POLITECNICO DI TORINO

Master of Science in Aerospace Engineering

Master Degree Thesis

STRATOFLY Project: analysis of the Concept of Operations of a Hypersonic Civil Passenger Transport Aircraft

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Abstract

In 2050 the number of passengers travelling globally aboard civil aircrafts is predicted to be six-fold higher than today. New and promising technologies in the fields of high-speed propulsion and high-temperature resistant materials make it possible to think about the exploitation of the stratosphere for long distance routes to be covered in shorter time frames with respect to conventional civil passenger aircrafts. The STRATOFLY project has received funding from the European Union's Horizon 2020 research and innovation programme for the development of a hypersonic civil passenger transport aircraft concept, addressed as STRATOFLY MR3, that shall be able to perform cruise at 30 km altitude and Mach 8 flight speed with the aim to drastically reduce transfer time, noise and emissions for long haul point-to-point missions. The project gains relevant knowledge from previous EU co-funded projects in the field of hypersonic transport.

The conceptual design of such kind of system and the related mission, however, is a complex challenge and the cooperation of many participants from different institutions is crucial to achieve project's goals. This Thesis gives a contribution to the STRATOFLY project in terms of Concept of Operations (ConOps) analysis and trajectory simulation via ASTOS software. The ConOps analysis has led to the development of the conceptual Design Reference Mission (DRM) in terms of mission phases definition and assessment. The mission has been also studied from an operational point of view through the definition of the subsystems level modes of operations and the development of operational procedures supported by useful logical decomposition tools. Furthermore, possible out-of-nominal scenarios have been identified in relation to possible critical events that can affect the propulsive subsystem during the mission. Both the DRM and some relevant out-of-nominal scenarios have been finally simulated and assessed via ASTOS software leading to important results about mission phases duration, fuel consumption and feasibility of certain operational procedures.

Thanks to interesting projects and outstanding technologies under investigation all around the world, the future of civil aviation is revealing to be promising and fascinating. Together with the work of other researchers, engineers and dreamers from and outside Europe, this Thesis is intended to play its very small part to make it happen.

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Last but not least, let me make a special greeting to the little Ludovica, born on the same day this Thesis was finished: I wish you a wonderful life.

Contents

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List of Abbreviations

AoA Angle of Attack

ATLLAS Aerodynamic and Thermal Load interactions with Lightweight Advanced materials for high-Speed flight

ATR Air Turbo Rocket

CoG Center of Gravity

CoM Center of Mass

ConOps Concept of Operations

CoP Center of Pressure

DMR Dual Mode Ramjet

DOF Degree of Freedom

DRM Design Reference Mission

EASA European Union Aviation Safety Agency

ECLSS Environment Control and Life Support System

ECSS European Cooperation for Space Standardization

ECS Environment Control System

EC European Community

ER Equivalence Ratio

ESA European Space Agency

ESTEC European Space Research and Technology Centre

EU European Union

FAA Federal Aviation Administration

FFBD Functional Flow Block Diagram

GUI Graphical User Interface

HST Hypersonic Transport

ISS International Space Station

LAPCAT Long-Term Advanced Propulsion Concepts and Technologies

LHS Left Hand Side

NASA National Aviation and Space Administration

RBCC Rocket Based Combined Cycle

RHS Right Hand Side

SABRE Synergetic Air Breathing Rocket Engine

SST Super Sonic Transport

STRATOFLY STRATOspheric FLYing opportunities for high-speed propulsion concepts

TBCC Turbine Based Combined Cycle

TCS Thermal Control System

TPS Thermal Protection System

TRL Technological Readiness Level

USAF United State Air Force

Introduction

Current and Future trends in Aviation are characterized by fascinating and outstanding technologies in the fields of high-speed flight, high-temperature resistant solutions and high-speed propulsion that are being developed all around the world.

Since the beginning of aviation history, engineers have worked on vehicle concepts able to reach always higher flight speeds. Several experimental vehicles have been developed, with the aim to gain knowledge about high-speed flight, before the implementation of such kind of concepts in real applications such as supersonic military jets, reusable space platforms and civil passenger supersonic aircrafts.

However, supersonic civil transport ended with the retirement of the famous *Concorde* [41] in 2003 due to high operational costs as well as high noise and emissions. As a result, today, only conventional subsonic aircrafts are providing civil passenger transport services worldwide, and this service can reveal to be not sufficient to satisfy an always higher number of passenger travelling by airplane everyday.

In fact, future visions for Aviation predict globally a six-fold increase in passenger by 2050 [42], and the exploitation of new air spaces as well as high speed and high propulsion technologies for reducing travel time, noise and emissions for long haul routes may become strategic for the sustain of future Civil Aviation.

For this reason, Europe has funded and co-funded several projects for the investigation and technology development in the field of high-speed transport. The last of this chain of European projects is *STRATOFLY*, that has received funding under the European Union's Horizon 2020 research and innovation programme [47] with the aim to develop a hypersonic civil passenger aircraft concept, the STRATOFLY MR3, able to perform point-to-point missions in unprecedented short travel time by flying at 30 km altitude and Mach 8 flight speed, drastically reducing at the same time noise and emissions and guaranteeing proper safety levels for passengers.

This Thesis was developed under the STRATOFLY project, thanks to Politecnico di Torino and the STRATOFLY Academy [53], with the purpose to perform a system engineering activity addressed as Concept of Operations (ConOps) analysis, as well as the trajectory simulation and assessment of the STRATOFLY MR3 vehicle.

In addition to the first two literature review and case study presentation Chapters, the Thesis can be conceptually divided in two parts:

1. Chapters 3, 4, 5, 6 and 7 describe the Concept of Operations analysis from a

system engineering point of view, as well as the method and tools implemented for the analysis and the achieved results.

2. Chapters 8 and 9 include a more technical content concerning the trajectory simulation, respectively in nominal and out of nominal conditions, of the STARTOFLY MR3 performed via the *ASTOS*® 9 Software, developed by Astos Solutions GmbH [1].

Furthermore, a general overview on what the reader will find in the single chapters of this Thesis is given in the following:

- **Chapter 1**: Literature review and State of the Art analysis about the background and future trends of Hypersonic Transport.
- **Chapter 2**: Overview on the STARTOFLY project; Case of Study presentation; system and subsystems design and description of the aero-database and the propulsion-database implemented in Chapters 8 and 9 for simulation purposes.
- **Chapter 3**: Overview on the Concept of Operations analysis from a theoretical perspective, including the presentation of methods and tools implemented in Chapters 4, 5, 6 and 7 for ConOps analysis purposes.
- **Chapter 4**: Conceptual development of the STRATOFLY MR3 Design Reference Mission: mission phases definition and analytical assessment.
- **Chapter 5**: Definition and assessment of system and subsystems level modes of operations as well as operational characteristics during the different mission phases.
- **Chapter 6**: Identification and analytical assessment of possible out of nominal scenarios related to eventual failures occurring to the propulsive subsystem during the different mission phases. The scenarios classification performed in this Chapter represents an input for the out of nominal scenarios simulation performed in Chapter 9.
- **Chapter 7**: Logical decomposition of operations and development of certain operational procedures that characterize the operability of a hypersonic passenger aircraft and to be considered as input for the mission trajectory simulation performed in Chapter 8.
- **Chapter 8**: Simulation and assessment of the Brussels-Sydney reference mission performed via ASTOS software.
- **Chapter 9**: Simulation and assessment via ASTOS software of some out of nominal scenarios related to failures affecting the propulsive subsystem.

The achieved results of the work performed in this Thesis are not only about ConOps analysis output (conceptual Design Reference Mission; Modes of Operations; Phases/Modes Matrices; Functional Flow Block Diagrams; out of nominal scenarios identification and classification), but also the Thesis has led to important results about mission duration, overall fuel consumption, feasibility of certain operational procedures and relevant aspects to be further assessed. Moreover, the Thesis contributes at giving major knowledge about the possible out of nominal scenarios that may occur during the STRATOFLY MR3 mission, as well as about the capability of the system to deal with out of nominal conditions and to react to possible critical events.

There is nothing left but to wish the reader a good reading, with the hope that he/she can find the content of this Thesis useful and interesting.

Chapter 1

Hypersonic Transport: Background & Future Trends

For as long as man has touched the sky with a flying machine, he has tried to get higher and to go faster. During the aviation history several solutions were investigated with different purposes and for different kinds of applications, in order to develop winged bodies able to fly in the atmosphere at a very high speed, or to perform an atmospheric reentry after reaching high altitudes for then to land in a runway as an aircraft. Beyond the vehicles developed for experimental purposes, for military or space applications, always more attention is being given to the exploration of high speed commercial transport concepts. After that commercial Supersonic Transport (SST) has been experimented thanks to the passenger aircraft *Concorde*, the next step, to which different companies and different countries are currently working, is not only to develop more affordable and sustainable SST technologies, but also and above all to investigate Hypersonic Transport (HST) opportunities that will allow people to move at a very high speed, in an unprecedented low time, from a point to the other of the Earth surface.

Aim of this Chapter is to give an overview of the most important historical achievements and vehicles developed that nowadays allow engineers to think about hypersonic passenger flight, and that push different countries to support projects in this field such as the European *H2020 STRATOFLY* Project.

1.1 High Speed Flight Overview

In the following several flying vehicles will be described, trying to make order about their category and function, some definitions have to be given. An *aircraft* is generally any craft developed to operate in air, it can be an airplane, a helicopter, an airship or balloon, a glider and so on. The different aircrafts are therefore classified on the basis of different characteristics, such as the physical principle thanks to which they fly, the operative altitude or the way the thrust, if any, is generated. An aircraft flying thanks to aerodynamics principles is defined as *airplane*. An airplane can be called *spaceplane* when it is able to reach an altitude of around 100 km above the sea level, defined as the space height. Moreover, if an airplane is powered by a rocket engine, it is possible to classify it as *rocketplane* [3]. Aircrafts can be also classified on the basis of the speed at which they fly. A *supersonic* aircraft is a vehicle able to fly at Mach numbers higher than 1, therefore when it is able to fly faster than the speed of sound. An aircraft can be classified as *hypersonic* when is able to fly at hypersonic speed. However, it's not immediate to define the hypersonic speed itself, it can be said that it is when dissociation of air begins to become significant and high heat loads exist, and it happens at a speed of about Mach 5 [60].

1.1.1 First concepts of Spaceplane

The earliest idea of *spaceplane* and *rocketplane* dates back to 1933, when the German scientist Eugene Sanger conceived the concept of a rocket powered airplane-like spacecraft. This design was called the *Silbervogel* (Silverbird), it should have been able to do a sub-orbital flight and an atmospheric re-entry with the purpose to bomb America during World War II. The *Silbervogel* represented a very innovative concept, even if it never flew because considered too much complex and expensive to produce. However, for the first time the new technology of the rocket engine was applied to a lifting body and for this reason the Silbervogel concept has inspired future development of spaceplanes.

One of the firsts and most important successor of the Silbervogel was the American *X-20 Dyna-Soar* (see Figure 1.1), short for Dynamic Soarer.

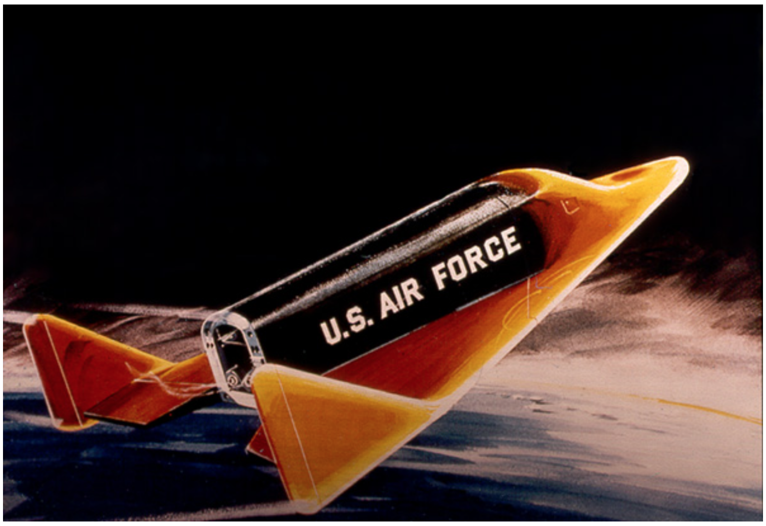


Figure 1.1. Illustration of the *X-20 Dyna-Soar* during atmospheric reentry.

The X-20 programme was carried out by the United States Air Force (USAF) between the 1957 and 1963, with the aim to develop a spaceplane to be launched vertically by a ballistic missile in order to perform a sub orbital flight working as an antipodal bomber or conducting reconnaissance over any spot on Earth, for then to reentry through the atmosphere as an hypersonic glider and perform an airplane-like landing. Despite some preliminary hardware was produced and a scale prototype was developed, the Dyna-Soar has never flown, but it was the basis for the successive development of similar concepts of spaceplane, but with different purposes, such as in the case of the famous *Space Shuttle*, indeed designed for scientific and space exploration missions instead of military applications [3].

1.1.2 Reusable Space Platforms

The first spaceplanes ever built for real applications, thus not only as experimental vehicles, were the Soviet *Buran* and the American *Space Shuttle*. Both designs consist on a lifting body launched vertically via a rocket, able to perform in-orbit operations and return from orbit as an aircraft with consequent precision landing on ground. The Soviet Buran, represented in Figure 1.2, has flown only once as an unmanned test in 1988, soon after the programme was cancelled because of the dissolution of the Soviet Union [57]. The Space Shuttle (see Figure 1.3), instead, represented a very important milestone of the Space Era. Five vehicle were built in total: Columbia, Challenger, Discovery, Atlantis and Endeavour. The fleet flew several manned missions between 1981 and 2011, helping to construct the International Space Station (ISS) and performing in-orbit microgravity experimentation through the embedded Spacelab [50].

Figure 1.2. The Russian Buran spaceplane atop of an aircraft at the Paris Air Show in 1989. Credit: [57]

Figure 1.3. The Space Shuttle Discovery performing liftoff towards the International Space Station, 2007. Credit: [49]

Since 2000's, also Europe has began to develop experimental vehicles for re-entry technologies, in the wish to gain relevant in-flight experience in order to consolidate its position and ambitions in the area of space transportation. With this aim it was conceived the concept of *IXV* (Intermediate eXperimental Vehicle), a lifting re-entry body, to be launched and injected on a re-entry path by the ESA Vega launcher via an equatorial trajectory, able to perform a set of dedicated manoeuvres prior to land in the Pacific Ocean for recovery and post flight analysis. The IXV Mission has been performed on February 11th 2015. After the recovery of the vehicle from the Pacific Ocean on board of a recovery ship, IXV returned back to Europe for post flight analysis. Today IXV is exposed to the Caselle Airport in Turin as it is shown in Figure 1.4. The direct successor of IXV is *SPACE RIDER* (see Figure 1.5), a reusable space platform able to perform atmospheric re-entry as his predecessor but also in-orbit operations and experimentation, by hosting different kinds of payload, and precision landing on ground instead of Ocean splashdown. The SPACE RIDER Mission, scheduled to be launched in 2021, represents the occasion for Europe to

Figure 1.4. (LHS) Illustration of the IXV Mission. Credit: [44] - (RHS) IXV exposed to Caselle Airport in Turin

Figure 1.5. Illustration of SPACE RIDER performing in-orbit operations. Credit: [44]

develop an affordable and reusable space platform allowing routine access into low earth orbit and to acquire and consolidate knowledge about atmospheric reentry technologies [46].

One of the most critical issues when designing a spaceplane is of course the reentry phase, when the vehicle moves at hypersonic speed through the atmosphere and the heat flow is very hight. Designing the thermal protection system is therefore not simple, and for this reason, engineers working on the projects of future hypersonic passenger transportation concepts can of course gain valuable knowledge from the reusable space platforms, such as Space Shuttle, Buran and IXV, developed in the past.

1.1.3 Experimental Vehicles

During the aviation history, several vehicles were developed with the aim to demonstrate different technologies, to support research in a multitude of technical fields and to acquire knowledge about certain physical phenomena such as the sound barrier or the hypersonic speed flow. Some of the most important examples of experimental vehicles ever built are the American *X - planes*, a series of airplane, rocketplanes and spaceplanes developed for experimental applications with different purposes.

The initiator of the X-planes series was the *Bell X-1* (see Figure 1.6), a rocket powered airplane that in the October 1947 flew faster than the speed of sound in level flight, reaching Mach 1.06, for the first time in the history. The rocketplane was drop launched from the bomb bay of a larger aircraft and performed level flight until the burnout of the engine, for then to glide and land on the dry bed of a lake. Although the Bell X-1, as it is possible to see in Figure 1.6, was equipped with a conventional tapered straight wing, after discovered to be not as good as a sweptback or a delta wing for the supersonic flight, it was inspiring for further development of supersonic aircrafts and also for more advanced concepts of experimental vehicles aimed to reach higher altitudes and hypersonic speed [56].

Other historical records were achieved by the *North American X-15* (see Figure 1.7), an hypersonic rocketplane that performed several missions between the 1959 and 1968. In 1961 the X-15 was the first aircraft ever reaching the hypersonic speed of Mach 5. Two years later, in 1963, it makes the first aircraft flight above the edge of outer space, therefore an altitude of 100 km. All the pilots that flew on board

Figure 1.6. The Bell X-1, first aircraft ever breaking the sound barrier, 1947. Credit: [49]

Figure 1.7. The North American X-15, first aircraft ever reaching hypersonic speed. Photo of 1967. Credit: [49]

Figure 1.8. Neil Armstrong next to the North American X-15, 1962. Credit: [49]

of the X-15 above an altitude of $80\,km$, the Air Force spaceflight criterion, were qualified as *astronauts*. Some of those astronauts worked also for successive NASA missions, such as in the case of Neil Armstrong, represented next to the X-15 in Figure 1.8, well known for being the first man walking on the Moon [3].

The X-15's velocity record of Mach 6.70 (7272.6 km/h), gained in 1967, was only broken in 2004 by the experimental scramjet X-43. However, since the X-43 was an unmanned aircraft, the X-15 is is still today the fastest aircraft ever flown with a pilot on board. In 2004 the X-15's altitude record of 107,8 km was also broken by the SpaceShipOne. Both the X-43 and the SpaceShipOne, described in the following, represents valuable examples of experimental vehicles in terms of important historical achievements.

One of the most crucial issues the engineers have to deal with when investigating new concepts of vehicles able to perform long cruises at hypersonic speed is the huge mass of propellant to be carried on board, translated in a lower mass and volume capability of the system that could be used for allocating payload or passengers. When flying at high altitude and high speed, in fact, the most suitable engine type is the rocket engine, the low air density on one end, therefore less quantity of oxygen to be used for combustion, and the difficulty in slowing the air flow to allow combustion on the other hand, makes an air-breathing engine to be very complex to use at high altitudes and hypersonic speed. An air-breathing engine, however, means the possibility to carry on board less propellant, therefore less mass on board to be used instead for carrying on payloads or passengers for longer distances. For this reason, a lot of effort has been given with the aim to develop air breathing engines able to drive an aircraft at hypersonic speed, this is the case of the *Scramjet* (Supersonic Combustion Ramjet) engine, that represented an important topic of research in the past decades [5].

A scramjet engine has been tested in flight for the first time on board of the American X-43. The *X-43A Hypersonic Experimental Vehicle*, also known as *Hyper-X*, represented in Figure 1.9, is an unmanned airplane powered by a scramjet engine, famous for being the first air-breathing vehicle to have reached hypersonic speed and also the fastest aircraft of the aviation history. In 2004, indeed, the X-43 reached in two different flight performed in March and October the speed of respectively Mach 6.8 and Mach 9.6 flying at about 33.000 m of altitude. The Hyper-X programme was crucial for NASA to consolidate the knowledge acquired about scramjet technology after decades of research, giving an important contribuite for future developments. Indeed, Scramjet engines applications include future hypersonic missiles, hypersonic airplanes, the first stage of two-stage-to-orbit reusable launch vehicles and single-stage-to-orbit reusable launch vehicles [16].

As it is possible to see, all the vehicles described above were developed under the supervision of governative agencies such as NASA and USAF, however, during recent years a lot of effort was given to explore solutions aimed to make private space travel and high speed passenger transport commercially viable. With this aim, the *X-PRIZE Foundation* launched a challenge, the *Ansari X Prize*, consisting of 10 million dollars for whom would have been able to develop a reusable, privately financed, manned spaceship capable of *"Carrying 3 people; To 100 Km about the*

Figure 1.9. The X-43A Hypersonic Experimental Vehicle, first air-breathing aircraft ever reaching hypersonic speed. Credit: [49]

Earth's surface; Twice within 2 weeks" [63].

The Ansari X-Prize was won in the October 2004 by the *SpaceShipOne* spaceplane developed by a venture controlled by Burt Rutan and his company *Scaled Composites*. The SpaceShipOne, represented in Figure 1.10, is spaceplane powered by a hybrid rocket motor and designed for sub-orbital flights to 100 km altitude, atmospheric reentry and precision landing on a runway. SpaceShipOne was therefore the first commercial aircraft able to carry on 3 people in a suborbital flight, and moreover it broke the altitude record of the X-15, flying untill $112\,km$ [52]. The SpaceShipOne project contributed to inspire further researches in the fields of commercial space travels and hypersonic transport. However, speaking about passenger transport, researchers working on commercial hypersonic transport concepts can gain valuable knowledge from the already experimented previous step, the commercial supersonic transport.

1.2 Commercial Supersonic Transport

After the first airplane ever, the Bell X-1, broke the sound barrier, during the 50's many companies in different countries developed supersonic aircrafts especially for military applications. Meanwhile, in post-World War II people started to travel around the world by airplane giving birth to the *Civil Aviation*. Civil aviation regulatory authorities started to introduce their provisions, many aircraft before used for military purposes, such as cargo or bomber airplanes, were converted to

Figure 1.10. The SpaceShipOne, winner of the Ansari X-Prize, 2004. Credit: [52]

civil airplanes, while new vehicles were projected and developed just for civil aviation purposes. With the aim to drastically reduce the travel time, especially for transoceanic routes, first SST (Supersonic Transport) projects took their origin at the same time of the increasing of popularity of the civil aviation on one hand and supersonic military jets on the other. At the beginning, SST aircraft were being projected starting from the projects of military supersonic aircrafts and rescaling them, but this revealed to be a very complex task since cruise time was required to be longer and there were many other constraints and safety issues to be taken into account when carrying passengers on board. For this reason, starting from the 60's, many countries among which USSR, England and France started to develop SST by designing new feasible and economically sustainable concepts [62].

USSR and the English-French front began to work approximately at the same time to the project of a supersonic transport aircraft able to fly at Mach 2 for a $6000-6500\,km$ range, carrying on 100-140 passengers. The two designs were respectively the Russian *Tu-144* (see Figure 1.11), developed by the Tupolev company, and the the Anglo-French *Concorde* (see Figure 1.12), developed by a consortium held by the companies British Aircraft Corp. and Aérospatiale. Despite the complexity in developing such kind of airplane, both the projects were financed by the respective governments and the prototyping phase could start.

