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MODELLING OF THE ASCENDER SPACEPLANE AND DEVELOPMENT OF AN AUTOPILOT AND FLIGHT CONTROL SYSTEM

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Abstract

The spaceplanes have been a feasible option to cut prices on the space missions. Because of their capability to be totally reusable, they can perform even more than one flight per day, launching small satellites in LEO orbits or carrying space tourists, which has become a very profitable market.

The goal of this thesis is to develop a mathematical model of Ascender, a spaceplane designed by Bristol Spaceplanes. The mode will be created in Simulink, which provides a set of very useful tools in the aerospace field to simulate and create the model. The geometric data of the aircraft will be obtained from a 3D view map provided by the company, which will also be the basis to estimate the inertia moments, weights and gravity center.

Around the aircraft model, a set of controllers will be created, each one operating in a different phase according to the propulsion system used in them (turbojet, rocket or thrusters). In the case of the turbojet, a proper autopilot will be designed which will enable the pilot to command an altitude, a speed and a waypoint route for Ascender to follow. In the rocket phase, the flight path angle and the Mach number will be controlled to obtain a suitable climb a limit the demand over the aircraft structure. Finally, during the unpowered phase (climb and glide back to Earth), the thruster will control the spaceplane attitude to facilitate the launch of the payload and to improve the comfort of the passengers.

Al the control systems will be checked through their response to the different commands sent to them, so the time history of the controlled variables will be plotted to assure a good performance.

Finally, a simulation of the whole flight of Ascender from a trim state at 4000 meters to the point where the turbojet starts again to help in the landing, will be carried out and the system variables will be monitored to guarantee a good system behaviour.

Acknowledgements

I would like to use this section to thank the people that has helped during the realization of this project, and during my academic life in general.

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1 Background

1.1 Introduction

A spaceplane is an aircraft that reaches space altitudes (more than 50 miles) and then returns to Earth's atmosphere landing on an airfield.

The current development of spaceplanes is due to the need of creating a reusable platform to put spacecrafts in orbit. Historically that was carried out by space shuttles made up of several stages (from at least 2 to 4 [1]), which detach from the main body after finishing their mission, falling then back to the surface or staying in orbit around Earth. A spaceplane could accomplish that mission and then land again in a conventional airport, which implies a great economic save. Moreover, the development of spaceplanes is also pushed by the market of space tourism. People are taken to a suborbital fly where they can experience the non-gravity and enjoy the astonishing views of the planet from there.

1.2 Origin

The history of spaceplanes begins with the development of the rocket aircrafts, which were airplanes fitted with a rocket instead of an airbreathing or piston engine. This propulsion system provided a greater amount of energy, which allowed the airplanes to fly faster and to reach higher altitudes. That opened a new world of possibilites to the design of aircrafts able to fly out of the atmosphere or even to orbit Earth.

The first rocket aircraft to be operational was the Messerschmitt Me 163 Komet, in 1941. It took-off from a wheeled cart that remained at the ground, made a step climb to high altitude and then it levelled to attack enemy's bombers. When the aircraft was out of propellant (about 8 minutes after taking-off), it turned into a glider than landed in an airfield with the help of an extendible skid.

After the creation of the Me 163, a lot of American designs were developed on the late 40s and 50s. The evolution of the airframes made it possible to create aircrafts able to fly supersonic and to reach higher altitudes than the Messerschmitt. One of them was the Bell X-1, the first airplane to fly supersonic during level flight (October 14, 1947). It had the shape of a 50-caliber gun bullet with stubby wings attached and used ethyl alcohol and liquid oxygen as propellant. The X-1 was released from a B-29 bomber at and altitude of 21.000 ft where the engines started the ignition.

On November 20, 1953, another american design, the Douglas Skyrocket, reached a speed of Mach 2, doubling the achieved by the X-1 only 6 years before. This new rocket aircraft improved the X-1 design by adding a 35 degree swept to the wings, increasing the wing area from 130 to 175 sq ft, using extensions on the engine nozzles and improving the fuel efficiency by increasing its density. Both airplanes mounted a 6.000 lb thrust rocket engine.

On the middle of the 50s Bell developed another rocket aircraft, the X-2. This airplanes was able to reach speeds up to Mach 3 due to his 15.000 lb thrust rocket engine. The X-2 was released from a Boeing B-50 at an altitude of 30.000 ft, where it started its operation. On September 7, 1956, Captain Iven C. Kincheloe reached an altitude of 126.000 ft with this aircraft, setting a new hight record [2].

1.3 Spaceplanes and types

Until the 60s, the rocket aircrafts created were each one faster than the another and able to reach always greater altitudes, but any design was capable of making a proper spaceflight (defined by the USA Air Force as a flight over 50 miles). It was the North American X-15 the first rocketplane to achieve this status during the 60s. Also it holds the record of the highest speed reached by an airplane: Mach 6.72. The X-15 could be consider the first spaceplane, because it was the first one to flight on the atmosphere then reach altitudes considered as space, and then land in an airfield. This breakthrough started the development of a series of spaceplanes during the end of nineteenth century and beginning of twentieth. This new designs can be differentiated depending on the sapceflight carried out by the aircraft. If the spaceplane when in the space, completes an orbit around Earth it is considered as an orbital spaceplane. On the other hand, if the aircraft reaches space flight and the re-enters Earth's atmosphere before completing an orbit it is considered as a sub-orbital spaceplane.

1.3.1 Sub-orbital

1. **North American X-15**

   The X-15 was the first spaceplane and also the first sub-orbital one. It reached a top altitude of 80 miles during two of its 199 flight tests. This aircraft was released from a B-52 at an altitude of 8.5 miles and at a speed of 500 mph. It was made of a long and cylindrical fuselage, rear wings and thick ventral and dorsal fin stabilizers. The landing gear was composed of a nose-wheel carrier and two rear skids and the propulsion system were two liquid propellant engines with a thrust of 57.000 lb [3].

Figure 1: North America X-15

2. **SpaceShipOne**

   The SpaceShipOne was the first private spaceplane ever created. It was designed by the company Scaled Composites and the inaugural flight was made on May 20, 2003.

   The functioning is similar to the one of the X-15: the spaceplane is released from a turbofan aircraft, called the "White Knight", at the launch altitude where the rocket engine starts the ignition giving the power needed to reach space altitude. Then the aircraft begins the gliding phase and lands in an airfield [4].

Figure 2: SpaceshipOne with Mothership

3. **Intermediate eXperimental Vehicle**

   The IXV is a sub-orbital spaceplane designed by the European Space Agency. It is a lifting body without wings (the lift force is generated by the fuselage), with flaps to control the re-entry phase. The IXV is launched from a Vega rocket at an altitude of 333 km. After reaching high altitude it re-entries on Earth's atmosphere and lands on the ocean with the help of parachutes.

Figure 3: IXV

   The first complete flight of the IXV took place on February 11th, 2015, and some more flight tests are planned for 2020 when the spaceplane will land on a runway by installing a landing gear [5].

1.3.2 Orbital

1. **Space Shuttle**

   In the early 80s NASA developed a new spaceplane, the Space Shuttle. It was formed of three different systems. The Orbiter Vehicle (OV) was the spaceplane itself, which after being put in orbit and finished its mission in space, returned to earth and landed on an airfield for a posterior use in another spaceflight ([6],[7]).
   In order to provide the thrust necessary to propel the OV during the lift off and ascendant phase, two systems were used.

   - The solid rocket boosters provided the majority of the thrust during the first two minutes of flight, after burned out were detached from the OV falling on the ocean and then

recovered for a future mission.

- The external tank provided the liquid propellants to the three rocket engines fitted on the OV. These engines are the responsible of the thrust for the ascendant phase. When it was empty, it was jettisoned falling on the ocean. This module was not reused on another mission.

Figure 4: Space Shuttle

2. **Buran** In 1988, the Soviet Union completed the flight of the Buran spaceplane. The functioning was the same as the one of the American Space Shuttle: an orbiter vehicle put in orbit that re-enters on Earth and lands on an airfield when the mission is finished. The differences in Soviet design were that the rocket used to propel the OV was only one system (boosters and tank in the same rocket called Energia) and that in this case there was not pilot, all the mission was unmanned (even the landing) [8].
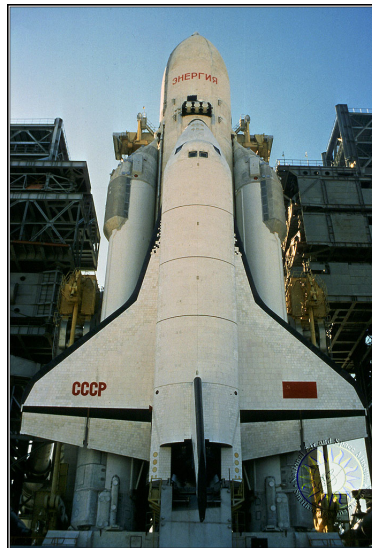
Figure 5: Buran

3. **Boeing X-37** The X-37 is an spaceplane designed by Boeing. Is an orbital reusable space-plane designed to replace the Shuttle. It is launched from an Atlas rocket that provides the energy needed to put it in orbit. This OV, as the Buran, is totally unmanned. The X-37 is the smallest spaceplane that has ever been constructed and flown. It weights only 500 kg [9].

Figure 6: Boeing X-37B

The first complete flight of the X-37 took place on 2010. It was launched April 22th and stayed in low Earth orbit until December 3th, when it landed in a military airfield of the USA.

1.4 SSTO

All the spaceplanes mentioned in the previous section have a difference with respect to the ideal concept of a spaceplane: they have more than one stage. In all the cases, the aircraft has two or more propulsion phases during its functioning. For the orbital spaceplanes there is a rocket that takes the spacecraft to the orbit, while in the sub-orbital spaceplanes there is a conventional airplane that carries the spaceplane to its launch altitude, where it is released.

An improvement on the case of the orbital spaceplanes is the SSTO vehicles. In this case there are not booster or fuel tanks that provided thrust during the lift off and ascending of the Orbital Vehicle. Is this last one which makes all the flight phases by itself. The SSTO would be the ideal concept of a spaceplane: an advanced spaceplane, a vehicle that behaves as an aircraft while flying on the atmosphere, and as a rocketship while flying in the space. An ideal sub-orbital spaceplane can also be considered as one that takes off directly from a runway, without a mothership [2].

There is not any constructed SSTO vehicle, but some designs and projects are currently being developed.

1.5 Current Designs

Actually there are several projects being development to construct both orbital and sub-orbital spaceplanes. In this section some of them will be detailed.

1.5.1 XCOR Lynx

The Lynx is a HTHL (horizontal take off horizontal landing) sub-orbital spaceplane developed by the company XCOR Aerospace. It takes off directly from the runway, reaching supersonic speed in one minute and weightless in five. It has four rocket engines mounted on the rear of the fuselage, providing each one 2900 lb of thrust [10].

Figure 7: XCOR Lynx

There are 3 models of the Lynx being developed:

- Mark I: this model has been created to test all the system for the future construction of the Mark II and Mark III.

- Mark II: this is the main model of the Lynx project. It would be used for space tourism and to carry out microgravity experiments.

- Mark III: this model is a modification of the Mark II. It features and external pod to carry out payloads for experiments or small satellites to put them in low earth orbit.

1.5.2 Skylon

The Skylon is a SSTO spaceplane developed by Reaction Engines Limited. It uses a SABRE engine created by the same company, which is an airbreathing rocket engine. This kind of propulsion system combines in a single system the way of functioning of airbreathing engines and rocket engines, so is the perfect engine for SSTO vehicles because the engine is adapted to each one of the flight phases: atmosphere and space flight.

Figure 8: Skylon

When the Skylon is flying in the atmosphere, the rocket engine sucks air as a source of oxygen to burn with the liquid hydrogen that the spaceplane has as fuel. When the speed and altitude reach Mach 5 and 28.5 km respectively, the inlet is closed and the engine works as a rocket engine fed with the liquid hydrogen and oxygen from an on-board tank. At this height the rocket engine provides the amount of energy needed to put the Skylon in orbit ([11],[12]).

1.5.3 Venture Star

The Venture Star was a SSTO spaceplane proposed by Lockheed and Martin. It would be used as a replacement of the Space Shuttle, that would reduce the cost of the space missions around a 90 %. This spaceplane would take off vertically and reach the orbit as the Space Shuttle but without the aid of boosters, then it would land horizontally on an airfield when the mission is finished. The Venture Star would use aerospike engines, which are a rocket engines that keep the efficiency over a higher range of altitudes than the rocket engines with bell shape nozzles [13].

Figure 9: Venture Star

After some failures with the X-33, which was the test vehicle of the Ventura Star, the project was cancelled in 2001.

1.5.4 AVATAR

Avatar is a design for a spaceplane proposed by India's Defense Research and Development Organization along with Indian Space Research Organization. The aim of the project is to create an unmanned SSTO spaceplane capable of putting small satellites in low earth orbit with only a cost of 67 dollars per kilo.

Figure 10: AVATAR

The Avatar would take off horizontally using a turboramjet engine that burns the air sucked and liquid hydrogen. Once the cruising altitude, then engine would work as a proper ramjet to

accelerate from Mach 4 to Mach 8. While in cruising altitude, the Avatar would still suck air from the atmosphere to store the oxygen for a future use. Finally, in the last flight phase, the rocket engine burns the hydrogen with the oxygen collected in the cruise to provide the amount of energy needed to reach the orbit [14].

The weight saved by not having an oxygen tank mounted from the take-off is what makes the Indian design so economic.

1.5.5 Ascender

The Ascender is a small two-seater spaceplane designed by Bristol Spaceplanes. It would take off horizontally from a conventional airfield using two turbofan engines, climbing to an altitude of 8 km where the rocket engines start working providing the thrust to reach altitudes up to 80 km by means of a steep climb. Finally it would glide back to Earth and land in an airport using the jet engines to manoeuvre. This spaceplane will be used to space tourism and to carry out experiments in microgravity environment [15].

Figure 11: Ascender

1.5.6 Spacecab

The Spacecab is a fully reusable orbital spaceplane designed by Bristol Spaceplanes to transport passengers to space stations or put small satellites in orbit by a relative small cost. It would be air launched from an aircraft similar to the Ascender, that would release the Spacecab at a speed of Mach 4 where it enters a LEO orbit. The Spacecab has be designed so it can be constructed with current technology, without the need to investigate and develop new propulsion systems [16].

Figure 12: Spacecab

1.5.7 Spacebus

The Spacebus is a larger version of the Spacecab. It is designed to carry up to 50 people or equivalent weight of cargo and its main purpose is to launch satellites and transport passengers to space hotels. It would also be air-launched as the Spacecab. The Spacebus is released from the carrier plane at a speed of Mach 6, then it accelerates to reach orbit [17].

Figure 13: Spacebus

1.6 Sub-orbital spaceplane Comparison

In this section the characteristics of all the sub-orbital spaceplanes will be detailed in order to compare the performance that each one is able to provide. Also some data of another designs will be indicated.

	Span (m)	Length(m)	Gross Weight (kg)	Max Altitude (km)	Max Speed
X-15	6.8	15.45	15420	108	7275 km/h
SpaceShipOne	8.05	8.53	3600	112	3518 km/h
SpaceShipTwo	8.3	18.3	9740	110	4000 km/h
XCOR Mark II	7.3	9.1	4850	103	2 (Ascendant Vel.)
Ascender	7.6	12.9	5500	100	Mach 3.3
IXV (ESA)	2.2	5	1900	412	27720 km/h

Table 1: Sub-orbital spaceplane Comparison

1.7 Orbital spaceplane Comparison

	Span (m)	Length(m)	Gross weight (kg)	I_{sp} (s)	Payload [LEO] (kg)
Space Shuttle	23.79	37.23	110000	269	27500
Buran	23.93	36.37	105000	338	30000
Boeing X-37	4.55	8.92	4990	337.8	-
Skylon	26.82	83.13	325000	460	15000
Venture Star	20.7	20.4	123800	439	20412
Spacecab	12.2	16.3	41000	-	750
Spacebus	21	34	90000	-	5000

Table 2: Orbital spaceplane Comparison

1.8 Propulsion Systems

The spaceplanes are aircrafts that have to fly in two different environments: the atmosphere and the space. The conventional engines developed so far are designed for either one or the other flight phase, so there is currently a challenge to create a new model of propulsion system that develops a good performance for the whole flight envelope of the spaceplane.

1.8.1 Rocket Engines

Rocket engines were the first propulsion systems fitted in the aircrafts developed in the 60's to flight hypersonic and to break the altitude records. Those engines provided a greater amount of thrust when compared with the conventional airbreathing engines mounted in the airplanes used until that time.

A rocket engine is a thrust producer system that carries both the oxidizer and fuel as storage, burning them in a combustion chamber to produce the required thrust. Because they do not need to get the air from the atmosphere to produce the combustion, this systems are the ones used for space flight.

There exist different types of fuels for this propulsion systems. The fuel liquid rocket engines use liquid propellants (oxidizer and fuel) that are fed into the combustion chamber to generate very hot gases (around 3000 ° during the combustion), which are then expanded in the nozzle to increase its velocity producing the thrust.
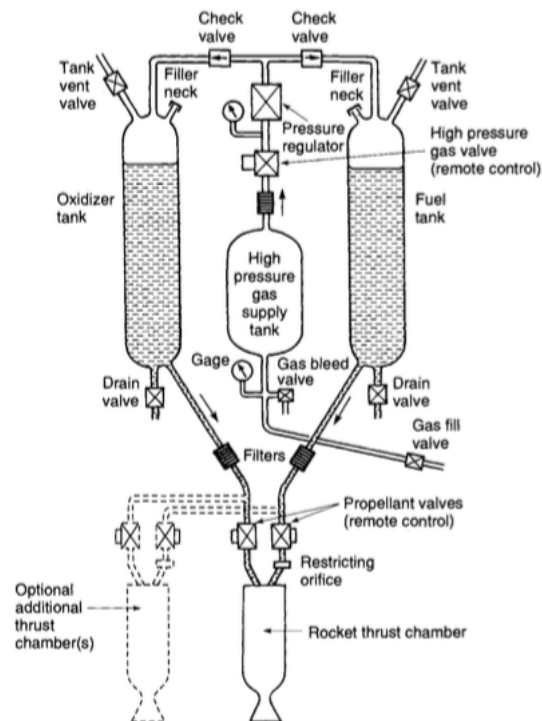
Figure 14: Liquid Rocket Engine

This type of rocket engines have a total control on the thrust produced, because the process can be started or stopped by cutting off the fuel feeding system, so that implies a great advantage with respect to other systems. On the other hand, the need of a complex pump system for the oxidizer and fuel make this systems difficult to maintain and more likely to have mechanical problems. The liquid propulsion rockets are used for example in the space launch vehicles.

In the solid rocket engines the propellant is contained within a solid piece called *grain*. The grain is located at the combustion chamber, and it has a "channel" perforated along it (as seen in figure 15). When the igniter creates the spark that starts the ignition, the combustion process propagates along the channel burning the grain at a constant rate and producing the hot gases that will be later expanded in the nozzle creating the thrust.
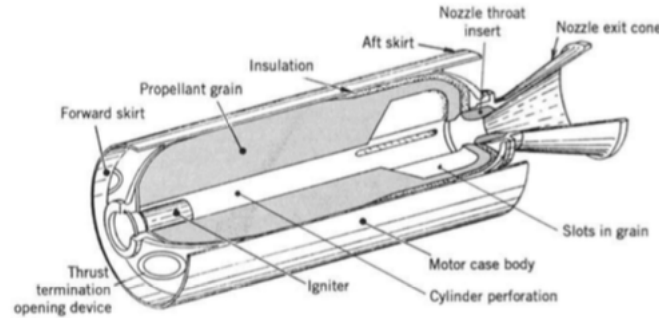
Figure 15: Solid Rocket Engine

The main advantage of this type of rocket is its simplicity. They do not have moving parts such as valves or pumps, their only components are the combustion chamber, the grain, the igniter and the nozzle. On the other hand, there is not control on the combustion, when it starts it can not be stopped so the thrust produced can not be regulated.

Finally, there exist a combination of the two systems detailed above called hybrid rocket engine. These engines normally use a liquid oxidizer that is feed into a combustion chamber where the solid fuel is stored. Both element react creating an exothermic reaction that release the gas that will be later expanded in the nozzle.
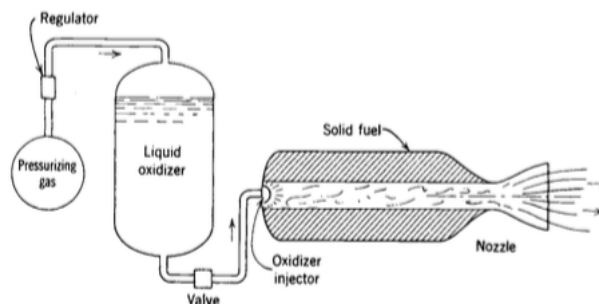
Figure 16: Hybrid Rocket Engine

1.8.2 Airbreathing Engines

The airbreathing engines are propulsion systems that take the air from the atmosphere and burn it with fuel to produce thrust. Unlike the rocket engines, the oxidizer is not store in the aircraft.

Normally, this kind of engines are made of the following sections:

- Compressor: its a device that takes the air from the atmosphere and compress it to increase the pressure. The air enters into the engine, when it encounters the compressor blades. This blades rotate, reducing then the velocity of the fluid and increasing the pressure, which has to be increase to achieve a greater power on the combustion process.

- Combustion Chamber: in this section the compressed air is mixed whit the fuel injected from the tanks. The mixture of both elements is then burned, increasing then greatly its pressure and temperature.

- Turbine: the air from the combustion chamber is expanded through the turbine, where its pressure is lowered and the velocity is increased. The energy taken from the fluid during this section is transmitted to the shaft of the engine that moves the compressor, i.e turbine and compressor are joint by a shaft and is the first one which moves the second. The high velocity fluid is then introduced into the last section of the engine: the nozzle.

