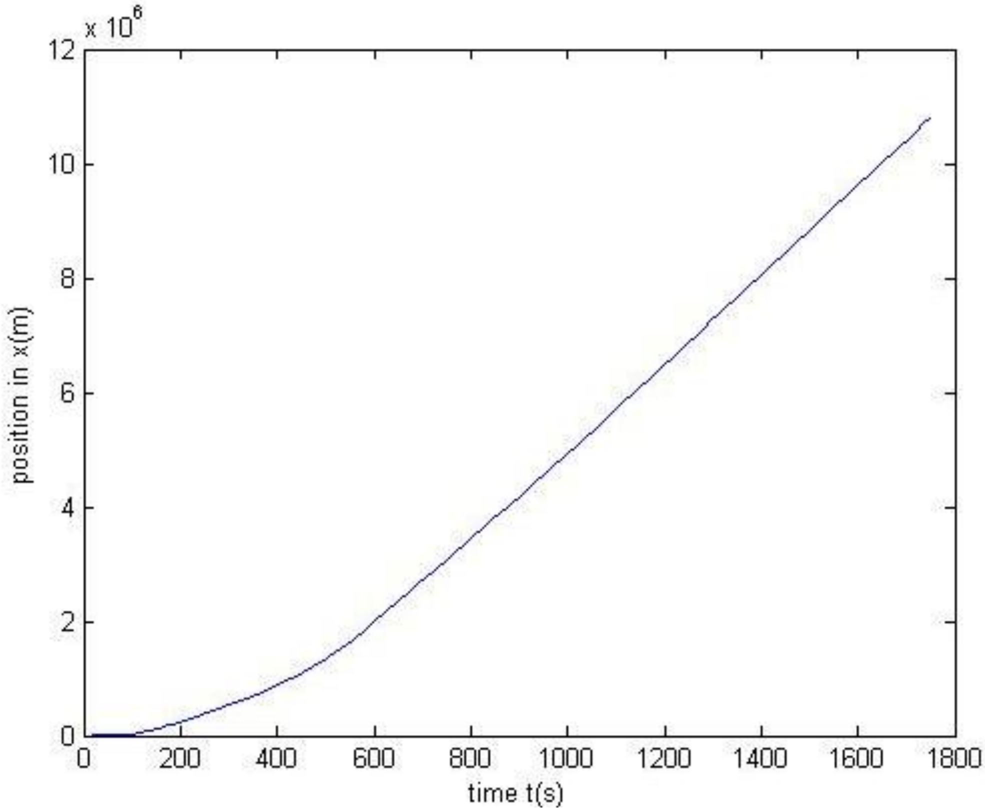

Figure 16. X position vs time (LEO launcher trajectory)

In this second plot it is interesting to notice the fact that at the beginning of the launch the variation in x position is much smaller than in height, in order to escape as fast as possible from Earth gravity.

Moreover the stage changes are seen due to the slope variation of the function.

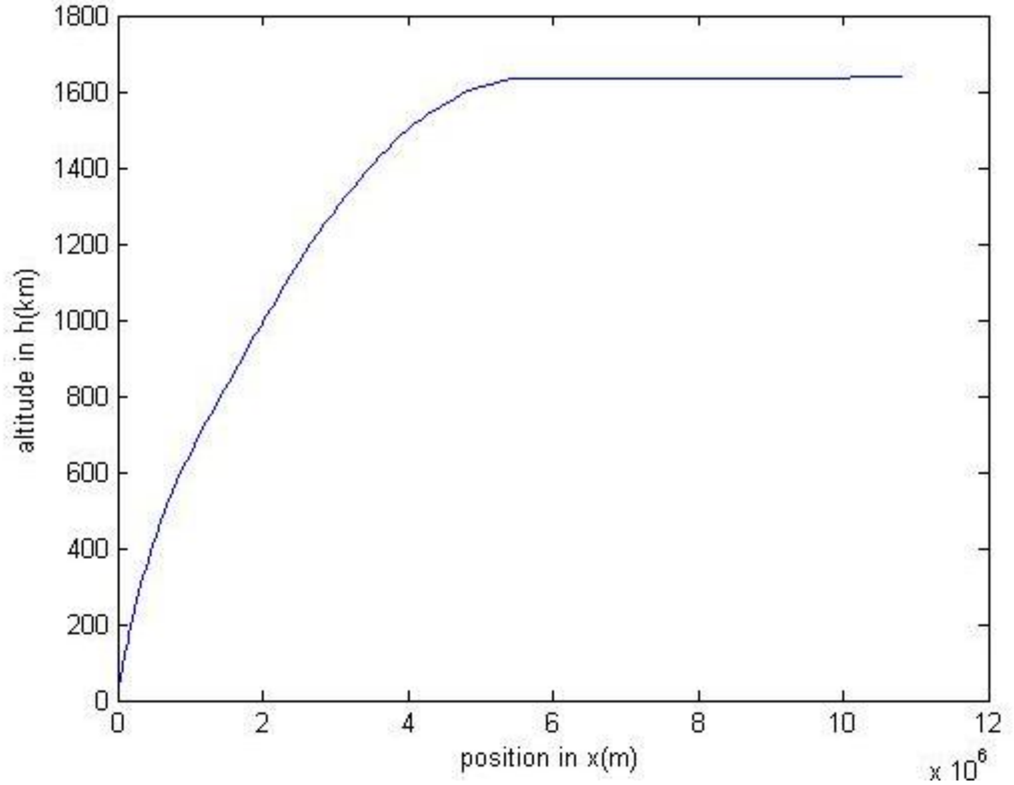

Figure 17. Height vs x position (LEO launcher trajectory)

In this figure the trajectory of the launcher in a 2D plane is shown

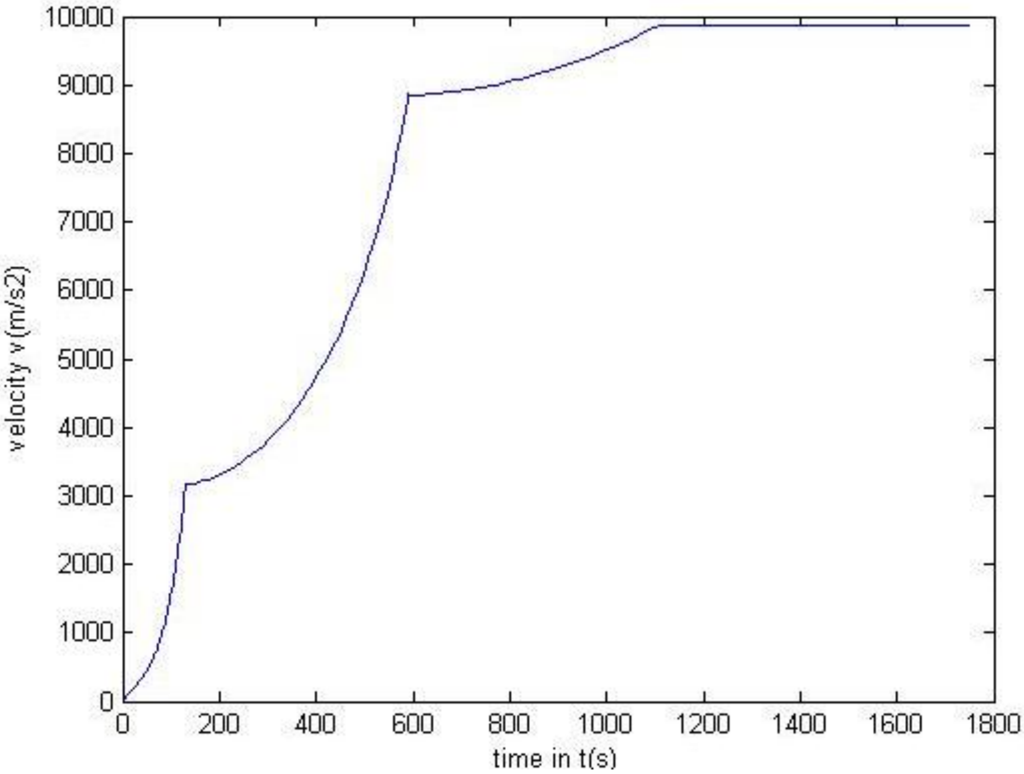

Figure 18. Velocity vs time (LEO launcher trajectory)

In figure 18 the velocity is shown with respect to time. In it the stage changes are highly noticed. It is mainly due to three reasons.

On the one hand, whenever a stage is discarded the amount of thrust available at each moment of time is much less (see table 8 in section 3.2.4) because of that fact the acceleration has a drop during stages transition.