The first prototype of an SST aircraft to be developed and able to take-off, was the Tu-144 (044 prototype), that in 1969 reached in a test flight the supersonic speed, representing an important milestone of the aviation history. Nevertheless, the first commercial SST flight was performed by the Concorde, that in 1976 flew

Figure 1.11. The Russian Tu-144 supersonic passenger aircraft. Credit: [54]

Figure 1.12. The Anglo-French Concorde supersonic passenger aircraft. Credit: [41]

from London Heathrow to Bahrain performing a cruise at supersonic speed carrying on passengers for the first time in the civil aviation history. First Tu-144 passenger flight was instead in 1977 on the Moscow-Alma-Ata route.

Despite the designs of the Concorde and the Tu-144 were apparently very similar, the two aircraft had some important differences, concerning the engines, the weight and the type of routes performed, that at the end, as it will explained later in this Section, made the Concorde programme to be more durable and more affordable than the Tu-144 one. In order to compare the main characteristics and performances of the two supersonic airplanes, it is possible to give a look at Table

1.1 that represents the data available respectively from the *British Airways* web site [41] for the Concorde, and from the *Tupolev* company web site [54] for the Tu-144. Both the Concorde and the Tu-144 were of course a technological and historical

	Concorde	**Tu-144**
Aircraft length	62.1 m	64.45 m
Wing span	25.5 m	28.8 m
Aircraft height	11.3 m	12.5 m
Maximum takeoff weight	185 $tonnes$	207 $tonnes$
Cruising speed	2160 km/h	2120 km/h
Range	6667 km	6200 km
Passengers seats	100	70
Engines	Rolls-Royce/SNECMA Olympus 593s	Kolesov RD-36-51

Table 1.1. Comparison between performances and characteristics of the Concorde and the Tu-144. Credit: [41] - [54]

achievement, but not a commercial success. Speaking about the Concorde, the operative costs were considerably underestimated at the beginning of the programme. Thus, the programme was not economically sustainable, and considering also that in 2000 a fatal accident occurred soon after take-off in Paris, in 2003 all the Concorde aircrafts were taken out of service, giving end to the only one existing supersonic passenger transport service in the world [36].

The faith of the Tu-144, instead, was still more unhappy than the Concorde one, since the last passenger flight performed by a Tu-144 was only in 1978. Reasons why the Tu-144 programme ended lie on the fact that, like in the Concorde case, economical problems incurred, and moreover two accident, one in the 1973 and the other in 1978, discouraged the continuation of the programme. However, the Tu-144 was used later as cargo aircraft and also as experimental aircraft by NASA [54].

According to the Tupolev company itself [54], the main reason of the different destinies of the Concorde and Tu-144 lies on the different type of route performed. The Concorde, in fact, was designed mainly for supersonic flights over uninhabited ocean spaces, therefore lower altitudes for supersonic cruising were allowed, because no related noise problems over the ocean, which resulted in smaller wing area, smaller takeoff weight, smaller demanded cruising thrust and smaller fuel consumption. The Tu-144, instead, was designed mainly to perform supersonic cruise over the land, thus higher altitudes were needed resulting in a design characterised by a bigger wing area, bigger take-off weight, thrust demanded and fuel consumption, for also a lower number of carried on passengers. It has also to be said that the Concorde's Olympus 593s engines were more efficient than the Tu-144's RD-36-51 engines.
Furthermore, supersonic transportation service costumers were the one for which the sentence *"time is money"* is a real truth, since flight tickets for a travel on

Figure 1.13. Illustration of the Lockheed Martin X-59 QueSST, experimental vehicle aimed to demonstrate low sonic boom technologies. Credit: [49]

board of the Concorde were quite more expensive if compared with the ones for a classic subsonic flight on the same route. In USSR there were fewer people, than in the western world, willing to pay such amount of money for this type of service, therefore the natural market, which the Tu-144 could have satisfied, just did not exist. For those reasons, the Concorde turned to be a more prestigious commercial programme than the Russian Tu-144.

However, both the programmes revealed to be not economically sustainable and they were characterised by common negative technical and environmental issues that were the cause of the end of the commercial SST in the world. One of the most important problems that was related to the supersonic passenger flight, was the noise produced by the sonic boom and the supersonic cruise. Now the regulations about the noise produced by an aircraft are much more strict than in the 70's. Nowadays, in fact, the aircrafts used in the civil aviation are 75% quieter overall than 40 years ago [36].

Regulatory authorities such as EASA in Europe and FAA in USA, already during the period in which the Concorde was operative, limited supersonic civil aircrafts to perform only subsonic flight, and moreover with controlled levels of noise, when flying over land. Today, indeed, supersonic civil flight is still banned over inhabited zones [43]. The regulations about the noise produced during subsonic flight and by the sonic booms during the supersonic flight represent a very important constraint for the future development of supersonic transport and hypersonic transport concepts. Regulations, however, may change if future technologies and SST aircraft designs will reveal to be able to reduce, at the level of the classic subsonic aircrafts, the noise produced during supersonic flight. With this aim, the American company Loockheed Martin, in collaboration with NASA, is working on an experimental supersonic aircraft to demonstrate how could be possible to drastically reduce noise produced by the future generation of SST aircrafts. The experimental vehicle that is being developed is the *Lockheed Martin X-59 QueSST* (see Figure 1.13), that is part of the X-planes series of experimental vehicles already presented in Subsection 1.1.3.The X-59 is a $29\,m$ long aircraft that should be able, thanks to its innovative aerodynamic design, to perform a Mach 1.42 cruise at about $16000\,m$ altitude creating a low 75 PLdB (Perceived Level decibel), the one required by FAA for a supersonic passenger flight to be acceptable. The first test flight is scheduled for 2022 [61].

Trying to make the point of this Section, it is possible to say that SST aircrafts are valuable examples for the future development of hypersonic passenger aircrafts. The SST vehicles such as Concorde and Tu-144, are indeed the most similar existing examples to what could in the future a commercial hypersonic aircraft. It can be said in fact that mission phases and operations of an SST flight are quite conceptually similar, despite the different speed, to the ones of an HST flight. Thus, engineers and researchers working on HST concepts should acquire knowledge and learn valuable lessons from the already experimented SST projects.

1.3 Commercial Hypersonic Transport

The commercial hypersonic transport seems to be the normal continuation in the civil aviation history of high speed passenger transportation. Already in the 70's, looking at the high international passenger growth ratio at that time and its forecast, NASA [5] - [10] understood the importance of hypersonic transport as the key to meet the need of travelling on long international routes in low time. Many researches were carried out at that time with the aim to develop an hypersonic passenger aircraft starting from the Space Shuttle concept and re-adapting it for 200 passengers and a point to point mission.

However, although still nowadays something similar to a hypersonic passenger aircraft has never flown, a lot of researches in different part of the world has been and are being carried out in order to put the basis to transform into reality the concept of a passengers aircraft able to fly at hypersonic speed. This Section aims to give an overview of some of those researches, the related aircraft concepts, the results achieved and possible future developments, with particular attention to the European projects representing the heritage on which the H2020 STRATOFLY Project is being carried out.

Before to speak about some of the HST projects worldwide, it is important to note that such kind of researches are strictly connected to other topics among which atmospheric reentry technologies, extensive access to space and space tourism, therefore researches in the field of HST and researches in other similar fields shall take reciprocal advantage. The similarity of the topics in the middle ground between high speed transportation and space access/atmospheric reentry lies on the common critical issues to be taken into account in such kind of researches. When developing a vehicle able to fly at hypersonic speed, indeed, the researchers must face with several difficulties, among which the need of new propulsion concepts, aero-thermo dynamic issues and the need of new materials technologies and appropriate thermal protection systems to resist the high heat flow.

The Japan Aerospace Exploration Agency, *Jaxa*, is currently working on a concept of a Mach 5 hypersonic passenger aircraft within the project *Sky Frontier* [48]. The main focus of the research is the development of a hypersonic turbojet engine, fuelled by liquid hydrogen, that can operate continuously from takeoff to Mach 5, the Jaxa's R&D in this field also includes system analysis of hypersonic passenger aircraft, aerodynamic design, heat resistance design, and other important features. The resultant concept design is represented in Figure 1.14. The flat-shaped aircraft is designed be 90 meters in length and about 10 meters across, to hold 100 passengers flying at an altitude of about 25 km. The Jaxa's aircraft would have a range of about 9000 km, with the aim to connect every point of the earth in less than 4 hours. Jaxa is carrying out experiments about the propulsion and aerodynamics using reduced scale models, and Japan aims to collaborate with others American

Figure 1.14. Illustration of the Jaxa's design concept of hypersonic passenger aircraft. Credit: [48]

and European projects in the same field for contributing to make HST happens [27].

In the United States, in the past NASA has carried out many researches about commercial hypersonic transport concepts [5] - [10] that have been of interests for future projects. Nowadays, private companies such as *Boeing* are working on the development of HST concepts [40]. In the Farnborough Air show in July 2018, Boeing stated that the passenger hypersonic aircraft, represented in Figure 1.15, could be airborne in 20 to 30 years.

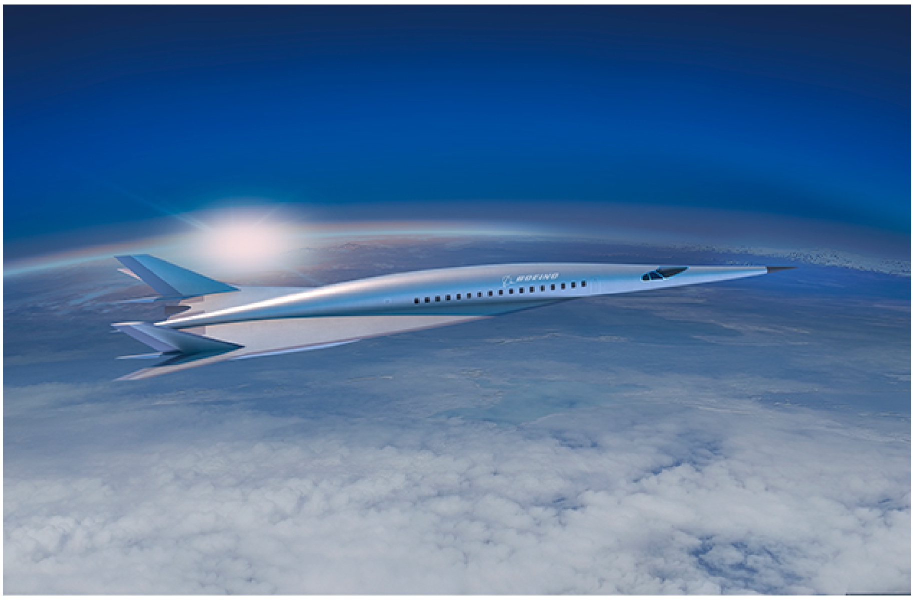


Figure 1.15. Illustration of the Boeing design concept of hypersonic passenger aircraft. Credit: [40]

To develop a big commercial hypersonic aircraft, characterized by hundred of tons of weight and able to carry on board hundred or more passengers, seems to be a very complex task and still a lot of effort and time is needed before to see such kind of aircraft in the sky. For this reason, many research is being done with the aim to investigate the possibility of smaller and simpler solutions, such as hypersonic business/executive jets, that may be more feasible and may need less time for the realization. This is the case of *HyPlane*, represented in Figure 1.16, a business jet able to fly in the stratosphere, at a speed of Mach 4 - 6, carrying on board six passengers. The aircraft would be able to perform horizontal take off and landing using common airports. The project has been carried out within the University of Naples Federico II in Italy, in collaboration with the company Trans-Tech [29]. Savino R., the coordinator of the project, states that the step before the actual realization of a large and complex hypersonic transport system shall be represented by the development of smaller solutions, such as a hypersonic plane of the size of an executive jet, that may take advantage of previous experiences in the general

Figure 1.16. Illustration of HyPlane, a hypersonic executive jets developed by the University of Naples Federico II in collaboration with the company Trans-Tech, Italy. Credit: [29]

aviation and represent the occasion to test and demonstrate new technologies in the fields of of high speed air-breathing propulsion, aerodynamics, materials and structure [29]. Thus, it would be possible in the future to see the realization of such kind of jet before to actually see in the sky large commercial hypersonic aircrafts. This smaller and simpler solution, however, can represent the initiator of future hypersonic transport, giving the opportunity of testing new technologies for not only high speed flight applications but also extensive space access and space tourism.

HyPlane is one example of the huge number of researches and projects that are being carried out in Europe in the field of hypersonic flight technologies. An overview of the most relevant projects co-founded by the European Community is given in the following.

1.3.1 Hypersonic Technology EU Co-Funded Projects

Europe has given a lot of effort, co-founding several projects, to the development of new concepts and technologies in the field of hypersonic transport. The results achieved by such projects represent the basis on which STRATOFLY, the H2020 European project on which this Thesis is based, is being currently taken forward.

Each EU Co-founded project in the field of hypersonic transport has been focused on a particular aspect and technology development representing a critical issues for the future realization of a hypersonic aircraft. The main projects that have been carried out are *LAPCAT-I* and *LAPCAT-II*, *ATLLAS-I* and *ATLLAS-II*, and *FAST20XX*.

The LAPCAT (Long-Term Advanced Propulsion Concepts and Technologies) projects were carried out since 2005, they focused on aerothermodynamics and high-speed propulsion. *LAPCAT-I* aimed to develop high-speed propulsion concepts, obtaining as outcomes two different hypersonic aircraft concepts related respectively to a Mach 5 and a Mach 8 vehicle. The *LAPCAT-II* project, started in 2008, exploiting the heritage of the results achieved by its predecessor, the *LAPCAT-I* project, continued to investigate possible high-speed propulsion solutions for a hypersonic passenger aircraft and carried out as important outcome the *LAPCAT-MR2* aircraft concept that represents the starting point on which the *STRATOFLY* Project is being developed.

The ATLLAS I and II projects were carried out since 2006 with the aim to develop innovative light-weight and heat-resistant materials concepts to be utilized as parts of a future hypersonic aircraft [33].

Another important project hat has been carried out with the collaboration of EC funds in the field of hypersonic transport is *FAST20XX*. This project, started in 2009, aimed to explore the borderline between aviation and space by investigating suborbital vehicles. The main aim, however, was the identification and mastering of critical technologies for such vehicles rather than the vehicle development itself. As important outcomes of the project, the *SpaceLiner*, represented in Figure 1.17 suborbital vehicle concept was developed [19]. The SpaceLiner concept was introduced by the German Aerospace Center (DLR) and then improved within the FAST20XX project. it consists of a vertically launched two-stage rocket space vehicle system concept able to carry on board 50 people over long distances at very short time by exploiting point to point suborbital trajectories. More details about the project are given by Mack A. and Steelant J. [19].

The most important achievements obtained by the LAPCAT projects will be discussed in the following subsection. Particular attention will be given to the LAPCAT-II project since it is of extreme importance for the purposes of this Thesis.

LAPCAT Projects and their Achievements

The LAPCAT-I project was carried out between 2005 and 2008 thanks to the cooperation of different European industries, research institutions and universities coordinated by the European Space Research and Technology Centre ESTEC-ESA in the Netherlands. The main challenge of the project was to develop new high-speed propulsion concepts in order to make it possible to reduce significantly the long-distance travelling time. For example, one of the most important baseline mission requirements was related to the Brussels-Sidney route, to be covered in about 4 hours. Thus, Mach numbers within a range from 4 to 8 had to be considered as cruise speed for such kind of passenger aircraft.

Figure 1.17. Illustration of the *SpaceLiner*, outcome of FAST20XX EU co-funded project. Credit: [30]

The first hypersonic aircraft concept, obtained as one of the outcomes of the LAPCAT-I project, is related to a Mach 5 vehicle, about 300tons, able to carry on 400 passengers in antipodal routes. This vehicle, called *LAPCAT-A2* and represented in Figure 1.18, was mainly developed by ReactionEngines, one of the industrial institutions taking part to the project. The LAPCAT A2's propulsive system is related to a turbine based combined cycle (TBCC) performed by 4 precooled Mach 5 engine, named Scimitar, employing a cycle based on the SABRE spaceplane engine fuelled by liquid hydrogen, that has been developed by Reaction Engines. The SABRE engine, represented in Figure 1.19, is able to drive the aircraft during supersonic and hypersonic phases, as well as when flying at subsonic speed over land and during take-off and landing. More information about the SABRE engine can be found on the ReactionEngines website [51] while more details about its thermodynamic cycle are given by A. Bond [4].

Another important outcome of the LAPCAT-I project is related to a Mach 8 vehicle able to cover long-haul trajectories in a lower time with respect with the Mach 5 concept. The Mach 8 civil aircraft concept was calle *LAPCAT MR1* and is represented in Figure 1.20. The LAPCAT MR1's high-speed propulsive system

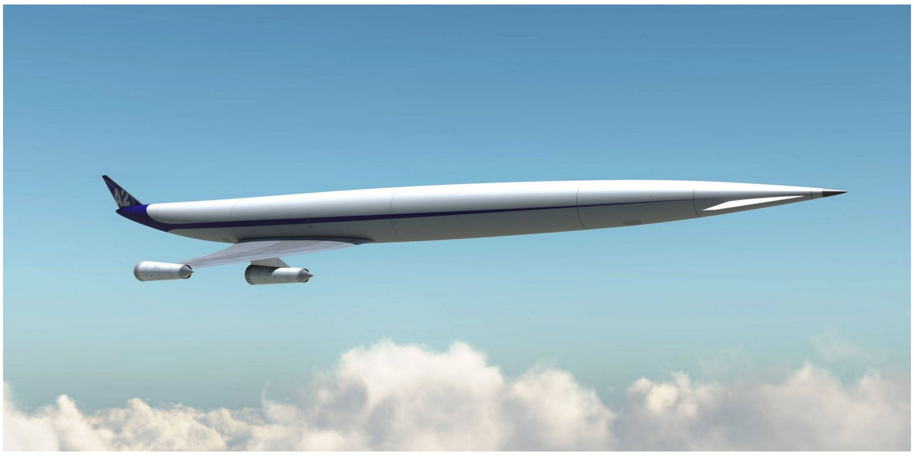


Figure 1.18. Illustration of the *LAPCAT A2*, outcome of LAPCAT I project for civil Mach 5 transport. Credit: [33]

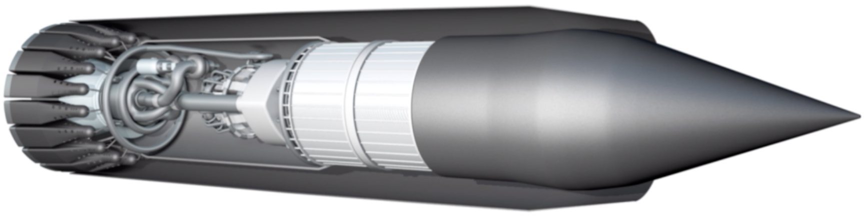


Figure 1.19. Illustration of the *SABRE* engine developed by ReactionEngines. Credit: [51]

concept is related to a gas-generator fed air turbo rocket/ramjet engine, hydrogen-fuelled, based on a dual mode ramjet cycle [34].

In conclusion, the LAPCAT-I project has given a relevant contribution in the assessing of new high-speed propulsion technologies and it has shown as the two Mach 5 and Mach 8 civil hypersonic aircraft concepts, able to fly antipodal routes, seem to be achievable in future, especially taking into account general trends in the evolution of aircraft performance and the possible aerodynamic and propulsive achievable efficiencies. However, further analysis and feasibility studies about the outcomes of the LAPCAT-I project had still to be performed when the project itself was closed. For this reason, in 2008 EU co-funded another similar project, LAPCAT-II, at which 16 partner institutions from 6 different European countries have participated. Proceeding along the outcome of LAPCAT-I, the project has

Figure 1.20. Illustration of the *LAPCAT MR1*, outcome of LAPCAT I project for civil Mach 5 transport. Credit: [33]

evaluated and cross-checked different configurations for the Mach 8 vehicle. The mission requirements of the LAPCAT-II project remain unchanged, but focus has been now directed towards critical points which arose during the LAPCAT-I project [33].

According to J. Steelant et al. [31], the early phases of the LAPCAT-II project have been aimed to the design of different Mach 8 civil hypersonic aircraft concepts. This design process produced basically three different conceptual configurations:

- An ONERA design based on the PREPHA re-usable launch vehicle with a ventral engine from ULB/UNIROMA
- An axi-symmetric design from MBDA
- A waverider configuration designed by ESA

The first conceptual design, represented in Figure 1.21, is based on principles and data resulting from the French program PREPHA, conducted in the 90's. The propulsion system of this concept was based at the beginning on a rocket based combustion cycle (RBCC), however, since such kind of propulsion concept could not realize long ranges, a redesign resulted into a shift towards a hydrogen-fuelled TBCC concept that was proposed in cooperation with ULB and Uniroma.

The Mach 8 aircraft design proposed by MBDA is shown in Figure 1.22. It consists on an axi-symmetric configuration, characterized by four GE90 turbojets engines on one side, to be used when the speed is lower than Mach 0.9, a Continuous

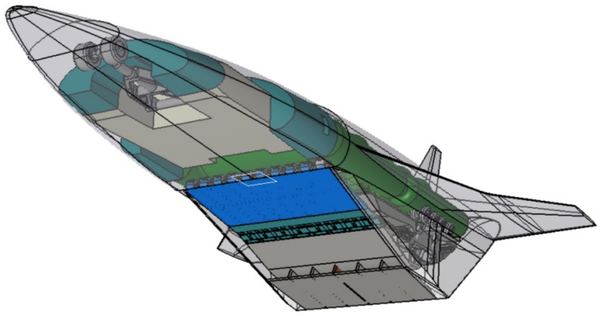


Figure 1.21. Illustration of the ONERA/ULB/UniROMA Mach 8 civil aircraft concept, conceived within LAPCAT-II project. Credit: [31]

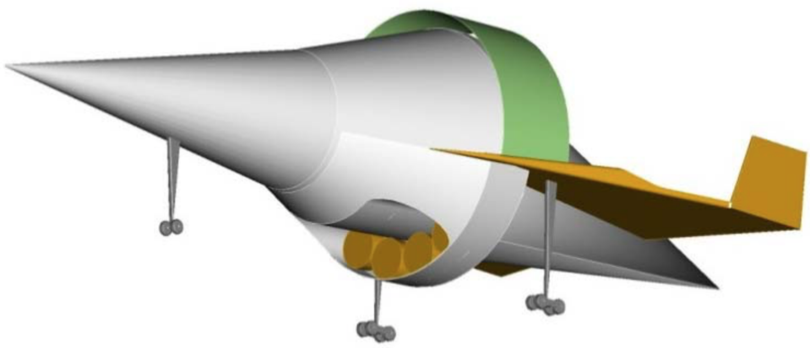


Figure 1.22. Illustration of the mbda Mach 8 civil aircraft concept, conceived within LAPCAT-II project. Credit: [31]

Detonation Wave Rocket Engine (CDWRE) to reach ramjet take-over speed, and a dual mode ramjet (DMR) to be used at supersonic and hypersonic speed after that the aircraft is rotated upside-down (180^o rotation).