- Nozzle: the fluid is expanded in the nozzle generating a high velocity jet. When the shape of the nozzle is convergent, the fluid can be expanded to as much as the sonic speed. In order to generate a jet with higher velocity, the shape of the nozzle has to change from convergent to divergent at the point where the Mach is 1. This two-shape nozzle is used because the subsonic flow needs a decreasing area section to increase the velocity while the supersonic flow needs an increasing area section to increase velocity.

- Afterburner: additionally, some engines are fitted with a second combustion chamber installed after the turbine. This section is used to increase the temperature and pressure of the fluid before the nozzle, so a greater velocity can be reached during the expansion process. The afterburner implies a very high fuel consumption rate (even 4 times greater than the one of the conventional combustion chamber), so is only use in specific configurations (commonly on military aicrafts)

Inside this type of engines there are a lot of different configurations, each one of them providing a set of characteristics that fit the best for a specific mission.

1. **Turbofan** The turbofan is a conventional airbreathing engine fitted with a fan before the compressor. The fan is used as a first compressor stage and also is used to separate the flow into two paths: one inside the core of the engine and another bypassing it from outside.

   The flow that goes into the core follows the conventional trajectory of an airbreathing engine (compressor, combustion chamber, turbine and nozzle). On the other hand, some air is bypassed and directed trough a duct concentric to the engine core, where it goes directly to the end of the nozzle where both flows get together again. The advantage of this flow separation is that because the flow is accelerate a little when it goes trought the fan, some additional thrust is created, and considering that the amount of extra fuel needed to move the fan (that is moved bu the turbine as the compressor) is very small, the fuel efficiency
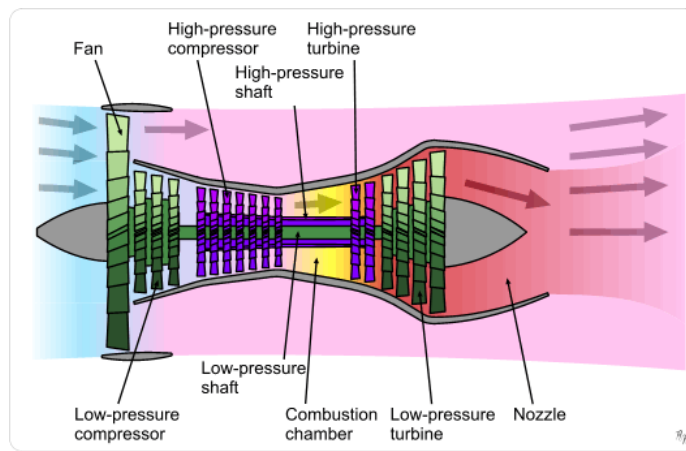
Figure 17: Turbofan Scheme

of the whole engine is greater than the one of a conventional turbojet. Moreover, the noise produced by the engine is reduced because the secondary flow blankets the one that is jetted from the nozzle.

2. **Ramjet and Scramjets**

A ramjet engine is a propulsion system used for high speed applications. This type of engine do not have a compressor nor a turbine because the compression of the fluid is produced directly on the inlet due to the high velocity of the incoming flow.
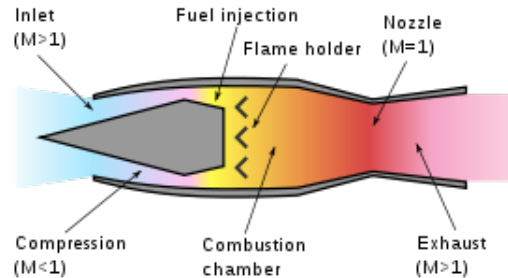
Figure 18: Ramjet Scheme

The air goes into the inlet of the engine at supersonic velocities. Because of that velocity and the cone shape of the inlet, a diffusion process is produced where the velocity of the air is reduced to subsonic values while the pressure and the temperature are increased. The flow goes then into the combustion chamber where it is mixed with the fuel and burned. Finally the flow is expanded in a nozzle to generate the thrust.

In the case when the combustion process is produced at supersonic velocities, the engine is called scramjet.

The benefits of this type of engines is the absence of mobile parts (no compressor and turbine), so essentially it is a duct with a fuel pump and a igniter and also the high velocities that could be reached by the aircrafts fitted with these systems. On the other hand, this engines start to work at velocities from 300 kilometres per hour, so they can not be used from the take-off phase of the flight. Normally they are used to provide extra power at certain flight conditions.

1.8.3 Spaceplanes Engines

The majority of the spaceplanes detailed in the previous sections have two stages. They need a rocket propulsion system (orbital) or another aircraft (sub-orbital) to reach the altitude and velocity needed to start its functioning. In this section the engines fitted in each one of the stages will be detailed.

The sub-orbital spaceplanes need a rocket engine during the final stage of its mission to reach orbital altitudes because the amount of air at this heights is very low and a conventional airbreathing engine will not work properly. The rocket engines are not used from the take-off because that will imply to store a lot of oxidant for the combustion process, and that means a lot of money, while the principal aim of the spaceplanes is to provide an economic platform to reach orbit. There are two solutions to this problem: the first one is the one used on the actual spaceplanes, which consist on using a mothership that is propulsed by an airbreathing engine to carry the spaceplane to the altitude where the rocket engine start its functioning. On the other hand, the new designs proposed will be propulsed by an engine capable of working as a turbojet in the atmosphere and as a rocket in the space. This type of engines are the best options because they will allow the creation of STTO spaceplanes that flight by themselves from the take-off to the landing. Besides, if an airbreathing engine is used when flying in Earth's atmosphere , there is not need to carry a deposit for the oxidizer because it is taken from the air, so the weight of the whole aircraft is reduced drastically, and then also the costs.

In the table 3 the engines of the sub-orbital spaceplanes detailed in previous sections are compared.

	Type	Oxidizer	Fuel	Thrust
X-15	Lyquid Rocket	Liquid Oxigen	Ammonia	254 kN
SpaceShipOne	Hybrid Rocket	Nitrous Oxide (liquid)	Rubber (Solid)	88 kN
SpaceShipTwo	Hybrid Rocket	Nitrous Oxide (liquid)	Polyamide (Solid)	270 kN
XCOR Mark II	Liquid Rocket	Liquid Oxygen	Kerosene	13kN (x4)
Ascender	Turbofan Liquid Rocket	- Hydrogen Peroxide	- Liquid Hydrogen	$\simeq$ 8000 kN (x2) 110 kN (x1)

Table 3: Sub-Orbital SpacePlanes Engines Comparison

Also the orbital spaceplanes engines are compared in table 4.

	Type	Oxidizer	Fuel	Thrust
Space Shuttle Main Engine	Liquid Rocket	Liquid Oxygen	Liquid Hydrogen	1859 kN
Buran	Liquid Rocket	Liquid Oxygen	RP-1	7257 kN (SL)
Boeing X-37	Liquid Rocket	Hydrogen Peroxide	JP-8	29.34 kN
Venture Star	Liquid Rocket	Liquid Oxygen	Liquid Hydrogen	13.39 MN

Table 4: Orbital Spaceplanes Engines Comparison

1.8.4 Combine-cycle Engines

The combined cycle engines are the future of the spaceplanes propulsion. This engines allow the aircraft to make all the mission in one stage, without the need of a external source to provide the propulsion (rockets or mothership) in the early phase of the mission. The combined-cycle engine that best fits the needs of a spaceplane mission is the air-breathing rocket, which is the one being develop for the Skylon. This engine is called SABRE and its functioning will be detailed on this section.

The SABRE is the first engine that combines two operating modes in a single propulsion system. When it is working in the atmosphere it uses the oxygen present in the atmosphere as the oxidizer, and when it is working in the space it operates as a conventional rocket engine burning the fuel with the oxidizer store on board. Sucking the oxygen directly from the atmosphere allows the spaceplane to save a lot of weight because the amount of oxygen stored drops drastically. This saved weight implies a great reduction in the costs of the mission and is one of the main reasons for the creation of the spaceplanes and this propulsion systems.

The SABRE engine has the conventional components of a turbojet. In the atmosphere, it sucks air which goes trough the compressor in order to increase the pressure and then it is burnt with the liquid hydrogen to generate hot gasses that are later expanded in the nozzle. The problem in this stage of operation, is that the air has to be compress to 140 atmospheres before being introduced in the combustion chamber so the temperatures that it reaches are extremely high, and the air would melt any material. In order to solve this problem the air is cooled before getting into the compressor, where it is compress to the desired pressure.
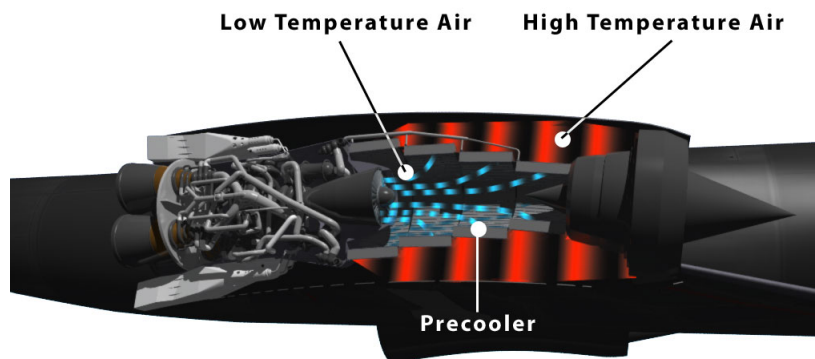
Figure 19: Pre-Cooling Process

When an altitude of 25 kilometres and a velocity of Mach 5 are reached, the inlet cone of the SABRE is closed and the engine starts to work as a conventional rocket engine, burning a mix of liquid oxygen and liquid hydrogen to produce thrust. The airbreathing mode can be used until this conditions, which represent the 20 % of the altitude and speed needed to reach orbit, so the remaining 80 % is achieved by the rocket mode.

2   Project Scope

After observing the information related with the state of the art technology in the field of the spaceplanes, it is clear that one of the main challenges nowadays is the development of an optimum propulsion system for a SSTO vehicle. As seen before, the best option would be an hybrid engine capable of providing excellent performance over all the flight envelope, but the problem with this design is its current feasibility.

The spaceplane appeared as a way to reduce drastically the cost of each kilogram of payload carried to space. In this days, with an economic crisis affecting the whole world, this necessity of a "cheap" way of reaching Earth's orbit is more urgent than ever, so the development of a propulsion system has to be done with the current technology. Here is where the British company *Bristol Spaceplanes* has focused their designs. They are developing a platform that could be built entirely with technology available currently, as opposed to the combined cycle engines, which being the optimal option, need a huge investigation in the materials and the final layout that would implement.

Having all what has been said before into account, the main purpose of this thesis will be the implementation of the propulsion system selected by Bristol Spaceplanes in Ascender. The engine models (turbojet and rocket) will be incorporated to a *Simulink* model of the whole aircraft in order to create an autopilot system for the spaceplane that will allow it to perform its mission in an optimal way. Moreover, the incorporation of a Thrust Vector Control System will be studied in order to improve the controllability of the aircraft during the final phases of the flight where the density is very very low ($2.8 \cdot 10^{-4}$ at 60.000 km).

3   Mission Requirements

The Ascender is a spaceplane created to reach orbit altitudes and then glide back to ground without completing a whole orbit around the planet, so it is considered a sub-orbital aircraft. According with the mission information provided on [15], the Ascender reaches an altitude of 100 kilometres and a top speed of Mach 3.6 when its returning to the ground. So with the information provided by the company, the model to be design will have a limitation on the aircraft velocity that has to be taken into account when the autopilot is created.

According to the mission that will be performed, the requirements set by the company that have to be considered during this project and that will mark its evolution are:

- Mission to be carried out by the spaceplane Ascender, which geometric information and the list of weights have been obtained from the company and from the data stored in its webpage [15].

- Aircraft fitted with two types of engines, each one of them used for a certain phase and required to reach certain flight conditions: (8 km with the turbojet and 100 with the rocket).

- The thrust requirements and the designed controllers for Ascender have to fulfil the main goal of this flight: the top altitude. This is the purpose of the project carried out by Bristol Spaceplanes, which wants to create a platform for space tourism and the launch of small satellites. This condition is the only one to be accomplished compulsory, while the speed is only set in the documentation as a maximum limit, being possible to perform the mission with lowers Mach number, considering that there is not anything established about the mission time (in the project is limited by the amount of fuel of both engines).

4 Thrust Characterization

The firs step to take in the development of this project is to obtain the thrust value for both the turbojet and the rocket, that will allow the Ascender to perform its final goal: reach an altitude of 100 km.

This task will be perform through a 2D trajectory calculation in which the engine power will be varied until each step of the aircraft mission is accomplished. So in this section, besides the thrust characterization, the whole mission of the Ascender will be explained in detail. There is no need to get involved in a 3D trajectory because considering the uncouple between longitudinal and lateral motion, it can be considered that the whole mission is performed in the same plane. Moreover, any of the objectives or limitations are related with the lateral/directional motion so at this point they will not be considered (it will be included in the six degree of freedom model of the aircraft).

There is another important thing to consider. Because of the early stage of this spaceplane design, there is no information available for the aero-derivatives and the control effectiveness. In order to overcome this obstacle, and considering that the study carry out in this section could be considered as a first approximation, the effect of the control surfaces will be applied directly with the values of the moments, i.e in order to achieve a certain climb angle for example, a certain value of pitching moment will be introduced in the model without any consideration about how this moment has been created. So the objective of this trajectory calculation is to vary moments and thrust in order to perform the desired mission having at all time reasonable values for the aircraft attitude angles, angular rates and velocities.

4.1 Trajectory Calculation

The trajectory of the spaceplane has been split in three different sections: first the ascendant flight propulsed by the turbofan, second the rocket steep climb and finally the unpowered gliding. For each one of these different phases, a Simulink model has been created and solved according to a set of input that will be detailed in this document.

4.1.1 Equations

The first step is to describe the equations that are solved by the Simulink block "Simple Variable Mass 3DOF (Wind Axes)". It solves the motion of the aircraft in the two dimensional case, having three degrees of freedom: two for the position of the CG of the vehicle and one for the rotation of it. The equations are presented in expressions (11) to (5).

$$\dot{V} = \frac{F_{x_{wind}}}{m} - \frac{\dot{m}V_{re_{x_{wind}}}}{m} - gsin(\gamma) \tag{1}$$

$$\dot{\alpha} = \frac{F_{z_{wind}}}{mV} + q + \frac{g}{V}cos(\gamma) - \frac{\dot{m}V_{re_{z_{wind}}}}{mV} \tag{2}$$

$$\dot{q} = \dot{\theta} = \frac{M_{y_{body}} - \dot{I_{yy}}q}{I_{yy}} \tag{3}$$

$$\dot{\gamma} = q - \dot{\alpha} \tag{4}$$

$$\dot{I_{yy}} = \frac{I_{yy_{full}} - I_{yy_{empty}}}{m_{full} - m_{empty}}\dot{m} \tag{5}$$

The diagram with the relative position of the three reference systems (earth, body and wind) along with the angles that represent the attitude of the aircraft is shown in figure 20.
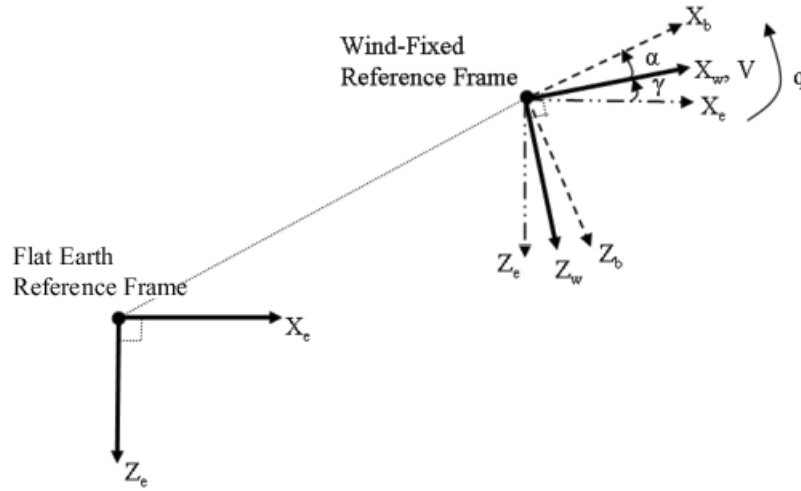
Figure 20: Reference Systems

In this case, the axis system use as reference is the wind one. That means that the forces that act on the aircraft have to be represented in this system. Figure 21 shows a diagram with the forces acting on the center of gravity and the decomposition of the forces in order to have a representation with respect to the wind axis system.

Figure 21: Forces Diagram

Considering the previous picture, the balance of forces in X_w and Z_w is represented in expressions (6) and (7).

$$X_w \rightarrow T\cos\alpha - D - W\sin\gamma \tag{6}$$

$$Z_w \rightarrow W\cos\gamma - T\sin\alpha - L \tag{7}$$

These two sets of forces represent two of the inputs of the block that solves the equations of motion. Figure 22 shows the Simulink block, where these and the rest of the inputs and outputs can be observed.
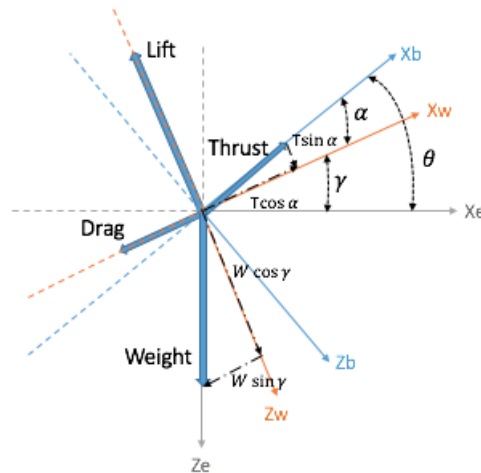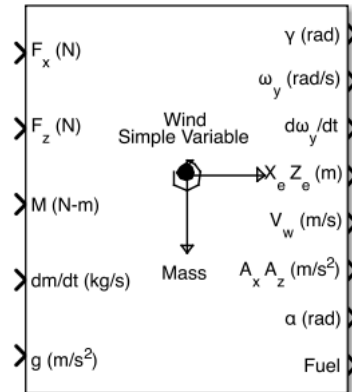

Figure 22: 3 DOF Equations Block

The variation of the flow will be the fuel consumption rate provided by the propulsion block that will be detailed later, the acceleration of the gravity will be kept constant at a value of 9.81 m/s^2.

As far as the outputs are concerned, the ones that are useful for the trajectory calculation are both the path and attack angles that are used for the computation of the forces acting on the aircraft, the position with respect to the Earth surface (X_e and Z_e) and the wind velocity.

Simulink also provides the option of changing some parameters related with the mass and inertia parameters of the aircraft and the initial values for the angles, the velocity and the position. In this case it will be considered that the aircraft starts its trajectory at the end of the runway, where it has a certain velocity, a zero path angle and a certain value for the angle of attack according with the position of the wings on the fuselage. The values selected for the Ascender trajectory are presented as follows (the inertia values have not been calculated, but chosen from similar aicrafts).

- Initial Velocity: 100 m/s

- Initial γ: 0°

- Initial angle of attack: 3°

- Initial position: [0 m, 0 m]

- Full mass: 5500 kg

- Empty mass: 2600 kg

- Full inertia: 50000 kg m^2

- Empty inertia: 40000 kg m^2

4.1.2 Turbofan Phase

The Ascender mounts two turbofans that are used for the take-off and the ascension to an altitude between 7-8 kilometres. In this section the trajectory of this stage will be computed and the thrust requirement to perform this mission will be obtained.

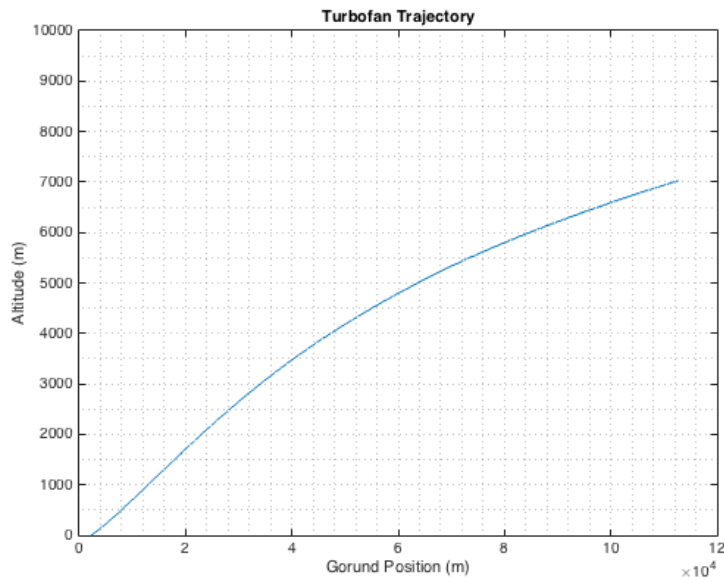The trajectory of the aircraft is presented in figure 23.

Figure 23: Trajectory (Turbofan)

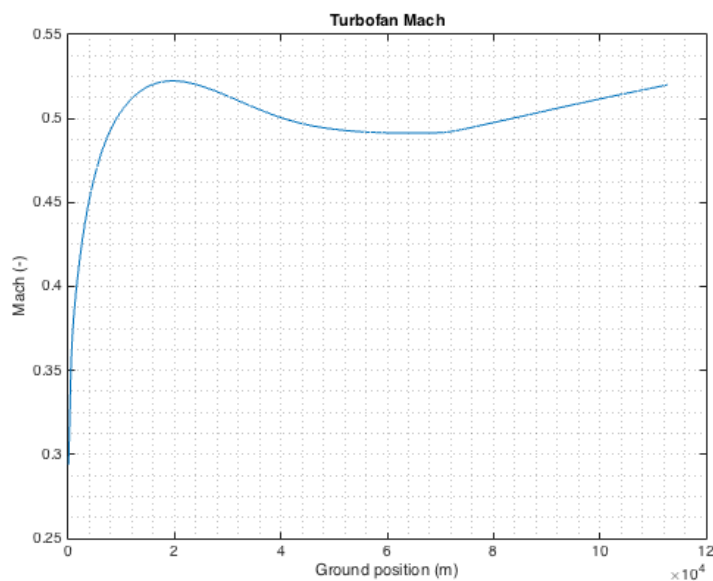The Mach number of the aircraft is shown in image 24.