On the other hand, there are two effects that increase the velocity slope, but not as fast as the decrease in acceleration due to the loss of thrust. During the stage transition an important amount of mass is lost very fast, so the velocity slope should increase (the difference between this effect and the decrease of thrust is much less). The other effect that increases launcher acceleration is the fact that the effective area of the launcher is decrease when a stage is discarded, so the total drag also decreases.

Furthermore, it is important to say the velocity is constantly increasing mainly due to two effects, gradual decrease of density (slow decrease in drag) and constant lost of mass, which reduces the total weight of the rocket so it accelerates easier.

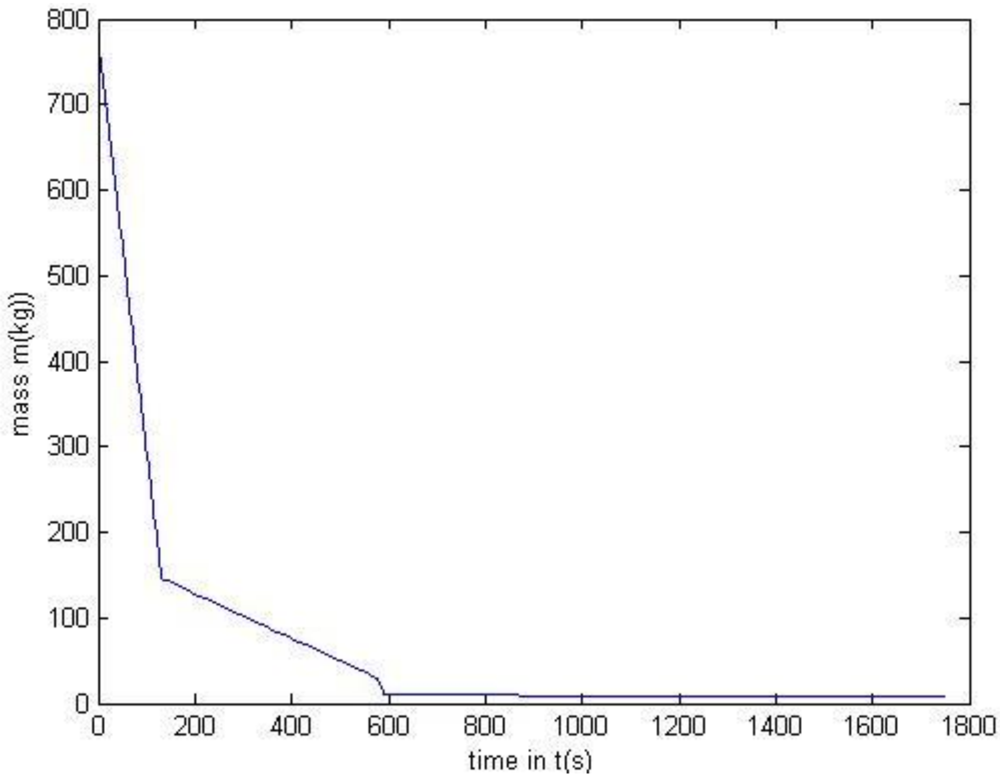

Figure 19. Mass vs time (LEO launcher trajectory)

In this section simply the changes in mass with time are shown. During stages the rate of mass lost is constant (because it has been assumed constant specific impulse of the engines) and in stages transition a sudden drop due to the loss of the stage discarded appears. The remaining mass is almost 21 tons (20.89 tons) because the payload imposed was 20 tons mass.

3.4.2 Results of a Ballistic Trajectory

This second case is almost a ballistic trajectory, with the difference it is pushed all the time, there is always a thrust component acting on the body. In this case the body does not have different stages. In this way it can be seen the different combinations the software allows to simulate.

In fact one of the purposes of the simulator was to do it as general as possible to be able to represent many different space launches or other long range atmospheric and space trajectories right after a launching.

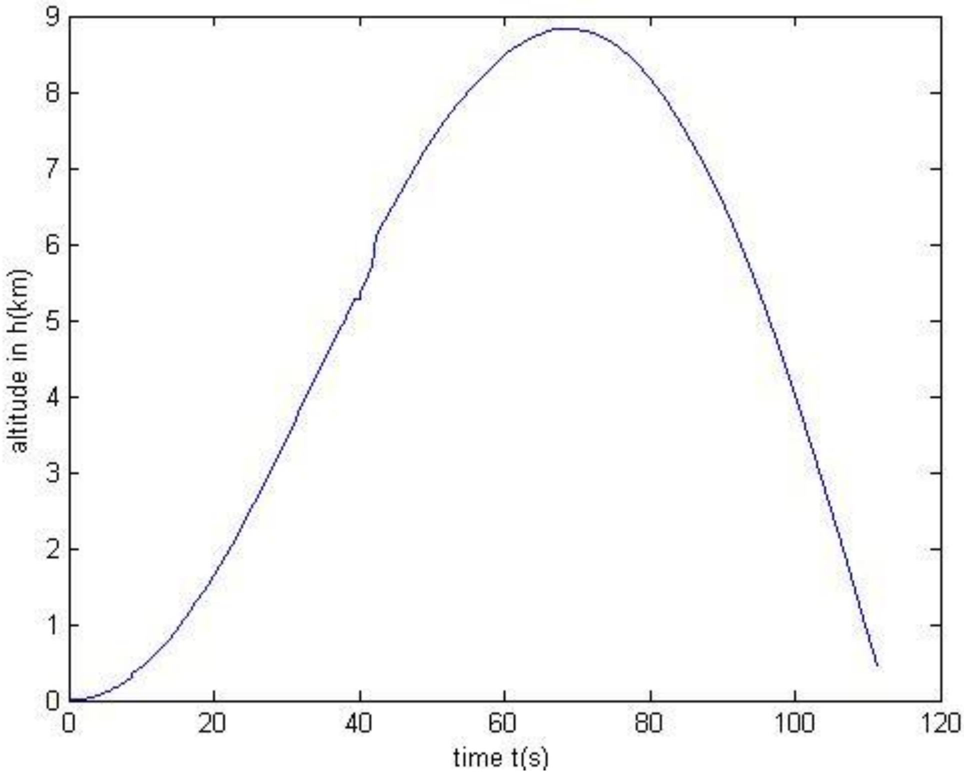

Figure 20. Height vs time (Ballistic trajectory)

In this second case as it can be seen the trajectory of the launcher does not escape Earth atmosphere because the angle after the pitch push maneuver has been highly reduced.

In this case to simulate the trajectory of for instance a missile the ascent phase has been reduced (although it could be completely deleted) and the initial angle of launch was kept vertical to Earth surface (maybe in other case would be interesting to deflect it, fixing an initial angle ɣ different from pi/2).

Below the value for the three main control parameters are shown:

t_{asc}	t_{pp}	γ_{pp}
3 s	40 s	0.5 rad

Figure 21. Value of the control launcher trajectory parameters for this ballistic trajectory.

The change of phase from the pitch push to the free turn phase can be seen in figure 20, as a strange change in height. It probably is an error in the solver while changing phases.

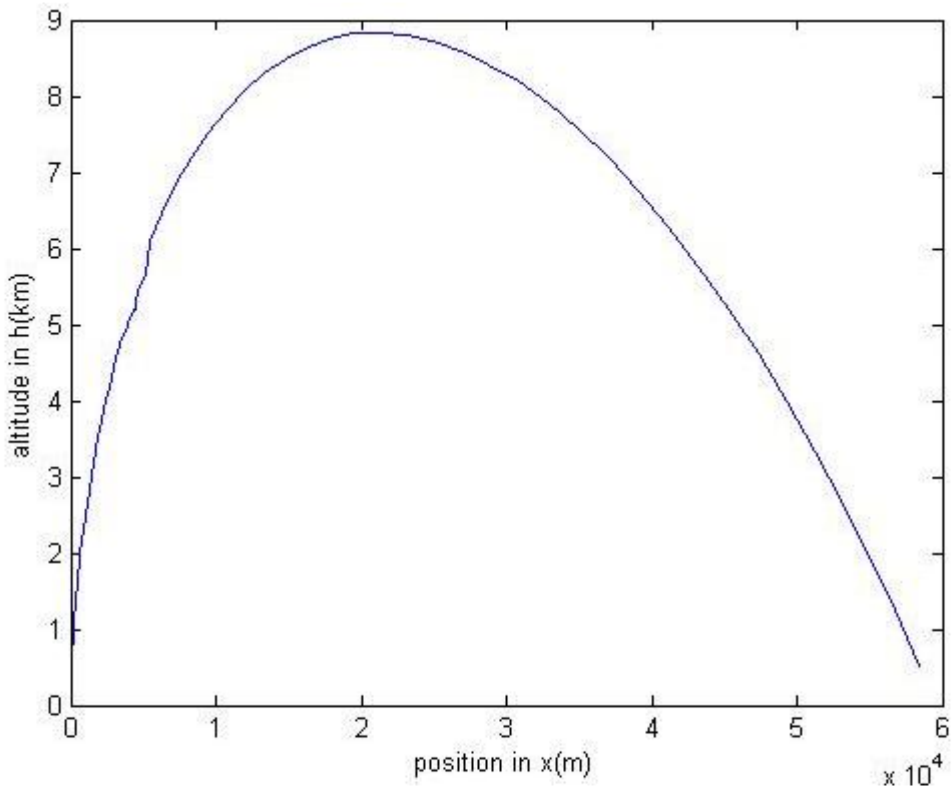

Figure 22. Height vs position (Ballistic trajectory)

In figure 22 the trajectory of the body is plotted.