Finally, the waverider configuration design proposed by ESA is related to the concept of the *LAPCAT MR2*, represented in Figure 1.23, that is considered as the main outcome of the LAPCAT-II project itself. The LAPCAT MR2 will be better described in Chapter 2, where details about some subsystems and the reference mission will be also given since this vehicle represents the basis on which the STRATOFLY MR3 concept, subject of this Thesis, is being currently developed. The vehicle, characterized by a Maximum Take-Off Weight (MTOW) of about 400 tons, is designed to provide commercial long-distance low-time flight services to 300 passengers [32]. As the LAPCAT projects have been mainly focused on new high-speed propulsion concepts and technologies, the LAPCAT MR2 design has been mainly developed around the propulsive subsystem concept. It consists on six Air

Figure 1.23. Illustration of the *LAPCAT MR2*, outcome of the LAPCAT-II project. Credit: [18]

Turbo Rocket (ATR) [12] and one Dual Mode Ramjet (DMR) [25], this set of engines, fed by liquid hydrogen (LH2), allow the vehicle to fly at all the regimes: subsonic, supersonic and hypersonic. A central intake is properly designed to drive the airflow either to the ATR or to the DMR depending on the flight conditions [20]. The maximum cruise speed is Mach 8 at an altitude of about 30 km, at which the aircraft cover the major part of the antipodal trajectory. As it will better explained in the next chapters, the main reference mission is related to the Brussels-Sidney route to be covered in 2 hours and 55 minutes [18].

1.4 High-Speed Transport: Future Trends

As a conclusion to this Chapter, this Section aims to summarize the relevant points about high-speed flight and to give an overview about some future trends and important aspects that characterize the commercial exploitation of the high atmosphere, speaking both about new commercial high-speed flight perspectives, suborbital trajectories for space tourism, fast access to space and atmospheric reentry technologies.

On the basis of the discussion held in this Chapter, it is possible to see how in the past the scene of high-speed flight was mainly covered by experimental vehicles. In the aviation history, indeed, the different flight speed and flight altitude records were broken by experimental vehicles, e.g. the Bell X-1 (see Fig. 1.6) broke the sound barrier for the first time and the X-43A (see Figure 1.9) was the first aircraft ever reaching hypersonic speed with an air-breathing engine. Moreover, the development of high-speed aircraft, such as supersonic jets, and the development of spaceplanes for space applications, e.g. Space Shuttle and Buran (see Figures 1.3 and 1.2), where carried out thanks to government funds for military application, in the case of supersonic military jets, or for space access and research purposes in the case of

Space Shuttle and the Russian Buran. However, what it is important to underline is that those type of projects were carried out for experimental, military, research or space access applications and not for commercial purposes. The first time a supersonic vehicle was used as civil transport aircraft was in 1976 with the Anglo-French Concorde (see Figure 1.12), that had to face many economical, social and environmental issues which decreed the end of the program in the early 2000's. For to see another commercial high-speed flight perspective, also if more for space-tourism purposes than passenger transport applications, the world had to wait until the 2004, year in which the SpaceShipOne vehicle (see Figure 1.10) won the Ansari X-Prize. Virgin Galactic, main investor of the Spaceship program, is indeed already selling [55] the first tickets for a space experience open to the general public aboard of the Spaceship vehicles.

However, recent projects, such as the ones Co-funded by the European Union in the field of hypersonic flight technologies, are showing how the exploitation of the higher layers of the atmosphere for commercial purposes can be not only oriented to the recreational experience as space-tourist of some rich guy, but instead there is the very interesting and useful possibility to revolutionise the way people think about long-distance travels, making it possible to reach each point on earth in a few hours thanks to new civil passenger hypersonic aircraft concepts such as the LAPCAT MR2 and its successor the STRATOFLY MR3.

The achievements obtained by the different EU co-funded projects, mentioned in Section 1.3.1, show how high-speed transport is conceptually feasible [31]. In particular, those projects have given relevant contribution in the understanding of the main technological drivers for the success of a future high-speed transportation program. As it is possible to see in Figure 1.24, showing different present or past operational aircraft and high-speed vehicle concepts as a function of their cruise Mach number and their Cruise Range Factor (proportional to the range covered during the aircraft's reference mission), while the classical designs, e.g. experimental vehicles such as the X-15 (see Figure 1.7), have been oriented towards high speed and low range, current hypersonic passenger aircraft designs such as le LAPCAT A2, the LAPCAT MR1 and the LAPCAT MR2 (see Figures 1.18, 1.20 and 1.23) go for longer ranges and higher Mach number. Thus, the figure also show that the potential future trend in high-speed transport concepts is oriented toward always major distances to be covered faster, therefore in always less time. The most important challenge for facing this trend is related to the propulsive system, the type of fuel to be used and the quantity of fuel that can be stored on board. Indeed, J. Steelant [31] states that the energy needed, in terms of fuel consumed, to cover a given range is independent from the cruise Mach number since the specific fuel consumption increases linearly with the flight speed. That means that the maximum range is determined by the maximum energy to be stored on board, so by the type and quantity of fuel, and also that, considering a given range, it is convenient to fly as fast as it is possible

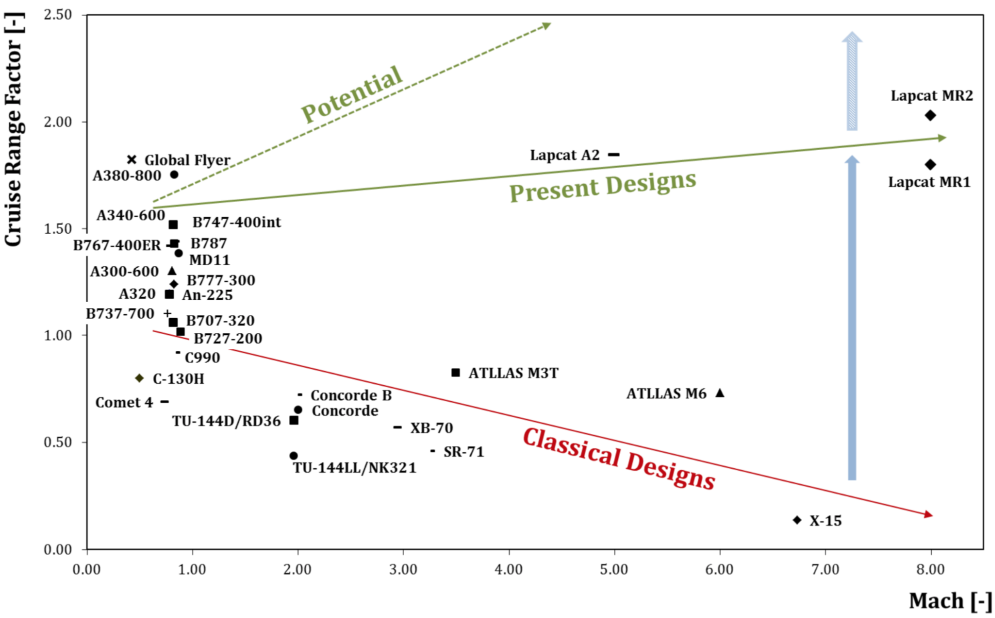


Figure 1.24. Different aircrafts as a function of their Cruise Range Factor and cruise Mach number. Credit: [31]

since the total fuel consumption does not increase when the mach number increases, and a higher Mach number means lower travel time. At this point, the best fuel to be used by such kind of vehicles is liquid hydrogen (LH2). Despite the low density of LH2, its high specific energy content dominates, indeed, the design choice, making it as the best fuel option to cover long-haul routes [31].

Another reason why it is better to fly at high Mach numbers lies on the fact that, given a defined range, the higher is the Mach number the lower is the total heat load absorbed by the structure. This phenomenon is well known under the name of *Thermal Paradox* [11]. It can be, in fact, considered a paradox because it is true that the higher is the Mach number at which the vehicle is flying, the higher is the instantaneous heat flow with which the structure has to deal with, but at the same time the lower is the flight time and therefore the lower is the integrated heat load[1] absorbed by the vehicle during the whole mission. Figure 1.25 shows, indeed, that at a given mission time, as expected, the integrated heat load related to a Mach 5 vehicle is lower than the one related to a Mach 8 vehicle, but nevertheless, at the end of the mission, considering the same range for the two vehicles, the integrated heat load results to be higher for the Mach 5 vehicle instead than the Mach 8 one.

On the basis of the above discussion it is possible to understand the reasons

[1]Integral on time and surface of the heat absorbed. It represents the total heat accumulated by the aircraft structure during the mission.

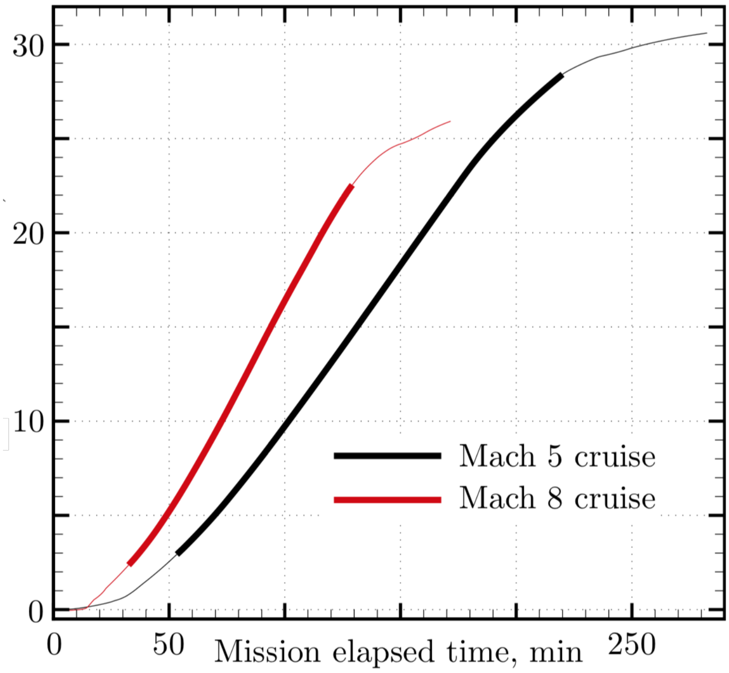


Figure 1.25. The thermal paradox. Integrated heat load vs. mission time for a Mach 5 and a Mach 8 vehicle. Credit: [11]

why a Mach 8 vehicle is better than a Mach 5 one, this is also the reason why the STRATOFLY MR3, direct successor of the LAPCAT MR2, is in fact a Mach 8 vehicle, hydrogen-fuelled and aimed for long range flight.

As the reference vehicle for this Thesis, the STARTOFLY MR3 will be better described in Chapter 2 while the Concept of Operation related to this vehicle will be discussed starting from Chapter 4.

Chapter 2

The STRATOFLY Project

The STRATOFLY project (STRATOspheric FLYing opportunities for high-speed propulsion concepts) has received funding from the European Union's Horizon 2020 research and innovation programme [42]. The project gains relevant knowledge from previous European projects in the field of high-speed transportation, in particular, it can be considered as a follow-up of the LAPCAT II project [31].

The vehicle that is being currently designed under the STRATOFLY project is called STRATOFLY MR3, characterized by a similar design to the one of the LAPCAT MR2, already described in Chapter 1, but with some relevant differences that will be discussed in this Chapter.

This Chapter aims at giving an overview on project objectives (Section 2.1), participants institutions (Section 2.1.1) and university students opportunities (Section 2.2). Furthermore, in Section 2.3, the STRATOFLY MR3 vehicle design will be described, including details of configuration, aerodynamics characteristics and subsystems design, accordingly to the current state of the design activities that are being carried out by the different participants to the project.

Another important objective of this Chapter is to describe the *aerodynamic database* and the *propulsion database*, respectively in Subsections 2.3.1 and 2.3.2, that have been implemented in the *ASTOS* Software for trajectories simulation purposes as it will better explained in Chapters 8 and 9.

2.1 Project Objectives

The STRATOFLY Project focuses on the investigation and feasibility analysis of high-speed civil passenger stratospheric flight opportunities. The project aims at refining the design of the LAPCAT MR2, considered as starting reference vehicle of the project, taking into account technological, economic and environmental factors for investigating the sustainable exploitation of possible new stratospheric routes, with the aim to drastically reduce transfer time, guaranteeing the required safety

Figure 2.1. STRATOFLY Project Logo.

levels and reducing noise and emissions.

One of the main reasons why EU puts lot of effort in projects like STRATOFLY and its predecessors lies on the fact that the number of civil aviation passengers is predicted to globally increase of six times in 2050 [42]. Therefore, the exploitation of new air space and the investigation of high-speed flight opportunities for long haul distances and shorter time frames with respect to conventional aircrafts may represent the key for the sustain of civil aviation future.

More information about the STRATOFLY Project can be found in the official website [47]. However, the main project objectives and requirements are summarised in the following.

- STRATOFLY hypersonic vehicle shall be designed to perform an antipodal civil passenger transport mission, flying at Mach number of 8 above 30 km of altitude.
- The vehicle concept shall reach the ambitious goal of TRL6[1] in 2035.
- To drastically decrease the transfer time of long range civil flights.
- To evaluate the sustainability of the future operability of hypersonic vehicles from an economical and also environmental point of view.
- To investigate new hypersonic trajectories in the stratosphere.
- To increase the maturity level of crucial technologies for future reusable space transportation systems.

The participants institutions to the project will be described in the next Section.

[1]Technological Readiness Level - 6: technology demonstrated in a relevant industrial environment.

2.1.1 Project Participants

The STRATOFLY project started in June 2018 and will end in November 2020. The project is being currently carried out thanks to the collaboration of 10 partner institutions from 7 different European countries, coordinated by the *Politecnico di Torino*. The project participants are hereafter listed.

- *POLITECNICO DI TORINO*, Italy. Project Coordinator.
- *STICHTING NATIONAAL LUCHT- EN RUIMTEVAARTLABORATORIUM*, Netherlands.
- *CENTRO ITALIANO RICERCHE AEROSPAZIALI (CIRA)*, Italy.
- *DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV (DLR)*, Germany.
- *OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES*, France.
- *CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS*, France.
- *TOTALFORSVARETS FORSKNINGSINSTITUT*, Sweden.
- *TECHNISCHE UNIVERSITAT HAMBURG*, Germany.
- *FUNDACION DE LA INGENIERIA CIVIL DE GALICIA*, Spain.
- *INSTITUT VON KARMAN DE DYNAMIQUE DES FLUIDES*, Belgium.

Beyond engineers and researchers, the project also involves students from different universities as it will be better explained in the next Section.

2.2 The STRATOFLY Academy

The STRATOFLY project gives the opportunity to university students to perform research activities in the field of civil hypersonic transport, thanks to the STRATOFLY Academy.

With the primary objective to inspire new generations of researchers and workers and getting inspired by possible new ideas useful for the project, the STRATOFLY Academy is organised as challenge at which students can participate individually or in team, with an academic supervisor that represents the interface between the student and the STRATOFLY project. This initiative represents a good opportunity for students to enrich their professional and cultural experience, thanks also to the heterogeneity of the teams composed of students from different countries. In fact,

Figure 2.2. STRATOFLY Academy Logo.

currently the Academy involves more than 7 universities, from 7 different countries, not only European. More information about the STRATOFLY Academy can be found in the official website [53].

This Thesis has also been carried out under the STRATOFLY Academy, and part of the thesis work has contributed to the activities performed in a team, simply called *Team D*, of 4 students from the Politecnico di Torino and the Stuttgart University. Anyway each team member had his own academic supervisor and the thesis work has been mainly performed individually.

2.3 The STRATOFLY MR3 Vehicle Design

The STRATOFLY MR3 vehicle concept is characterized by a waverider configuration and a bubble-structure approach with a dorsal engine, located on top of the vehicle, multi-lobe tank structure that maximizes fuel storage capability and minimizes weight, and an integrated passenger cabin located in the ventral part of the vehicle. A scaled model of the vehicle is represented in Figure 2.3.

The STRATOFLY MR3 vehicle design can be considered as a refinement of the LAPCAT MR2 concept [31], shown in Figure 2.4-a. Both the vehicles, indeed, are characterized by a similar shape, 94 m long and about 400 tons of weight, similar subsystems and shall perform the same reference mission characterized by hypersonic cruise at 30 km altitude and 8 Mach velocity. Although the main characteristics are the same for the two vehicles, there are some important differences concerning both the external configuration and the internal layout that will be discussed hereafter.

By looking at Figure 2.4, it is possible to understand one of the main differences among the two vehicles concerning the absence of the canard, aerodynamic surface

Figure 2.3. Scaled model of the STRATOFLY MR3 vehicle showcased at AERO days 2019 in Bucharest.

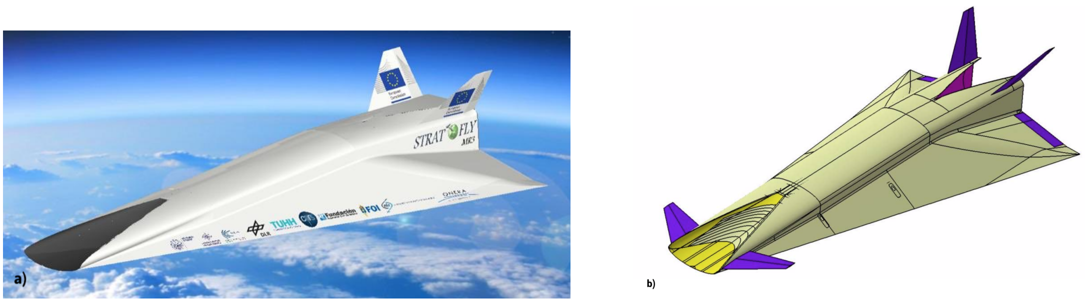


Figure 2.4. a) STRATOFLY MR3 vehicle concept - b) LAPCAT MR2 vehicle concept.

at the nose of the vehicle. The reason why this change lies on aerodynamics simulation performed within the STRATOFLY project for which the canard is not longer deemed necessary.

Another important difference is related to the internal layout and especially to the passenger cabin configuration. The different cabin layouts can be seen in Figure 2.5, while the details of the STRATOFLY MR3 cabin design are shown in Figure

2.6. The STRATOFLY and the LAPCAT passenger cabins have a similar internal volume, respectively $1200\,m^3$ and $1400\,m^3$ [31], and both can host a maximum of 300 passengers.

There are different reasons why such kind of change in the cabin design has been deemed necessary for the STRATOFLY MR3 vehicle. First of all there is a safety reason related to the better compartment location with respect to other subsystems such as tanks and engines, and to the organisation of boarding procedures as well as cabin escape thanks to the better location and size of doors. Another reason lies on the fact that a unique environment, instead of separated and restricted compartments, is a better solution for passenger comfort in terms of more volume available and limited isolation. The last reason is related to the range of variability of the vehicle CoG position during the mission, a unique environment for passenger cabin located at about the center of the vehicle ensures, in fact, a better weight balance.

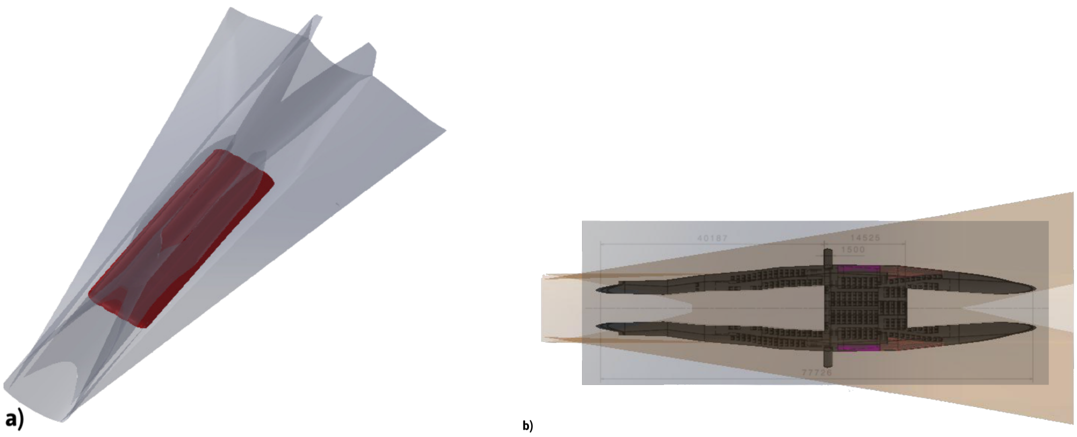


Figure 2.5. a) STRATOFLY MR3 passenger cabin design - b) LAPCAT MR2 passenger cabin design.

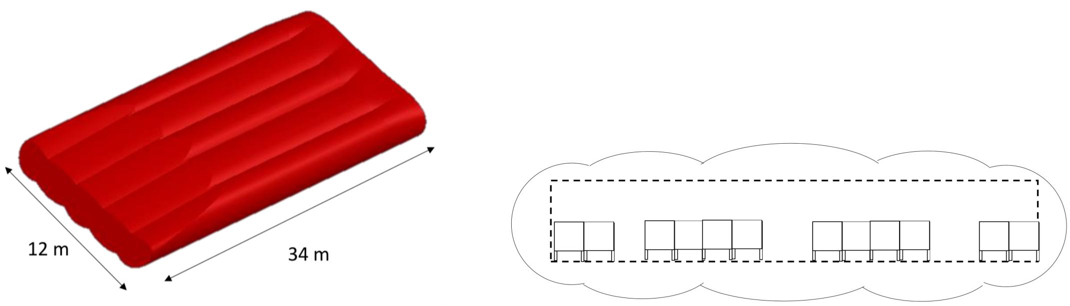


Figure 2.6. STRATOFLY MR3 passenger cabin dimensions and internal configuration.

Once the main differences between the two vehicles have been described, let us focus the attention to the STRATOFLY MR3 system and subsystems design. Beyond structural and aerodynamics characteristics, the vehicle is composed of the following subsystems.

- Propulsive Subsystem
- Thermal and Energy Management Subsystem (TEMS)
- Thermal Protection Subsystem (TPS)
- Environmental Control an Life Support Subsystem (ECLSS)
- Propellant Subsystem
- Flight Control System (FCS)
- Avionic Subsystem
- Electric Subsystem
- Landing Gear

An overview on the aerodynamics characteristics and the different subsystems will be given in the following sections. However, it is important to note that not all the subsystems have reached the same level of design detail. The most investigated subsystems are the propulsive one and the TEMS, in particular, the propulsive subsystem has been the first one to be designed and it is the subsystem around which the other elements of the vehicle have been designed. The TPS, the ECLSS and the propellant subsystem are at a good level of design thanks especially to their interfaces with the TEMS, as it will be better explained later in this Chapter. Other subsystems like the FCS, the Avionics and the electric subsystem have been only designed at high level, in terms of generic characteristics, mass budget and power budget on the basis of similarities with existing aircrafts.