Figure 24: Mach Number (Turbofan)

Finally, the three angles that indicate the attitude of the aircraft and its direction are represented in figure 25.
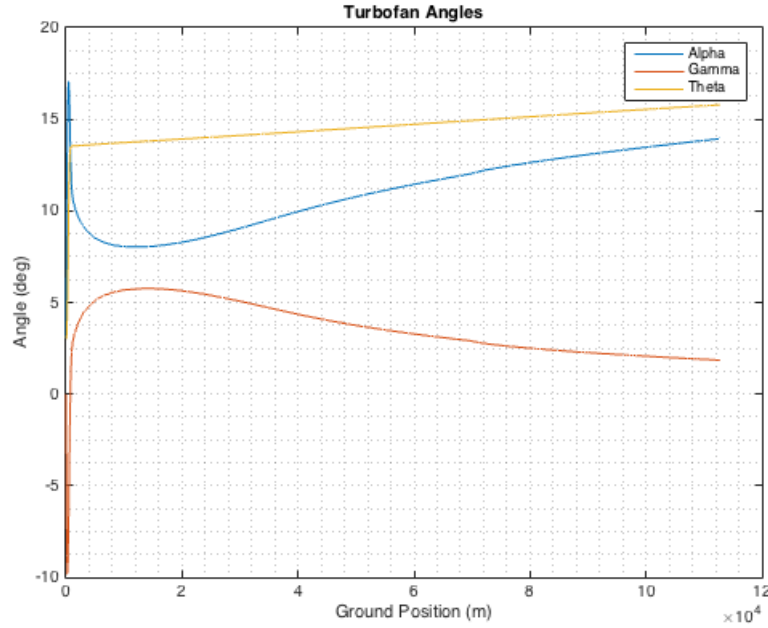
Figure 25: Angles (Turbofan)

The propulsion system for this trajectory has been modelled with the block provided by Simulink for this task. The parameters that characterize the turbofan used are presented as follows.

- Thrust (sea level): 45000 N

- SFC: $8 \cdot 10^{-5}$ kg/s·N

So, considering that the Ascender has two turbofans, the engine that will be suitable to perform the required mission should provide **22500 Newtons** of thrust and have a SFC of around $\mathbf{4 \cdot 10^{-5}}$ **kg/s N**.

4.1.3 Rocket Phase

When the aircraft is at 7 km of altitude, the pilot starts the rocket engine and begins a steep climb to reach the maximum height of 100 km. For this stage, the thrust provided by the engine has been considered to be constant since the beginning of this phase until the point where it is cut-off. To perform the trajectory calculation, the initial values for angles, velocity and mass are the ones from the last point of the previous situation.

The first graph show both the previous trajectory and the one performed when the rocket engine is working.
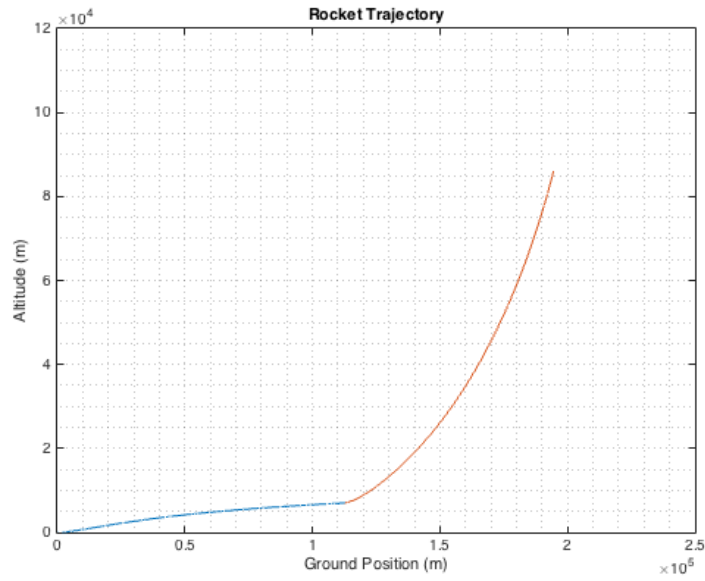
Figure 26: Trajectory (Rocket)

Figure 27 shows the Mach number of the aircraft during the rocket engine phase.
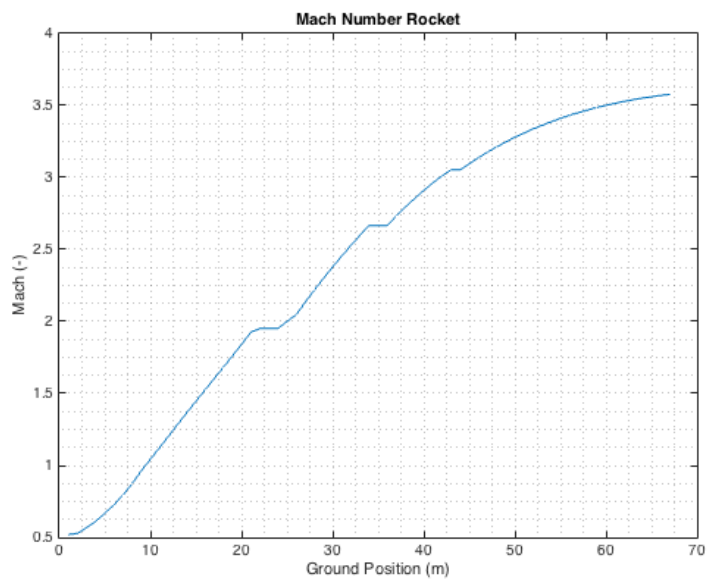
Figure 27: Mach (Rocket)

Finally, the three angles of the aircraft attitude and direction are represented in 28.
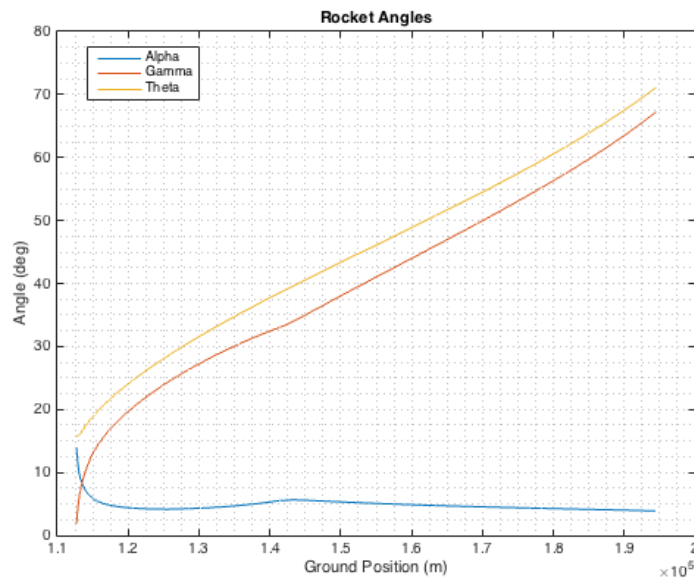
Figure 28: Angles (Rocket)

The values of the propulsion model use to obtain the desired performance are presented as follows.

- Thrust: 95000 N

- SFC: $1 \cdot 10^{-4}$ kg/s·N

4.1.4 Gliding Phase

In this phase there is not propulsion (turbofan or rocket), and the aircraft flies from the en of the rocket phase to the maximum altitude because of the inertia that it has.

This phase of the flight begins with a climbing to a height of 100 kilometres. During this stage the pitch angle is decreasing until zero (at top altitude). Then it continues going down until the desired gliding angle is reached, which will be followed during this phase until the landing.

The trajectory of the unpowered phase, together with the other two is represented in figure 29.
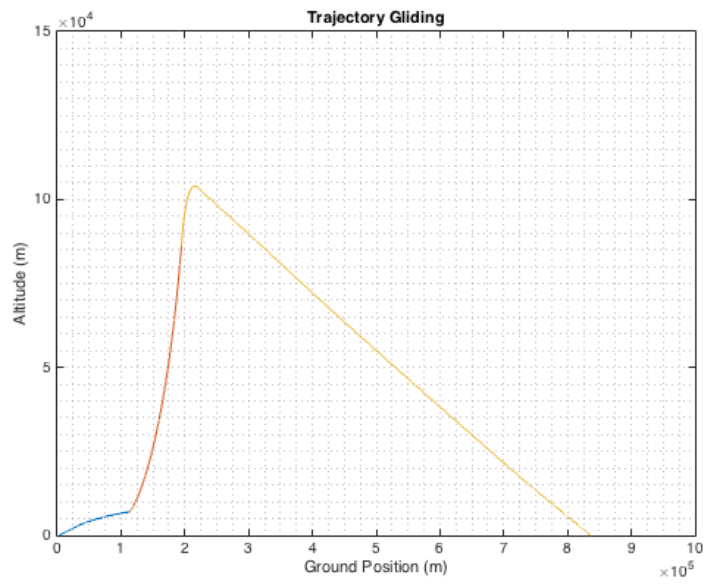
Figure 29: Trajectory (Unpowered)

The velocity of the gliding phase is represented by the Mach graph shown in figure 30.
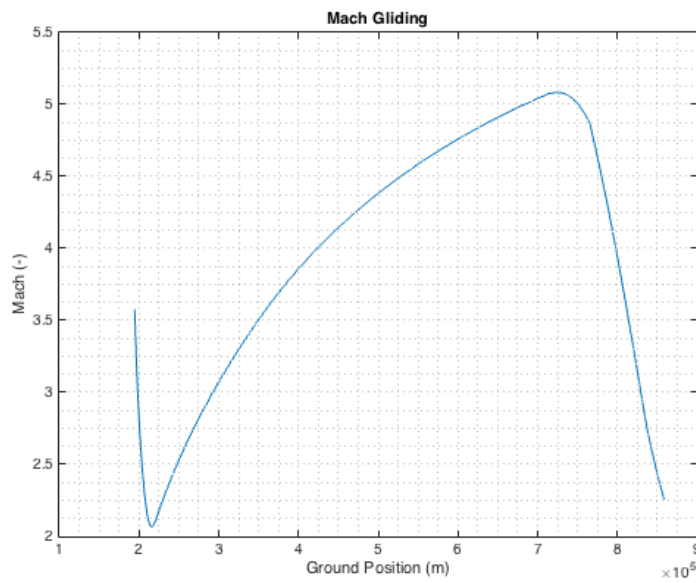
Figure 30: Mach (Unpowered)

The angles of this stage are shown in figure 31.
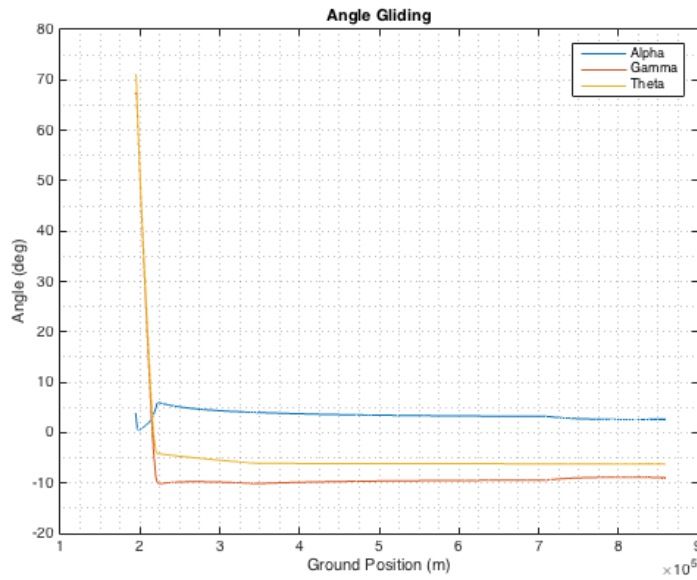
Figure 31: Angles (Unpowered)

5   Ascender Model

The design of the Ascender spaceplane is yet in a very preliminary phase, so there is not much information about it to create a proper model that could be used as a faithful tool of the aircraft behaviour. Taking that into account, a *Simulink* model of Ascender has been created having as a reference the 3D view of the aircraft that can be found in the company webpage.

5.1   Geometric and Weights Data

The figure 32 shows the 3 views of the Ascender spaceplane at the current stage of design.
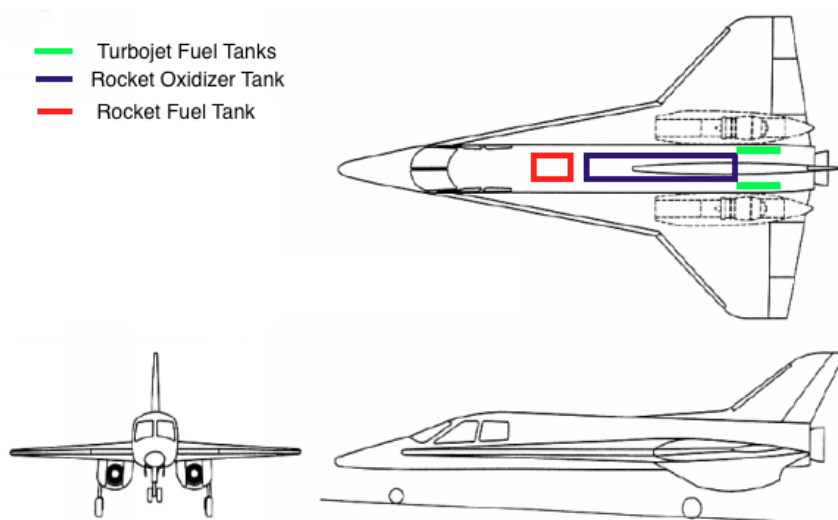
Figure 32: Ascender 3D View

All the measures of the aircraft have been taken from this image by measuring them directly on the views, considering a conversion rule taking as reference its spam (which is provided by the company). Regarding the weights, they have been obtained from a document provided by the company with the weights of another spaceplane, the Microsonic. To obtain the Ascender parts weights, the values have been scaled according to the MTOW. The position of the fuel tanks that appear on figure 32 have been assumed, considering the layout of the XCOR Lynx spaceplane, which has all the tanks in the fuselage.

The weight of wings, fuselage and so on, are used to estimate the inertia moments of the aircraft. Also to this process are needed the center of gravity from the whole aircraft and from each one of the elements separately. The table 5 contains all this information.

Element	Weight (kg)	X Position (m)	Z Position (m)
Fuselage Cone	70.72	2.7	0.2
Fuselage Body	426.05	8.39	0.31
Rocket	250	12.01	0.24
Turbojet (x2)	480	10.54	-0.61
Wing	379.7	9.59	0
Tail	65.29	12.54	1.84
Oxidizer Tank	2425.06	8.06	0.5
Rocket Fuel Tank	329.94	5.64	0.5
Turbojet Fuel Tank	177.8	10.48	0.5
Aircraft Systems	230.65	2.7	0.2
Nose Landing Gear	68.75	2.27	-0.44
Rear Landing Gear	206.25	9.76	-0.44
Operator Items	390.32	3.5	0

Table 5: Ascender Weights and CGs

The X positions are taken with respect to the aircraft nose, and the Z positions with respect to the wings level. The Y position is not considered because the aircraft is symmetric.

The inertia moments have been calculated through the expressions obtained from [19], where all the measures required in them are obtained from figure 32. Table 6 shows the inertia moment values for the three axis and XZ plane (the other two values are not considered because the symmetry of Ascender).

Element	I_{xx} $(kg \cdot m^2)$	I_{yy} $(kg \cdot m^2)$	I_{zz} $(kg \cdot m^2)$	I_{xz} $(kg \cdot m^2)$
Fuselage	6243	38630	36530	7911
Rocket	1025.78	37196	36186	6036
Turbojet (x1)	709.43	28461	28345.7	3325
Wing (Inboard)	1618	9426	9737	0
Wing (Outboard)	5741	27006	27503	1591
Tail	646	10972	10520	0
Oxidizer Tank	12382	171481	159529	43405
Rocket Fuel Tank	1684	12147	10521	4131
Turbojet Fuel Tank	453	10184	9747	2064
Aircraft Systems	3051	2855	1880	1268
Nose Landing Gear	123.5	482	360	208
Rear Landing Gear	366	20050	19686	2677
Operator Items	94	4875	4875	0

Table 6: Ascender Inertia Moments

The global values for the inertia and the center of gravity of the aircraft are presented as follows. It has to be taken into account that there are two different configurations: full (with all the fuel) and empty (without fuel), so the inertia and cg position of the fuel tanks will not be considered in the second case.

- Full Configuration

    - Center of Gravity: [7.94,0,02.5] m
    - Moments of Inertia: [24237,42663,46017,4175] $kg \cdot m^2$

- Empty Configuration

    - Center of Gravity: [7.96,0,-0.014] m
    - Moments of Inertia: [15787,35750,39320,4042] $kg \cdot m^2$

5.2   Simulink Model

The model of the aircraft has been created in Simulink, which provides a lot of very useful tools very to carry out simulations of aircraft performance through its "Aerospace Toolbox ". Figure 33 shows the whole Simulink model, that later will be explained in detail in this section.
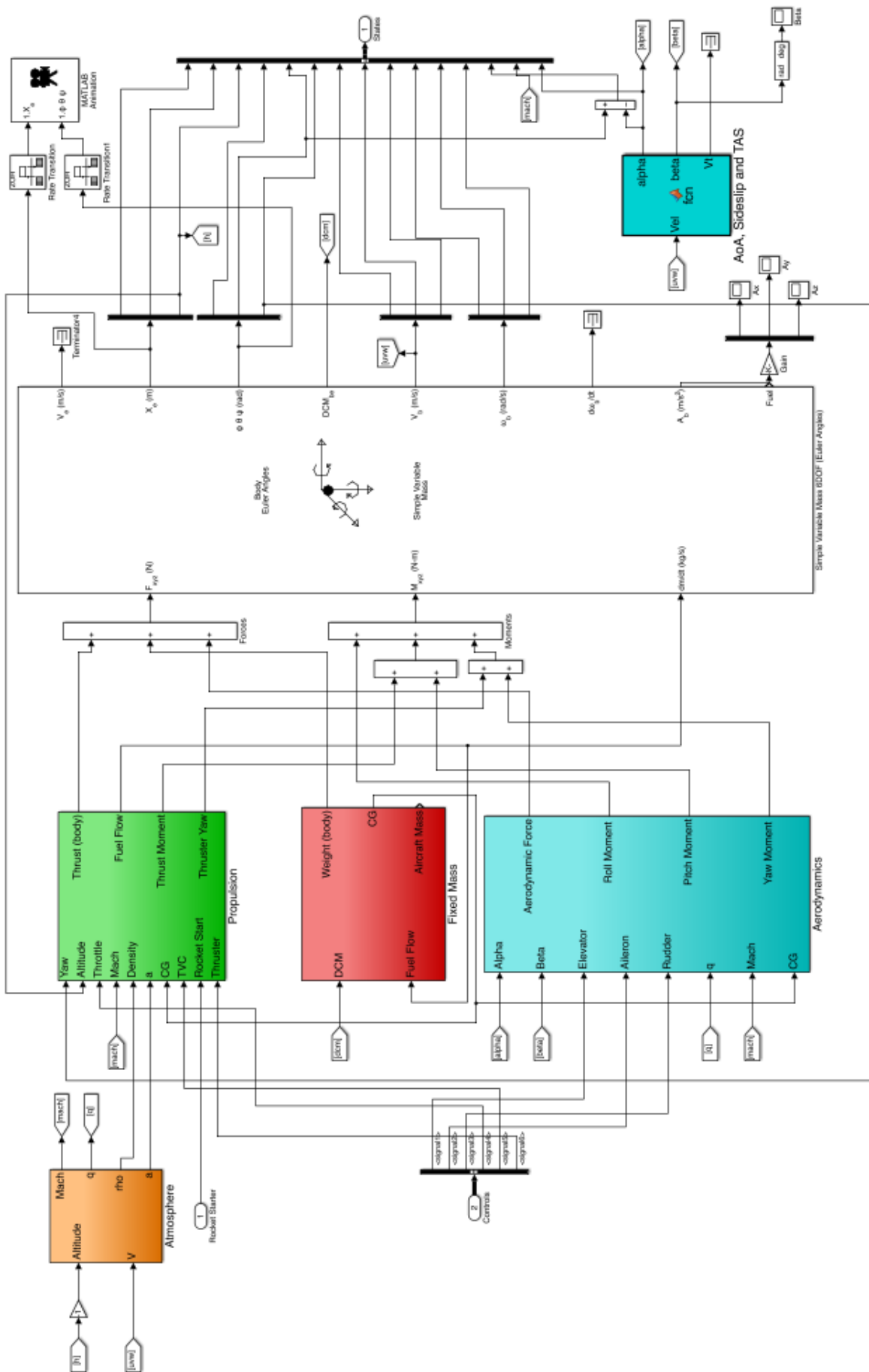
Figure 33: Simulink Model

The core of the model is the block that solves the six degree of freedom equations. Around it there are the blocks that calculate the aerodynamic, weight and propulsion forces, and the atmosphere parameters. In the following sections all these systems will be explained in detail.