Also just to mention for this case the thrust values, the mass of the body and the aerodynamic conditions were modified, in order to try different characteristics applicable for simulation body trajectories.

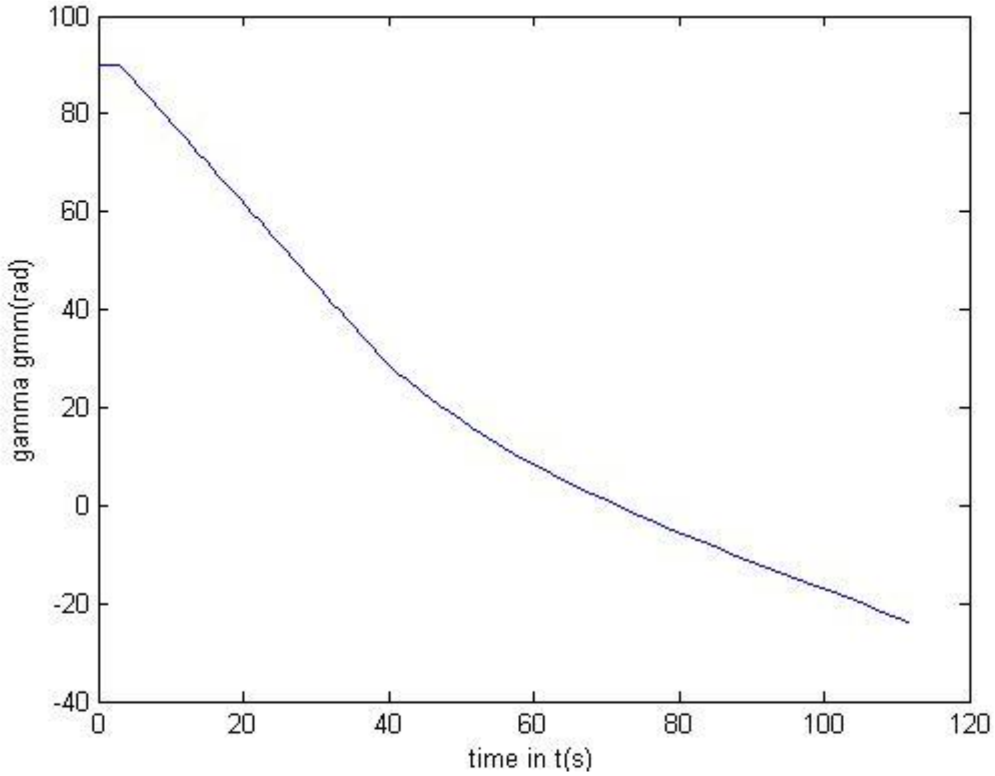

Figure 23. Gamma vs time (Ballistic trajectory)

Finally in this last plot the evolution of angle ɣ with time is analyzed. The ascent phase can be distinguished at the first part of the plot, then a smooth change in the variable value is registered.

3.5 Applications

It is interesting to point out here some applications of the launcher trajectory definition software. At this point it is needed to point the important role of simulators for academic and understanding purposes.

It is a way to make easy and visual some no intuitive concepts, so this software and a trajectory simulator in general could be used to familiarized space launchers with students.

Moreover simulation applications could be directly related to be used in video games and other leisure simulation activities. For instance it is well know a space simulator developed as a game, it is called Space Kerbal Program. In figure 24 it can be seen a picture taken from the game during the launching phase.

Figure 24. Kerbal Space Program image taken during launch. Source: KSP.

However, going directly to technical purposes, they are the use of this simulator as a first approach for a new design trajectory (in the early stages of the launchers design).

Furthermore the optimizations that can be performed using the trajectory simulator (as it will be seeing on module 4) could be used for finding optimal solutions. The particular optimization method proposed would allow finding a medium size range in which the optimal solution is (it should be small enough to ensure other methods accuracy when finding optimal solution), to in future steps use other optimization method in this smaller range.

4. Launcher Trajectory Optimization

4.1 Introduction

The second part of this project was focused on the optimization of a desired trajectory for a launcher; in this module the optimization will be focus on Low Earth Orbit insertion trajectories.

In order to solve this optimization problem genetic algorithms technique was chosen due to the capacity this method gives us to find optimal solutions in large areas of the solution space. Due to the complexity of the problem and the variables that enter in it analytical solutions cannot be applied.

In the comparison between genetic algorithms and other numerical solutions two differences have to be accounted for:

On the one hand typical numerical approaches calculate one solution at each iteration, those solutions tend to converge to the optimal solution. However genetic algorithms method calculates several solutions each step, one solution is computed for each of the individuals, all the individuals form the population for which as many solutions as individuals are calculated in each iteration step.

On the other hand, the genetic algorithms use random choices to select the next population (population evolves in each iteration in order to approach the optimal, final solution), while conventional methods do not include random choices in its computation.

So the main difference is not only an individual reaches the optimal solution but the whole population tends to the solution.

It is interesting to know that the name genetic algorithms is given due to its similarity to biological evolution process by which the best species and individuals survive, improving and evolving to individuals better adaptively speaking.

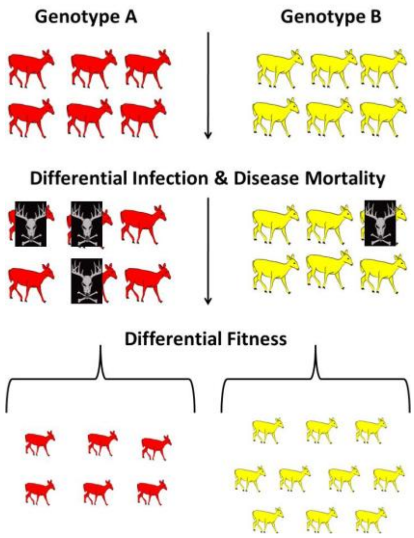

Figure 25. As in nature, population best individuals will survive, producing better individuals and finally reaching the optimal solution. Source: USGS.

In the present document a preliminary study of the trajectory optimization will be performed. It could be useful for mission studies during the design phase of the launcher or could be used in order to see the feasibility of some kind of missions, but it is important to remark the fact that the optimization performed here could not be used for accurate final trajectory launcher definitions. To do that more accurate launcher characteristics are required, also the models used to simulate external and environmental conditions have to be more precise.

Remark again the usefulness of the method to find solution in larger ranges, so the next possible step to get a finer optimal solution could be apply other optimal method in the range indicated by the genetic algorithms.

4.2 Genetic Algorithms Technique

4.2.1 Introduction to Genetic Algorithms

An introduction to the genetic algorithms technique will be performed at this step in order to give the reader the key ideas in which the method is based to know the cases in which the algorithm is useful and the possible issues it can originate.

The scheme in figure 26 will be used to easier understanding of how they work.