2.3.1 Aerodynamics Characteristics

The different activities to be carried out for the conceptual design of an hypersonic civil passenger aircraft must be supported by appropriate experimental models and numerical tools to be developed in order to acquire the necessary knowledge and know-how to get confident with new high speed transport technologies. Lot of effort, indeed, has been given in the investigation of high speed aerodynamics in terms of supersonic to hypersonic transition, supersonic combustion and maximization of the aerodynamic efficiency. The overall aerodynamic performances of a high-speed transport vehicle, indeed, depends mainly on the L/D ratio, studies about the intake performances and the integration between internal and external flowpath are therefore important to avoid the generation of additional drag [31].

The aerodynamics characteristics of the vehicle have been computed and validated through CFD simulations performed during the LAPCAT II project and taken forward during the STRATOFLY project. As a result of the CFD computations, an aerodynamic database has been developed in order to describe the properties of the aerodynamic coefficients. This database, described hereafter, represents an important input for part of this Thesis work.

Aerodynamic Database

The aerodynamic database is of extreme importance for the description of the aerodynamic behaviour of the STRATOFLY MR3 vehicle, to be considered as input for the trajectory simulation via the ASTOS Software performed as work of this Thesis and fully described in Chapters 8 and 9.

The ASTOS software has also been used for the simulation and optimization of the LAPCAT MR2 trajectory performed by ESA [18], in this occasion the aerodynamic data, deemed necessary as input for the software, have been collected in the aerodynamic database. The data collected for the simulation of the LAPCAT MR2 trajectory can be also used for the purposes of this Thesis since the relevant aerodynamics characteristics remain the same for STRATOFLY MR3.

The database contains information about the drag and lift coefficients as function of different independent variables such as Mach number, angle of attack and, in the case of C_D, also dynamic pressure. Information about aerodynamic moment coefficient and aerodynamic surfaces deflection are not implemented in ASTOS since for the purposes of this Thesis the vehicle can be considered as a material point, coincident with the CoM, in which thrust, aerodynamic and weight forces act. The angle of attack depends, in fact, on a control law defined by the user and the software computes a 3 DOF dynamics that does not consider the rotational dynamics of the vehicle. More information about the utilization of ASTOS are provided in Chapter 8.

The reference Area for both lift and drag computation is:

$$A = 2365\, m^2$$

For a better understanding and ease of reading of the aerodynamic database, this is provided as graphics instead of the tabular format implemented in ASTOS.

The drag coefficient, plotted in Figure 2.7, is a combination of both viscid and inviscid drag. Thus, C_D values have been provided as a function of Mach numbers from M=0.3 to M=8, different angle of attacks (AoA=-2; 0; 2 deg) and different dynamic pressures. The dependency on dynamic pressure is necessary to describe the contribution of the viscous component on the combined drag coefficient. The additional drag related to the air flow spillage of the propulsive duct is not described by the C_D but it has been subtracted from the net thrust as described in Section 2.3.2.

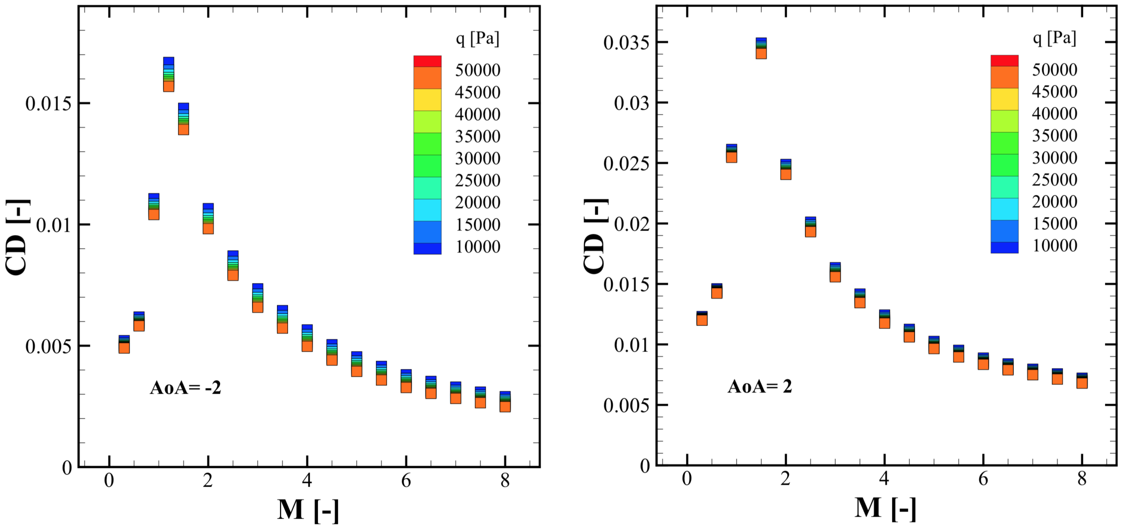


Figure 2.7. Drag coefficient for two different angles of attack as a function of Mach number and dynamic pressure, as used in ASTOS. Credit: [18]

In Figure 2.7 it is possible to see the typical behaviour of the drag coefficient as a function of the Mach number: the C_D increases in the subsonic regime until reaching a maximum in the subsonic to supersonic transition, and then decreases in the hypersonic regime. Furthermore, the lower is the AoA the lower is the C_D, in fact the drag basically doubles when passing from $AoA = -2^o$ to $AoA = 2^o$.

The lift coefficient is described as a function of the Mach number and the angle of attack in Figure 2.8. However, the C_L must be corrected with a negative contribution related to the mass-flow rate spilled by the engines. This internal lift component is called $C_{L_{spill}}$, and it is not negligible especially at low supersonic regime, when a high amount of mass-flow is spilled in the in the lift direction. On the right hand side of Figure 2.8 it is possible to see the effect of the spillage correction on the lift coefficient for $AoA = 0^o$.

The C_L trend with the Mach number and the AoA is similar to the one already discussed for the drag coefficient.

2.3.2 Propulsive Subsystem

The propulsive subsystem has been designed during the LAPCAT II project and its configuration remains the same for the STRATOFLY MR3 vehicle, that, therefore, preserves the same propulsive performances of its predecessor.

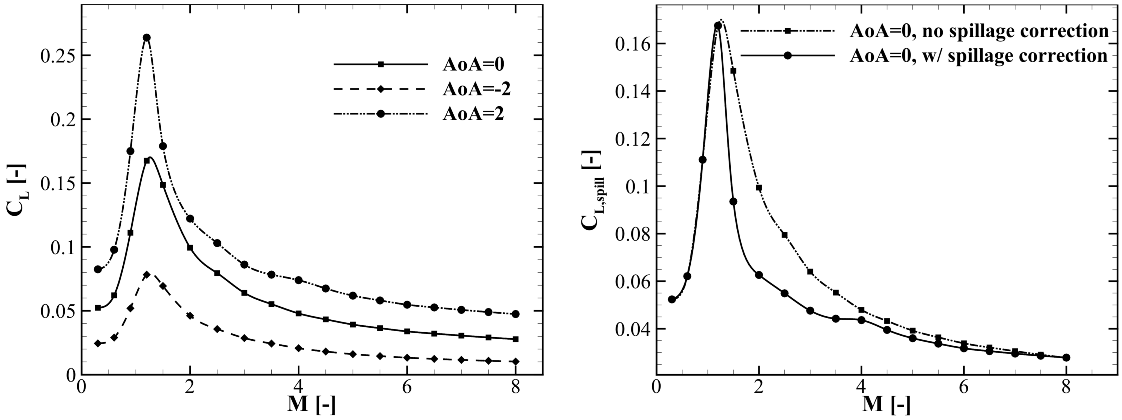


Figure 2.8. Lift coefficient as a function of Mach number and angle of attack with and without spillage correction, as used in ASTOS. Credit: [18]

The propulsive subsystem, represented in Figure 2.9, is located on top the vehicle and it is composed of two main engine units that allow to cover all the flight conditions and speed range during the mission. The two units are respectively related to 6 Air Turbo Rocket (ATR) engines [31][12] enclosed in two different bays, containing 3 engines each, located on two sides, and one Dual Mode Ramjet (DMR) [25] located at the center. The propellant is liquid hydrogen (LH2) for both the engine units. The ATR operates at Mach numbers from 0 up to 4-4.5, therefore during take-off, subsonic and supersonic acceleration, and, at the end of the mission, final approach and landing. The DMR cover the hypersonic flight conditions, operating from M=4-4.5 up to M=8 in order to power the aircraft during hypersonic acceleration and cruise.

As it is possible to see in Figure 2.9, the intake and the duct are designed properly to drive the air flow towards one or the other engine unit on the basis of the flight condition [20], while the exhaust gases produced by the ATR or DMR at different regimes are expelled by a common nozzle [23].

The propulsive subsystem performances have been evaluated during the LAPCAT II project and have been collected in a database described hereafter.

Propulsion Database

The propulsion database is a necessary input for the simulation of the STRATOFLY MR3 trajectory described in Chapters 8 and 9. This database has been developed under the LAPCAT II project and it has already been implemented for the LAPCAT MR2 trajectory simulation performed by ESA [18]. However, the propulsion database can be also used for the purposes of this Thesis, hence for the STRATOFLY MR3 trajectory simulation via ASTOS software.

The engines performances are provided as a function of different independent

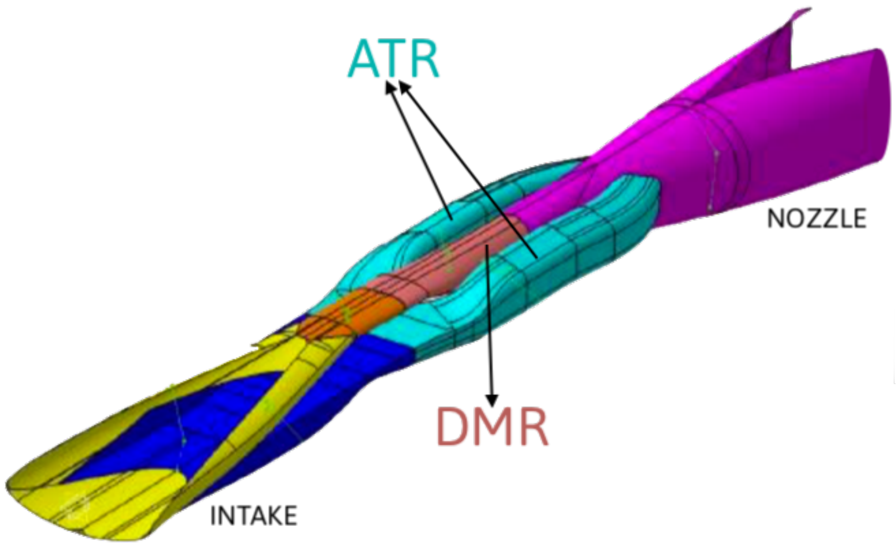


Figure 2.9. Illustration of the Propulsive Subsystem.

variables, among which altitude, mach number, equivalence ratio (ER) and angle of attack. The ER is defined as the ratio of the actual fuel ratio to the respective stoichiometric ratio. For liquid hydrogen, ER can be defined as:

$$ER = \frac{\dot{m}_{LH2}}{\dot{m}_{LH2_{stoich}}} = \frac{\dot{m}_{LH2} \cdot 34.33}{\dot{m}_{air}}$$

The ER is an important parameter since it allows to control the ratio of effective net thrust to the maximum thrust potentially generated by the engine at stoichiometric conditions.

The dependancy on the AoA is only considered for the DMR performances description, this is deemed necessary for taking into account the variation of the internal flow path at different vehicle attitudes.

The propulsion database is provided as graphics, and not as tables, for a better understanding and ease of reading.

The ATR performances have been provided in terms of net thrust and massflow rate for altitudes from 0 km up to 26 km, Mach numbers from M=0.01 up to M=4.5, each at ER=0, ER=0.5 and ER=1. Hence, the ATR net thrust is described by Figure 2.10. The ATR performances provided in the database already include the additional drag, considered as negative contribution to the net thrust, caused by the off-design conditions of the air intake, designed for hypersonic cruise, and the massflow captured by the DMR working as an open duct when ATR is the operative engine unit.

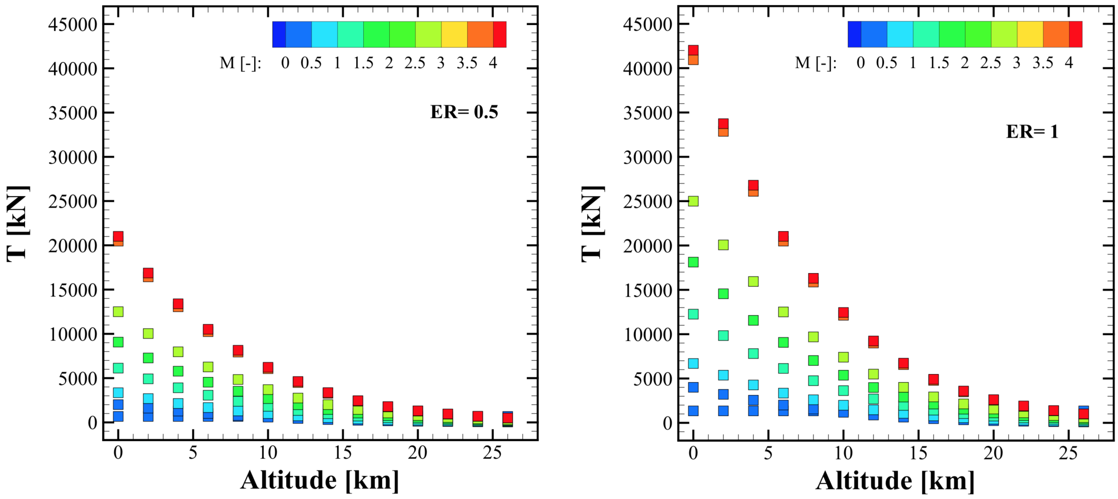


Figure 2.10. ATR performances as a function of altitude and Mach number at ER=0.5 and ER=1, as used in ASTOS. Credit: [18]

As it is shown in Figure 2.10, the higher is the Mach number at the same altitude the higher is the net thrust, this is because the net thrust is primarily a function of the mass flow rate, that, indeed, increases at higher mach numbers. Furthermore, the mass flow rate decreases when altitude increases, therefore a higher altitude leads to a lower net thrust. The ER-dependancy of the net thrust is clearly visible since when passing from ER=1 to ER=0.5 there is also a helving of the ATR performances.

The ATR mass flow rate is not given as graphic, however it can be said that its trend is similar to the one of the net thrust. The maximum mass flow rate is $\dot{m} = 1050.68\,kg/s$ related to minimum altitude ($h = 0\,km$) and maximum Mach number ($M = 4.5$), anyway this condition can never happen and for the real flight conditions the mass flow rate is never higher than $\dot{m} = 100\,kg/s$.

The DMR performances have been provided in terms of net thrust and mass flow rate for altitudes from 18 km up to 40 km, Mach numbers from M=4 up to M=8, each at ER=0; 0.5; 1 and AoA=$-2^o; 0^o; 2^o$. Thus, the DMR net thrust data are plotted in Figure 2.11. For each altitude, six different sets of data are available for different angles of attack and equivalence ratio: 3 values of AoA (-2, 0, 2) times two values of ER (0.5, 1). The description of the case ER=0 is not needed since both the net thrust and mass flow rate are equal to zero in this condition.

The DMR net thrust and mass flow rate trends are similar to the one already discussed for the ATR. Also in this case mass flow rate data are not represented, however it is possible to state that the maximum rate of $\dot{m} = 395.12\,kg/s$ is related to minimum altitude and AoA and maximum Mach number and ER ($h = 18\,km$, $AoA = -2^o$, $M = 8$ and $ER = 1$). Anyway, for the real flight conditions the mass flow rate is never higher than $\dot{m} = 50\,kg/s$.

More information about the propulsive subsystem performances will be given

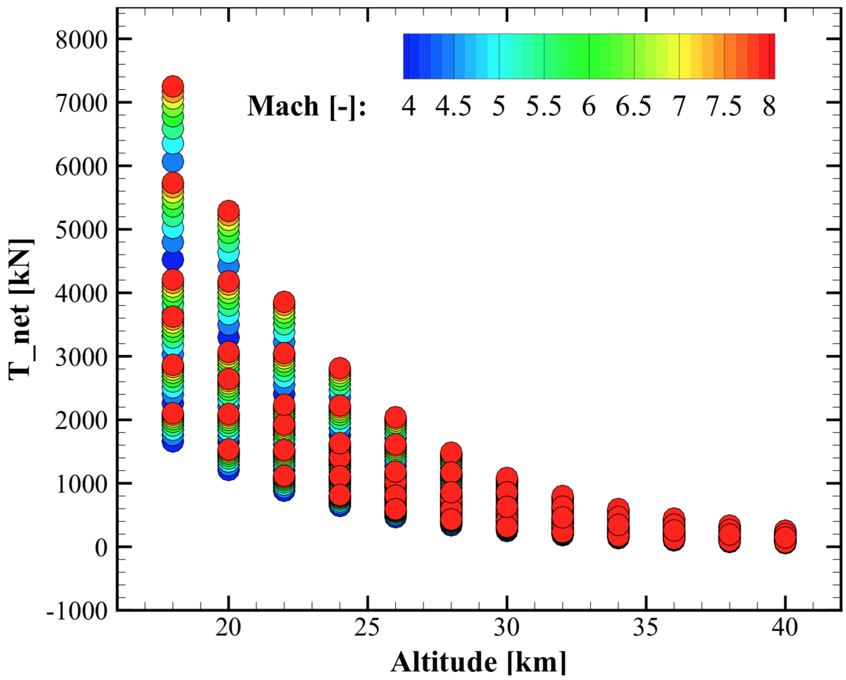


Figure 2.11. DMR performances as a function of altitude and Mach number at different sets of ER and AoA, as used in ASTOS. Credit: [18]

in Chapters 8 and 9 when the STRATOFLY MR3 nominal and out of nominal trajectories will be simulated.

2.3.3 Thermal and Energy Management Subsystem

One of the most difficult and interesting challenges for engineers when designing high-speed vehicle concepts is related to the techniques and solutions developed for dealing with the high-temperature and high heat loads that characterize the hypersonic flight. Although in the past many solutions for the Thermal Control System (TCS) and the Thermal Protection System (TPS) have been envisaged to protect aircrafts and reentry vehicles from high heat fluxes as well as to manage internal and external temperature, a multifunctional and highly-integrated technology has been considered for the development of the Thermal and Energy Management Subsystem (TEMS) of LAPCAT MR2 [2][14], that has been also considered and refined for the STRATOFLY MR3 vehicle.

The external vehicle surfaces can reach, for the selected mission, temperatures up to $T = 1000 - 1200\,K$, while the tanks contain fuel at the cryogenic temperature of about $T = 20\,K$, this difference of temperature between external and part of the internal environment can lead to strategic advantages. On the basis of the TEMS way of working there is the idea to exploit high-temperatures typical of hypersonic flight and to integrate the functions of different subsystems, among which the TPS the ECLSS and propellant subsystem. With the main purpose to manage energy and temperature, the TEMS, indeed, is highly-interfaced with other subsystems helping them to accomplish the expected goals. Thus, purposes of the TEMS are also to protect the aircraft from external heat loads, to cool the passenger cabin and to contribute feeding the propulsion plant.

The TEMS is represented in Figure 2.12. Here how it works: the aerodynamic heating penetrates the aeroshell and, once conducted to the tanks, allows LH2 boil-off which is used through an appropriate thermodynamic cycle for two purposes, on one hand the gaseous H2 is used directly to cool down passenger cabin, on the other hand H2 is used as coolant for the air pack of the ECLSS an the propulsion plant after being compressed. After boil-off, the liquid hydrogen is directly pumped in the combustion chamber, while the gaseous H2 is also injected in the combustion chamber only at the end of the aforementioned cooling cycle.

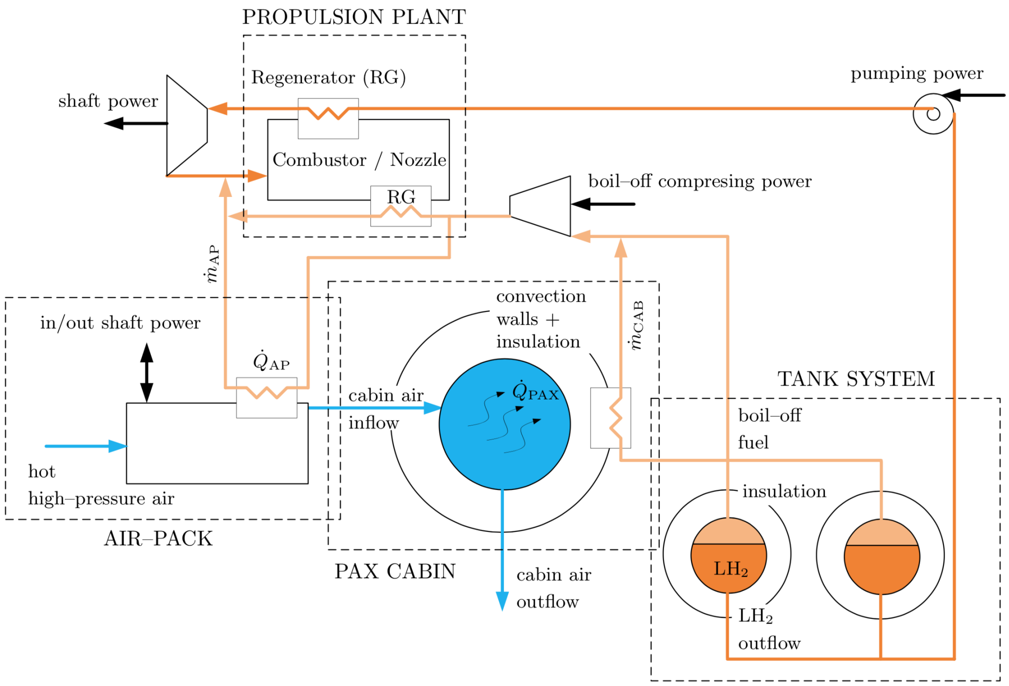


Figure 2.12. Illustration of the Thermal and Energy Management Subsystem. Credit: [12]

It is important to note that the integration of functions among TEMS, TPS, ECLSS and propellant subsystem depends on the specific flight condition. A fully cooperation, indeed, is only possible when the external heat flux is sufficiently high, therefore at high supersonic and hypersonic regimes rather than subsonic flight conditions. This last aspect will be better discussed in Chapter 7 where a description of the subsystems synergy will be given under an operational perspective.

2.3.4 Thermal Protection Subsystem

The Thermal Protection System (TPS) is aimed at protecting the aircraft from the external heat flux, that can be very high for a hypersonic vehicle. As already discussed in the previous Section, the TPS is integrated, for some aspects, with the TEMS.