5.2.1 Aerodynamic Forces

The aerodynamic forces that affect the aircraft are obtained from the aerodynamic coefficients and the geometry of the Ascender. Because at this design stage the aero-derivatives and control effectiveness have not been calculated yet, in order to generate a first estimation, the aerodynamic data of the Space Shuttle will be used due to the similar shape of both aircrafts: a spaceplane with double delta wing, without tail and three control surfaces (elevons and rudder). The figure 34 shows a comparative between the two aircrafts to highlight the similarities between them.
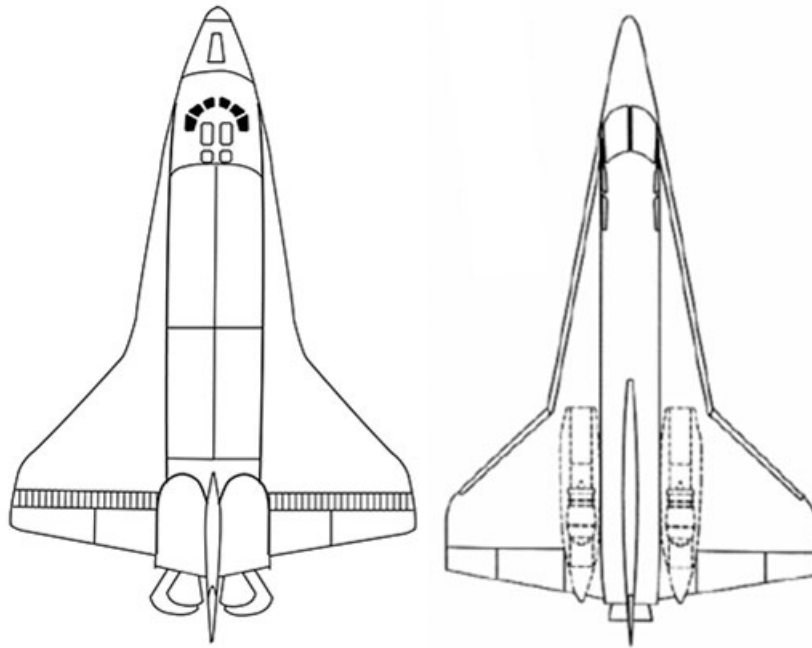
Figure 34: Space Shuttle - Ascender Comparative

It is appreciable that the wing shape is almost identical, and also the fuselage. The main difference is the engines position, and of course the size of both spaceplanes, but this effect is considered when calculating the forces and moments through the wing surface, span and mean aerodynamic chord.

The aerodynamic coefficients of the space shuttle have been obtained from [18]. In this document appear all the aerodynamic coefficients for all the possible conditions of flight: Mach number, angle of attack, angle of sideslip and control surface deflection.

In the longitudinal motion, the forces considered are the lift and drag. The lift is applied in the aerodynamic center of the wing and it varies with the Mach number, the angle of attack and the effective elevator angle (from the elevons movement). The expression used to obtain the total lift coefficient is: $C_L = C_{L_{basic}} + \Delta C_{L_\delta}$

The basic lift coefficient for the Mach numbers of flight reachable by Ascender is represented in figure 35.
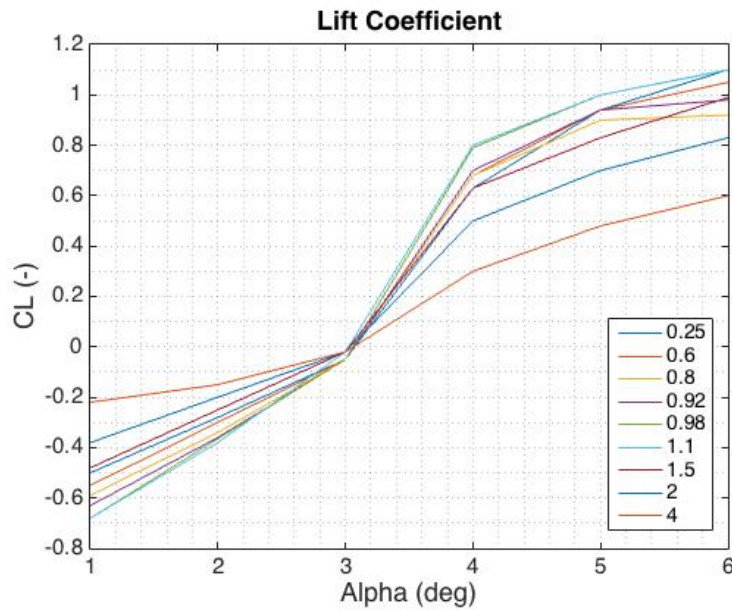
Figure 35: Basic Lift Coefficient

The contribution of the elevator to the lift coefficient depends on α, β and M. The figure36 illustrates the ΔC_{L_δ} variation for a Mach of 0.8.
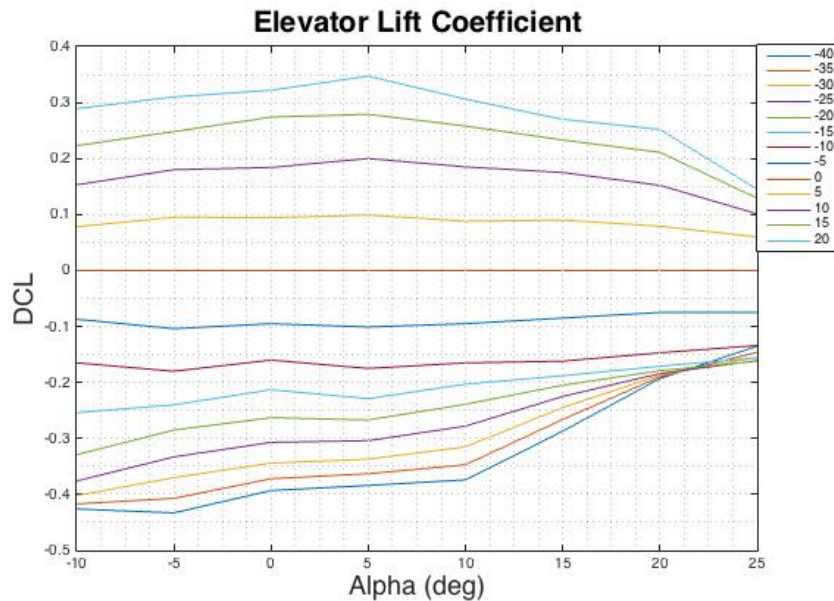
Figure 36: Elevator Lift Contribution (M=0.8)

The pitching moment produced by this forces is calculated by multiplying the forces times the distance from the wing aerodynamic center to the center of gravity.

$$M = (Lsin\alpha - Dcos\alpha)xCG + (-Lcos\alpha - Dsin\alpha)zCG + M_0 \qquad (8)$$

where M_0 is the zero angle of attack wing moment. This value is modified by the elevator deflection and is one of the mechanisms used to compensate the moment created by the aerodynamic forces and equilibrate the aircraft. The variation of this parameter is also taken from [18].

The forces and moments that form the lateral/directional dynamics of the Ascender have been obtained in the same way as detailed before for the longitudinal motion. In both cases, the coefficients are introduced in Simulink through LookUp Tables that interpolate the value from the inputs: wind angles, control deflections and Mach number.

The global model used to obtain the aerodynamic forces and moments is represented in figure 37.
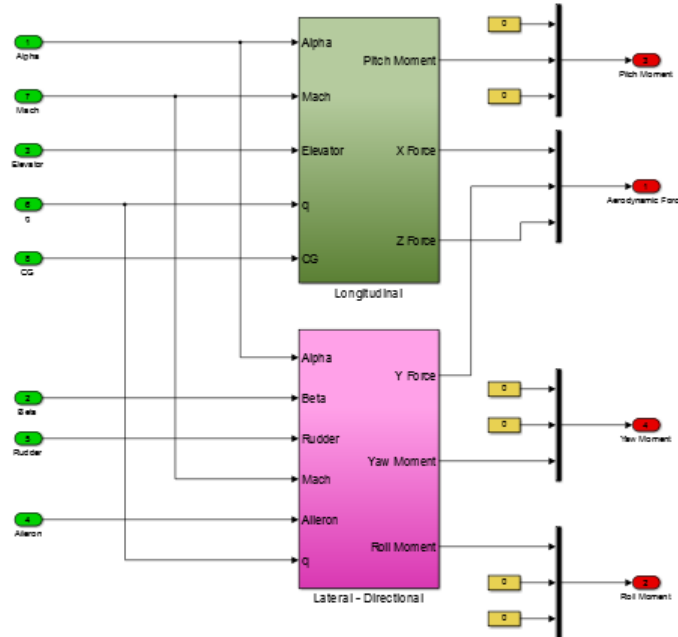
Figure 37: Aerodynamic Forces Subsystem

5.2.2 Propulsion Forces

The are three different propulsion systems on Ascender, each one of them with its own model: one corresponding to the turbojet engine, one to the rocket and another one for the thrusters.

The turbojet model is built from the expression (9), which considers the variation of the thrust with the velocity and altitude of the aircraft. Also the pilot has control over the thrust thanks to the throttle (τ).

$$T = \tau T_{sl}(1 + 0.7M)\frac{\rho}{\rho_{sl}} \tag{9}$$

The fuel consumption varies with the speed of sound and the thrust according to expression 10.

$$FC = SFC(\frac{a}{a_{sl}})T \tag{10}$$

The Simulink model that represents the turbojet engine is shown in figure 38.
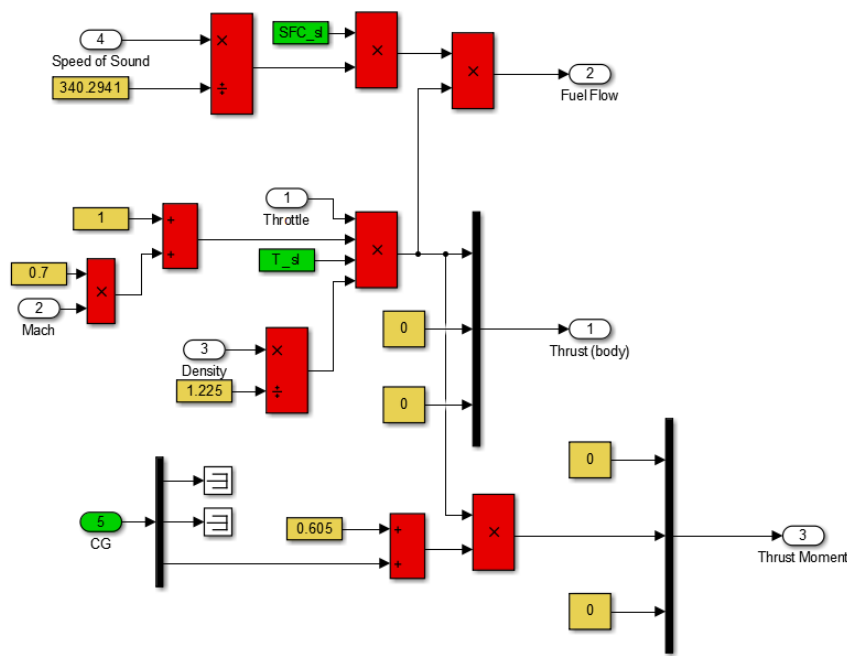
Figure 38: Turbojet Subsystem

The rocket engine thrust is considered to be kept constant during all the flight, and it is only modified by the throttle, which regulates the amount of oxidizer and fuel that goes into the combustion chamber. The fuel consumption is also considered constant for this engine.
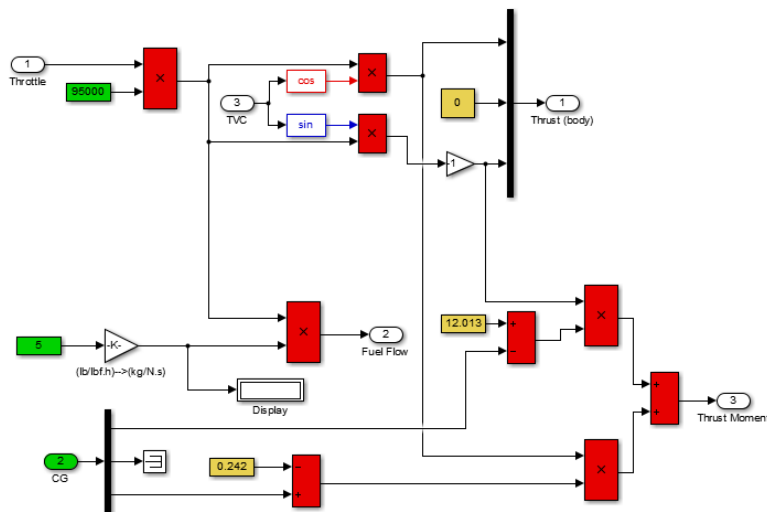
Figure 39: Rocket Model

In the previous figure, TVC is the angle that the thrust vector is deflected. Corresponds to the thrust vector control and its function in Ascender will be explained in following sections. On the other hand, the input "Rocket Start" is a variable used to simulate a switch used to change from turbojet to rocket propulsion.

Finally, the thrusters are also considered to have a constant value, only change by the throttle position. The fuel consumption is very low in this case, so it will not be considered. Figure 40 shows the Simulink model for this system.
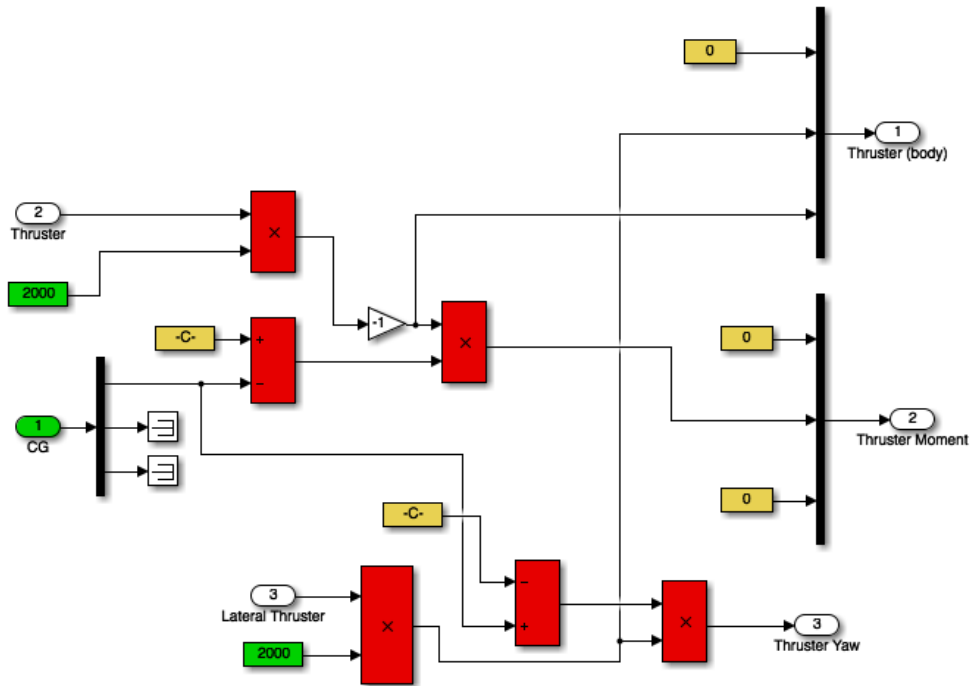
Figure 40: Thrusters Model

The global propulsion system with the three systems is represented in figure 41
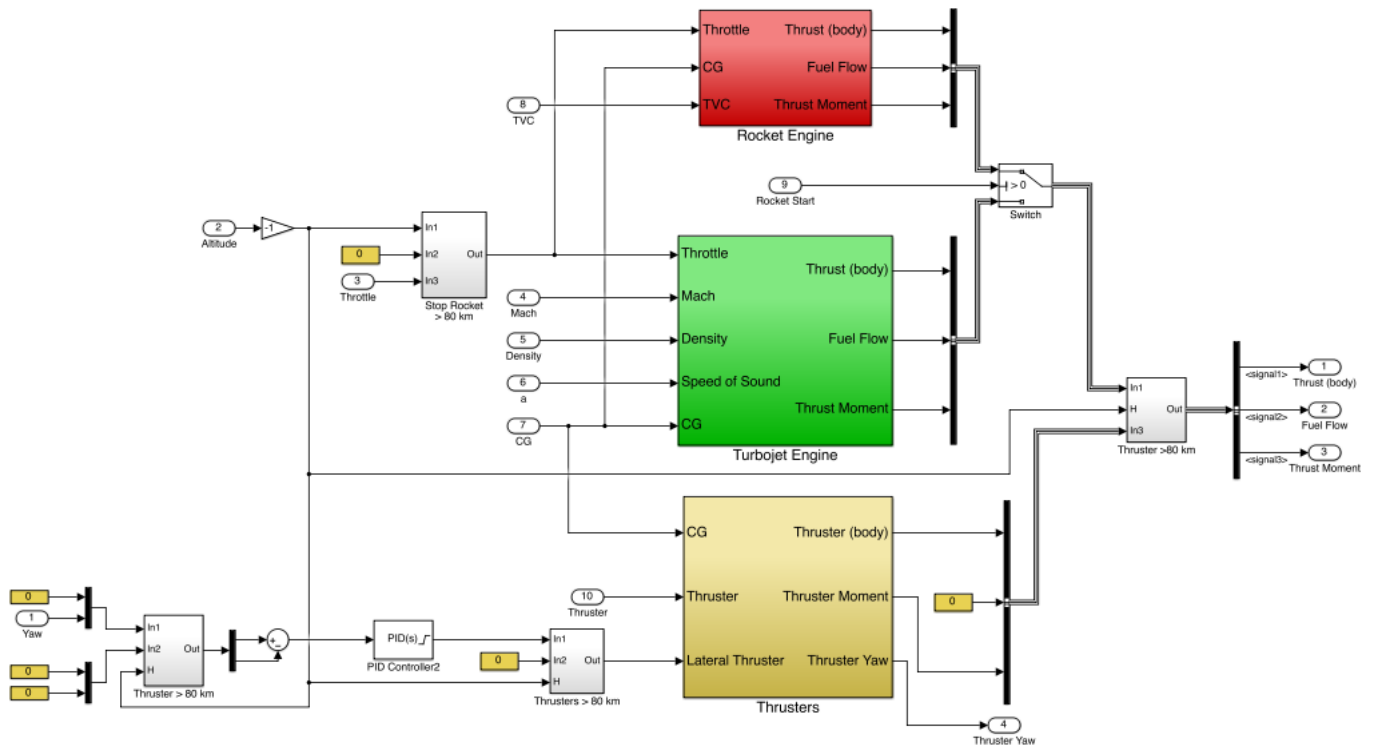
Figure 41: Propulsion System

5.2.3   Weight Forces

This subsystem calculates the weight force at each instant of time and the position of the center of gravity considering that it is moving constantly due to the fuel consumption.
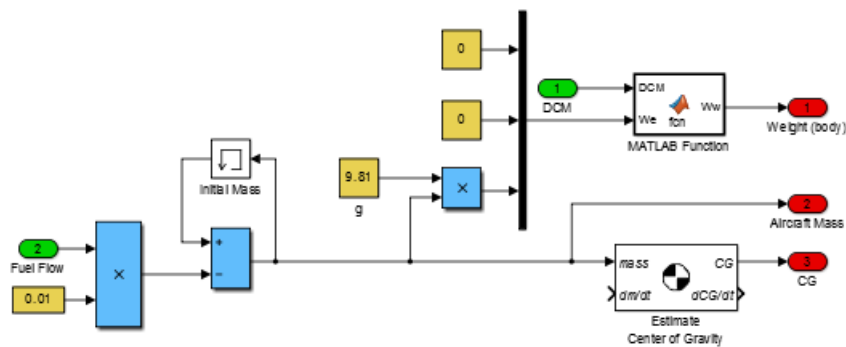
Figure 42: Weight Force

The fuel flow is multiplied by the simulation time step to obtain the amount of mass that the aircraft "loses" at each step. This value is subtracted to the current aircraft mass to obtain the current value. The weight vector, which has the direction of the z axis of the earth axes system, is then rotated with the director cosine matrix to obtain the weight vector components in the body axes system.

5.2.4 Atmosphere

Using the blocks provided by the Aerospace Toolbox, the atmosphere conditions, the Mach number and the dynamic pressure are obtained. Figure 43 shows the subsystem used to obtain these values.
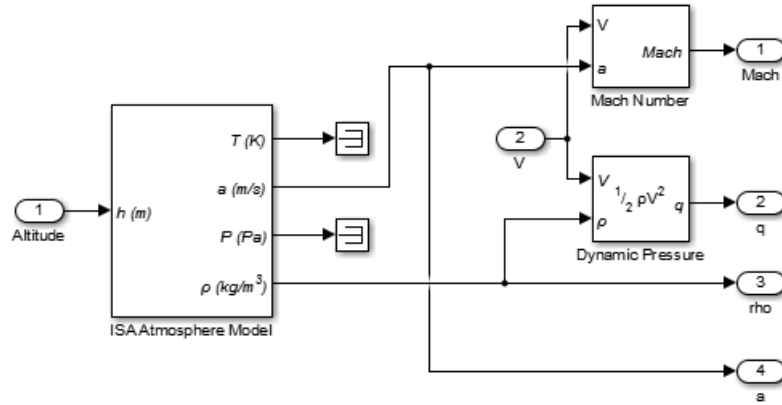
Figure 43: Atmosphere Subsystem

5.2.5 Wind Angles

This block calculates the angle of attack and sideslip and the total wind velocity, using the components of the velocity in the body axis system. The equations (11), (12) and (13) show the calculations performed in the Matlab Function Block.

$$V = \sqrt{u^2 + v^2 + w^2} \tag{11}$$

$$\alpha = atan\left(\frac{w}{u}\right) \tag{12}$$

$$\beta = asin\left(\frac{v}{V}\right) \tag{13}$$

6 Model Trimming

Once the model of the aircraft has been created in Simulink, the next step is to develop the trimming process that will determine the control inputs that have to be introduced to maintain a stable flight condition. This condition will be the start point for the simulations carried out in this project.