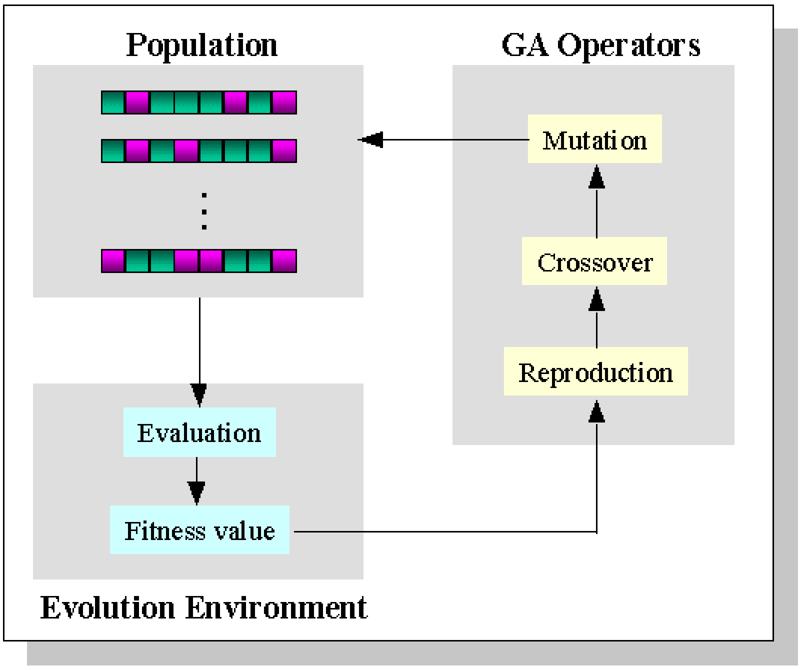

Figure 26. Scheme with the basic phases of a genetic algorithm to reach an optimal solution. Source: IEEE

As every optimization method, genetic algorithms require a given fitness or merit function to find the maxima or minima on it. The fitness function selection in the launcher trajectory case is one the key parameters in order to perform a successful optimization.

The fitness function will have variables that change the behavior of the fitness function allowing looking for the optimal solution by changing them. Each of those variables is called gene for the genetic algorithm method. Also the vector of a row of genes is called an individual, because it is a case for which the fitness function has a value.

As it was presented in the introduction of genetic algorithms, the interesting fact about them is that for each iteration many solutions are obtained, as many as individuals are in the population.

This way of computing many solutions at each iteration allow us to have greater diversity of solutions, looking for a larger area in the fitness function.

However, not only many solutions are computed at each iteration, the interesting advantage of genetic algorithms is the way new generations (populations created from previous individuals) are produced.

Depending the fitness score of each individual it has more possibilities to survive or to be parent of a new individual of the next generation. So better individuals (closer to the optimal solution) remain in consecutive generations.

Essentially there are three ways in which new generation individuals are produced. In figure 27 a brief scheme is shown.

- Elitism. Best individuals are kept unchanged to ensure best merit function value never decreases.
- Crossover. Two individuals of the previous generation are mixed to produce new children (there are several crossover methods).
- Mutation. One individual of the previous generation is modified randomly (or it can follow some pattern) to generate new children.

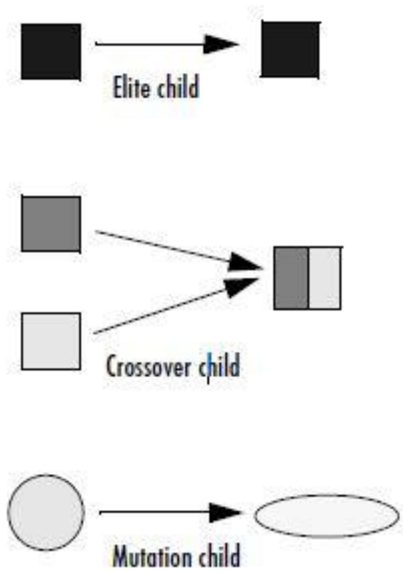

Figure 27. Types of children depending on how they were obtained. Source: [9]

When working with genetic algorithms some stopping criteria has to be set, optimization time (for a given value of the merit function), number of generations with no significant changes, total of number of generations…

The stopping criteria also can have an important impact on the final result, because genetic algorithms result can significantly vary from one generation to another.

4.2.2 How was it implemented? Merit function

First task in order to apply genetic algorithms optimization method is to define the merit function that will be used for computing the minima. Below in equation (19) it is presented the merit function used[23]:

[23] The idea of using this fitness function was taken from [5] although it was not totally sure if it was the ideal way for defining it (because the merit function is a dimensional parameter.

$$z = \frac{-h_f}{1 + |v_f - v_{orb}|}$$

(19)

Where v_{orb} stands for the orbital velocity required for keeping the final orbit stable, it is defined as follows:

$$v_{orb} = r_E \sqrt{\frac{g}{r_E + h_{orb}}}$$

(20)

In equation (20) $r_E$stands for Earth radius, h_{orb} is the height at which the payload will orbit and g is gravity acceleration constant.

The fitness function is expressed as shown in equation (19) because the final goal is to obtain the maximum stable orbit possible, so what is desired is the maximum height possible with a speed as closer to the orbital speed required to keep the payload in orbit. So the addition of the absolute value of the orbital speed and actual speed is added to avoid too high fitness function values if the launcher velocity is not close to the orbital velocity required.

Although equation (19) was the final merit function used, at some point during the optimization other alternatives were proposed, first of all, merit function in equation (19) is dimensional, so the effect of one of the parameters (h_f and v_f) over the other can be overrated.

Other merit functions proposed were to do it a nondimensional value, and to add in the equation the final ɣ angle in order to ensure the velocity is directed horizontally with respect to Earth surface.

However including those parameters produce apparently incoherent results, so those options were discarded, and the optimization method was intended to obtain similar results to [5] following a similar procedure.

More than the merit function issues there was an important factor in genetic algorithms which basically is the mutation rate you apply to your population, so the children engender through this method are more similar or dissimilar to the individuals they are generated from.

Modifying mutation parameters to high values produce not desired results even when the solutions were constrained to some range area. However in case the mutation rate was too low the methods did not cover all the solution area.

4.2.3 Ariane 5 Optimization Results

Below in table 28 they are shown the results obtained with genetic algorithms optimization for the Ariane 5 case taken as an example from [1].

t_{asc}	t_{pp}	γ_{pp}
7.959 s	62.242 s	1.472 rad

Figure 28. Optimal control launcher parameters using genetic algorithms.

In the table are presented the best results, in terms of the merit function given by equation (19), they provide a orbit height of 4709 km surpassing the 4000 km allowable using Ariane 5 rocket following the User's Manual [1].

However it is possible a margin is given in the users manual in order to ensure reaching the orbit. It is important to say that using genetic algorithms you will obtain one optimal value each time, because randomness is present.

Because of that in the table 29 below the range of optimal control parameters found for a total of 8 calculations (if the two furthest values for each parameter are not considered).

	t_{asc}	t_{pp}	γ_{pp}
Maximum	12.021 s	74.241 s	1.489 rad
Minimum	6.301 s	45.688 s	1.250 s

Figure 29. Optimal control launcher parameters range using genetic algorithms.

However, the optimal solution given in [5], and it will be the case applied in the software validation section was:

t_{asc}	t_{pp}	γ_{pp}
8.91 s	21.94 s	1.465 rad

Figure 30. Optimal control launcher parameters for [5].

Those differences can be explained due to difference in model (although they are too small to influence them), or the conditions applied when using genetic algorithms, which was the value given to the fitness function when the launcher did not reach an orbit.

4.3 Software Validation

In this section it is presented the validation of the launcher definition simulator. The usual way to proceed would be compare the results the developed simulator provides with a given simulator of similar characteristics. However this kind of software could not be found available on the Internet, so the validation of the software would be made by comparing the results for a given trajectory of known parameters.

In the first subsection this comparison is done. In the next two sections the next step to improve the simulator is presented. Initially it was expected to include a feature to compute latitude and longitude of the launcher to simulate a real mission in 3D space. This problem will be stated in case in a near future this feature could be added.

Finally, in the last subsection two simulators of similar characteristics are presented, unfortunately there was no access to the data they provide for several reasons. But they are examples of real developed tools similar to the project.

4.3.1 Comparison with an Ariane 5 Mission

As it was said in this section the comparison of a LEO trajectory of the Ariane 5 rocket produced by the simulator developed and other papers results. In particular, it will be compared with the same trajectory presented in [5] and some approaches and data will be also taken from [1].

In each subpart of this section there will be presented two plots the first one will correspond to this project simulator results while the second one is taken from [5]. In this [5] paper the optimization for an Ariane 5 LEO trajectory is made so, this will be the case used in order to validate the simulation software.

While presenting the results the conditions and characteristics of the trajectory and launcher will be described.