The TPS can be considered under two different aspects. On one hand the TPS works as passive system, composed of appropriate materials for protecting the aeroshell from heat loads. The high-temperatures typical of the case study application leads to the adoption of ceramic materials instead of metal alloys. On the other hand, for higher heat fluxes the TPS works also as active system thanks to special heat pipes configurations located under the aeroshell that allow the conduction of heat from the external to the tanks in order to produce the fuel boil-off needed for the TEMS's operations. An illustration of the active aspect of the TPS is given in Figure 2.13.

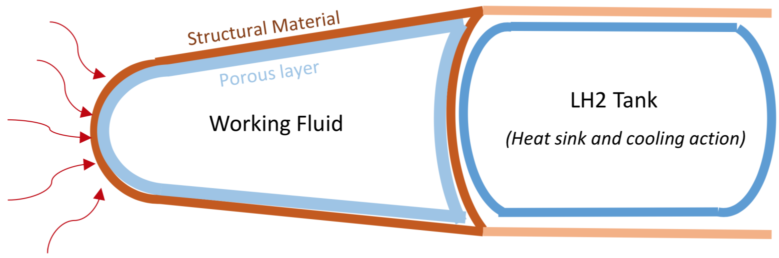


Figure 2.13. Illustration of the heat conduction concept of the Thermal Protection Subsystem. Credit: [12]

2.3.5 Environmental Control and Life Support Subsystem

In all the aerospace systems designed to carry humans on board, it is important to preserve the life by guaranteeing the presence of a breathable internal atmosphere and appropriate levels of pressure, temperature, humidity and an acceptable presence of bacteria and contaminants. In conventional aircrafts, this function is accomplished by the Environmental Control System (ECS), while for space applications it is better to speak about an Environmental and Life Support System (ECLSS). The difference between the ECS and the ECLSS lies on the way oxygen is provided and on the different kind of cycle on the basis of which the subsystem works.

Conventional aircrafts, indeed, usually fly in the troposphere or low stratosphere where the air density is sufficiently high to allow the implementation of open cycles for the internal environment control, based on compressed and air to be injected, after proper temperature, humidity and contaminants controls, in the passenger cabin for then to be expelled outside in a continuous open cycle. The appropriate oxygen partial pressure is ensured by the compression of the oxygen already present in the external atmosphere.

Spacecrafts, instead, usually operate at higher atmosphere layers in which the air is so rarefied to make it necessary to adopt a closed cycle for environmental control and life support. In this case, it is necessary to carry on board some oxygen to be provided on board for assuring the appropriate level of oxygen partial pressure for a breathable internal atmosphere. Furthermore, since the air on board is always the same, this must be properly "cleaned" and controlled cyclically during the mission.

The STRATOFLY MR3 vehicle, however, is not a conventional aircraft but neither a spacecraft. During its mission, in fact, it covers different flight conditions at different altitudes making it necessary to consider a mixed cycle for the environmental control, more open in the lower layers and more closed when flying in the stratosphere. Thus, the designated subsystem will be something in-between of an ECS and an ECLSS. However, since this subsystem will also have the function to support life on board, from now on, in this Thesis, it will be addressed as ECLSS.

Although the ECLSS has still not been fully designed and no data about the subsystem configuration and components are available, for the purposes of this Thesis the important aspect of the ECLSS to underlined is the integration with the TEMS and the cooperation in synergy with other subsystem such as the TPS and the propellant subsystem at high-speed, so high external temperature, conditions. This aspect will be better described in Chapter 5.

2.3.6 Propellant Subsystem

The propellant subsystem objectives are to store the fuel on board and to fed the propulsion plant. The LH2 tanks have been designed with a bubble-structure approach in order to increase the efficiency of the internal volume and minimize weights [31].

The propellant subsystem, in terms of tanks configuration, designed for the LAPCAT MR2 had to be slightly modified and refined for the STRATOFLY MR3 in order to take into account the changes between the two vehicles in the internal space layout, especially passenger cabin location and shape, and to optimize internal space for other subsystems and components allocation.The tanks configuration for both the LAPCAT MR2 and the STRATOFLY MR3 can be seen in Figure 2.14.

The different acronym reported in Figure 2.14 for the LAPCAT MR2 stem for the different tanks identification, they mean respectively:

- **BCFT**: Body Center Forward Tank
- **BSFT**: Body Side Forward Tank
- **BCAT**: Body Center Aft. Tank

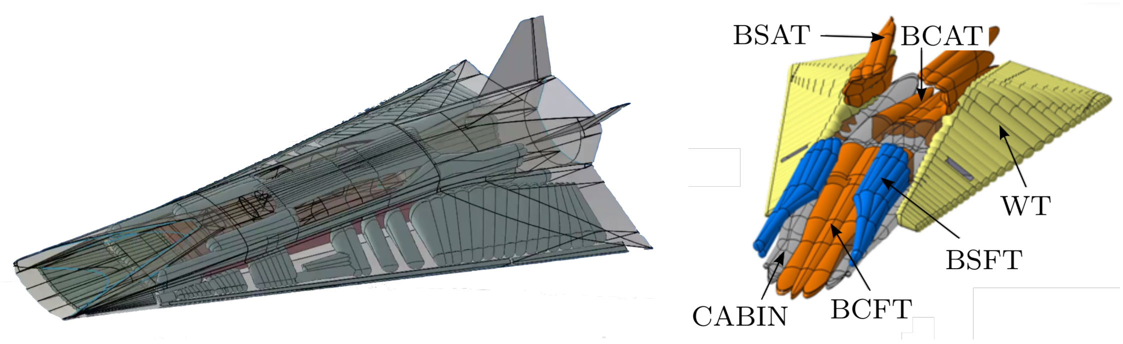


Figure 2.14. Tanks configuration for STRATOFLY MR3 (LHS) and LAPCAT MR2 (RHS).

- **BSFT**: Body Side Aft. Tank
- **WT**: Wing Tank

By looking at the differences between the LAPCAT MR2 and the STRATOFLY MR3 tanks configurations, it is possible to see that in the refined case (STRATOFLY) there is more free space to be used for other subsystem allocation and for boarding and emergency exits.

An important aspect to be taken into account when designing the propellant subsystem is the emptying law that shall minimize CoG range of variability during the mission.

When flying at high-speed, as already discussed in Section 2.3.3, the aerodynamic heating is exploited to produce LH2 boil-off and the propellant subsystem operates in cooperation with other subsystems like TEMS, ECLSS and TPS.

2.3.7 Flight Control System

The Flight Control Subsystem (FCS) aims at controlling the aircraft direction and attitudes in flight. The FCS consists of the aerodynamic surfaces as well as the respective cockpit controls, operating mechanisms, hardwares and softwares to control the aircraft in nominal and out of nominal conditions.

Since a hypersonic cruiser such as STRATOFLY MR3 is not a conventional aircraft, the design of the FCS, in terms of aerodynamic surfaces identification and sizing, actuators design and software development, is not an easy issue. At this stage of the subsystem design, it can be said that the vehicle will be controlled through two aerodynamic surfaces units, a canted vertical tail and a horizontal control surfaces assembly, for a total of 8 aerodynamic surfaces: 2 ailerons, 2 canted rudders and 4 elevators.

Moreover, STRATOFLY MR3 will be an innovative aircraft not only for the high-speed and short time-long distance flight, but also for the on board subsystems characteristics. The vehicle subsystems, in fact, are being designed with the approach of more/all electric aircraft [26][25], therefore no hydraulic system is being considered for power transmission and this affects the control actuators design. The aerodynamic surfaces, in fact, will be probably moved by electro-mechanic, or electro-hydrostatic, actuators rather than electro-hydraulic actuators typically used on board of conventional aircrafts.

Anyway, it is beyond the purposes of this Thesis to describe the STRATOFLY MR3 FCS design. The FCS subsystem, in fact, has not been fully designed and further development will be discussed in future literature. However, also if the subsystem design will be better defined in future, purpose of this Thesis is the investigation of the subsystem characteristics from an operational perspective, as it will be discussed in Chapter 5.

2.3.8 Avionic Subsystem

The Avionics is another of those subsystems still at an early design stage. Currently, different tools and methodology are being developed for performing functional analysis and investigating all the components needed to satisfy the different functions.

The mass and power budget estimation is supported, at this stage of design, by analogies with existing aircrafts and no much data about the avionics characteristics are available. As it will be discussed in Chapter 5, however, purpose of this Thesis is to describe the subsystem from an operational perspective, and this can be done independently from the specific subsystem design.

2.3.9 Electric Subsystem

The electric subsystem is responsible for electrical energy management, in terms of energy storage as well as power and signals transmission. The approach currently implemented for the STRATOFLY MR3 subsystems meets the goal of more/all electric aircraft, no hydraulic subsystem is indeed considered for power transmission and this function is only addressed to the electric subsystem. This means that much effort must be given when designing such kind of subsystem in order to avoid any kind of critical failure that could lead to the impossibility to control the aircraft putting in danger the mission or also passengers life.

Both because this subsystem is not relevant to be designed early in the aircraft project and because maybe in future more technologies will be developed making it possible to realise the goal of an all-electric aircraft, the electric subsystem is still at a very early design stage.

Anyway, beyond what will be the subsystem characteristics, this Thesis gives a contribution, as discussed in Chapter 5, in the understanding of the way the electric subsystem shall operates in different mission phases, in nominal as well as out of nominal conditions.

2.3.10 Landing Gear

As important element of an aircraft design, also the landing gear has been investigated as STRATOFLY MR3 subsystem. At the current stage of design, the landing gear subsystem consists of four legs, two in the front and two in the rear, organised in a tandem cycle layout. Each leg is provided with four wheels, for a total of 16 wheels touching the ground. Figure 2.15 shows the landing gear geometrical characteristics designed for the LAPCAT MR2 vehicle. However, the STRATOFLY MR3 landing gear high-level layout will be not much different from the one of its predecessor.

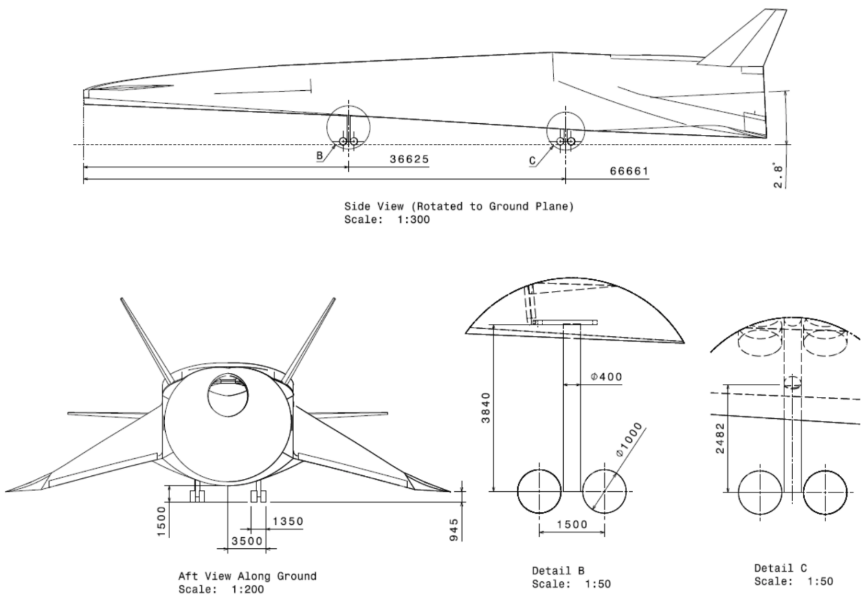


Figure 2.15. LAPCAT MR2 landing gear geometrical characteristics.

As it is possible to see in Figure 2.16, an aft-inwards retraction method is being considered for the front gear, while the rear gear will be retracted through a conventional direct-inwards mechanism.

The landing gear design, however, is still at an early stage, further detail and possible changes in the subsystem characteristics will be achieved in the STRATOFLY project and discussed in future literature. In this Thesis, anyway, the landing gear will be investigated under an operational perspective as discussed in Chapter 5.

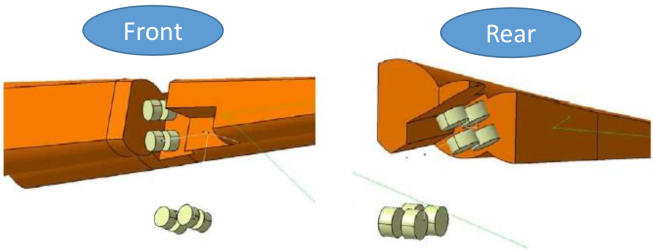


Figure 2.16. Illustration of conceptual landing gear deployment.

2.4 How this Thesis fits in the Project

This Chapter has been mainly focused at giving an overview on the STRATOFLY project and the current state of system and subsystem design. All the information here included have been provided by different institutions participating to the project, with an interface between the project and this Thesis represented by the Politecnico di Torino.

The next chapters, however, are intended to describe the original work performed in this Thesis. The contribution of this Thesis in the STRATOFLY project lies on the Concept of Operations (ConOps) analysis and the trajectory simulation via the ASTOS software, that represent something never done before within this project.

The contents of this Chapter are important to understand some aspects of what will be discussed later in the Thesis. In fact, the different subsystems, described above in terms of configuration and functions, will be investigated under an operational perspective in Chapter 5, in which details about the subsystems' way of working as a function of different flight conditions and mission phases will be given and discussed.

Moreover, the aerodynamic database and the propulsion database presented respectively in Sections 2.3.1 and 2.3.2, have been implemented in the ASTOS software for trajectory simulation purposes. The simulation of both nominal (see Chapter 8) and out-of-nominal (see Chapter 9) trajectories represent an important contribution of this Thesis in the project as it will be better discussed in the respective Chapters.

Chapter 3

Overview on the Concept of Operations

The project and development of an aeronautic or space product is structured in a series of complex and interconnected activities to be carried out. Among all the work to be performed within a project, the system engineering activities are of extreme importance during all the different project phases for capturing project objectives. As a typical system engineering activity, the Concept of Operations (ConOps) is an important driver in the requirements definition process, in particular for the identification, together with the functional analysis, of functional and system requirements to be defined soon after the definition of the mission objectives. Thus, the ConOps has to be considered early in the project of a system.

Since the analysis of the Concept of Operations, applied on the STRATOFLY project case study, is the main purpose of this Thesis, this Chapter aims to give an overview on ConOps related activities, methods and tools, in order to put the basis for the understanding of the next Chapters' contents. The ConOps analysis can be performed, with the appropriate considerations, for any kind of aerospace project, thus both for an aeronautic system or a space mission. The STRATOFLY project cannot be considered a typical aeronautic system neither a space mission due to its unprecedented and innovative characteristics as aerospace product. However, in this Chapter the Concept of Operations will be described from a generic point of view.

Furthermore, the last part of the Chapter contains relevant information about how the contents introduced in this Chapter will be applied for the STRATOFLY mission case of study.

3.1 Concept of Operations

Before to start talking about the ConOps related activities, it is important to give a definition of what the Concept of Operations actually is. To define the ConOps, however, it is not that simple since many different definitions are available in the literature. In the *System Engineering Handbook* [21], the NASA's engineers define the Concept of Operations as *"an important component in capturing stakeholder expectations, requirements, and the architecture of a project"*. Another perspective is instead provided by G. Nelson [22], that, discussing about the purposes of the ConOps, states that it *"properly transforms the allocated what to the how and so completes a chain all the way to an instantiation or realization ... of the system that enables capabilities"*. In other words, trying to summarize the G. Nelson point of view, the ConOps is an important tool for the understanding of *how "what is logically planned physically happens"* [22].

The considerable variance in the application of the term "ConOps" has been detected and analysed by J. Frittman and R. Edson [13], that, indeed, show that this definitions variance is related to a misunderstanding of the ConOps's purposes in such a way that the ConOps analysis appears to be underutilized. J. Frittman and R. Edson state that, despite the "ConOps" term application variance and its underutilization, the Concept of Operations *"plays a role across the entire life-cycle: from need identification, to system inception and development, to system disposition and disposal"* [13] and it adds value to the development of a generic system in a huge number of ways. It is highly recommended, therefore, to take into account the ConOps when developing a system. The benefits of the ConOps according by J. Frittman and R. Edson are represented in Figure 3.1.

CONOPs Value
Helps scope the problem & solution
Bridges where we are and want to be
Illustrates how a system will function
Facilitates communications among stakeholders
Provides a logic trail of capability
Provides baseline for measuring system efficacy
Provides basis for requirements

Figure 3.1. The Value of the Concept of Operations to System Development. Credit: [13]

On the basis of the discussion above and the different ConOps definitions that have been given, it is possible to understand that the Concept of Operations is something related to requirements identification and the analysis of *how* a system should work in order to meet stakeholders expectations.

For the purpose of this Thesis, the Concept of Operations will be defined as the set of methods and tools aimed at describing the system from an operational point of view. The ConOps shall provide information about the major mission phases, how the system will work during the different phases, eventual critical events and out of nominal scenarios definition. Thus, typical outcomes of the ConOps analysis are the Design Reference Mission aimed at describing the nominal mission scenario, the modes of operations of the system and the different subsystems, operation timelines, logical operations decomposition and out of nominal scenarios identification and assessment.

3.1.1 Mission Phases Definition

One of the main objectives of the ConOps analysis is to describe the mission nominal scenario, that means to define the Design Reference Mission (DRM). The DRM provides an insight on the major mission phases, charaterized by a start and an end events, a certain external environment and eventual physical, environmental or social constraints. The definition of the design reference mission is of extreme importance for the understanding of how a mission is being planned for capturing stakeholders expectations, therefore it shall be developed during the early phases of the project, in parallel with the functional analysis, in order to contribuite on the requirements definition. In fact, if on one hand the functional analysis and the product tree are needed for the identification of the functional, configuration and interfaces requirements, on the other hand the ConOps in terms of mission phases definition is the main source for environmental requirements[1]. For an explanation about the meaning of the different kinds of requirements, the reader can refer to the respective ECSS standard [6].

The Design Reference Mission is typically described by a graphical illustration showing in one image the sequence of all the different mission pahses in a comprehensive context. A famous example of Design Reference Mission is given in Figure 3.2, representing *Apollo 11*, one of the most important space missions in the human history thanks to which 50 years ago Neil Armstrong (already mentioned in Section 1.1.3 and represented in Figure 1.8) was the first man walking on the Moon.

It is important to note that Figure 3.2 is to be intended merely as an example since it gives immediately an idea of what a DRM illustration is. The STRATOFLY Design Reference Mission will be described and represented in Chapter 4.

[1]Requirements related to the environment in which a system will work during its life cycle. This includes the natural environments (e.g. atmoshpere chemical composition, pressure, free space and dust) and induced environments (e.g. radiation, electromagnetic, heat, vibration and contamination).

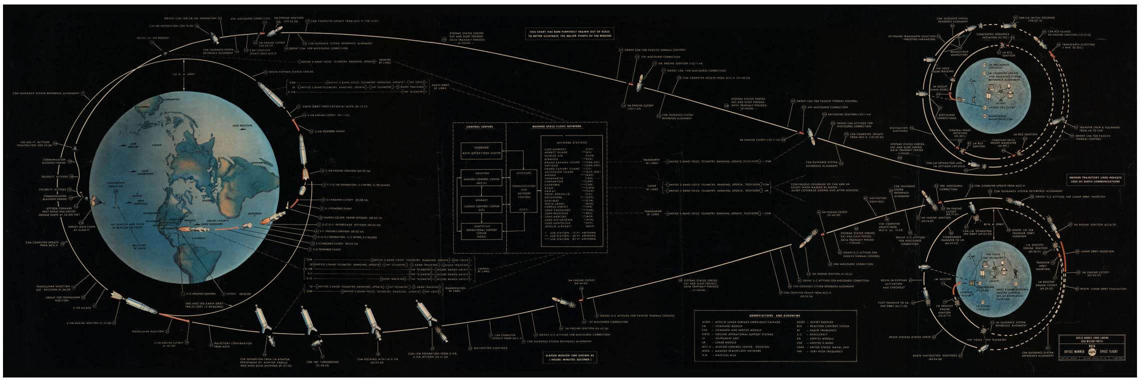


Figure 3.2. Example of Design Reference Mission: Apollo 11. Credit: [49]

3.1.2 Modes of Operations Definition

Once the major mission phases have been identified, it is necessary to define how the system and the subsystems will work during the mission. The DRM, indeed, focuses on the external environment and does explain how the mission is expected to be performed, but does not give information about the way the system is working in order to accomplish mission objectives. For this reason, it is necessary to add another piece to the ConOps analysis related to the definition of the *Modes of Operations* and the Phases/Modes Matrix.

The modes of operations can be defined at system or subsystem level, they provide important information about the way a generic system (or subsystem) operates. From now on in this Section, the term "system" is considered generically for a system itself but also for a generic subsystem, e.g. the propulsive *sub*system of an aircraft can be called as propulsive system, and it can be divided in turn into different subsystems such as, for example, the different types of propulsive actuators of which it is composed. A system mode of operation, thus, establishes which subsystems and equipment are active or not active within that specific mode. Just like the mission phases definition enables the environmental requirements identification during the early phases of the project, the ConOps in terms of Modes of Operations definition it is also an important tool for deriving operational requirements. Those kind of requirements are related, indeed, to the system operability [6].

The modes of operations, however, are not enough for the complete understanding of how the system will work during the mission, the missing information is in fact related to which mode is active during a specific mission phase. This is the role of the Phases/Modes Matrix, that is able to describe all the possible modes of operations that can be entered during all the mission phases. It is important to note also that more than one modes of operations can be potentially entered during a specific mission phase. Further explanations about the Modes of Operations and the Phases/Modes tool, including some valuable examples, are given by M.A. Viscio, N.

Viola and R. Fusaro [39].

3.1.3 Logical Decomposition Tools

For the purposes of this Thesis, the Logical Decomposition is the process for defining at different level the complete set of operations that a system shall perform in order to meet mission objectives. This includes information of how and under which conditions the transition between different modes of operations happens and information about the interfaces among the subsystems from an operational perspective.

Although it is possible to find many techniques available on the literature [21], the typical tools utilized for the logical decomposition, that are also the most useful for our purposes, are the Functional Flow Block Diagrams (FFBDs) and the N2 diagrams.

Functional Flow Block Diagrams

The FFBDs aim at describing the sequence of all the functions and operations that a system shall perform. Those diagrams are developed through the implementation of basic logical functions, e.g. "or"; "and"; "iterate" etc., applied to a series of *functions* of the system, usually identified by a function ID. The diagrams are organized in different levels, each one characterized by a sequence of functions at the same level of decomposition. Each function, therefore, can be in turn divided into sub-functions representing the a lower level of decomposition. An example of a three level FFBD, related to a generic space mission and provided by NASA [21], is given in Figure 3.3.

The FFBDs are important drivers, together with the modes of operations definition, for deriving the operational requirements [39].