The aircraft trimming is done with the Matlab function "trim". This one generates the inputs, states and outputs for a flight condition (speed and altitude) and a set of initial values for angles and angular rates, which are forced to remain zero in order to a have a wings-level stable flight. The whole code for the trimming process is depicted in Appendix A.

The trim point will be considered as the beginning of the Ascender flight. Taking into account that the take off will not be simulated in this work, the trimming of the aircraft will be done at an altitude of **4000 meters** and a speed of **160 m/s**. With this condition, the control values that will guarantee a stable flight are represented in table 7.

Control	Value
Right Elevon	$-3.3°$
Left Elevon	$-3.3°$
Rudder	$0°$
Throttle	0.44

Table 7: Trim Controls

7 Autopilot

At this point, the Ascender model has been created and trimmed, so now it is possible to develop the autopilot system that will aid the pilot during flight.

The idea is to create an autopilot like in the case of commercial aircrafts. It is a simple system that allows the pilot to set an altitude or a speed and a also enables the creation of a route of waypoints that the plane follows during the cruise phase. In the case of Ascender, the autopilot will only be used during the turbojet phase because the main objective during the rocket climb is to reach the top altitude of 100 km, so there is not point there to fix an altitude, speed or follow a certain path. In this case the controller will be used to set a flight path angle and a Mach number.

On the other hand, the unpowered phase will also be fitted with an autopilot for the attitude control. Like in the case of the space shuttle, where is the autopilot the one who controls the thrusters during the re-entry to set an optimal angle, a system will be designed for this phase to control the pitch and yaw of the aircraft to improve the passenger experience during the flight back to Earth.

Figure 44 shows the complete model of Ascender including the controller for rocket, gliding and turbojet phase, the actuators and the command signals.
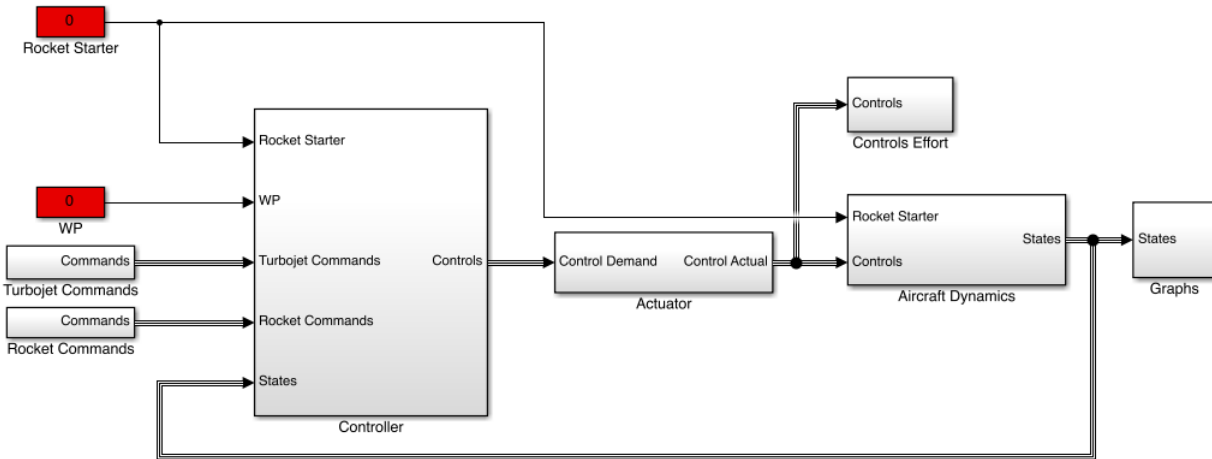
Figure 44: Ascender Complete Model

The figure 45 shows the subsystem with the three system controllers, and the blocks used for the transition between them according to altitude or switch position.
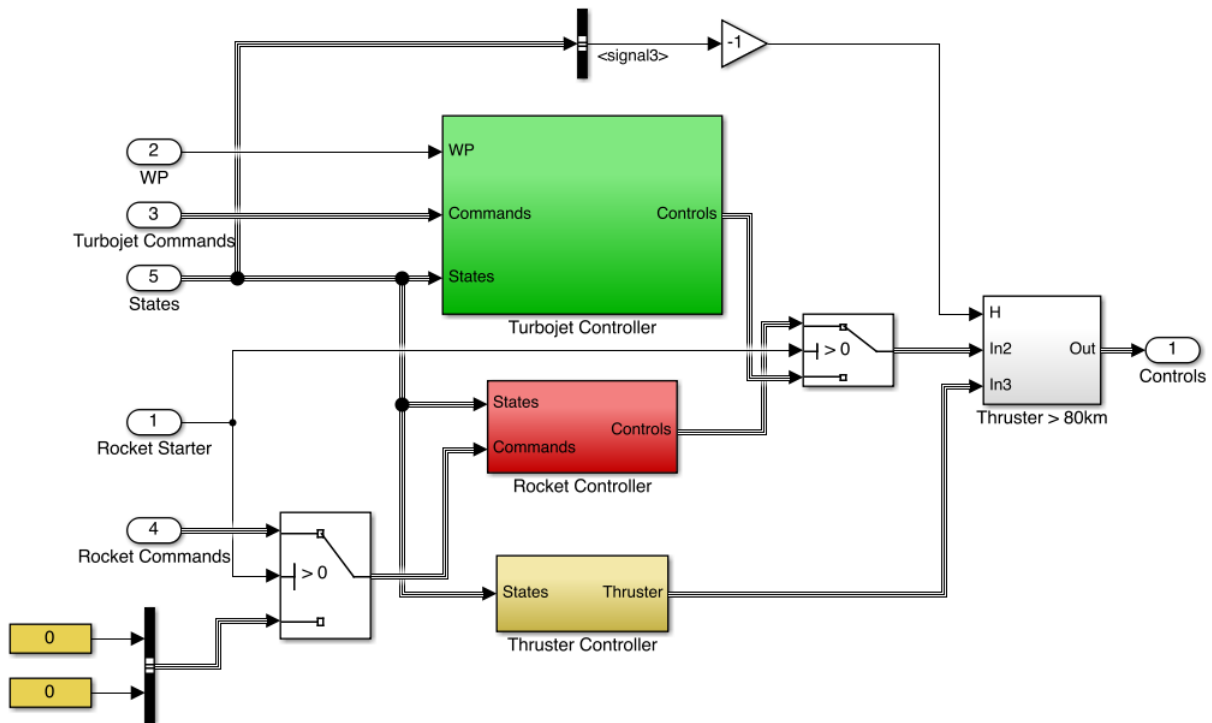
Figure 45: Ascender Controllers

7.1 Actuators Model

The actuators have been modelled according to the maximum rate that each one of them can produce when moves. The information about each control surface has been obtained from [18] and is presented in the following table.

Control	Deflection [min,max]	Max. Rate
Elevons	$-35°,20°$	20 deg/s
Rudder	$-22.8°,22.8°$	10 deg/s
Throttle	0,1	-
Thrusters	-1,1	-

The blocks used for the actuator system are presented in figure 46.
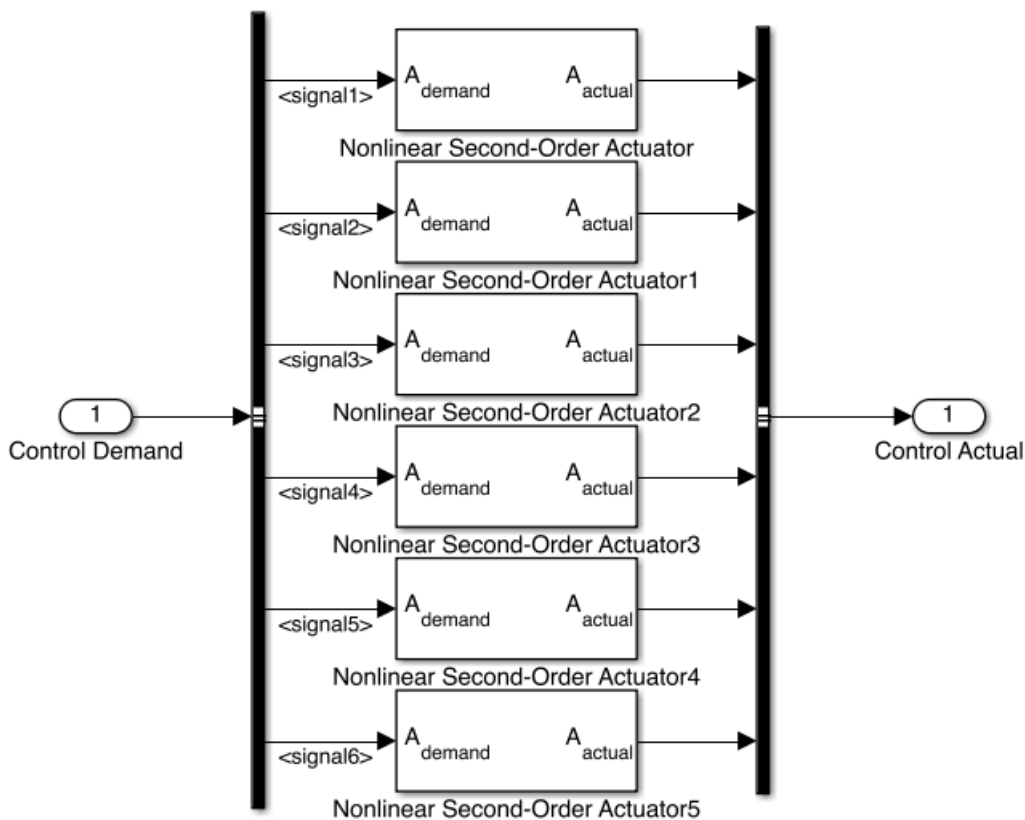
Figure 46: Actuator System

8 Turbojet Phase Autopilot

The turbojet autopilot is a system used to set a certain flight altitude and speed for Ascender to achieve. A series of PID controllers will be implemented to model the aircraft response in order to make it reach the desired values fast and exactly.

The turbojet autopilot will have two different modes: one where the heading is set by the pilot and will be followed by the aircraft, and another one where the pilot introduces a set of waypoints and the aircraft automatically changes its heading to reach them. In both operation modes the altitude and speed can also be varied by the pilot. Figure 47 shows the structure of the controller

for this phase.
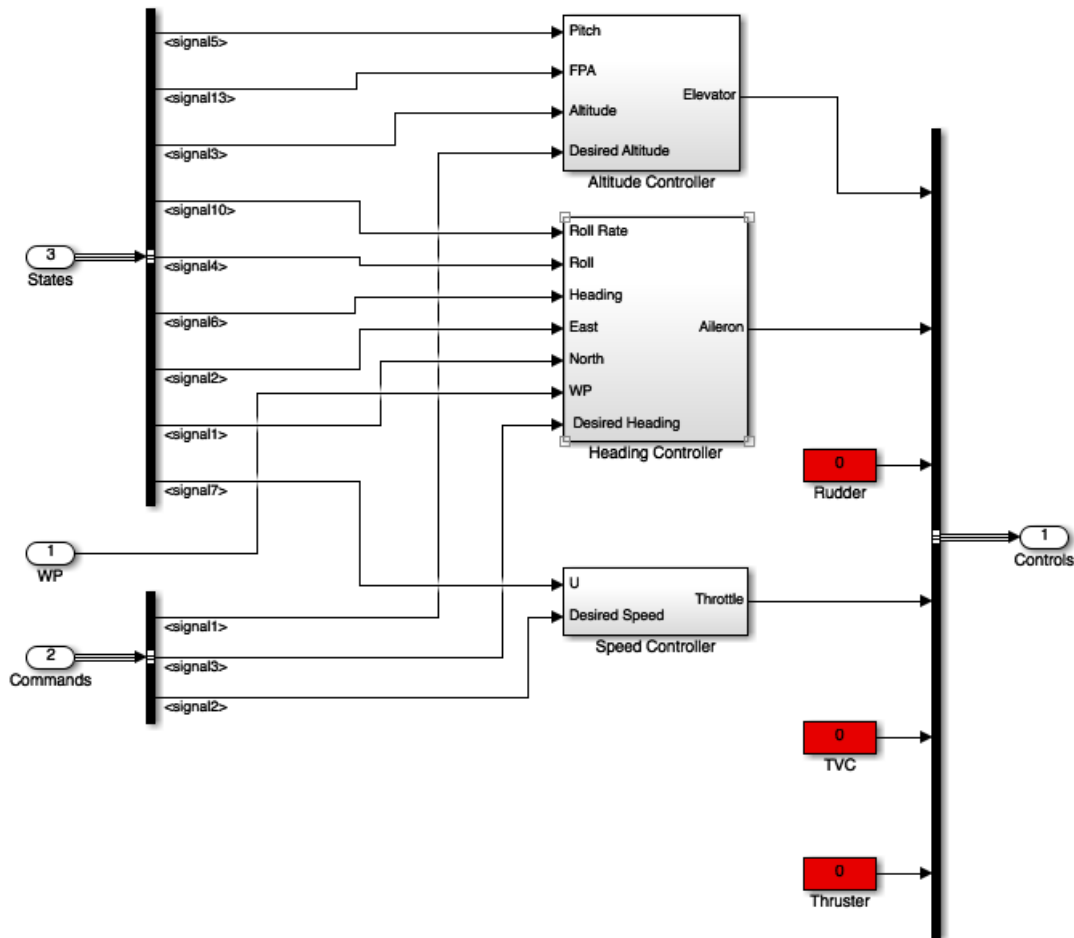
Figure 47: Turbojet Autopilot System

The controller block contains the PID controllers used to make the aircraft follow the parameters set by the pilot. During the turbojet phase, there are four controls: elevator, aileron, rudder and throttle (elevator and aileron as a combination of elevon deflection), so each on of the commands will be controlled by a different control. The speed will be controlled by the throttle, the altitude with the elevator and the heading with the aileron.

In the following sections, each one of the control channels will be detailed and the tunning parameters for each controller will be presented. The tunning process will be carried out with the PID block provided by Matlab. Afterwards, the gains will be adjusted manually when performing a series of simulations.

8.1 Speed Controller

The forward speed of Ascender (u), will be controlled by the throttle position. The best choice for the controller design has been the proportional-integral controller with the gains presented in table 8.

	Proportional	Integral
Gain	0.25	0.0005

Table 8: Speed Controller Gains

The Block configuration for this controller is presented in figure 48.
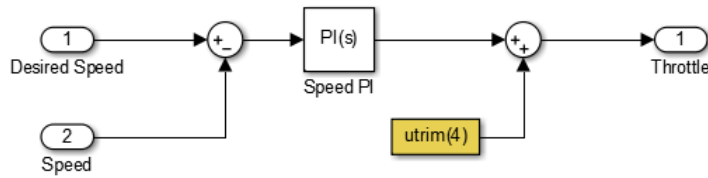
Figure 48: Speed Controller

In order to observe the system response, a series of speed commands will be sent to the controller and the reponse of the system will be represented in order to check the Ascender behaviour to the pilot inputs. Figure 49 shows U time history.
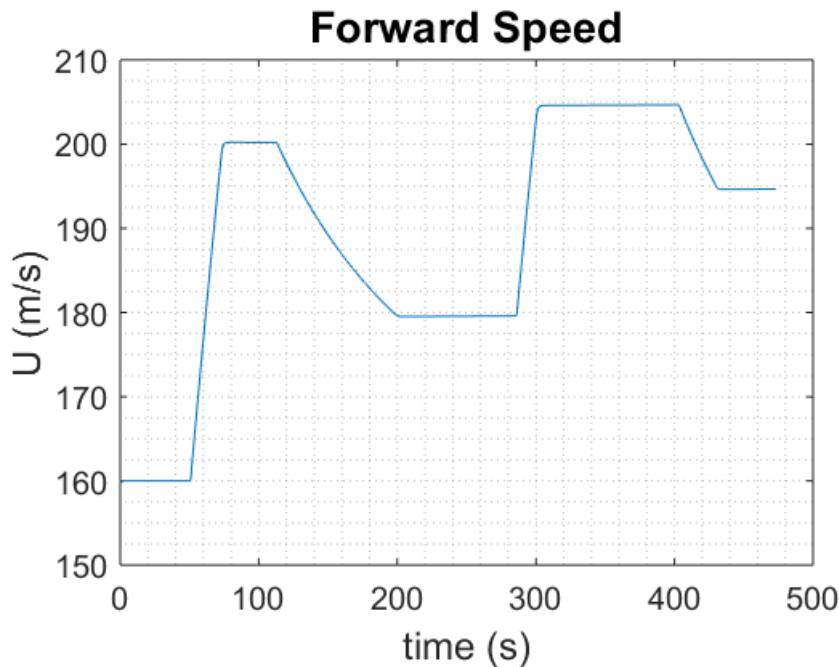
Figure 49: Speed Response

The simulation begins at the trim speed: 160 m/s. Then an acceleration command is sent to set U to 200 m/s, later a deceleration until 180, another acceleration to 205 and finally a command to set the speed at 195 m/s. It is observed in the figure that all the commands are reached with practically no error. There is only an small difference when the velocity is decreased because the deceleration has to be carried out by the drag force and is something not controlled by the pilot.

8.2 Altitude Controller

The control of the aircraft altitude will be done trough the flight path angle. The altitude error will be applied to a PID to produce a value for the desired path angle. Then the flight path angle will be calculated and introduced in another PID to generate a desired pitch that will go through the final PID to obtain the elevator deflection that will make the aircraft climb or descent to the desired altitude. Figure 50 shows the blocks that conform the altitude controller.
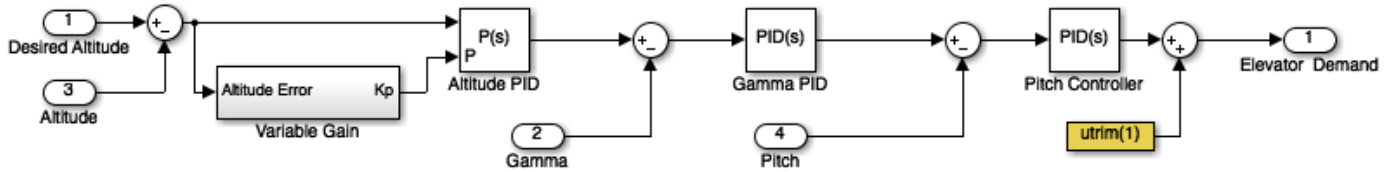
Figure 50: Altitude Controller

The pitch controller will have proportional, integral and derivative effect, the flight path angle controller will also have the three effects (P,I and D), and finally the altitude controller will have a P controller with a variable gain. This one will depend on the difference between the current altitude of the aircraft and the desired altitude commanded by the pilot.

The gains for the pitch rate and flight path controllers are presented in the table 9.

	Proportional	Integral	Derivative	Filter
Pitch	-1.5	-0.25	-0.75	1000
Flight Path	0.956	0.386	-0.431	2.218

Table 9: Flight Path/Pitch Rate Gains

The altitude controller will have a P controller with a variable gain that depends on the altitude error. This option has been choose because the size of the error in this case is very different depending on the commanded altitude, i.e it is not the same climb from 4000 to 4500 meters than climb until 8000. If K_p is kept at a constant value, the system will lead to a malfunction when the error is big, so the proportional gain is varied according to the error size: for small error values the gain is big and for big error it is small. Figure 51 shows how this method has been implemented in Simulink.
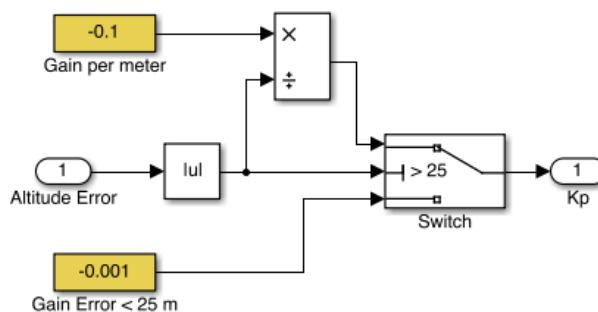
Figure 51: Variable Gain System

When the aircraft is close to the commanded altitude, the gain will tend to huge values (even infinity), so when Ascender is 250 meters far from the objective, the gain is set to a constant value in order to avoid a failure in the system. Figure 52 shows the time history of the spaceplane altitude, when a set of altitude commands have been sent to the system.
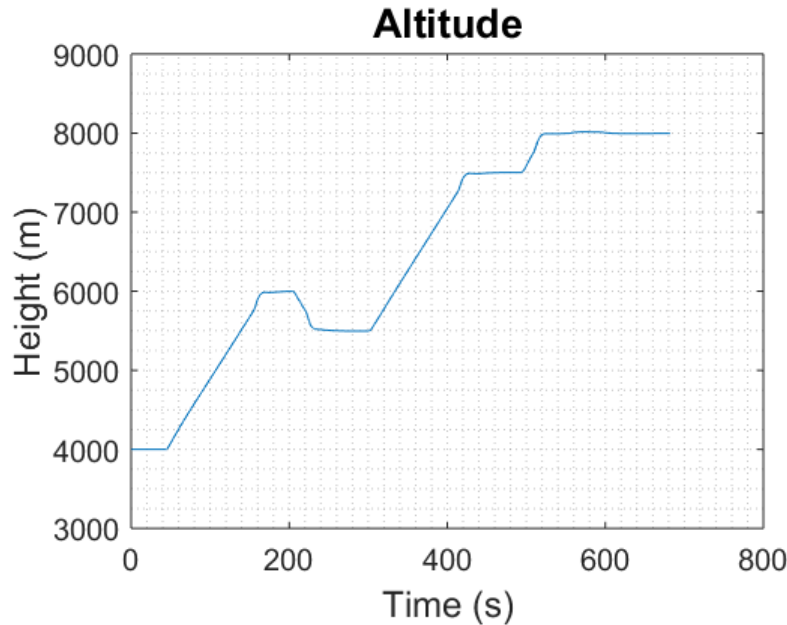
Figure 52: Altitude Response

The series of desired altitudes commanded to the aircraft are: 4000, 6000, 5500, 7500 and 8000. It can be observed on the graph that the values are reached with an error almost zero, and that the time that it takes Ascender to climb is also reasonable, having a rate of climb (RoC) between 15 and 20 meters per second.