Altitude vs time plots

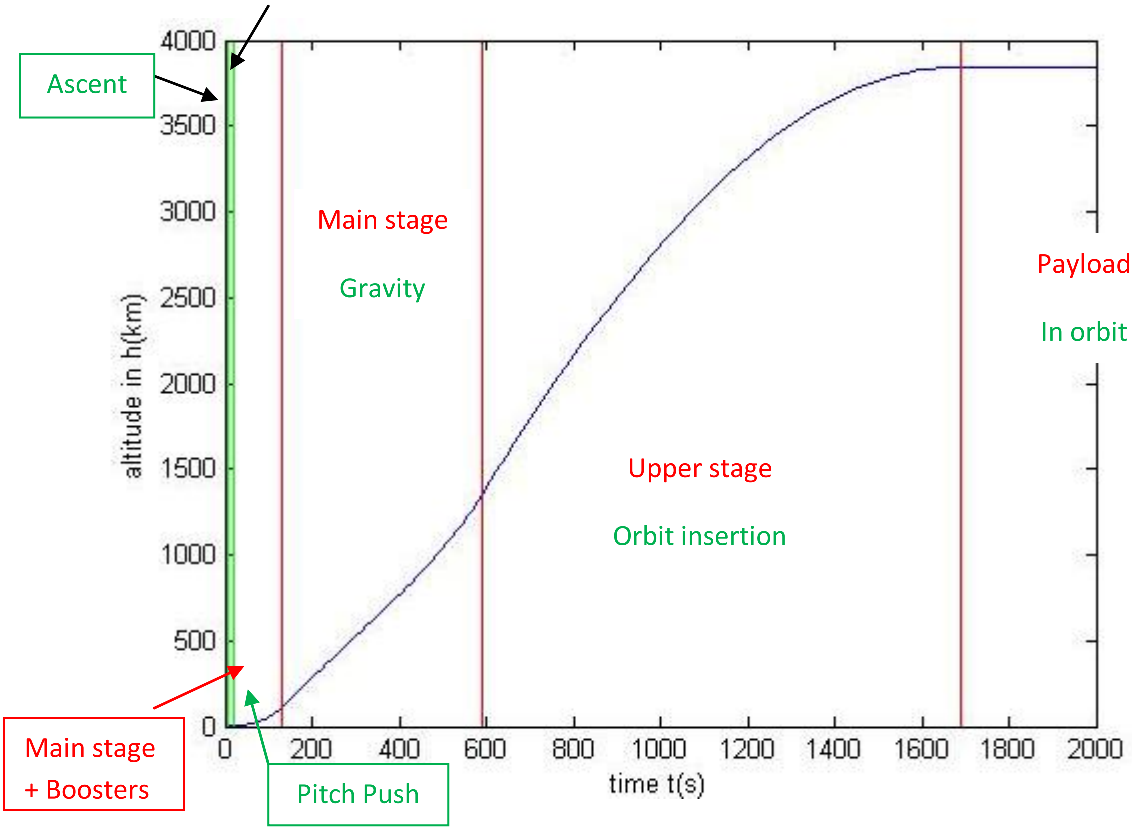

Figure 31. Altitude vs time using the own developed simulator.

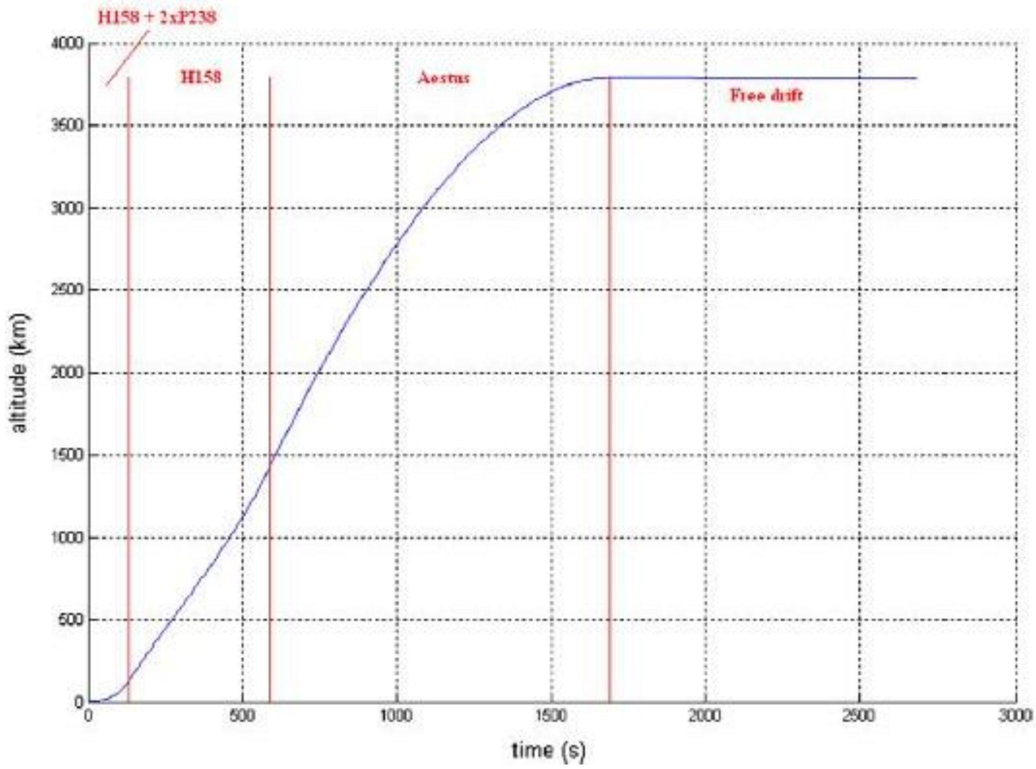

Figure 32. Altitude vs time using the trajectory given on [5].

First of all the meaning of the vertical lines presented in both figures will be explained. Each of the lines represents a change in phase or stage of the launcher.

First of all Figure 31 will be explained, it is the one produce by the simulator developed in this project.

The first two green lines in Figure 31 are the transition points from the ascent to pitch push maneuver and the transition between pitch push maneuver and gravity turn respectively, while the red lines indicate stage changes.

Summarizing:

- **Before** the **first green line** the launcher is in **ascent phase.**
- **Between first and second green lines** the launcher is in **pitch push maneuver.**
- **Before** the **first red line** the launcher is in **stage 1** (boosters + main stage active).
- **After** the **first red line** the **boosters** have been **discarded**.
- **After** the **red second line** the **main stage** have been **discarded**, this change in stages coincide with a change in phases, because from this point on the gravity turn maneuver is finished and the **bilinear tangent maneuver** to insert the payload in the orbit **begins**.
- The final part of the plot from the **last red line** on shows the **payload** already **in orbit.**

In Figure 32 the red lines indicate in the same way change of stages, they are identified by the name of the engine[24] active in each of the stages.

It can be seen that both launchers deliver its payload at a stable LEO orbit, the one developed in this project leaves it in a slightly higher orbit (3847 km LEO) while the [5] model leaves the payload at 3790 km LEO.

[24] See table 8 in section 3.2.4.

Following rocket user's manual [1] 20 tons (it is the payload in this case) of payload can be put in an orbit between 500 and 4000 km. So, both models are close to that mark. The tricky point here is that for the simulator developed during this project the solution proposed here was not the optimum trajectory as it was seen in section 4.2.3. Following the optimization got during the project, it is possible to take 20 tons payload above 4000 km. Maybe it is a factor to ensure the payload reaches the orbit. Any case the difference between the optimizations can be due to the conditions applied in the genetic algorithm.

Height vs x position plots

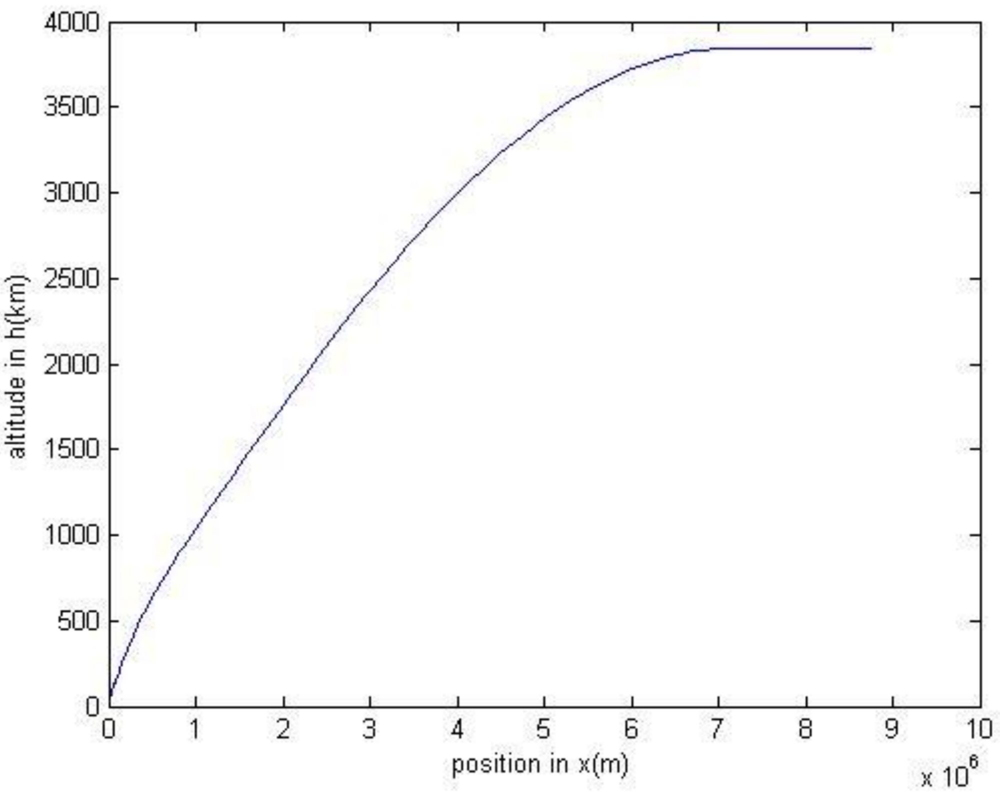

Figure 33. Altitude vs x position using the own developed simulator.