N2 Diagrams

The N2 diagram gives relevant information about the number and type of interfaces among different objects or functions. The "2" in the "N2" term stands for *squared*, the diagram is indeed developed on the N objects or functions disposed on the diagonal of a N x N square, where the interfaces are highlighted in the nodes connecting the different elements on the diagonal. The N2 diagram provides also information about the inputs and outputs of an interface and the type of interface, e.g. mechanical or electrical. An example of a generic N2 diagram provided in the NASA's system engineering handbook [21] is given in Figure 3.4.

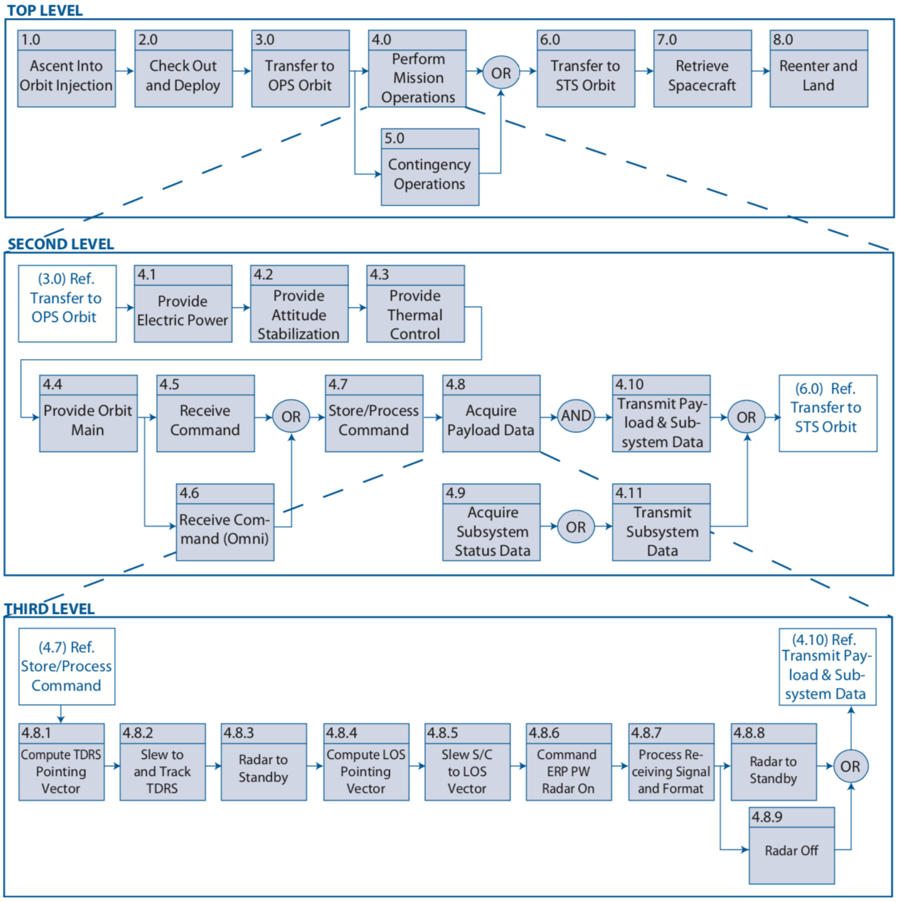


Figure 3.3. Example of a Functional Flow Block Diagram. Credit: [21]

3.1.4 Critical events Identification and Assessment

Another important purpose of the ConOps analysis is to identify and assess different operational scenarios. An operational scenario can be defined as the sequence of operational phases concerning a certain situation on which the mission is being performed. It includes information about modes of operations and mode transitions and interfaces with the external environments. A typical example of operational scenario is represented by the mission nominal scenario explained by the design reference mission, described in Section 3.1.1, together with additional information coming from the modes of operations and the Phases/Modes matrix. Other operational scenarios, however, can be identified as consequences of critical events that may occur during the mission, such kind of scenarios are well known under the name of *out of nominal* scenarios.

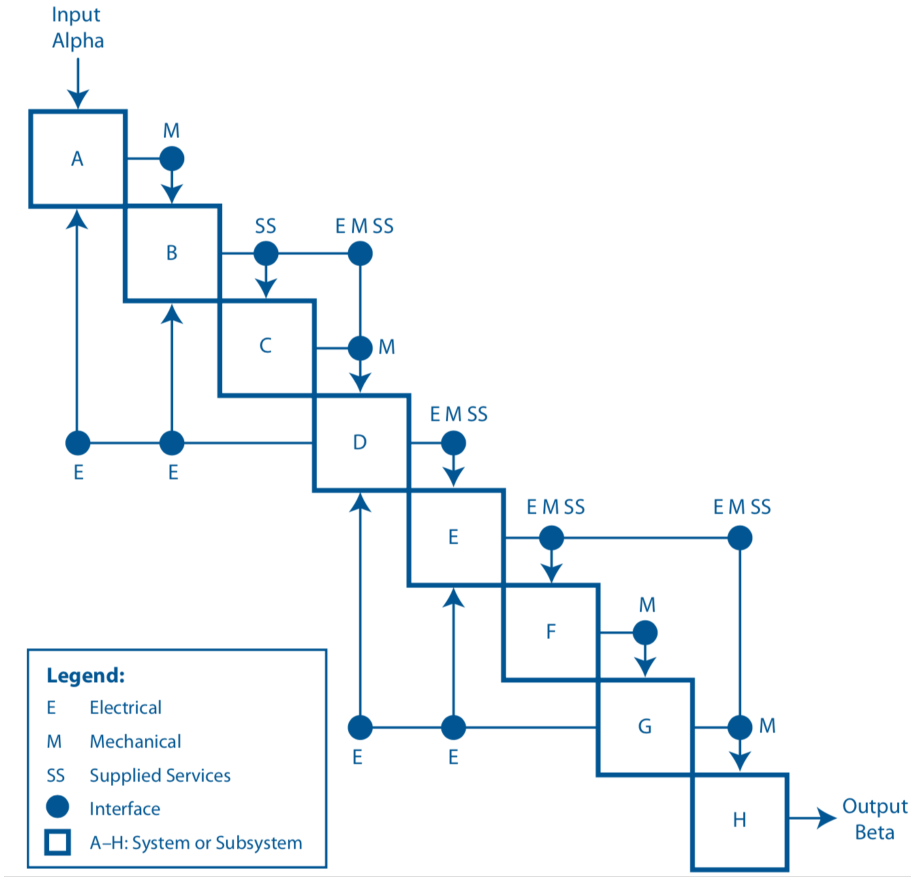


Figure 3.4. Example of a N2 diagram. Credit: [21]

To identify and to study the out of nominal scenarios from an operational perspective is of extreme importance for the derivation of additional requirements related to system capabilities otherwise not requested in a nominal scenario. The critical event assessment might, indeed, make it necessary to perform some modifications on the system architecture. If, for example, an ocean splashdown is deemed necessary to avoid a catastrophic event related to a failure occurred on the the propulsive subsystem of an aircraft, the aircraft structure must be designed in order to be able to float in sea water, not a necessary capability for a simple nominal scenario in which the aircraft only lands on ground.

3.2 Overview on the STRATOFLY ConOps

The discussion above has given the basis for the development of the next chapters, where the aforementioned ConOps methods and tools will be applied on the

STRATOFLY MR3 Mission case study. In particular, the Design Reference Mission will be described in Chapter 4, the modes of operations and Phases/Modes matrices will be discussed in Chapter 5, some out of nominal scenarios will be defined in Chapter 6 and the FFBDs will be used in practice in Chapter 7.

From the discussion held in this Chapter it emerges that the ConOps is related, among other things, to the process of requirements definition. However, it is important to underline that a preliminary list of requirements for the STARTOFLY MR3 vehicle has already been drawn up at this phase of the project, therefore, the purpose of the ConOps analysis performed in this Thesis is not to manage and eventually change the list of requirements, but mostly to give a contribution to this complex but outstanding project for highlighting some relevant issues to be taken into account when developing the system architecture at an increasing level of detail.

Furthermore, the ConOps analysis performed in the next chapters represents an important input for the scenario modelling and trajectory simulation performed in Chapters 8 and 9, considering respectively nominal and out of nominal conditions in which the mission is performed.

Chapter 4

Design Reference Mission

Aim of this Chapter is to describe the nominal scenario of a generic mission performed by the STRATOFLY MR3 vehicle. The nominal scenario is related to the situation in which the vehicle is performing the mission as expected, therefore in nominal conditions. To describe the nominal scenario means to define all the different mission phases, identifying the main characteristics of each one of them in terms of *start* and *end* events, external environment and eventual constraints. This study provides the so called *Design Reference Mission* (DRM), that represents one of the most important outcomes of the ConOps analysis.

According to the NASA *System Engineering Handbook* [21], the DRM can be considered as a starting point for the development of the Concept of Operations analysis. Indeed, for each mission phase defined by the DRM, additional information, not provided by the DRM, will be included in the ConOps in terms of modes of operations at system and subsystem level as well as operational procedures definition. Thus, it is important to pay attention to not to confuse the description of the major phases of the mission with the modes of operation of the system. The design reference mission, in fact, does not include information about the way the different subsystems are working and about the operations to be performed during a specific phase. Those information, indeed, are provided as part of the ConOps analysis in which the modes of operations at system and subsystems level will be associated to the mission phases, as already discussed in Chapter 3.

The starting point from which the STRATOFLY MR3 design reference mission has been defined is represented by the reference mission trajectory of its predecessor, the LAPCAT MR2, that has been defined and simulated by ESA within the LAPCAT-II Project [18].

The STRATOFLY MR3 design reference mission described in this Chapter from an analytical and qualitative perspective, will be further assessed and simulated via ASTOS software in Chapter 8.

In Section 4.1, the LAPCAT MR2 design reference mission is therefore described in order to understand the basis on which the STRATOFLY MR3 design reference mission, described in Section 4.2, has been developed.

4.1 LAPCAT MR2 Design Reference Mission

The LAPCAT MR2 is a Mach 8 civil hypersonic aircraft concept aimed to provide commercial long-distance flight services covering antipodal routes. The main route that has been considered as reference mission for the LAPCAT MR2 is Brussels-Sidney. The simulation and optimization of the reference Brussels-Sidney trajectory, performed by *ESA* [18], gives relevant information about the major phases of the mission that can be extended, with some considerations, for the STRATOFLY MR3 case.

According to T. Langener et al. [18], the LAPCAT MR2 Brussels-Sidney mission has been simulated via ASTOS software by using as input aerodynamic and propulsive databases that have been already described in Chapter 2, respectively in Sections 2.3.1 and 2.3.2.

The reference vehicle characteristics are 400 tons of weight in total, divided in 181.25 tons of fuel and 218.75 of aircraft structure and payload. The absence of cross winds and the standard spring atmosphere implemented in the ASTOS software were assumed.

The Brussels-Sidney mission is represented in Figure 4.1, while the details about take-off from Brussels and landing in Sidney are given in Figure 4.2. The LAPCAT

Figure 4.1. Illustration of the LAPCAT MR2 Brussels-Sidney trajectory. Credit: [18]

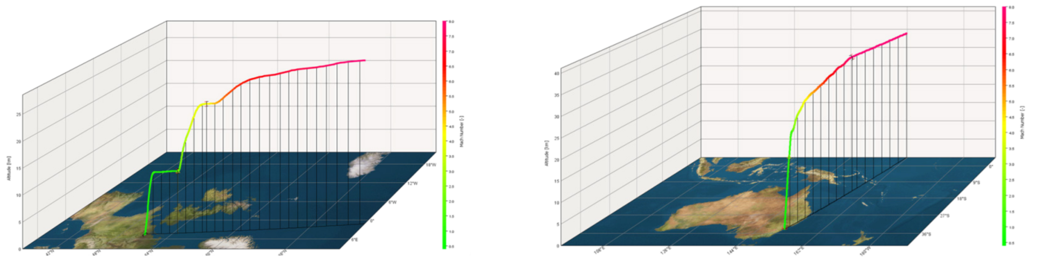


Figure 4.2. Illustration of the take-off trajectory from Brussels (LHS) and landing trajectory to Sidney (RHS) of the LAPCAT MR2. Credit: [18]

MR2 reference mission can be defined as *step climb* trajectory: a particular type of point-to-point mission in which both the climb and the descent are divided in different legs, or steps.

After the take off from Brussels, the aircraft reaches an altitude of about 12 km at which it covers a certain distance at constant subsonic speed and altitude. As it is possible to see in Figure 4.2 (LHS), this phase is characterized by a sort of subsonic cruise aimed at reaching the right point, far enough from inhabited zones, in which it is possible to break the sound barrier and to fly at supersonic speed. The main reason why the subsonic cruise is needed lies, in fact, on the current regulations about supersonic flight that put certain limits on the noise an aircraft can produce, banning in general supersonic flight over inhabited land [43].

After the subsonic cruise, the vehicle performs a supersonic ascent until reaching an altitude of about 22 km and a speed equal to Mach 4-5. Thus, the aircraft is now flying at hypersonic speed and it continues to increase speed and altitude for then to perform a hypersonic cruise at an altitude of about 30 - 35 km and a velocity of Mach 8. The hypersonic cruise ends when a distance of 15200 km from the Brussels airport has been reached. The descent phase is considered to be an unpropelled gliding to the arrival airport in Sidney. The engines, indeed, are no more utilised for to power the aircraft untile the end of the mission, resulting however in high flight speed at landing (about Mach 0.5) as well as steep flight path (higher, in absolute terms, than 5^o).

Relevant information about the Mach number and flight altitude versus mission time are given in Figure 4.3 that is another outcome of the LAPCAT MR2 reference mission simulation performed by T. Langer et al. [18]. The graphic represented in Figure 4.3, especially the one related to the altitude vs. mission time, can be considered as the most important input for the development of the STRATOFLY MR3 design reference mission, described and explained in the next Section.

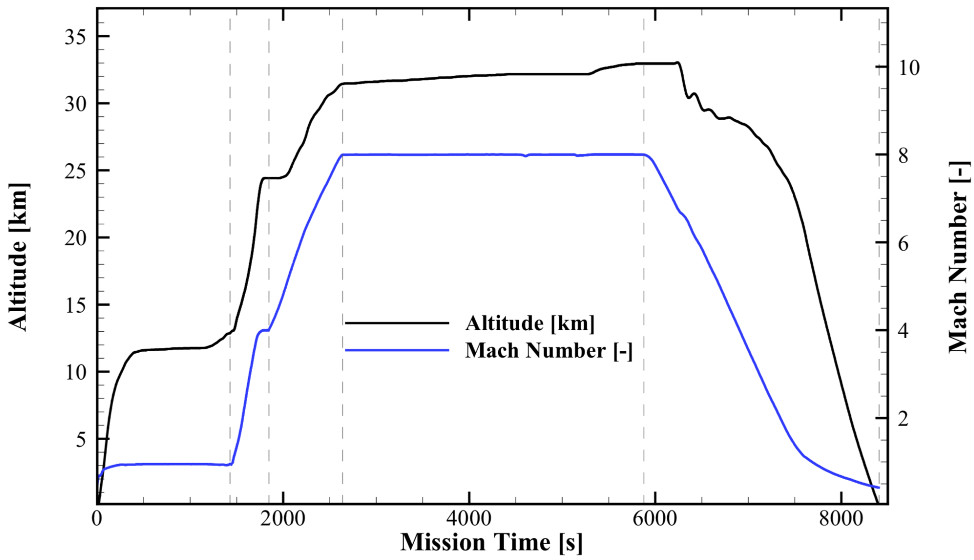


Figure 4.3. Mach number and flight altitude versus mission time during the Brussels-Sidney LAPCAT MR2 reference mission. Credit: [18]

4.2 STRATOFLY MR3 Design Reference Mission

This Section is aimed at describing the design reference mission (DRM) of the STRATOFLY MR3 vehicle. The major phases of the STRATOFLY MR3 Mission have been defined through an analytical and qualitative assessment based on the important knowledge gained from the LAPCAT-II project.

The STRATOFLY MR3 design reference mission defined in this Section is not related to a specific route, e.g. the Brussels-Sidney as in the case of the LAPCAT MR2 one. Thus, the mission phases have been defined for a generic mission and the departure and arrival airports are not defined.

However, the STRATOFLY MR3 DRM presents one important differencee with respect to the LPACAT MR2 Mission: the descent phase is not completely unpropelled like in the case of the LAPCAT MR2 mission, but the engines are reactivated at a certain flight altitude after an unpropelled descent for to perform final approach and landing.

The flight altitude and flight speed for different mission phases stem directly, at this point of the discussion, from the LAPCAT MR2 reference trajectory simulation. Better defined values for flight altitude and velocity, however, will be assessed by performing a proper trajectory simulation as discussed in Chapter 8

The process of definition of the major phases of a generic STRATOFLY mission, produced as outcome 11 different phases. Those are:

1. Pre-departure

2. Taxi
3. Take-off
4. Subsonic Climb
5. Subsonic Cruise
6. Supersonic Climb
7. Hypersonic Climb
8. Hypersonic Cruise
9. Descent
10. Final Approach
11. Landing

An illustration of the Design Reference Mission for the graphical visualization of the different mission phases is given in Figure 4.4. In Table 4.1 it is possible to see the details about start and end events that characterize the different mission phases.

The design reference mission of the STRATOFLY MR3, represented in Figure 4.4, is hereafter explained and described.

Pre Departure

The phase starts when the crew reaches the aircraft and consists on all the needed tests and procedures to check if the system is ready for the departure. During this phase the interfaces between ground systems and aircraft shall be opened and operating in order to allow fuelling, water charging and other needed procedures. The phase end when the boarding is completed and the aircraft is authorised to leave the parking area.

Taxi

The aircraft leaves the parking area and moves until it reaches the beginning of the take off runway. The phase ends when the engines are started to be run up at high power in order to allow take off.

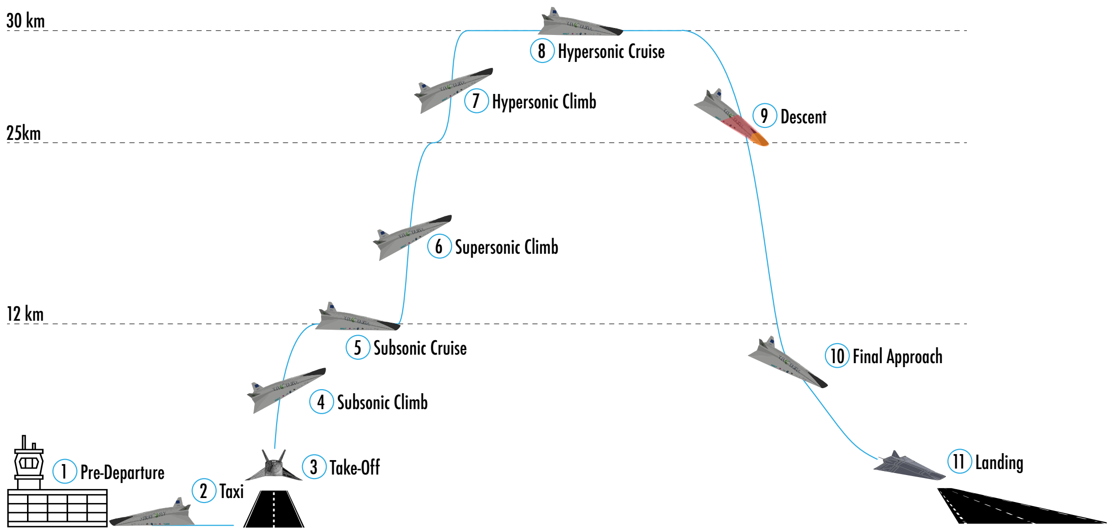


Figure 4.4. STRATOFLY MR3 Design Reference Mission.

Take-off

The aircraft moves on a runway increasing its speed until it reaches the minimum required speed allowing the generation of the necessary lift, thus the pitch angle increases and the aircraft can perform take off. The phase ends when the hypothetic obstacle, whose height depends on the airport characteristics, is cleared. The take off can be safely aborted if the aircraft is running at a speed lower than the decision velocity, otherwise it must continue the take off manoeuvre for avoiding dangerous events that can compromise aircraft integrity and passengers safety.

Subsonic Climb

Soon after take off, the vehicle increases flight altitude and speed until it reaches the subsonic cruise velocity of about Mach 0.9 and an altitude of about 12 km.

Subsonic Cruise

This phase is aimed to increase the distance between the aircraft and inhabited areas in order to then perform a sonic boom without giving problem to the population, as requested by the current regulations about supersonic flight [43]. The duration and length of this phase can be different on the basis of the different routes and therefore the distance between the departure airport and the air zone where sonic boom is allowed.

Mission Phases	Start	End
Pre-Departure	Crew arrival	Boarding completed
Taxi	Boarding completed	Take-off approach
Take off	Take-off approach	Obstacle clearance
Subsonic Climb	Obstacle clearance	$M = 0.9$ - $h = 12.000\,m$
Subsonic Cruise	$M = 0.9$ - $h = 12.000\,m$	Sonic boom
Supersonic Climb	Sonic boom	$M = 4.5$ - $h = 25.000\,m$
Hypersonic Climb	$M = 4.5$ - $h = 25.000\,m$	$M = 8$ - $h = 30.000\,m$
Hypersonic Cruise	$M = 8$ - $h = 30.000\,m$	Engines shut-down
Descent	Engines shut-down	Engines reactivation
Final approach	Engines reactivation	Landing gear unlocking
Landing	Landing gear unlocking	Landing completed

Table 4.1. Mission phases start and end events.

Supersonic Climb

After the sonic boom, the aircraft increases its already supersonic speed and its altitude until it reaches a Mach number equal to about 4.5-5, that represents the boundary between supersonic and hypersonic regime, and an altitude of about 25 km.

Hypersonic Climb

In this phase altitude and flight speed continue to increase but the aircraft is flying at a hypersonic speed. The shock wave angle is lower and the heat flow is more intense. The phase ends when the aircraft reaches the cruise altitude of about 30 km and and the velocity of Mach 8.

Hypersonic Cruise

This is the longest phase in which therefore the major part of the ground distance is covered. The altitude is kept as much as possible constant and equal to 30 km and the speed is kept constant and equal to M=8. The external environment is characterized by a high heat flow. However, the main constraint is represented by the Mach number that shall be equal to 8 during the hypersonic cruise, while the altitude can varies in a range from 30 km to 35 km.

Descent

At the end of the hypersonic cruise the engines are shut off and the aircraft is decelerated thanks to atmospheric drag and it decreases the altitude before starting the final approach.

Final Approach

The engines are reactivated in order to allow proper manoeuvres for approaching to the arrival airport.

Landing

This phase begin when the aircraft is aligned with the arrival airport run and it is ready to land, with the support of on ground information the vehicle can perform landing and the phase finishes when the the brakes are activated and the aircraft is decelerated until all the kinetic energy is dissipated and it is possible to manoeuvre the aircraft on ground.