8.3 Heading Controller

The heading controller will make the aircraft follow a commanded heading angle by moving the ailerons (which result from a combination of the elevons movement). The heading introduced in the controller can come from both sources: a constant value directly indicated by the pilot or a varible heading which comes from the waypoint following system. figure 53 shows the block diagram of the heading controller implemented in Simulink.
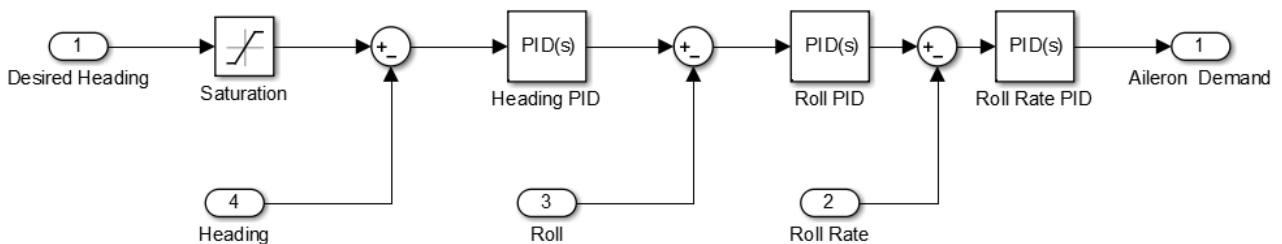
Figure 53: Heading Controller

The heading error produced when a command enters in the system generates a desired roll angle after going through a PID controller, this roll angle compared with the actual roll will generate a roll error that is introduced in the controller to generate a desired roll rate. This one will finally produce the aileron command to be sent to the control surface to achieve the desired heading. Table 10 contains the gains of the three PIDs that form the heading controller.

	Proportional	Integral	Derivative	Filter
Roll Rate	1.46	5.48	0.096	2144.63
Roll	0.17	0.0029	-0.0082	20.83
Heading	1.18	0.00076	-2.58	0.27

Table 10: Heading Controller Gains

In order to check the response of the controller, a set of heading angles will be commanded and the response will be recorded to see the heading controller behaviour. Figure 54 shows it.
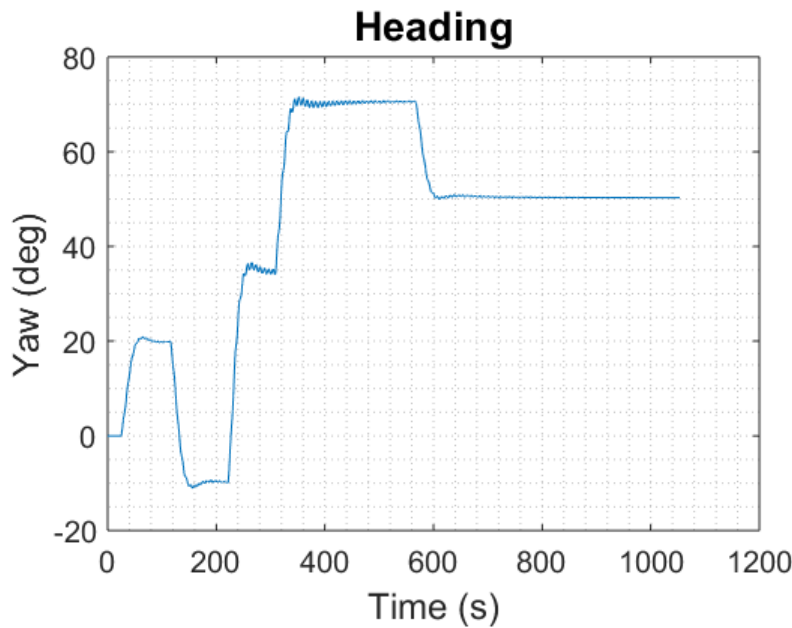
Figure 54: Heading Response

The series of commanded heading angles is: 20, -10, 35, 770 and 50 degrees. In all cases it takes a very little time to Ascender to reach the value. The problem arise in the settling at the value as there are oscillations around it for a certain amount of time. Actually, this oscillations can be ignored because is amplitude is quite low compared with the angle value, and also it can be seen that eventually they disappear (as in the case of 50 degrees). So, globally, the heading controller can be considered to provide a good performance.

8.4 Pilot Commands

The commands subsystem contains the variables that can be modifies and sent to Ascender.There are three different commands: altitude, speed and heading. The first two are establish by indicating its value, which can be changed during flight to make the aircraft climb, descent, accelerate and decelerate. On the other hand, the heading can be set as he other two variable, or the pilot can introduce the waypoints that form a route that is followed by the aircraft, and the heading will change automatically to reach each one of them. Figure 55 shows the blocks that form the Commands Subsystem in Simulink.
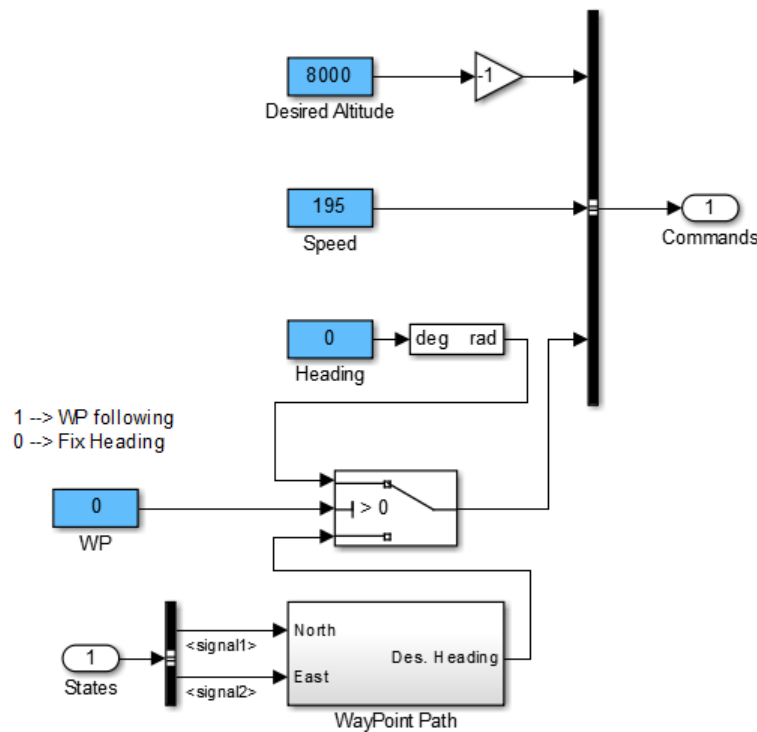
Figure 55: Commands Subsystem

In order to change the heading mode, there is a switch that allows the change between a constant heading and a path following. The waypoint block contains the Matlab code used to generate the heading according to the next point of the route. The heading is calculated using the current position of Ascender and the position of the following waypoint. The details about the algorithm and its implementation are in Appendix B.

9 Rocket Phase Controller

As was said in previous sections, in the rocket phase there is no need to set a waypoint route for the aircraft to follow, or to determine which will be the desired altitude and speeds. In this section the only objective is climb, and reach the top altitude of 100 kilometres, without exceeding a Mach number of 3.5 (structural limit). It is clear then that the controllers developed for the turbojet phase will not be used here, because the control needs are different. In this case, the variables that will be controlled are the flight path angle and the Mach number.

During the operation of the rocket, the purpose is climbing so it makes sense that the variable to control here is the flight path angle. The pilot will be able to select which will be the angle that Ascender will follow during this phase. Besides, the throttle will also be controlled to keep the Mach number under the limit of 3.5.

But in this phase there is another problem to overcome. As the flight altitude increases, the density becomes smaller and smaller. For example at 45.000 meters the density is 0.0018 (almost 500 smaller than the one at 8000 meters). This fact decreases the control surface effect as the aircraft climbs, because the low density makes the aerodynamic forces to have a negligible value. So at high altitude, the controller will not be able to keep the flight angle at the commanded value, because the elevator will not produce the force to keep that situation. To overcome this problem, a thrust vector control system will be modelled for the Ascender rocket engine.

The TVC deflects the thrust vector produced by the rocket engine. This deflection produces a force in a direction perpendicular to the aircraft longitudinal axis, making then possible to manoeuvre at the point where the control surfaces have no longer effect. How the deflection is created will not be studied in this project, it will be only considered that the pilot can control the deflection angle directly, making then possible to obtain a certain force in X and Z axes (and the corresponding moments).

After the simulations, it has been proved that after 20.000 meters the elevator can not achieve the FPA command sent by the pilot, so it will be at this altitude when the thrust vector control will start its functioning. Figure 56 shows the Simulink subsystem for the rocket phase controller.
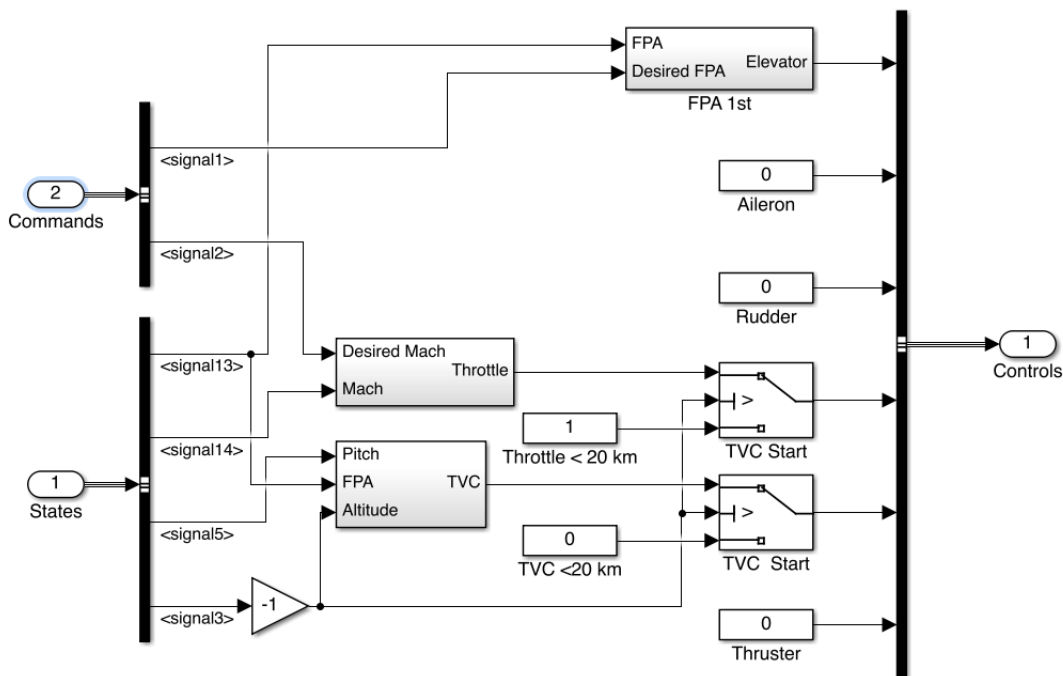

Figure 56: Rocket Phase Controller

9.1 Flight Path Angle Controller

The flight path angle controller will control the elevator and the TVC to produce a certain path angle for Ascender to follow. This operation will be divided in two controllers. First the elevator will be the control use, and then at an altitude of 20.000 meters, the TVC will begin to be controlled to keep the desired flight path angle. Above that height the elevator control will continue to work although its effect at big altitudes will be very small.

9.1.1 First Section (8-20 km)

The controller used in this stage will be a proportional one. Its structure is shown in figure 57.
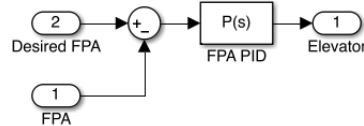
Figure 57: FPA Controller (8-20km)

The value of the gain is -0.7858.

9.1.2 Second Section (20-80km)

Once the elevator starts to lose its power, the TVC will start to control the flight path angle of Ascender. In this case the desired FPA, after being compared with the actual value, will be passed trough a PID controller to generate a command for the pitch controller, which will be the one to produce the value of the TVC. This structure has been choose because it has been proved that the pitch PID provides better response on the system than if the flight path angle controller is used directly on the platform. The FPA controller structure is represented in figure58.
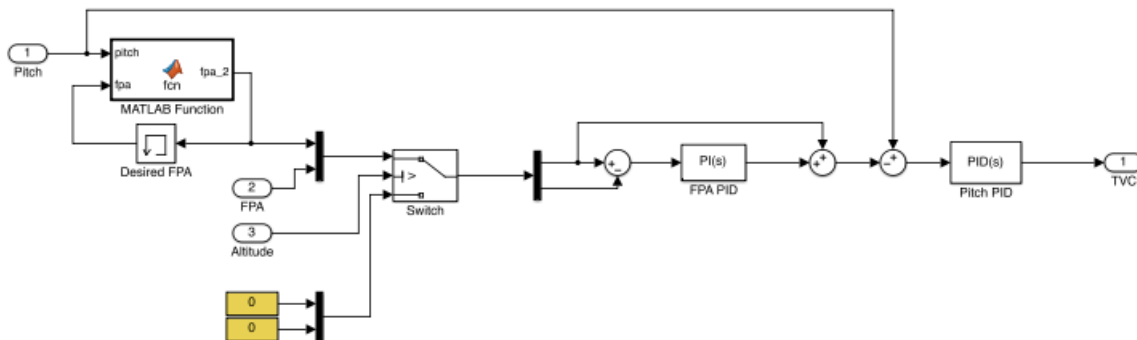
Figure 58: FPA Controller (20-80km)

There are a few details to explain in the previous figure about the structure of the controller. The yellow blocks are used to fed the system with zero values for the FPA and the desired FPA. With that, the error accumulation because of the effect on the integrator is avoided, when the altitude to begin the second stage of the rocket phase is reached, the commands for this controller start to flow into the PIDs.

On the other hand, the Matlab function that appears on the figure is used to bound the maximum pitch angle of Ascender. When a flight path angle is commanded, and because of the velocity

limitation set (Mach 3.5), the aircraft will increase the pitch angle to maintain the flight path, even to values higher than 90 degrees. To avoid this effect, when the pitch angle is 75 degrees or more, the desired FPA will slightly decrease its value to relax the demand on the controller and to keep the pitch angle under 90 degrees. The code used in this block is shown in figure 59.

```
function fpa_2 = fcn(pitch,fpa)

    % FPA is reduced when the pitch angle is greater than 75 degrees.

    fpa_2=fpa;
    if pitch>=75*(pi/180)
        fpa_2=fpa-0.005*(pi/180);
    else
        fpa_2=fpa;
    end
```

Figure 59: Pitch Limiting Algorithm

Finally, the gain for the two PID controllers that appear on figure 58 are presented in table 11. It has also to be highlighted that the command signal is fed forward to the point just before the PID block, because this control strategy improves the stability of the response, and in this case its use has proved it.

	Proportional	Integral	Derivative	Filter
Pitch	-7	0	-4	1000
FPA	1.4	0.4	0	0

Table 11: FPA PIDs Gains

9.2   Mach Controller

The Mach controller will use the throttle to keep the Mach number of Ascender to a value set by the pilot. This control does not have as primary objective to make the aircraft to fly at certain speed, it will be used as a way to keep the Mach under the maximum value supported by the structure. So the command of the pilot will be kept at 3.5 during the flight (it could be lowered if the operation needs it). On the other hand, the first section of the rocket phase will have a throttle value of 1 (maximum) because in the distance covered is not possible to exceed the Mach limit, and also because only with the maximum thrust level the elevator will keep its effect as much as possible.

The figure 60 shows the structure of the Mach controller.
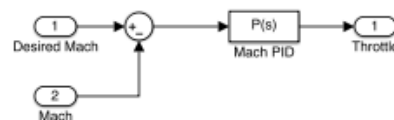
Figure 60: Mach Controller

The PID only has proportional effect, and its value is 1.2.

9.3   Rocket Simulation

The figure 61 shows a simulation of a rocket flight by Ascender. The value of the desired flight path angle has been set to 60 degrees and the Mach number to 3.5.
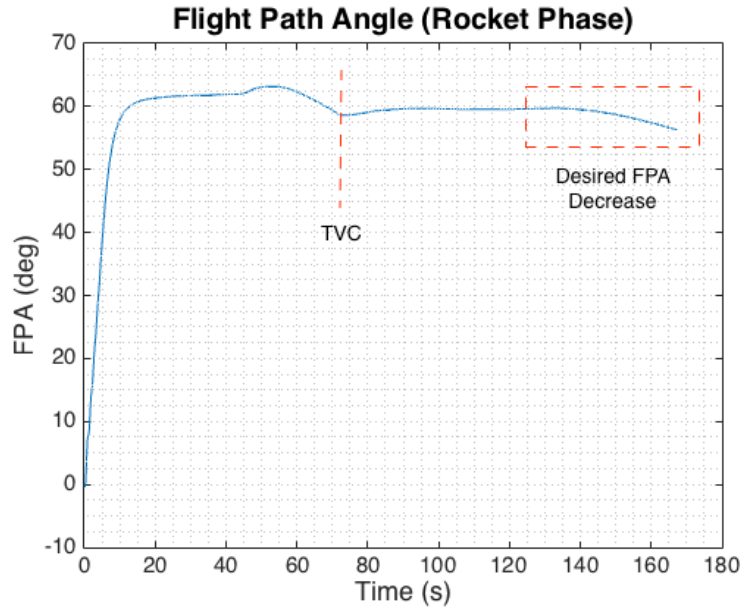
Figure 61: FPA (Simulation)

In the figure they are observed two important facts. First the point where the TVC starts its functioning, and second the decrease in the flight angle value in order to avoid and excessive increase in the pitch angle of Ascender. Regarding to the system response, it can be seen that the FPA is kept approximately to 60 at the first section (value not reached becuse of the elevator limitations), and exactly at 60 in the TVC section.

The velocity during this simulation is shown through the Mach number. The time history for this variable is represented in figure 62.
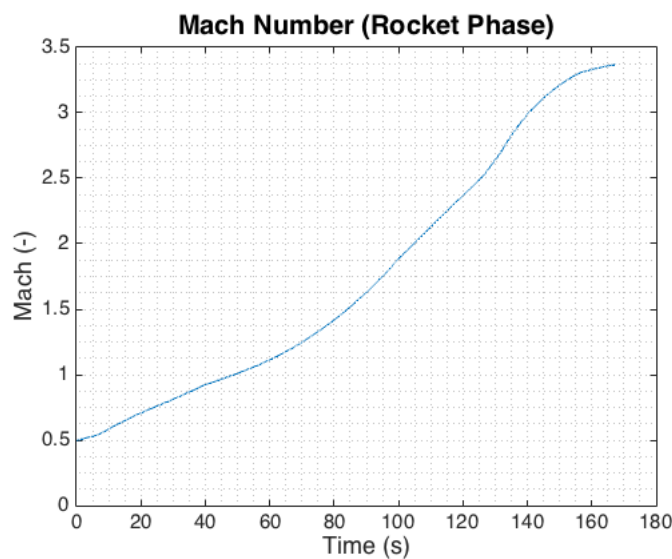
Figure 62: Mach (Simulation)

It can be seen that the limit establish by the designer is not exceeded.

10 Gliding Controller

Once the rocket engines are stopped at an altitude around 80.000 meters, Ascender will not have any propulsion system and its flight will be totally unpowered.

In this phase, all the controls shown previously can not be used (control surfaces, throttle or TVC), so the attitude control of the aircraft will be made through the use of a thrusters (small rockets) located in the "nose" of Ascender. There will be four rockets in total: two to control the pitch and two for the yaw. Its disposition is represented in figure 63.
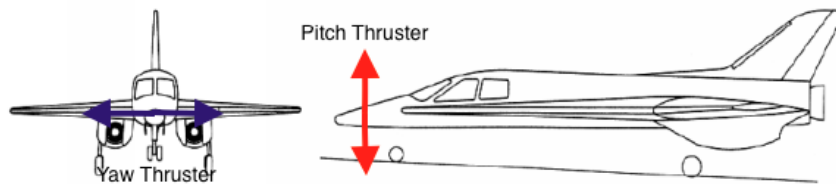
Figure 63: Thrusters

There are two thruster per system, one in each direction. In the controller, the direction is modelled with a throttle that varies from -1 to 1.

The ideal trajectory planned for this phase is that the aircraft will decrease its pitch attitude from the value of the rocket climb (around 60 degrees) to a value around 0. When the top altitude of 100 km is reached, the autopilot will use the thruster to level the aircraft, i.e make the pitch angle to be 0, allowing then the space tourists to enjoy the Earth vies from a comfortable position. Ascender will remain at this position during 90-120 seconds, then the thrusters will mad the aircraft to get a pitch attitude around-10 degrees that will carry during the descent into the atmosphere. Finally, at an altitude about 40 km, the turbojet engine and the controller of this phase will start to work to level the aircraft and help it during the landing.