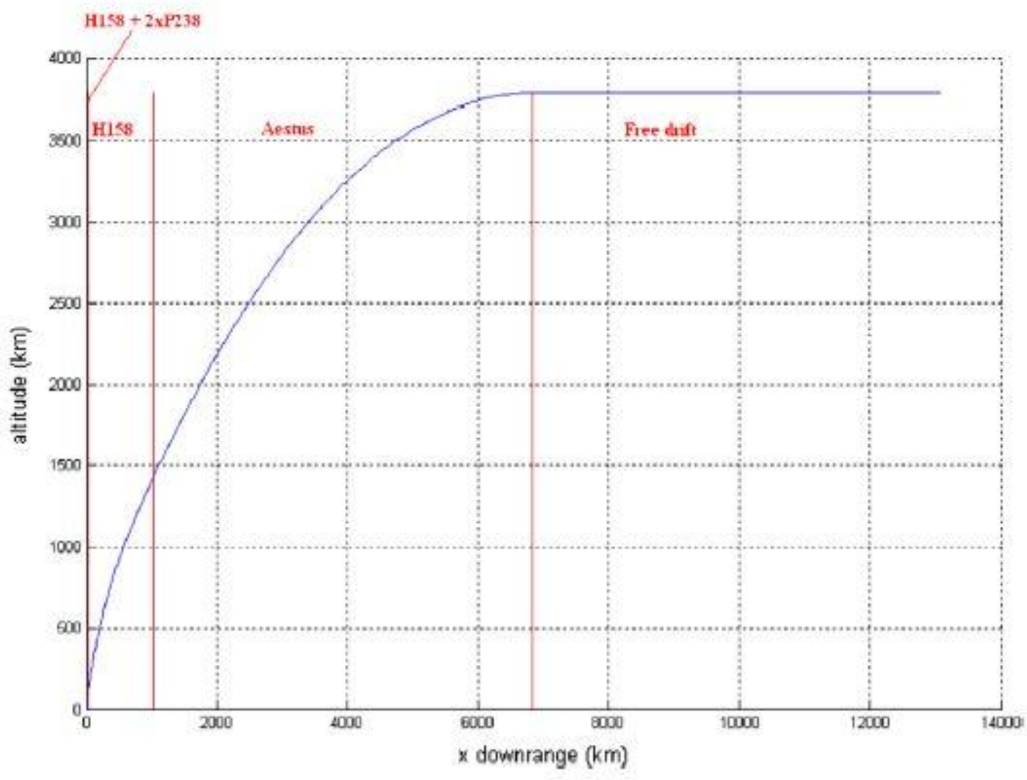

Figure 34. Altitude vs downrange using the trajectory given on [5].

In this subsection the trajectory in a 2D plane is shown. The lines in both plots have the same meaning in those two plots figures 30 and 31, and in all the subsequent ones.

They are pretty similar again, when the payload is in orbit the lateral distance covered by the [5] simulator is almost 7000 km while the one given by the simulator developed during the project is 7187 km. Those differences can be due to many conditions, models accuracy, or small differences in the way the transition between stages and phases was defined, etc.

Here the control parameters of the trajectory will be exposed in a table for the reader to know which parameters are being used (together with the technical characteristics of the Ariane 5 rocket).

t_{asc}	t_{pp}	γ_{pp}
8.99 s	21.49 s	0.5 rad

Figure 35. Value of the control launcher trajectory parameters for the Ariane 5 LEO trajectory validation case.

Speed vs time plots

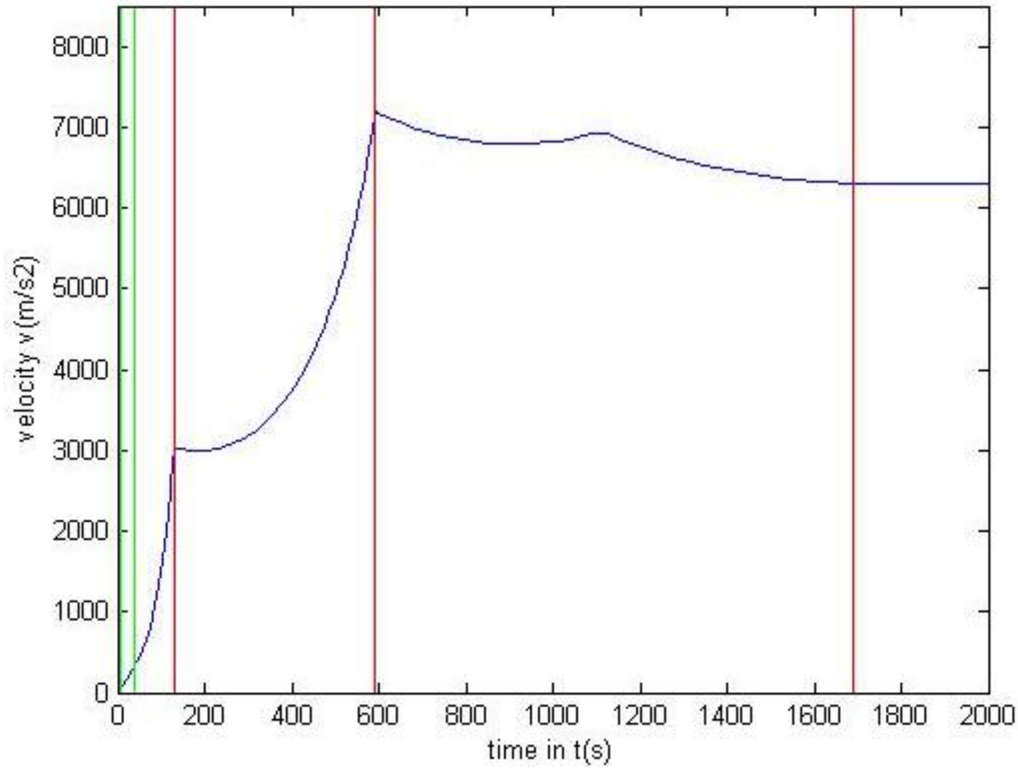

Figure 36. Velocity vs time using the own developed simulator.

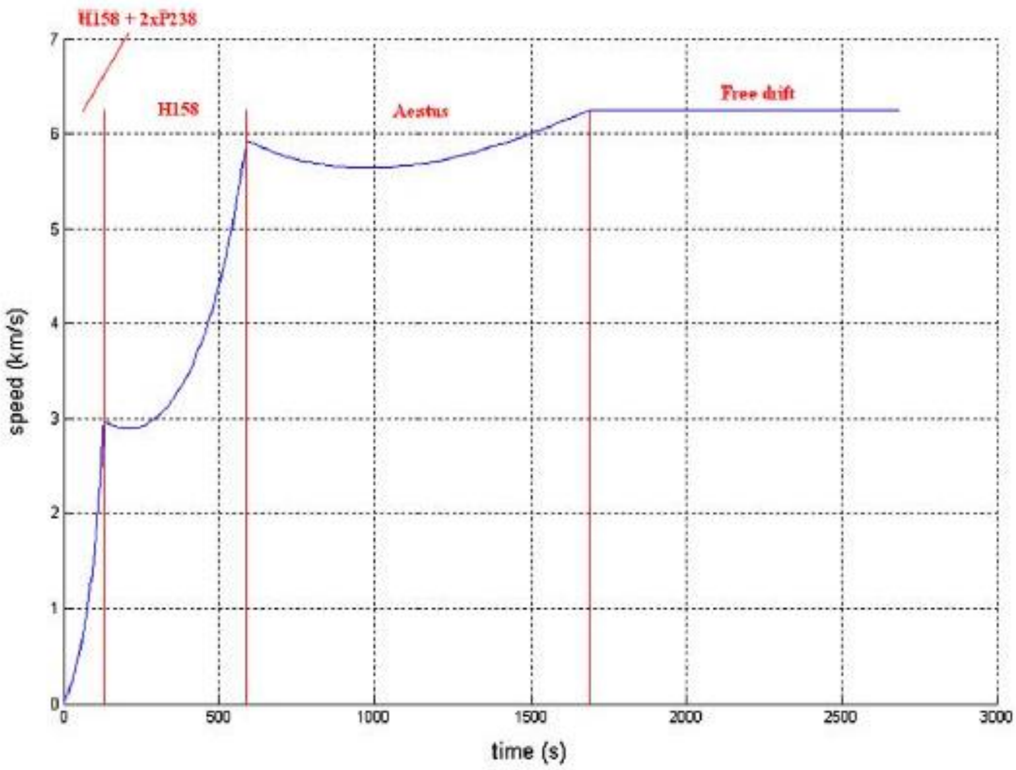

Figure 37. Velocity vs time using the trajectory given on [5].