4.3 Considerations

On the basis of the above discussion, it is possible to understand how a generic mission performed by the STRATOFLY MR3 vehicle is carried out. When defining certain departure and arrival airports, then the DRM, described qualitatively in this Chapter, can be applied on a real case and a proper mission simulation can lead at evaluating the actual duration of the different mission phases as well as the overall fuel consumption.

The DRM, indeed, represents an important input for the trajectory simulation performed in Chapter 8 by taking into account the specific Brussels-Sydney route.

Chapter 5

System and Subsystems level Modes of Operations

Once the STRATOFLY MR3 Design Reference Mission has been described in Chapter 4, it is important to describe and understand how the system will work during all the different mission phases in order to meet mission objectives.

This Chapter aims at providing an overview from the operational perspective of the overall system and the different subsystems' behaviour in order to define the modes of operation at different levels and how they are related to the phases of the mission. The role of the definition of the *Modes of Operation* and the *Phases/Modes matrices* in the ConOps analysis has been already described in Section 3.1.2.

Starting from the overall system point of view, for then to see in detail each one of the different subsystems already mentioned in Chapter 2, the Modes of Operations and the Phases/Modes matrices are reported and described hereafter.

It is important to note that such kind of ConOps analysis is being done for the first time in the STRATOFLY project, therefore the modes of operations definition is part of the work of this Thesis performed on the basis of design data internal to the project as well as external references, especially related to the LAPCAT MR2.4 since there are still not papers in the literature about the STRATOFLY MR3, that will be properly cited when deemed necessary.

5.1 System Level

The system level modes of operations definition is related to the highest level, referred, indeed, to the overall system with the aim to describe the way the system will work, with particular attention to which kind of subsystems and components are active or not active, during the different phases of the mission.

The *System Level Modes of Operations* are listed and described in Table 5.1 while the respective *Phases/Modes Matrix* is represented in Figure 5.1.

System Level	
Modes of Operations	**Description**
Off mode	The overall System is turned off.
Ground mode	Only components aimed to provide energy, maintain the internal environment and check the state of the system are active. Interfaces with On-ground facilities are also active.
Low speed flight mode	All the subsystems aimed to allow the flight and control the vehicle are active; Others active components are those related to internal energy production and internal environment management.
High speed flight mode	Sinergy between propulsion, propellant, thermal protection and energy management subsystems is needed to allow the flight and survive the external environment characterized by high speed and high heat flow. Other active components are aimed to control the flight and manage internal environment.
Reentry mode	All the subsystems needed to control the vehicle during flight, produce energy, manage internal environment and survive external environment are active. Engines are shut off.

Table 5.1. Modes of Operations System Level

By looking in Figure 5.1, it is possible to see that the two modes of operations *Low speed mode* and *High speed mode* are related to the situation in which the aircraft is flying with the engines turned on, in particular the Low speed mode refers to the subsonic-early supersonic phases while the High speed mode is related to the supersonic and hypersonic phases. The *Reentry mode* is instead related only to the *Descent* phase, in which the engines are shut off and the aircraft shall survive the high external heat flow during the atmospheric reentry. The other two modes of operations, *Off mode* and *Ground mode*, are finally related to the phases in which the aircraft is still on ground.

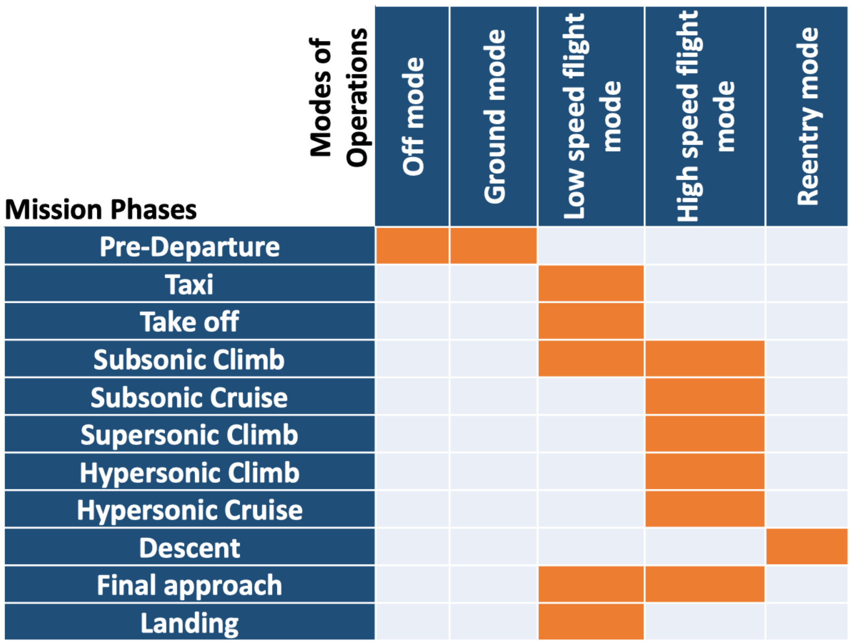


Figure 5.1. System level Phases/Modes Matrix.

5.2 Propulsive Subsystem Level

The most important subsystem of the STRATOFLY MR3 vehicle is the Propulsive Subsystem, both because this is the first subsystem that has been developed and around which the other elements of the vehicle design have been developed, and also because it plays a crucial role in the development of the mission concept. The other elements of the ConOps analysis performed in this Thesis, in fact, such as the out of nominal scenarios definition and the part of the FFBDs development described in the next chapters have been performed taking especially into account the Propulsive subsystem rather than the other subsystems. Moreover, the propulsive subsystem level modes of operations definition has been an important input for the trajectory simulation performed via ASTOS software and described in Chapter 8.

As already explained in Chapter 2, the Propulsive Subsystem is composed of two main propulsive elements: a group of six Air Turbo Rocket (ATR) engines and the Dual Mode Ramjet (DMR). This subdivision is one of the basis of the definition of the different *Propulsive Subsystem Level Modes of Operations* reported in Table 5.2. The two situations in which the propulsive subsystem is working as ATR or DMR, are each of them divided into two modes of operations: a *Low* and a *High thrust* mode, for a total of four accessible modes of operations for when the aircraft is actually flying with active engines, therefore with the only exception of the *Descent* phase, as it is possible to see in the *Propulsive Subsystem Level Phases/Modes Matrix* represented in Figure 5.2, during which, indeed, the engines are deactivated. Thus, the Descent phase is supported by the *Stand-by mode* of the propulsive subsystem in which the engines are not active but are ready to be activated (or reactivated). The last mode of operations to be mentioned is the *Off mode*, for which all the components of the propulsive subsystem are turned off, therefore related to the situations in which the aircraft is parked on ground and is not being operated. If the aircraft is stopped on ground but ready to start a mission, however, the propulsive subsystem shall work in the *Stand-by mode* for which the engines are ready to be activated to start the taxi and take off phases.

However, it is important to clarify that the words *high* or *low* thrust are referred to the throttle, and not to the effective net thrust, in particular: *high* is intended for a throttle grater than 0.5, whilst *low* for a throttle smaller than 0.5. The net thrust, as already explained in Chapter 2 Section 2.3.2, where the propulsion database has been described, depends on several factors such as flight altitude and Mach number in addition to throttle, while throttle is unequivocally set for simulation purposes or, more in general, decided by the pilot and therefore is more suitable than net thrust for the definition of the modes of operations.

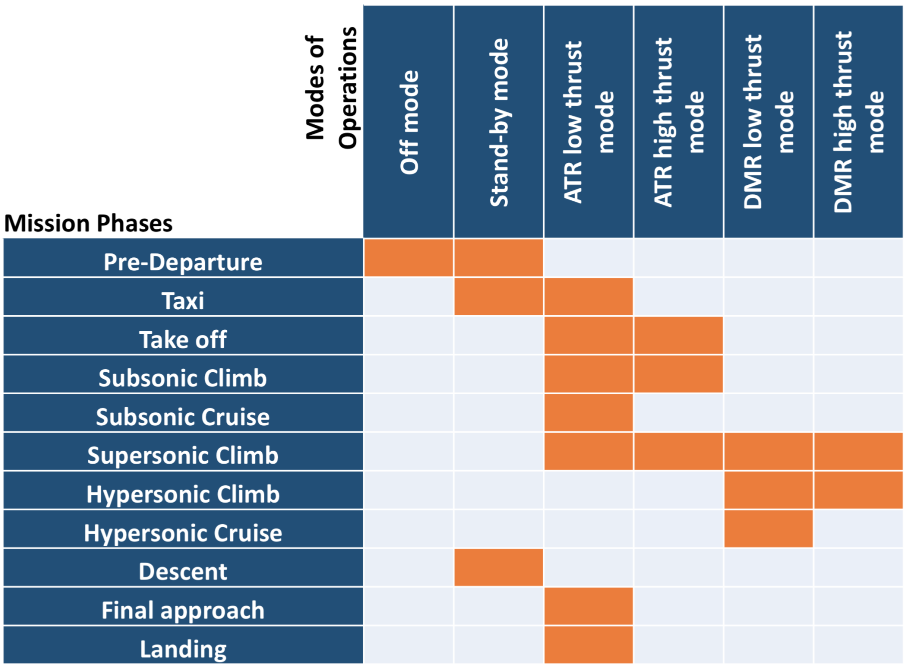


Figure 5.2. Propulsive Subsystem Phases/Modes Matrix.

As it is possible to see in Figure 5.2, the ATR works when the aircraft is flying at subsonic-early supersonic regime, therefore until Mach equal to 4-4.5, while the DMR works during the high speed flight, for higher Mach numbers between 4 to 8. The transition between ATR and DMR happens during the *Supersonic Climb* phase,

Propulsive Subsystem	
Modes of Operations	**Description**
Off mode	All the components of the Propulsive Subsystem are shut off.
Stand-by mode	The subsystem is not active but it is ready to be reactivated. Tests aimed to check the state of the components are allowed.
ATR low thrust mode	The ATR engines are active and generating a relatively low power with the consequence of a lower fuel consumption. The throttle is smaller than 0.5.
ATR high thrust mode	The ATR engines are active and generating high power. The fuel consumption is high and may be necessary to decrease power consumed by other subsystem since it is necessary to sustain the aircraft during important manoeuvres. The throttle is greater than 0.5.
DMR low thrust mode	The DMR engine is active and generating a relatively low power with the consequence of a lower fuel consumption. The throttle is smaller than 0.5.
DMR high thrust mode	The DMR engine is active and generating high power. The fuel consumption is high and may be necessary to decrease power consumed by other subsystem since it is necessary to sustain the aircraft during important manoeuvres. The throttle is greater than 0.5.

Table 5.2. Modes of Operation Propulsive Subsystem.

at the end of the which the DMR is working as *DMR high thrust mode* in order to allow the next *Hypersonic Climb* phase for which the maximum thrust is needed to reach the cruise altitude and the cruise speed of Mach 8. As already explained in Chapter 2 Section 2.3.2, where the propulsion database has been described, the more is the altitude and the Mach number, the lower is the net thrust provided by the DMR. Thus, the *Hypersonic Cruise* can be performed with the propulsive subsystem in *DMR low thrust mode.*

Finally, the engines are deactivated for the *Descent* while the ATR is working as *ATR low thrust mode* during the *Final Approach* and *Landing* performed at subsonic speed.

The analytical assessment performed above about propulsive subsystem level modes of operations has been of extreme importance for the trajectory simulation modelling described in Chapter 8, in particular for the throttle control settings during the different phases of the mission. A comparison between the analytical assessment performed in this Section and the actual simulation results can be performed by looking at, respectively, Figure 5.2 and Figure 8.11 reported in Chapter 8.

5.3 TEMS Level

The Thermal and Energy Management System (TEMS) purposes and characteristics are discussed in Chapter 2. The *TEMS Level Modes o Operations* are listed and described in Table 5.3 and the related *Phases/Modes Matrix* is represented in Figure 5.3.

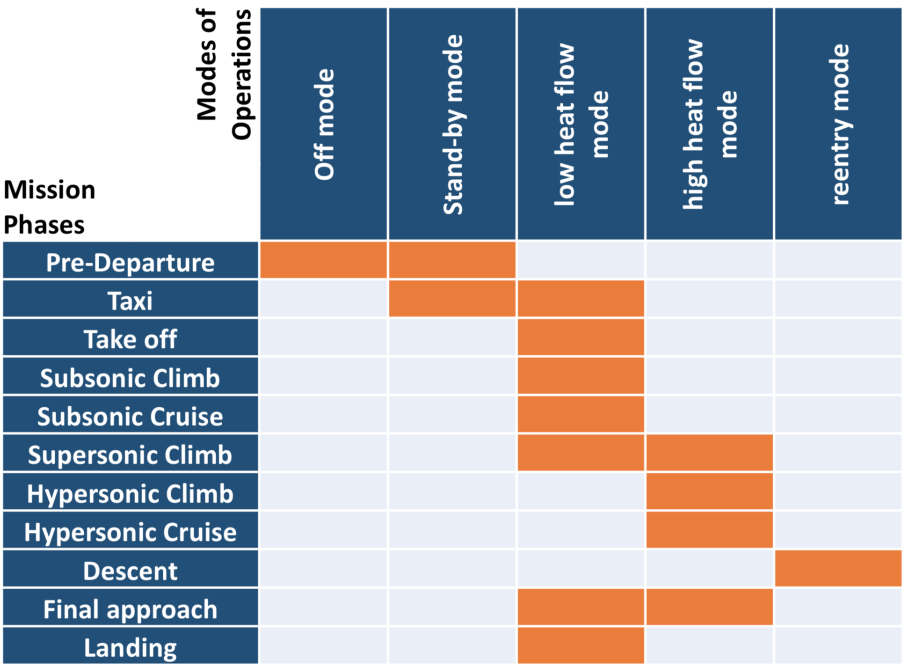


Figure 5.3. TEMS Phases/Modes Matrix.

The first two modes of operations, the *Off mode* and the *Stand-by mode*, are respectively related the first one to the subsystem components turned off and the other to the situation in which the subsystem is ready to be operative. The other three modes of operations, the *Low heat flow mode*, the *High heat flow mode* and the *Reentry mode*, have been identified on the basis of two characteristics: the external heat flow and the other subsystems the TEMS is working with. When working as

TEMS (Thermal and Energy Management System)	
Modes of Operations	**Description**
Off mode	The TEMS is shut off.
Stand-by mode	The subsystem is not active but it is ready to be reactivated. Tests aimed to check the state of the components are allowed.
Low heat flow mode	The TEMS is working without high thermal loads that penetrate the aeroshell, all the components aimed to perform the expected goals are active. The TEMS is working in synergy with the ECS and the propellant subsystem, but not with the TPS.
High heat flow mode	All the components aimed to perform the expected goals are active, the external heat flow penetrating the aeroshell allows LH2 boil-off. The TEMS is working in synergy with the ECS, the TPS and the propellant subsystem.
Reentry mode	All the components aimed to perform the expected goals are active, the external heat flow penetrating the aeroshell allows LH2 boil-off. The TEMS is working in synergy with the ECS, the TPS and the propellant subsystem also if engines feeding is not needed since the engines are shut off.

Table 5.3. Modes of Operation TEMS Subsystem.

Low heat flow mode, the TEMS working in synergy with the propellant subsystem and the ECLSS, but not with the TPS since an active thermal protection system is not needed due to the low external heat flow. For higher external heat flows the TEMS works also together with the TPS to allow an active thermal protection method, this is the High heat flow mode. Finally, the only difference between the High heat flow mode and the Reentry mode consists on the fact that within the Reentry mode the TEMS is still working in synergy with the propellant subsystem for heat exchanges between the external environment and the LH2 but there is not fuel consumption because the engines are deactivated. The Reentry mode, indeed, is only active during the Descent phase. In Figure 5.3 it is possible to see which TEMS Level modes are active during the different mission phases.

More information about the synergy among the TEMS, the TPS, the ECLSS and the Propellant Subsystem, with particular attention to the interfaces between those systems, will be given in Chapter 7.

5.4 TPS Level

The Thermal Protection System (TPS) aims to protect the aircraft from the external heat flow. As it is possible to see in Table 5.4, the modes of operations of this subsystem have been identified on the basis of the magnitude of the external heat flow. There are, in fact, three modes of operations: Low heat flow mode; High heat flow mode; and Reentry mode. The Low heat flow mode is related to the situation in which the aircraft is still on ground or the TPS is working as passive system to resist a low external heat flow, thus, the crucial role in this mode of operations is played by the aircraft structure itself. For higher external heat flow the TPS works together with the TEMS and the propellant subsystem with the aim to provide an active thermal protection that exploit difference of temperature between the cold LH2 in the tanks and the external environment, this is the High heat flow mode. The Reentry mode, finally, is very similar to the High heat flow mode with the only difference that there is not fuel consumption since the engines are deactivated, this is in fact the case of the Descent phase.

TPS (Thermal Protection System)	
Modes of Operations	**Description**
Low heat flow mode	TPS is working as a passive system, thermal protection is not needed or external heat flow is low enough to avoid the utilization of active thermal protection methods.
High heat flow mode	TPS is working as an active system, external heat flow is high and active thermal protection methods are needed. Moreover TPS is working in synergy with the TEMS and propellant subsystem.
Reentry mode	The external heat flow is extremely high and the engines are shut off. The TPS is working in synergy with the TEMS and propellant subsystem also if there is not fuel consumption.

Table 5.4. Modes of Operation TPS.

By looking at Figure 5.4 it is possible to see how the TPS shall operate during the mission. For to understand the transition between the *Low* and the *High heat flow mode*, it is important to note that the heat flow depends mostly on the flight speed,

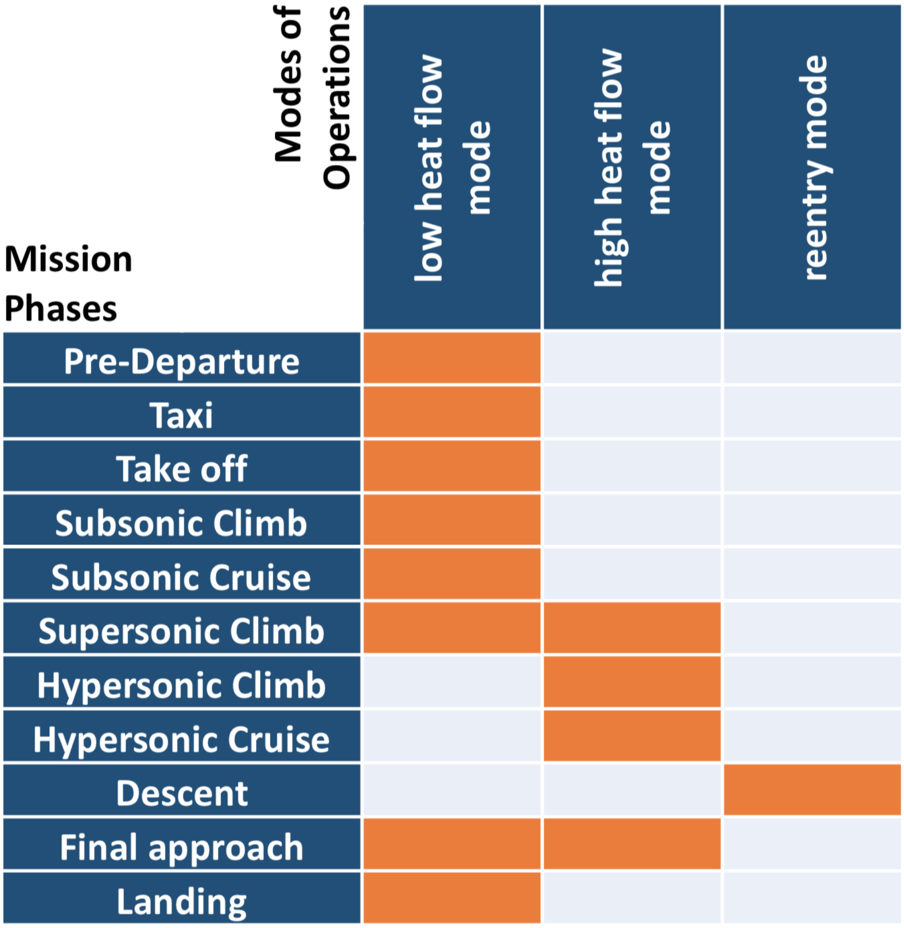


Figure 5.4. TPS Phases/Modes Matrix.

therefore this transition happens during the Supersonic climb when the aircraft speed change from supersonic to hypersonic. Finally The TPS works in Low heat flow mode, therefore as passive system, during Final Approach and Landing.

5.5 ECLSS Level

As already discussed in Chapter 2, the subsystem aimed at controlling the internal environment has still to be better designed in the STRATOFLY project. This system will be something in between a classic aircraft's Environment Control System (ECS) and a space system-kind Environment Control and Life Support System, however, this subsystem is mentioned just as ECLSS in this Thesis.

The understanding of the possible ways of working of the ECLSS, generally a mixed method more oriented towards open or closed cycles, related to the flight altitude, is the basis of the identification of the modes of operations of this subsystem described in Figure 5.5. In addition to a simple *Ground mode*, in which basically the internal and external environment communicate and cabin pressurization is not needed, two main modes of operations have been identified, those are a *Low altitude mode* and a High altitude mode. The difference between the two modes lies, indeed, on the kind of cycle implemented by the ECLSS. When the aircraft is flying at lower altitudes at which the air density is high enough to allow an open-like cycle related to the pressurization of the cabin from compressed external air, then the accessible mode is the Low altitude mode. If otherwise the aircraft is flying at higher altitudes related to lower air density, the ECLSS shall work more as a closed-like cycle, in which the pressurizzation of the cabin is performed not only by compressing external air but also by providing Oxygen, eventually stored on board of appropriate tanks, as it is usually done for space-like applications.

An additional *Emergency mode* has been identified in order to describe the behaviour that the ECLSS shall have after a critical event that compromises the pressurization of the cabin occurs. This mode describes the system capability of guaranteeing the passengers survival by eventually providing appropriate devices, like for example oxygen masks.