The figure 64 shows the thruster controller system implemented in Simulink.
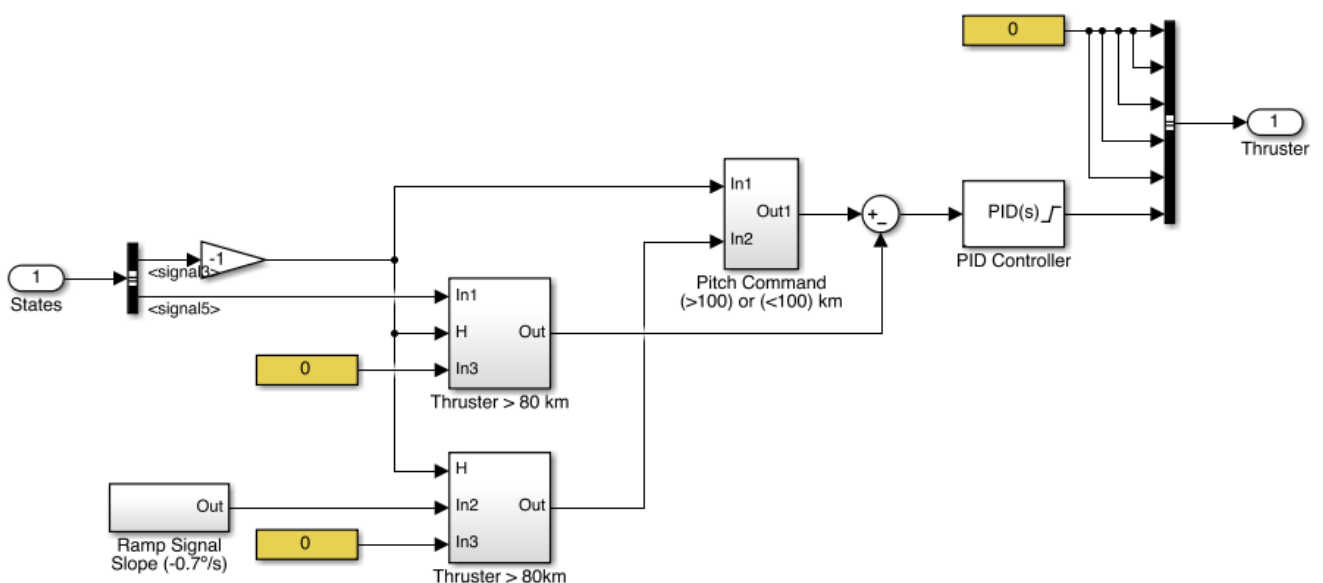
Figure 64: Thruster Controller

When the spaceplanes reaches an altitude greater than 80 km, the rocket engine stops and the thrusters begin to operate. From an altitude of 80 km to 100 km, the aircraft pitch is decreased gently by introducing in the PID a ramp signal with a slope of -0.7 ° per second. Then, when the height is 100.000 meters, the command of a zero pitch angle is sent to the controller in order to level Ascender. The aircraft with remain levelled until the altitude is again lower than 100 km, when the thruster autopilot will keep the spaceplane at an angle of -20 degrees. The gains used for the thruster PID controller are detailed in table 12.

	Proportional	Integral	Derivative	Filter
Pitch	7	1	4	1000

Table 12: Thruster PID Gains

11   Flight Simulation

Once that the controllers system for the different flight phases have been detailed, in this section a simulation of a complete operation of Ascender will be carried out.

The main purpose of that simulation is to check if the combined actions made during a phase work properly, for example, if the altitude and speed systems provide good results when the aircraft is following a path defined by a set of waypoints. Also the transitions are a important point to cover in this section. When the turbojet is stable at an altitude of 8000 meters, the rocket engine is started and the turbojet is shut off, beginning from this point the rocket climb. It will be necessary to check that the transition works correctly and the values obtained from the most important variables make sense. The other transition, from rocket climb to unpowered gliding, will also be revised.

The simulation will start at an altitude of 4000 meters and a speed of 160 meters per second, with the aircraft trimmed. From this point, the pilot will command a path to follow until the point desired to start the rocket phase. Also, the altitude will be increased from 4000 to 8000 meters and Ascender will be accelerate to an altitude of 200 m/s. With the aircraft stable a this point, and following a constant heading now, the rocket engine will be started making the aircraft climb until an altitude of 80.000 meters. A this height, the rocket engine is shut off and the inertia acquired by the aircraft because of the thrust makes it climb until the top altitude (100 km), while its attitude is controlled by the thrusters.

In this section, the time history of some of the system variables will be displayed to check the behaviour of Ascender when performing a complete mission.

11.1 Altitude

The aircraft altitude is controlled during the turbojet phase, where the autopilot makes the aircraft climb to the commanded value. The time history for the Ascender height in this mission is presented in figure 65.
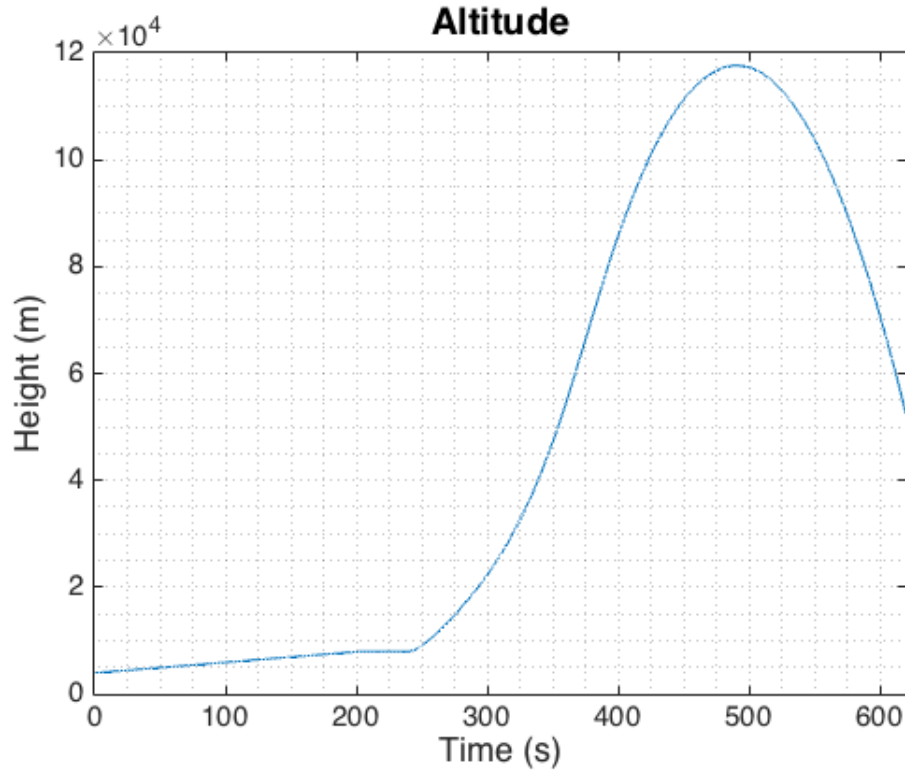
Figure 65: Altitude

During the turbojet phase, the aircraft climb from the trim altitude (4000 meters) to the pilot commanded altitude, 8000 meters. Ascender remains there until the rocket engine is started and it starts the steep climb.

The top altitude reached is 120 km. The objective of the mission was 100 km, but the configuration of the controller was set to not to descent when this altitude is reached, but level the aircraft and leave it at that position while in altitudes higher than 100.000 meters. The passengers have then 125 seconds to admire the views of the plant from a comfortable position.

11.2   Pitch Angle

The pitch angle is directly controlled only during the unpowered phase. Its time history is shown in figure 66.
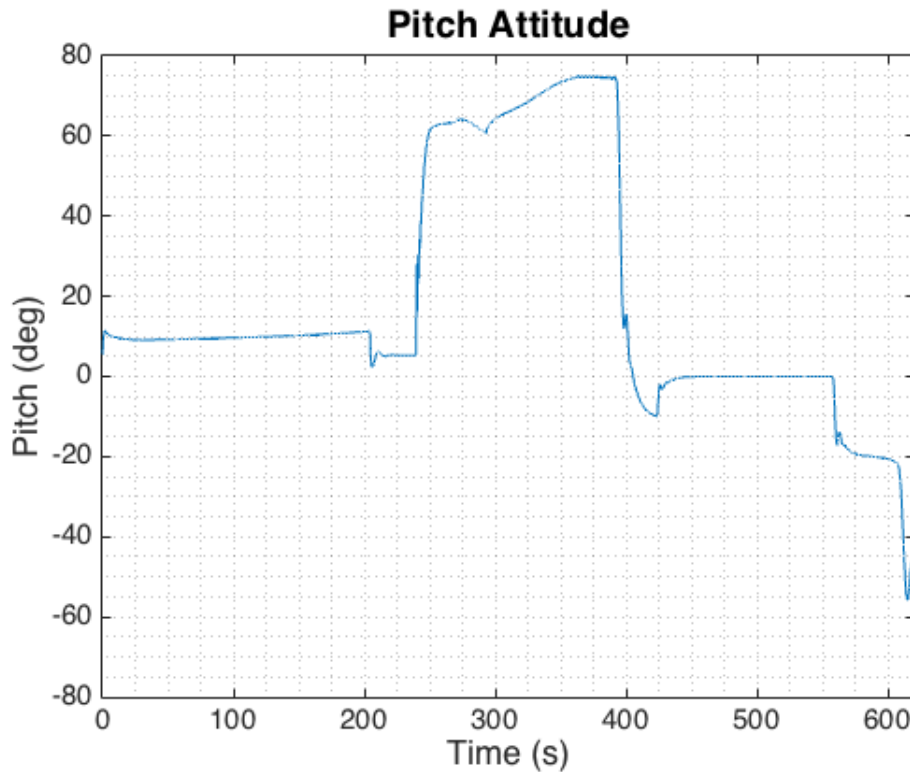
Figure 66: Pitch

Observing the figure, the pitch angle is kept at a constant value when the aircraft is climbing from the trim state to 8 kilometres during the turbojet phase. When that altitude is reached, the pitch angle goes to the trim value of 10 degrees. At the point of the start of the rocket engine, the pitch angle starts to increase, and it stays stable during the time the elevator is controlling the flight path angle. When the TVC starts to operate, the pitch increases until the maximum establish in the controller (75 degrees). This value is kept until the rocket engine is stopped, when the pitch decreases strongly to -10 degrees, to increase later to the level flight value, zero (in both cases controlled by the trusters). When the aircraft has again an altitude lower than 100 km, the pitch is reduced to -20 degrees, which will be the value kept during the descent until the turbojets start again.

11.3 FPA Angle

The flight path angle is directly controlled during the rocket phase. Its time history can be seen in figure 67.
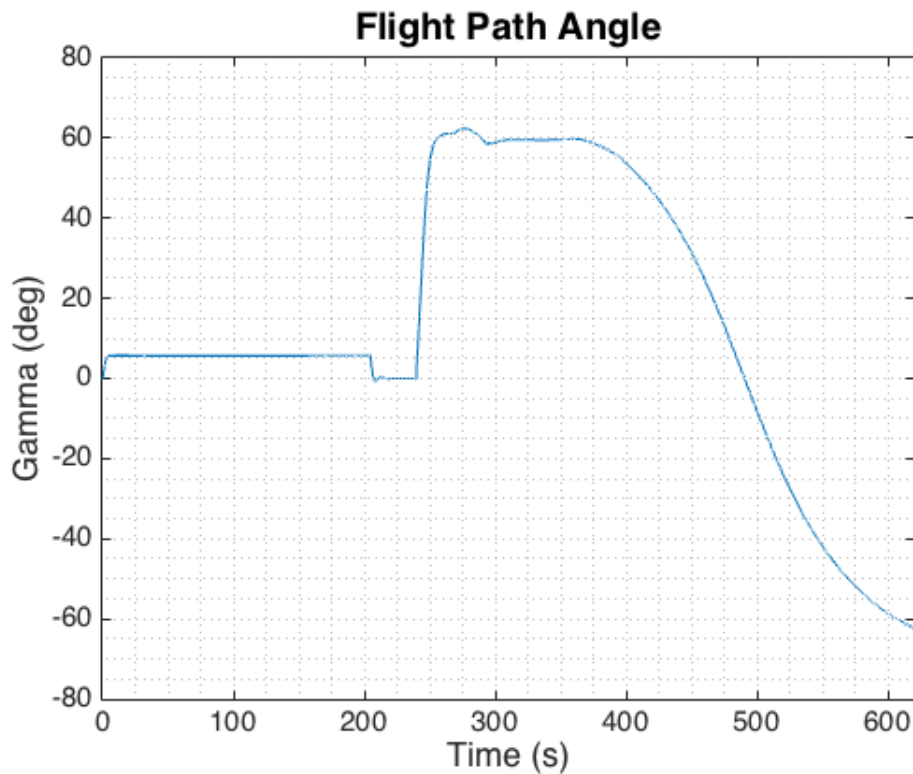
Figure 67: Flight Path Angle

The flight path angle begins from a zero value. When the command of climbing to 8 km is sent to the controller, the FPA is set to a constant value during all the climb. Once the commanded altitude is reached, its value gets back to zero again.

During the rocket phase, the flight path angle is directly controlled by the pilot. In this case the value set is 60 degrees, and it is seen in the figure that this value is reached with some difficulties when the control is carried out by the elevator (because of the low density), but is totally achieved by the thrust vector control system. When the rocket engine is stopped, the FPA decreases gently to a value of -60 degrees, where the turbojet would have to get it back to a smaller value.

11.4 Mach Number

The Mach number is directly controlled during the rocket phase. Its time history is presented in figure 68.
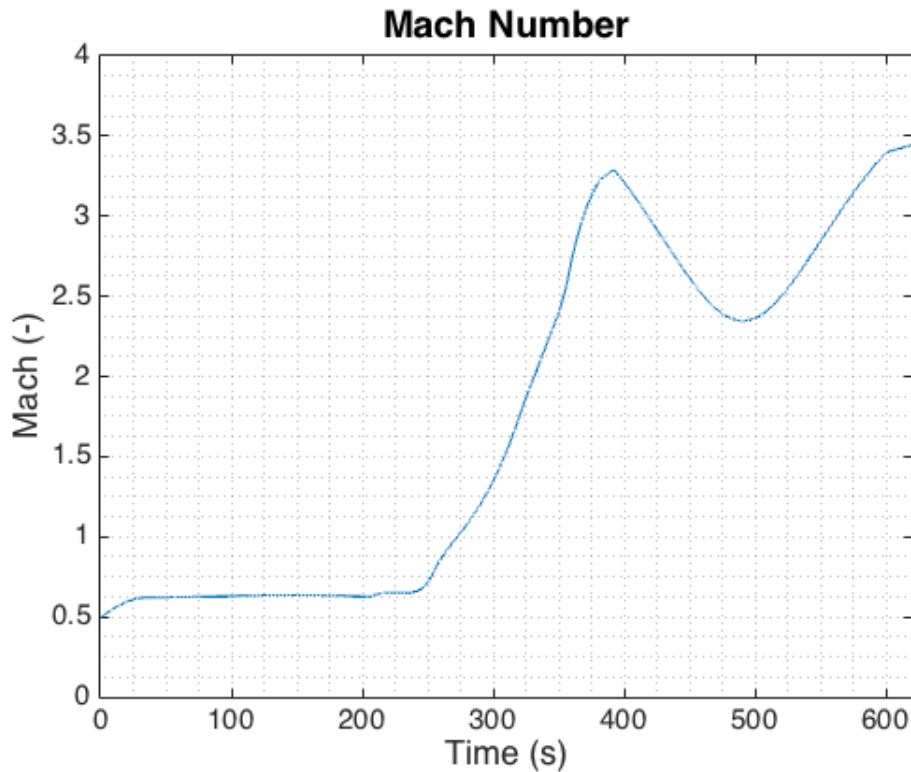
Figure 68: Mach Number

During the turbojet climb, the Mach number is practically constant because the throttle controls the engine to keep a speed of 200 m/s (the slight change comes from the increasing altitude).

Once the rocket is started, the Mach increases because of the great acceleration of Ascender in this point. To avoid the excess of the limit value of 3.5, the rocket throttle controls the Mach number, and it can be seen that the value is not reached. When the rocket is stopped, the aircraft velocity decreases until a value of 2.5. The Mach number increases again during the descent, but even at this point where there is not velocity control, the Mach limit is not exceed, because the pitch angle has been set to a value that does not imply a very steep trajectory.

11.5   Waypoint Following

Finally, the last graph of the mission report will be the trajectory followed by the aircraft during the turbojet phase, where, in addition to the climbing and acceleration, a set of waypoints have been commanded to be followed by Ascender. Figure 69 shows the spaceplane path and the waypoints marked in the map.
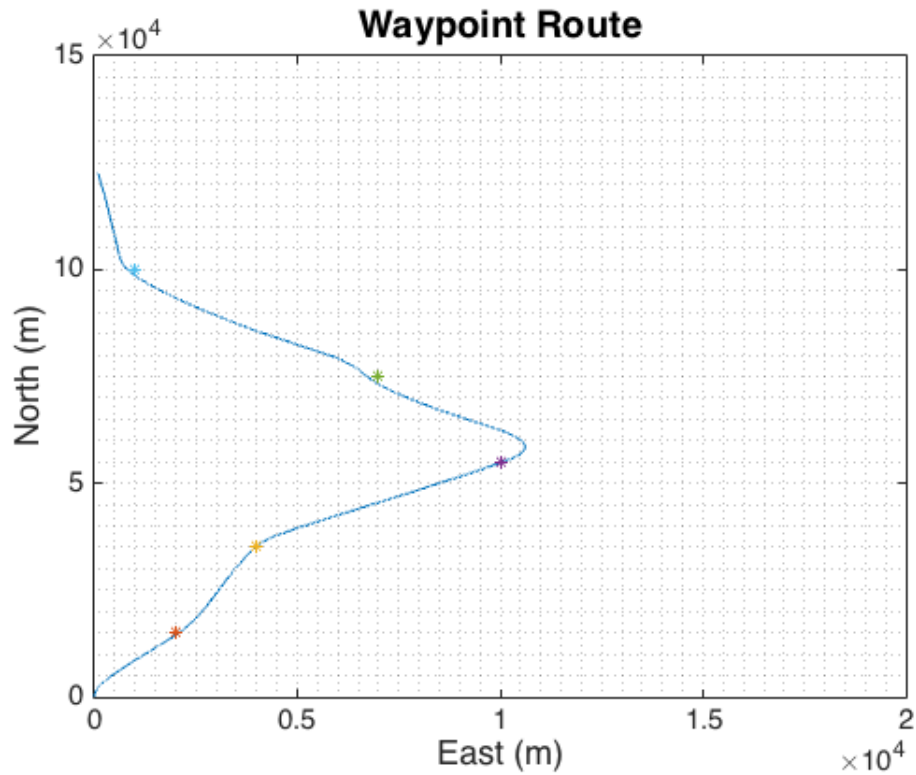
Figure 69: Waypoint Route

12 Conclusions

The objective of the project was to model the design of a spaceplane made the company *Bristol Spaceplanes*, and to create a control system for all the flight phases.

The model has been created using the 3D Views of the aircraft and the weight information provided by the company. As said previously, because of the early stage of the design process, the model will not be a fully faithful one that could be used to simulate a controller to implement in the real Ascender. But regarding this fact, the model has been proved to be sufficiently good to allow the design of the other systems (controller and actuators) around it.

The controller designed for the turbojet phase has been proved to be very good. The altitude and speed commands are reached quickly and almost with zero steady state error, and during a flight those can be changed and the aircraft will respond to this demanded changes perfectly. Also the waypoint following algorithm has provided good results, although in this case the response is not as good as in the other cases, considering the problems of the lateral dynamics because of the coupling between rolling and yawing, the behaviour of the platform is pretty accurate.

The rocket phase presented a series of challenges that have been accomplished greatly. The first section of this phase, where the elevator controls the flight path angle, showed a pretty good accuracy taking into account the limitation. Regarding the TVC system, it proved that is the best option to control an spaceplane at high altitudes, giving an amazing accuracy for the flight path angle commanded to the system.

Finally, the gliding controller also showed very good results. The thrusters system controlled the aircraft attitude when there is not propulsion, making possible to increase and decrease the pitch angle during this flight section. The results showed in the simulation show a lost of power of the system for the final part (about 50 km) of the flight, but at this point the turbojet engine will start and the pilot will take the aircraft to a levelled condition and finally to the airport runway.

To sum up, taking into account the limitations of the project, all the milestones set at the beginning have been accomplished and the results obtained can be considered to be totally succesfull. The following steps would be the creation of a more faithful aircraft model carrying out aerodynamic test to generate the data necessary to create a more accurate representation of Ascender.

13 References

[1] Wikipedia contributors, "Launch vehicle," Wikipedia, The Free Encyclopedia, `https://en.wikipedia.org/w/index.php?title=Launch_vehicle&oldid=702127056` (accessed February 14, 2016).

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A   Trimming Process

The trim procedure will be done with the "trim" function of Matlab. This function needs the Simulink model of the aircraft, the initial values for the inputs, states, outputs and state derivatives, and an indication of which of these values must remain fixed after the trimming process.

In the case of the Ascender, the trim is done to achieve a wings level flight, at a certain altitude and velocity. Considering that, the values that will remain fixed are the Altitude, the forward speed (U), the roll and yaw angles (kept to zero) and the lateral velocity (kept zero to avoid sideslip). Regrading the outputs, in the model the flight path angle is set as an output of the system (it is not a state), so it can be kept zero to have a levelled flight (no climbing).With this information, the Matlab code used in the trimming of Ascender is presented in figure 70.