The evolution of speed with time is very similar till the main stage, then the simulator results taken from [5] are slower than the ones obtained with the project tool, it could explain why one of them reaches a slightly higher orbit than the other.

The differences appearing seem to be a consequence of small differences in gamma angle values as it will be seen in figures 35 and 36.

Gamma vs time plots

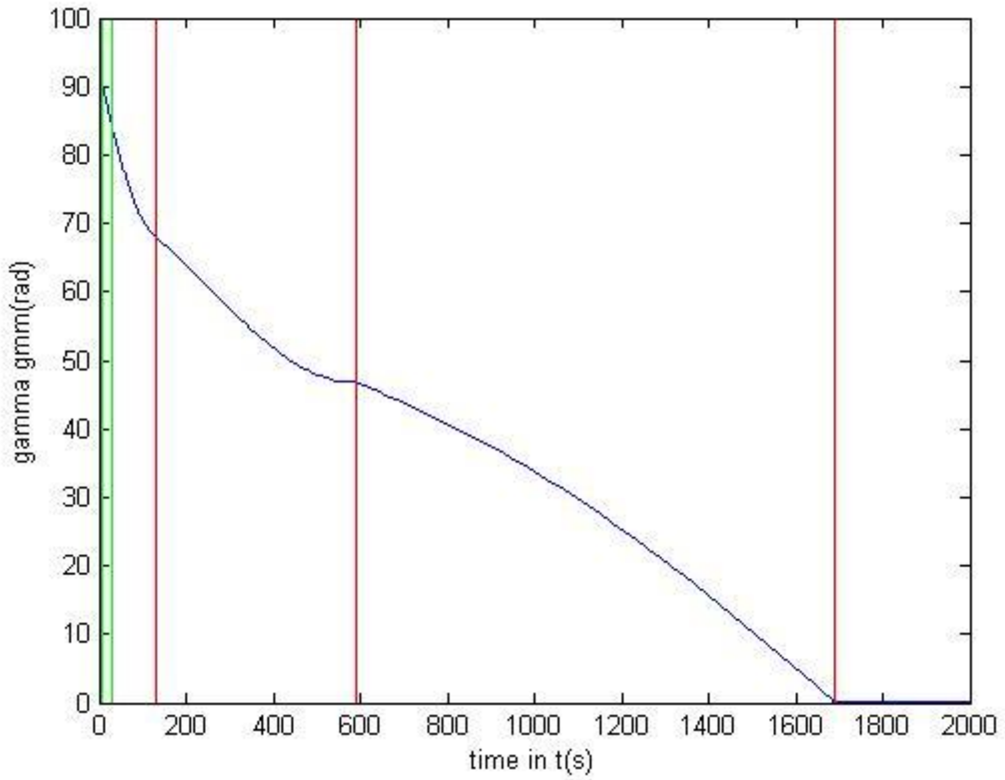

Figure 38. Gamma angle vs time using the own developed simulator.

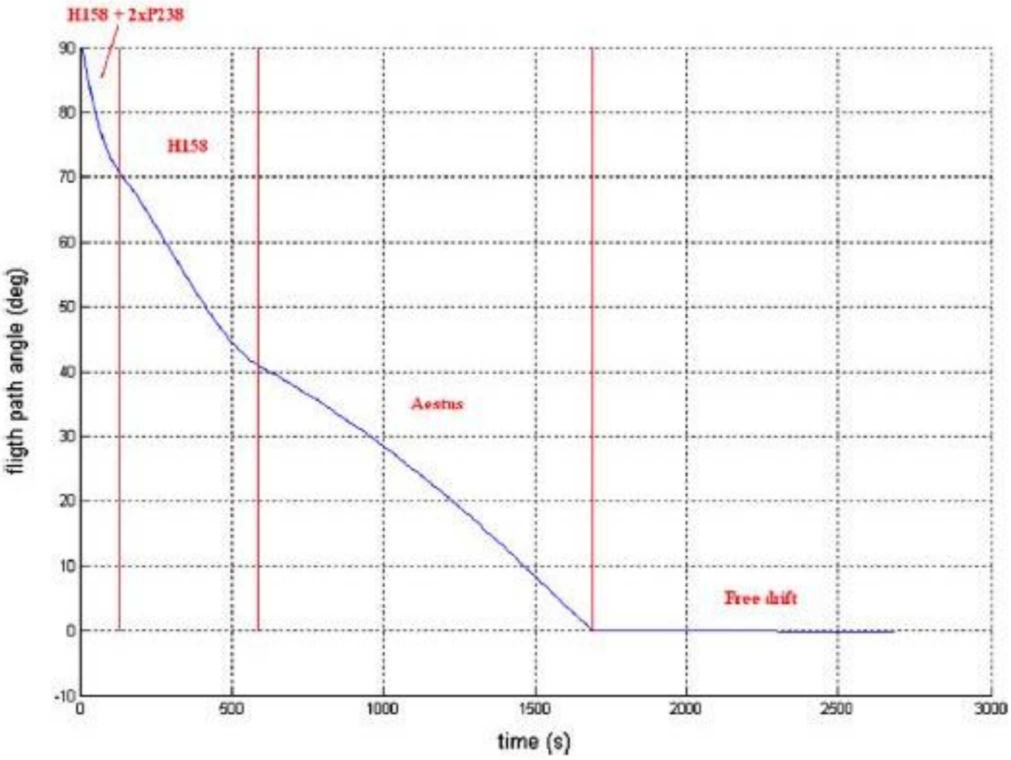

Figure 39. Gamma angle vs time using the trajectory given on [5].

The variation of the angle ɣ with respect to time is shown in figures 35 and 36. As it can be seen the evolution of both is very similar till the main stage. At the end of the main stage the difference between the values of both ɣ angles is a maximum (around 5 degrees).

Mass vs time plots

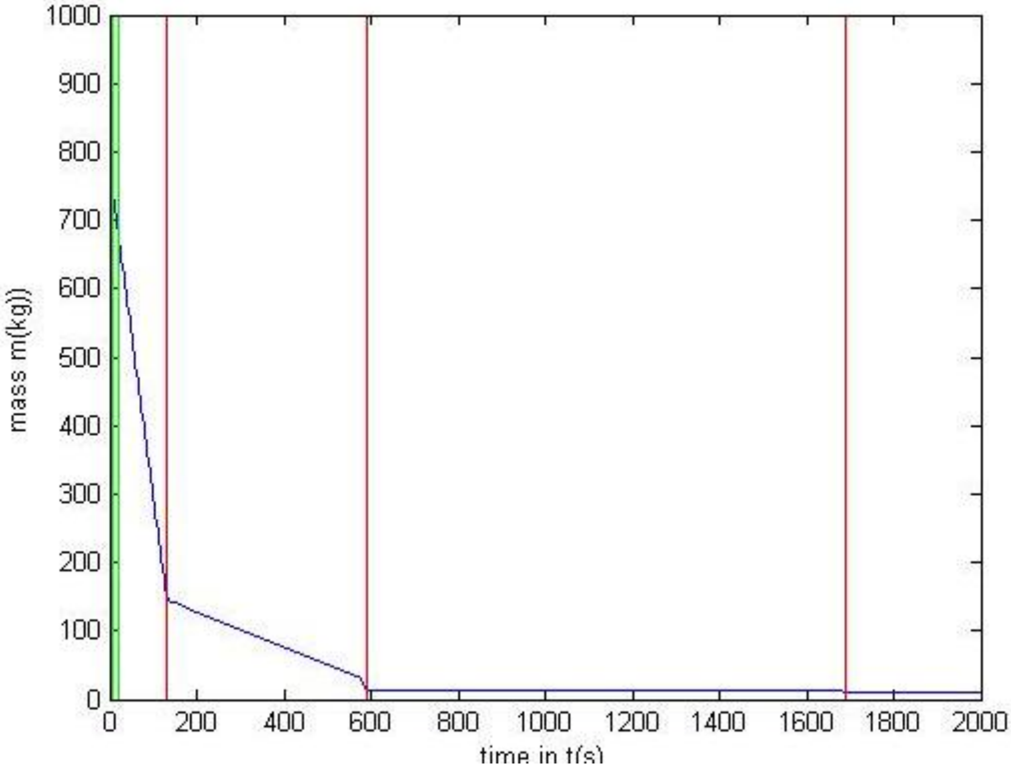

Figure 40. Mass vs time using the own developed simulator.

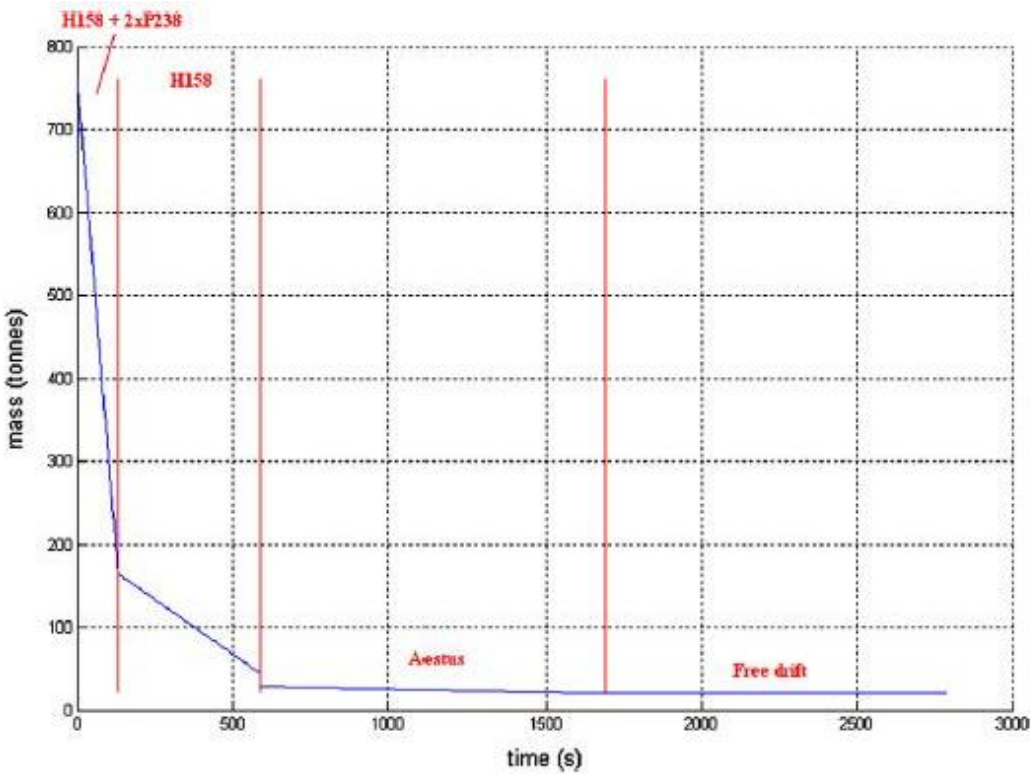

Figure 41. Mass vs time using the trajectory given on [5].

Mass evolution with time is shown for both simulators. They finally insert at orbit with a payload around 20 tons.

As a conclusion it can be said that some differences appear, but they can be produced by many factors in a problem of this complexity. In fact results and variations of the variables are very similar (differences of the values are always lower than 10% and global results are very close together.

Of course the simulator developed during this project can be improved, but for initial design phases or to get estimations of the behavior of a launcher it can be very useful.

4.3.2 Application: Ariane 5 from Guyana (Galileo)

At the beginning of the project it was thought about validating the code with a real Ariane 5 mission, launched from Guyana, however some problems appear in the process.

It was difficult to find tracking data of the launchers available to be able to reproduce a mission.

Moreover the latitude and longitude variations are currently not been computed properly by the simulator (as an extra feature), so the simulation to track the launcher and to compare its trajectory with a real one is still not done. It could be an interesting improvement of the software for the future.

4.3.3 Similar software already developed

It is important to mention other similar software that it is already available. If data from these programs (or other equivalent) could be exported, finally the simulator could be validated with a similar more accurate model.

There was a program on the Internet that simulate trajectories in a way very similar to the tool developed during this project, it is FLIGHT – Rocket Trajectory Simulation Software (See section 6.2 “Similar software”), unfortunately it was not free, so it could not be used in this case.

Other similar program already commented was the video game simulator Kerbal Space Program, see references and section 3.5.

5. Conclusions

The tasks of the project have been covered. In particular the development of the trajectory simulator was satisfactory due to the way it was done; enabling in the future to add easily new features to the simulator (for instance the latitude/longitude feature to be able to track and to simulate launcher simulated missions).

Moreover the made software enables the easy change of the external models used and launcher characteristics and conditions.

The results obtained with the simulator match and would be useful as first approach trajectory calculations for launchers.

On the other hand the optimization of trajectories did not work as expected, at least not totally, because the results obtained do not match completely with previous experiments.

This fact can be due to some condition mistaken in the optimization tool, a bad choice of the merit function, or the results obtained in the present project are correct, because the reasons in which [5] is based to support its results is not strong enough. This problem with Genetic Algorithms Optimization could be checked by using other optimization method in the future.

An important event to mention was the lack of time for the development of the project, especially optimization part and some additional features that could be added to the project have not been included due to this lack of time.

The core of this project, the launcher simulation tool developed provides a good basis to continuing developing a more accurate and realistic simulation tool easily as well the trajectory simulator could have several applications as it was explained in section 3.5.

Looking into the future the project developed has been interesting due to expected increase in launches and in space activity, which makes more and more important the improvement on efficiency of all space related aspects including launch trajectories.

6. References

6.1 Main References

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http://www.arianespace.com/launch-services-ariane5/Ariane-5-User's-Manual.asp

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http://www.astronautical-engineering.com/

[4] An Initial Guess Generator for Launch and Reentry Vehicle Trajectory Optimization
Albert Walter Markl (University of Stuttgart)

[5] Multi-criteria genetic optimisation of the manoeuvres of a two-stage launcher
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Matilde Santos Peñas (University Complutense de Madrid)

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[8] Solving the Goddard problem with thrust and dynamic pressure constraints using saturation functions
Knut Graichen and Nicolas Petit (Ecole des Mines de Paris)

[9] Genetic Algorithm and Direct Search Toolbox (MATLAB User's Guide)
The Mathworks Inc.

6.2 Other References

Similar software: Launcher Trajectory Simulators

FLIGHT – Rocket Trajectory Simulation Software
http://www.space-rockets.com/flight.html

Kerbal Space Program Game

Official Webpage: https://kerbalspaceprogram.com/

History of space launchers

ALLSTAR Network

Aeronautics Learning Laboratory for Science, Technology, and Research)http://www.allstar.fiu.edu/aero/rocket-history.htm

NASA History Program Office
https://history.nasa.gov/SP-4402/

Legal space framework

Dirección de Desarrollo Aeroespacial (Ecuadorian Air Force)

http://www.dda.gob.ec/

Enciclopedia Cosmonáutica

http://www.cosmonautica.es/

Launchers state of the art

Space Exploration Technologies Corporation (SpaceX)

http://www.spacex.com/

Gravitational field model

Analysis and Implementation of Gravity Field Models for planets and asteroids

Diego García Pardo (University Carlos III Madrid – Bacherol Thesis)

Figures

Figure 1. Source: TrinityP3
http://www.trinityp3.com/

Figure 2 and 3. Source: NASA.
http://www.nasa.gov/

Figure 4. Source: Smithsoian Air and Space Museum
http://airandspace.si.edu/

Figure 5. Source: Urbana High School
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Figure 6. Source: SpaceX Company.
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Figure 10. Source: Wikipedia.org (Article: Gravity Turn)
http://en.wikipedia.org/wiki/Main_Page

Figure 11. Source: Astrium Website (EADS)
http://www.astrium.eads.net/

Figure 12. Source: NASA website
http://www.nasa.gov/

Figure 13. Source: U.S. Centennial of Flight Comission
http://centennialofflight.net/index.htm

Figure 24. Source: Kerbal Space Program (KSP) game.
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Figure 25. Source: USGS (U.S. Geological Survey)
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