The states of the system appear in the vector (14). The outputs are the same but with a 13th element which is the flight path angle, γ.

$$x = [North, East, Down, \phi, \theta, \psi, u, v, w, p, q, r] \tag{14}$$

```
%% Trim Point
W_trim=5500;
H_0=-4000;
V_0=160;
TAU_0=0.65;


%% Initial Values
x0=[0,0,H_0,0,0,0,V_0,0,0,0,0,0]';
u0=[0,0,0,TAU_0]';
y0=[0,0,H_0,0,0,0,V_0,0,0,0,0,0,0]';
ix=[3,6,7,8]'; % 1,2,6 es la buena, variando el thrust
iu=[];
iy=[3,6,7,8,13]';
dx0=[V_0,0,0,0,0,0,0,0,0,0,0,0]';
idx=[4,5,6,7,8,9,10,11,12]'; % todos menos 1, 2 y 3


%% Trimming of the model
[xtrim,utrim,ytrim,dxtrim,options]=trim('trim_model_turbojet',x0,u0,y0,ix,iu,iy,dx0,idx);
options(14)=10^9;
options(2)=10^(-7);
options(3)=10^(-7);
options(4)=10^(-7);
[xtrim,utrim,ytrim,dxtrim,options]=trim('trim_model_turbojet',x0,u0,y0,ix,iu,iy,dx0,idx,options);
```

Figure 70: Trimming Code

- x0: states initial values

- u0: inputs initial values

- y0: outputs initial values

- ix: fixed states

- iu: fixed inputs

- iy: fixed outputs

- dx0: state derivatives fixed values

- idx: fixed state derivatives

The attribute "options" contains the parameters related with the trim algorithm. The 9th value is the number of iterations, and the 2nd, 3rd and 4th are the error values that truncate the process (related with the precision).

B   Waypoint Following Algorithm

The waypoint following algorithm is used to change the desired heading that the aircraft has to reach in order to follow the path marked by the points introduced by the pilot.

The idea of this task is very simple: at each position, Ascender will locate the next waypoint that has to reach. According to the relative position of this point with respect to the aircraft, the system will identify if the waypoint is in the first, second, third or forth quadrant. This division of the space is represented in figure 71
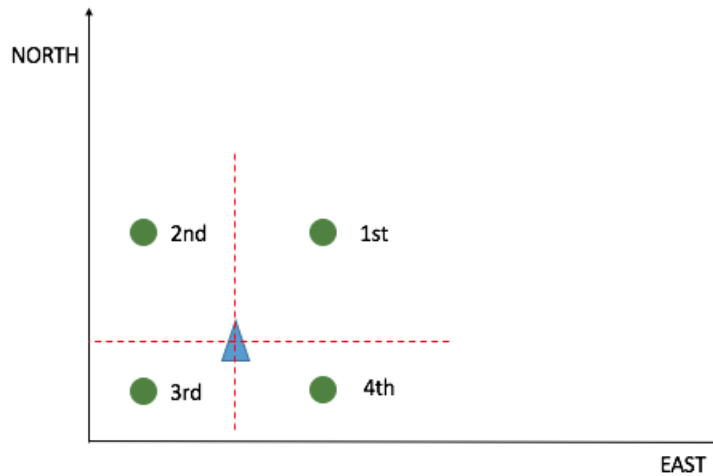
Figure 71: Space Quadrants

The expression used to obtain the angle from the aircraft to the waypoint is presented in (15).

$$\psi = s_y \left(s_y \cdot s_x \frac{\pi}{2} - s_y \cdot atan \left(\frac{wp_y - North}{wp_x - East} \right) \right) \tag{15}$$

The variable s_x and s_y are used to estimate the quadrant where the waypoint lays. Using the matlab function "$sign$", will provide the sign of the distance between Ascender and the waypoint, which will tell the position of the next point. These expressions are: $s_x = sign(wp_x - east)$ and $s_y = sign(wp_y - north)$.

The Matlab code of the "Waypoint Following" system is presented in figure 72.

```matlab
function [des_heading,j] = fcn(north,east,i)

% Waypoint List
wp=[2000,15000;4000,35000;10000,55000;7000,75000;1000,100000];
j=i;
if j<=length(wp)
    s_x=sign(wp(j,1)-east);
    s_y=sign(wp(j,2)-north);
    r=sqrt((wp(j,1)-east)^2+(wp(j,2)-north)^2);
    if r>400
        des_heading=s_y*(s_y*s_x*pi/2-s_y*atan((wp(j,2)-north)/(wp(j,1)-east)));
    elseif r<400

        j=i+1;

        des_heading=pi/2-atan(north/east);
    else
        des_heading=pi/2-atan(north/east);
    end
else
    des_heading=0;
    r=0;
end
```

Figure 72: Waypoint Matlab Code

C   Simulink Blocks

There are some blocks ans subsytems in the models presented in this thesis that have not been explained. These blocks are not related with the aircraft performance, but with the algorithm use to generate the simulations in Matlab and Simulink. In this appendix these systems will be explained to provide a following user of this model with all the necessary information.

C.1   Custom Switch System

The block used in figure 73 is used to change between the controllers of Ascender.
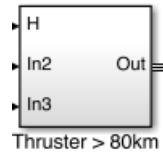
Figure 73: Switch Subsystem

In this case, the switch block provided by Simulink can not be used because if the altitude is set as the parameters to decide, for example, if the rocket controller or the thruster controller is used, when the altitude is below the limit during the gliding phase where the aircraft is descending the rocket controller will start again. In order to avoid that, a simple algorithm has been used to separate between the ascending and descending part. Figure 74 shows the structure of the subsystem created for this task.
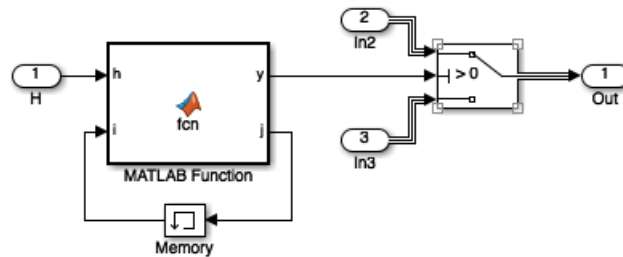
Figure 74: Switch Subsystem Structure

When the aircraft is climbing and the transition altitude has not been reached yet, the value of i (j) is 0. Once the altitude is greater that the value to change between controllers, this flag is set to 1. The value of this flag is what differentiates between the two sections of the flight. The code that implements this idea is shown in figure 75.

```
function [y,j] = fcn(h,i)

j=i;
if h<80000 && j==0
    y=1;
elseif h>=80000
    y=0;
    j=1;
else
    y=0;
end
```

Figure 75: Switch Subsystem Matlab Code

C.2 Thruster Pitch Command

This system inputs a pitch angle to the thruster controller depending on the aircraft altitude. The subsystem structure is shown in figure 76.
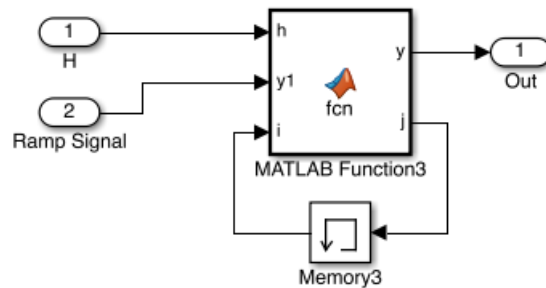

Figure 76: Pitch Command - Thruster

The code that determines which value of the pitch is introduced in the controller is detailed in figure 77.

```
function [y,j] = fcn(h,y1,i)

j=i;
if h<100000 && j==0
    y=y1;
elseif h>=100000
    y=0;
    j=1;
else
    y=-20*(pi/180);
end
```

Figure 77: Pitch Command Code - Thruster

When the altitude of the aircraft is smaller than 100 km, the pitch input in the controller is the instant value of the ramp signal that is one of the inputs of this block. Then, during the time that Ascender is above 100 km, the desired pitch is zero to keep a level flight to improve passenger comfort. Finally, when the altitude is again smaller than 100 km, the pitch command is -20 degrees.

D Aerodynamic Data

As was said in the thesis, the aerodynamic data used for the model has been obtained from a document with information about the Space Shuttle. In section 5.2.1, the graphs with this data for the basic lift coefficient and the elevator effect on the lift were represented as an example of the data obtained. In this section a deeper analysis of how the aerodynamic coefficients have been implemented in Simulink will be carried out.

The example will be done for the roll moment (part of the lateral/directional motion). The information is provided in the document in the following way: a 3D graph for each Mach number evaluated in the experiments, where the value of the coefficient is obtained from an angle of attack and a sideslip or surface deflection angle. The expression used for the roll moment coefficient (C_l) is represented in (16).

$$C_{l_{total}} = C_{l_{basic}} + C_{l_{\delta_a}} \delta_a + C_{l_{\delta_r}} \delta_r \tag{16}$$

The basic lift coefficient graphs have the layout represented in figure 78.

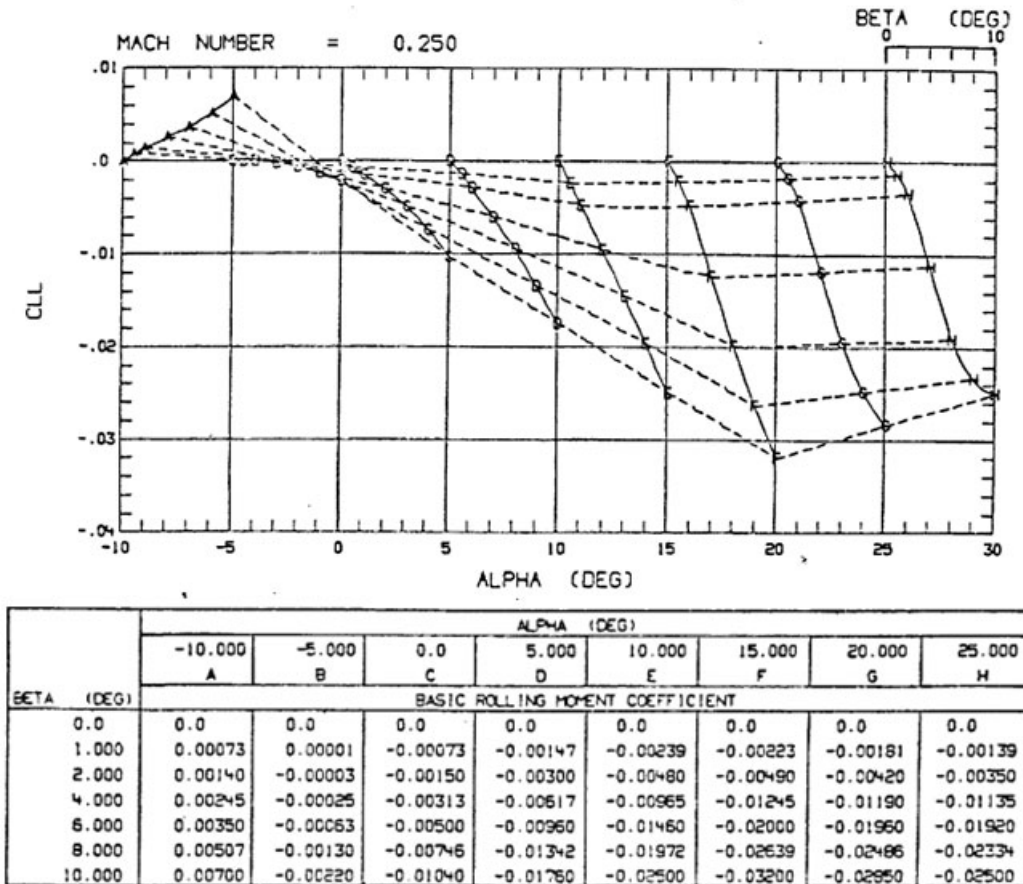| ALPHA (DEG)								
	−10.000	−5.000	0.0	5.000	10.000	15.000	20.000	25.000
	A	B	C	D	E	F	G	H
BETA (DEG)	BASIC ROLLING MOMENT COEFFICIENT							
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.000	0.00073	0.00001	−0.00073	−0.00147	−0.00239	−0.00223	−0.00181	−0.00139
2.000	0.00140	−0.00003	−0.00150	−0.00300	−0.00480	−0.00490	−0.00420	−0.00350
4.000	0.00245	−0.00025	−0.00313	−0.00617	−0.00965	−0.01245	−0.01190	−0.01135
6.000	0.00350	−0.00063	−0.00500	−0.00960	−0.01460	−0.02000	−0.01960	−0.01920
8.000	0.00507	−0.00130	−0.00746	−0.01342	−0.01972	−0.02639	−0.02486	−0.02334
10.000	0.00700	−0.00220	−0.01040	−0.01760	−0.02500	−0.03200	−0.02950	−0.02500

Figure 78: Basic Roll Coefficient

The basic roll coefficient is obtained then with the angles of attack and sideslip, and the Mach number (for the other Mach values the process is the same). The following step is introduce this data in Matlab. In the case of the Space Shuttle there is information up to Mach 20, but in the case of Ascender it is only need data until Mach 4.

The figure 79 shows the code to implement the table for the case of Mach 0.25.

```
%% Basic Roll Moment Coefficient

% Mach -> 0.25
Cll_025=[0,0.00073,0.0014,0.00245,0.0035,0.00507,0.007;...
        0,0.00001,-0.00003,-0.00025,-0.00063,-0.0013,-0.0022;...
        0,-0.00073,-0.0015,-0.00313,-0.005,-0.00746,-0.0104;...
        0,-0.00147,-0.003,-0.00617,-0.0096,-0.01342,-0.0176;...
        0,-0.00239,-0.0048,-0.00965,-0.0146,-0.01972,-0.025;...
        0,-0.00223,-0.0049,-0.01245,-0.02,-0.02639,-0.032;...
        0,-0.00181,-0.0042,-0.0119,-0.0196,-0.02486,-0.0295;...
        0,-0.00139,-0.0035,-0.01135,-0.0192,-0.02334,-0.025];

Cll_basic=cat(2,Cll_025,Cll_08,Cll_09,Cll_098,Cll_12,Cll_15,Cll_3,Cll_4);
Cll_basic_table=reshape(Cll_basic,[8,7,8]);

mach_cll_basic=[0.25,0.8,0.9,0.98,1.2,1.5,3,4];
alpha_cll_basic=[-10,-5,0,5,10,15,20,25];
beta_cll_basic=[0,1,2,4,6,8,10];
```

Figure 79: Basic Roll Coefficient Matlab Code

The tables for the other Mach numbers are created in the same way. All the tables are concatenated in *Cll_basic* and then reorganized in three dimensions matrix (*Cll_basic_table*). The vector *mach_cll_basic* contains the Mach numbers evaluated for this coefficient (the tables), *alpha_cll_basic* and *beta_cll_basic* contain the values of the angles of attack and sideslip of the tables respectively.

Once the information has been introduced in Matlab, it has to be implemented in Simulink through the Lookup Tables. As an example, figure 80 shows the configuration of the Lookup table for this coefficient, with the basic one and the contributions from the rudder and aileron.
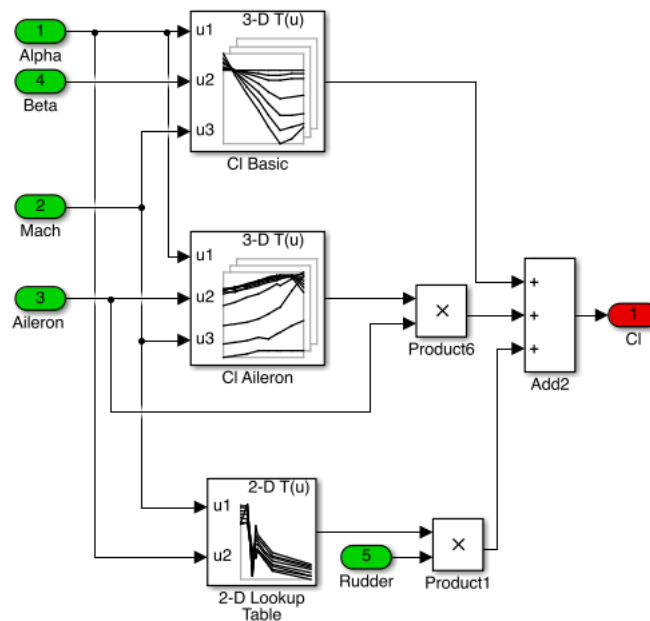

Figure 80: Basic Roll Coefficient Lookup Table

Finally, figure 81 shows how to introduce the vectors and the table shown for the case of the basic roll coefficient.
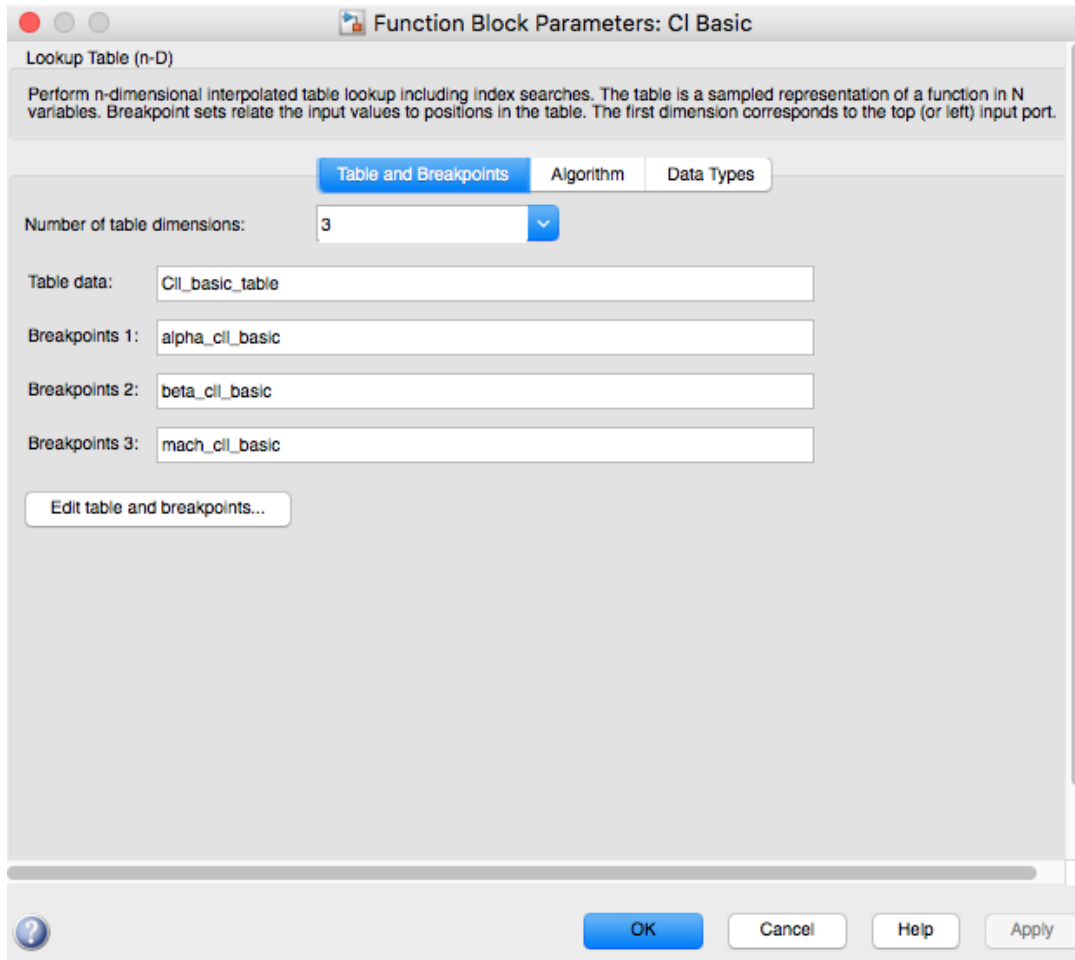

Figure 81: Basic Roll Coefficient Lookup Parameters

When considering the contributions of a control surface to a coefficient, the only difference from the previous example is that each table depends on α and in the deflection angle instead of the sideslip, and also that the value obtained is an increment that has to be multiplied by the deflection angle itself. In the case of the rudder, the coefficient depends only on the angle of attack and the Mach number.

E Geometric Data

The geometric data of all the parts that form the Ascender platform will be presented in this appendix.

E.1 Wings and Tail

The geometric information about the wings and the tail is presented in table 13.

Part	Span (m)	t_r (m)	t_t (m)	Mean Chord (m)	Δ_{LE} (deg)	Δ_{LE} (deg)
Inboard Wing	1.81	0.52	0.4	6.17	79.26	-8.4
Outboard Wing	2.3	0.4	0.16	4.07	60.31	-8.4
Tail	1.53	0.32	0.08	2.39	52.76	26.56

Table 13: Wing/Tail Geometric Data

The inboard and outboard part of the wing are the two sections that conform the whole double delta wing.

E.2 Fuselage

The fuselage is split in two parts: the nose and the main body. Its geometric data is shown in table 14.

Part	Length (m)	Height (m)	Width (m)
Nose	4.07	1.05 (mean point)	1.05 (mean point)
Body	8.95	1.53	1.29

Table 14: Fuselage Geometric Data

E.3 Engines

The geometric data of the two propulsion systems fitted in Ascender is presented in table 15.

Engine	Radius (m)	Length (m)
Rocket	0.355	2.2
Turbojet (x1)	0.465	4.273

Table 15: Engines Geometric Data

E.4 Fuel Tanks

In table 16 there is information about the size of the three tanks carried by Ascender.

Tank	Length (m)	Width (m)	Liquid Density (kg/m^3)
Turbojet Fuel	0.73	0.15	810
Rocket Fuel	0.89	0.73	810
Rocket Oxidizer	3.03	0.73	1450

Table 16: Fuel Tanks Geometric Data

The combustible used in the turbojet engine is kerosene. In the case of the rocket, it uses a combination of hydrogen peroxide and kerosene. The weight of each tank has been obtained from the fuel consumption of the trajectory calculations realized in section 4. The total mass lost during the rocket phase (fuel consumed) has been divided in oxidizer and fuel according to the optimal stoichiometric ratio of these components, 7.35, and its densities.

E.5 Landing Gear

Finally, the last table, 17, presents the geometric information of the three landing gears of Ascender: one in the nose and two in the wings (rear).

Landing Gear	Length (m)	Width (m)
Nose	0.93	0.4
Rear	1.49	0.16

Table 17: Landing Gear Geometric Data