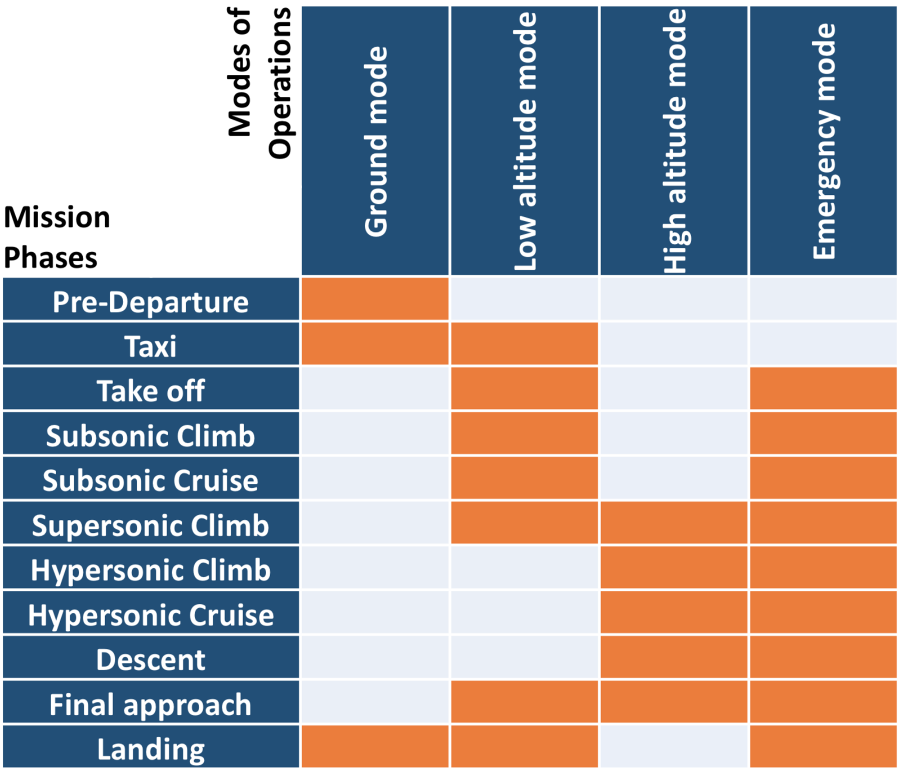


Figure 5.5. ECLSS Phases/Modes Matrix.

ECLSS (Environment Control and Life Support System)	
Modes of Operations	**Description**
Ground mode	The internal environment is in direct communication with the external environment. Pressurization is not needed, although internal temperature and humidity control may be necessary.
Low altitude mode	The ECLSS shall provide the right environment in the cockpit and the cabin through a mixed cycle, more open than closed, in which a consistent part of the air is taken from outside the aircraft. Pressurization is needed.
High altitude mode	The ECLSS shall provide the right environment in the cockpit and the cabin through a mixed cycle, more closed than open, in which a small part of the air is taken from outside the aircraft while a consistent part of the air is recycled on board. The system shall provide pressurized air or pressurized oxygen, or in case a mix of both.
Emergency mode	In case of depressurization of the cabin after an eventual critical event, appropriate devices for passenger survival, such as oxygen masks, shall be provided by the ECLSS system.

Table 5.5. Modes of Operation ECLSS.

In Figure 5.5 the ECLSS modes of operations are related to the different mission phases. As it is possible to see in the figure, the transition between the *Low* and the *High altitude* mode shall happen during the Supersonic Climb, when the aircraft is flying at an altitude between 12 km and 25 km, this is, however, a heuristic assumption and further analysis about the ECLSS capabilities has still to be done when the ECLSS will be actually designed and is beyond the purposes of this Thesis.

The *Emergency mode* can be activated in all the mission phases in which the aircraft is flying and the cabin is pressurized, therefore with the only exception of *Pre-departure* and *Taxi* phases where the aircraft is still on ground.

5.6 Propellant Subsystem Level

The Propellant subsystem can be considered as a passive system basically composed of the fuel tanks and all the other components aimed at distribute and manage the fuel, allow refuelling, and eventual interfaces with other subsystem like the TEMS, the TPS and the ECLSS. However, five different modes of operations have been identified for the propellant subsystem and those are described in Table 5.6. The *Stand-by mode* and the *Refuelling mode* are related to the aircraft still on ground, eventually during refuelling in the case of the homonym mode of operations. The two main modes of operations are the *Feeding mode* and the *Thermal mode*, those are related to two basic functions of the propellant system, respectively: To feed the propulsive subsystem and To work in synergy with other subsystems, as mentioned above, for thermal management purposes.

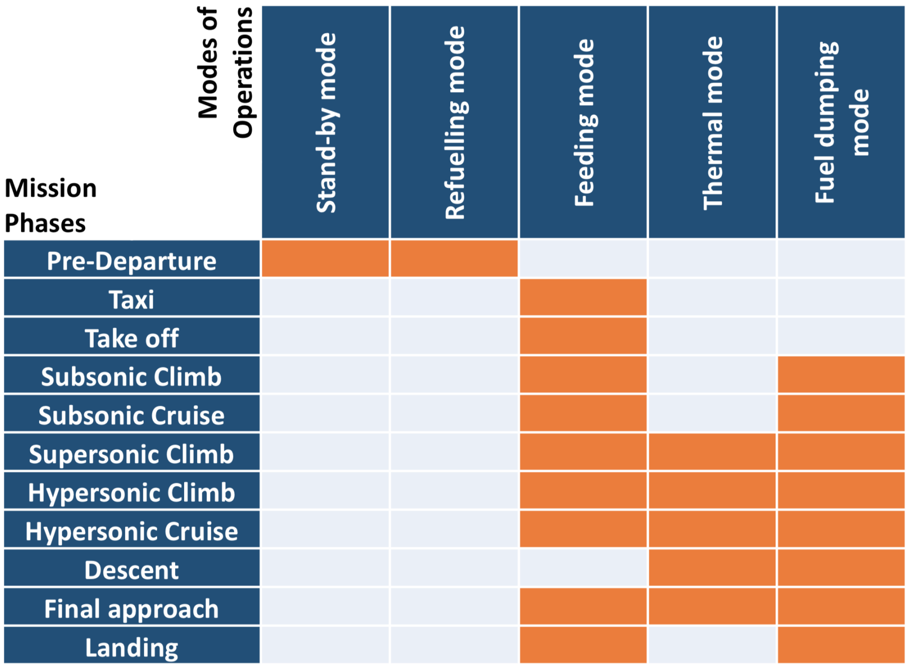


Figure 5.6. Propellant subsystem Phases/Modes Matrix.

As it is shown in Figure 5.6, the Feeding mode is active during all the flying phases with the only exception of the *Descent* phase in which in fact the engines are deactivated and no feeding is needed. The Thermal mode of the propellant subsystem is instead active when a high external heat flow must be faced, therefore when the aircraft is flying at supersonic-hypersonic regime and the TEMS passes from the Low heat flow mode to the High heat flow mode (see Figure 5.3).

An addition *Fuel damping mode* has also been identified to describe the capability that the propellant subsystem shall have to manage contingency situations in which

Propellant Subsystem	
Modes of Operations	**Description**
Stand-by mode	Only components and sensors aimed to monitor the quantity of fuel in the tanks and to avoid out of nominal events, such as fire, are active.
Refuelling mode	The refuelling interfaces with the on ground facilities are opened and operative. Components aimed to monitor the system and the level of fuel in the tanks are active.
Feeding mode	The propellant system shall be able to feed the engines. The fuel emptying law shall take into account the position of the C.G. to be maintained with in certain tolerances.
Thermal mode	The propellant system shall work in synergy with the TPS and the TEMS in order to exploit the low temperature of LH2 and the LH2 boil off for thermal and energy management purposes. The emptying law shall take into account the areas on which the external heat flow is more intense.
Fuel dumping mode	The propellant system shall be able to dump the fuel out the aircraft when an emergency landing or splashdown are being performed and the tanks must be emptied in order to decrease weight and avoid explosions.

Table 5.6. Modes of Operation Propellant Subsystem.

a fuel damping is needed to allow for example an emergency landing after a critical event occurs. More detail about the role of fuel dumping will be given in Chapter 6.

5.7 FCS Level

The Flight Control System (FCS) is one of the STARTOFLY MR3 subsystems still not fully investigated in the project. What is known is that the control of the aerodynamic surfaces shall be performed by electric, or at least electro-hydrostatic, actuators to meet the philosophy of the concept of *More electric aircraft* or *All electric aircraft* [26] - [28] and also because no hydraulic subsystem is currently being considered in the vehicle design making impossible to think about the classical electro-hydraulic actuators.

Beyond the design characteristics of the FCS, purpose of this Thesis is to investigate the possible modes of operations of this subsystem. The approach for identifying the modes of operations of the FCS, listed and fully described in Table 5.7, has been based on the classic definition of FCS modes for a typical civil passenger aircraft [59].

FCS (Flight Control System)	
Modes of Operations	**Description**
Stand-by mode	The FCS is not working since commands from the pilot are not needed. The subsystem, however, is able to monitor the state of the components, to eventually perform tests and is ready to be activated.
Nominal mode	The FCS works as expected: the commands from the cockpit are checked and elaborated by the FMC (Flight Management Computer) and transmitted as electrical signals to the actuators. The FMC works as a filter for increasing passengers comfort during flight and for avoiding dangerous manoeuvres out of the flight envelope.
Alternate mode	If one or more known failures occur, this mode is automatically activated. In this case the pilot's commands are more direct, the FMC still controls eventual manoeuvres out of the flight envelope but does not filter manoeuvres eventually against passenger comfort.
Direct mode	If one or more unknown failures occur, this mode is automatically activated. In this case the pilot's commands are direct, the FMC does not filter any kind of manoeuvres.
Emergency mode	If the FCS is not working anymore, a redundant line in which the commands are transmitted and redundant actuators shall be activated and operate in emergency situations.

Table 5.7. Modes of Operation FCS.

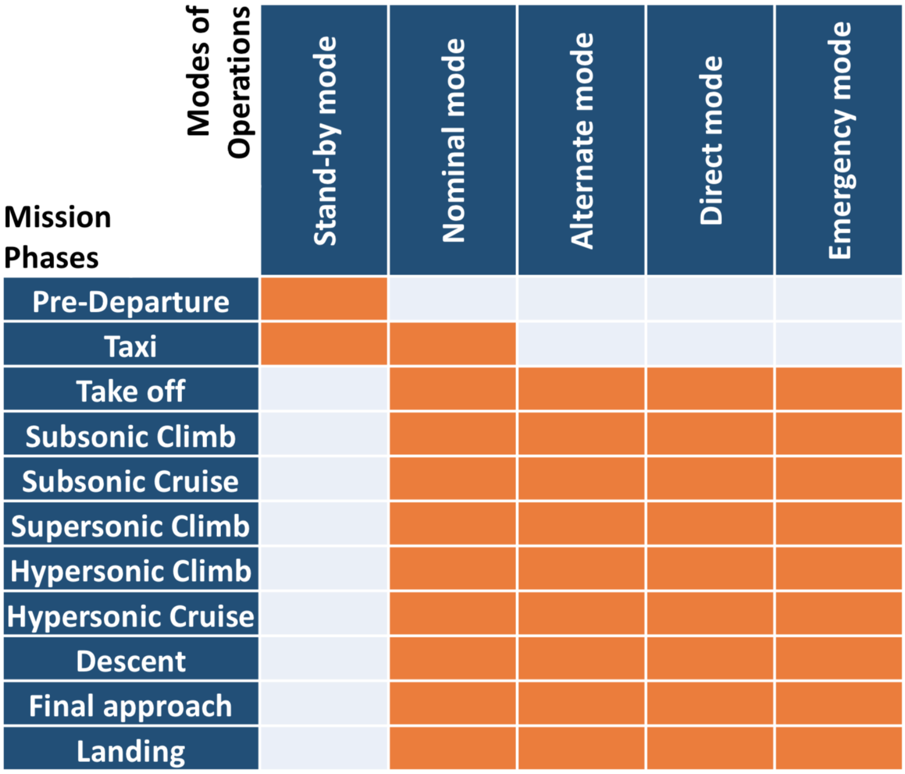


Figure 5.7. FCS Phases/Modes Matrix.

The Figure 5.7, representing the FCS Level Phases/Modes Matrix, shows how all the modes of operations can be activated during all the flying phases. The transition between one and another mode of operations depends on possible contingency situations and critical events that may occur during the mission and make it necessary to change the way the FCS works and the role of the pilot in the system.

5.8 Avionic Subsystem Level

The Avionic subsystem generally includes all the avionic components within in the aircraft. Also if this subsystem has still to be designed for the STRATOFLY MR3 vehicle, the possible modes of operations needed to meet mission objectives and to face critical situations have been investigated. The Avionic Subsystem level modes of operations are listed and described in Table 5.8.

By looking at Figure 5.8, representing the different modes of operations of the Avionics with respect to the mission phases, it is possible to see that, beyond the *Off mode* and the *Ground mode* accessible only in the ground phases, the other modes of operations can all be activated during all the flying phases with the only exception

Avionic System	
Modes of Operations	**Description**
Off mode	The overall Avionic Subsystem is shut off.
Ground mode	Avionic components aimed for monitoring and checking the system are active. The interfaces with the external facilities needed for refuelling, water charging, and other on ground procedures are active.
Nominal mode	The Avionics is working as expected, the active components depend on the specific flight phase and activity to be carried out.
Saving mode	If more power is needed to a specific subsystem or some specific components, part of the avionics equipment can be deactivated in order to save energy. However, components aimed to maintain a comfortable internal environment and to control the aircraft must be operative.
Safe mode	If one or more failures occur, some of the avionic components can be deactivated in order to save electric energy. However, components aimed to support passengers and crew life on board and to control the aircraft must be operative.

Table 5.8. Modes of Operation Avionic System.

of the *Saving mode* that is not accessible during the cruise phases. Reason why the Saving mode is not activated during the subsonic or hypersonic cruises lies on the fact that those are considered as stable phases in which no more power is usually requested by a specific subsystem and a constant level of thrust is provided by the engines, the correct mode of operations that shall be activated during the cruises if something has to change in the Avionics behaviour is the *Safe mode* since it is aimed to manage contingency situations and critical events at avionics level.

5.9 Electric Subsystem Level

The Electric subsystem aims at providing electric power to all the other subsystems and is extremely important for the success of the mission since there is not a hydraulic subsystem in the current design of the STRATOFLY MR3 vehicle that

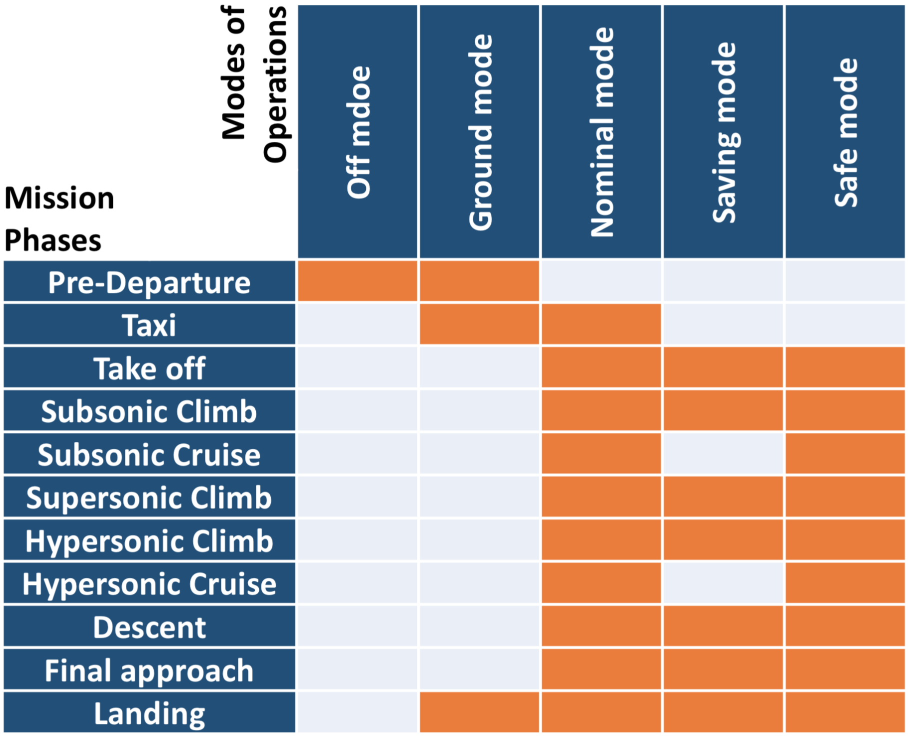


Figure 5.8. Avionic subsystem Phases/Modes Matrix.

typically represents an additional power transmission method, especially for the controls actuation, to the electric subsystem. A complete failure to the electric subsystem, therefore, shall be avoided because it can compromise aircraft controllability, mission success and passenger life.

The modes of operations that have been defined at electric subsystem level are listed and described in Table 5.9, those are similar to the ones already mentioned for the Avionic subsystem since the two subsystems, Avionics and Electric, are strictly correlated.

Also the Electric subsystem level Phases/Modes Matrix, represented in Figure 5.9, reminds the one already shown for the Avionic subsystem in Figure 5.8. As mentioned above, extremely important is the *Safe mode*, to be properly designed in the Project in order to face eventual critical situations and avoid the lost of the electric subsystem that may compromise the passenger life.

5.10 Landing Gear Level

The last subsystem to be investigated from the operational perspective is the Landing Gear. This subsystem plays a crucial role in the success of the mission and

Electric Subsystem	
Modes of Operations	**Description**
Off mode	The overall Electric Subsystem is shut off.
Nominal mode	The electric subsystem provides, as expected, the distribution of electric energy and electric signals to all the other subsystems.
Saving mode	If more power is needed to a specific subsystem or some specific components, the electric subsystem can transfer a certain amount of energy where it is more needed or can reduce the amount of produced electric energy from the propulsive system if particular high thrust is needed. However, components aimed to maintain a comfortable internal environment and to control the aircraft must be fed by the needed power.
Safe mode	If one or more failures occur, some components can be deactivated in order to save electric of energy. However, components aimed to support passengers and crew life on board and to control the aircraft must always receive the necessary amount of energy.

Table 5.9. Modes of Operation Electric Subsystem.

appropriate modes of operations have been defined on the basis of the characteristics and capabilities that the landing must have to meet mission objectives.

The modes that have been investigated are four in total, three related to nominal conditions and a fourth one related to out of nominal conditions. The Landing Gear modes of operations are described in Table 5.10. The three nominal modes are related to the different operative situations in which the landing gear shall work. In fact, the *Ground mode*, the *Extracted mode* and the *Retracted mode* cover respectively the situations in which the landing gear is extracted and the aircraft is running or is parked on ground; the aircraft is flying with the landing gear extracted; the aircraft is flying with the landing gear retracted. An additional *Emergency mode* has been considered in order to describe the capability of the system to manage out of nominal situations in which, in particular, the landing gear is extracted and there are problems in the retraction (e.g. soon after take-off) or the landing gear is retracted and there are problems in the extraction (e.g. before landing). In this kind of situations the system shall be able to permit, forcing in case the landing

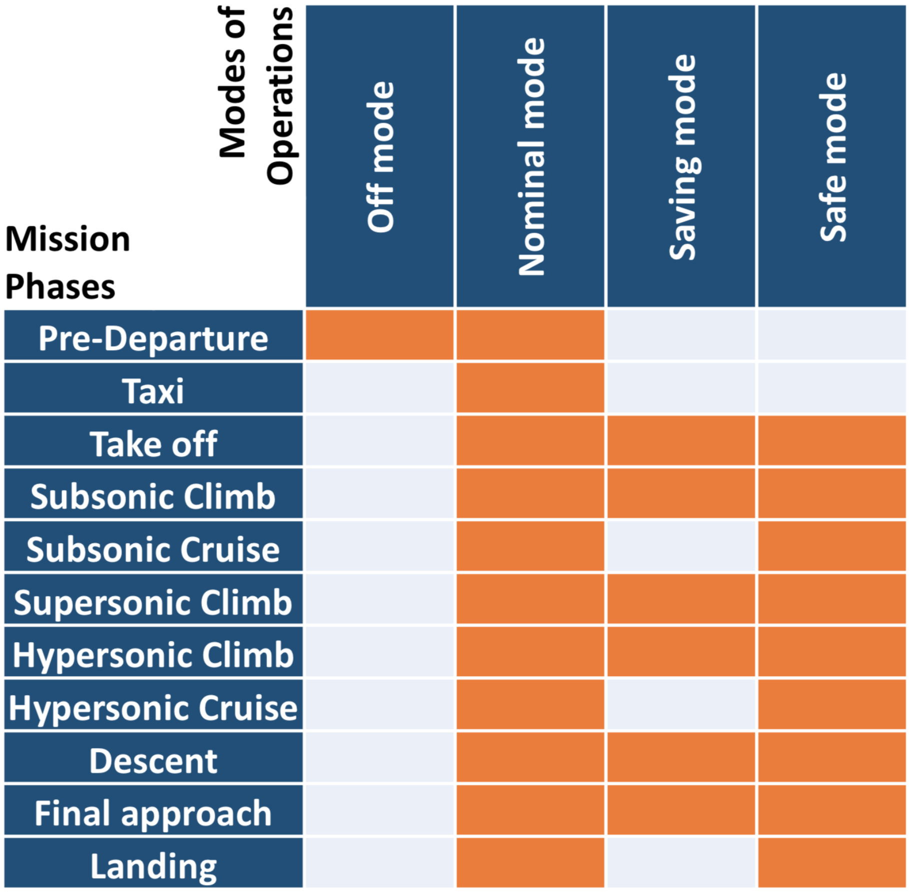


Figure 5.9. Electric subsystem Phases/Modes Matrix.

gear whit appropriate methods and devices, the gear extraction (or retraction) in order to avoid critical events.

The Landing Gear level Phases/Modes Matrix is represented in Figure 5.10. As it possible to see in the figure, the Ground mode is related to mission phases n which the aircraft is on ground, the Extracted mode is common to the Take off, Final Approach and Landing phases while the Retracted mode is common to all the mission phases in which the aircraft is nominally flying. Finally, the Emergency mode can be generally accessed in all the phases, but in particular in the phases in which typically failures to the landing gear can occur, therefore Take off, Final approach and Landing.

Landing Gear	
Modes of Operations	**Description**
Ground mode	The landing gear is correctly extracted and wheels are touching the ground, therefore suspension, braking system and thermal dissipation devices shall be active and operative.
Extracted mode	The landing gear is deployed and is ready to eventually touch the ground. The deployment actuators are active and the gear shall resist the aerodynamic drag.
Retracted mode	The landing gear is retracted inside a cargo bay of the aircraft. The components aimed to monitor the state of the gear, especially of the actuators, are active in order to predict and avoid failures when the gear has to be deployed.
Emergency mode	If failures occurs and the landing gear cannot be deployed or retracted properly, the system shall provide the opportunity to extract or retract it otherwise. Components and sensors aimed to monitor the actual state of the gear are active.

Table 5.10. Modes of Operation Landing Gear.

5.11 Considerations

It is important to note that the contents of this Chapter, therefore the System and Subsystem level modes of operations definition and analysis, have been carried out by performing a qualitative analysis based on the different subsystems' characteristics at this level of the vehicle design and the capabilities that those subsystems should have in order to meet mission objectives and to work as expected. A quantitative analysis, however, that takes into account the actual properties of the system and able to describe the modes of operations from a physical and analytical perspective, shall be performed as soon as the different subsystems are better designed within the STRATOFLY Project and goes beyond the purposes of this Thesis.

The most important subsystem, as already mentioned in the respective Section (5.2), is the Propulsive Subsystem. The modes of operations and the phases/modes matrix of this subsystem, indeed, are extremely important for the further development of the FFBDs described in Chapter 7 and the definition of possible failures and related out of nominal scenarios that will be discussed in Chapter 6.

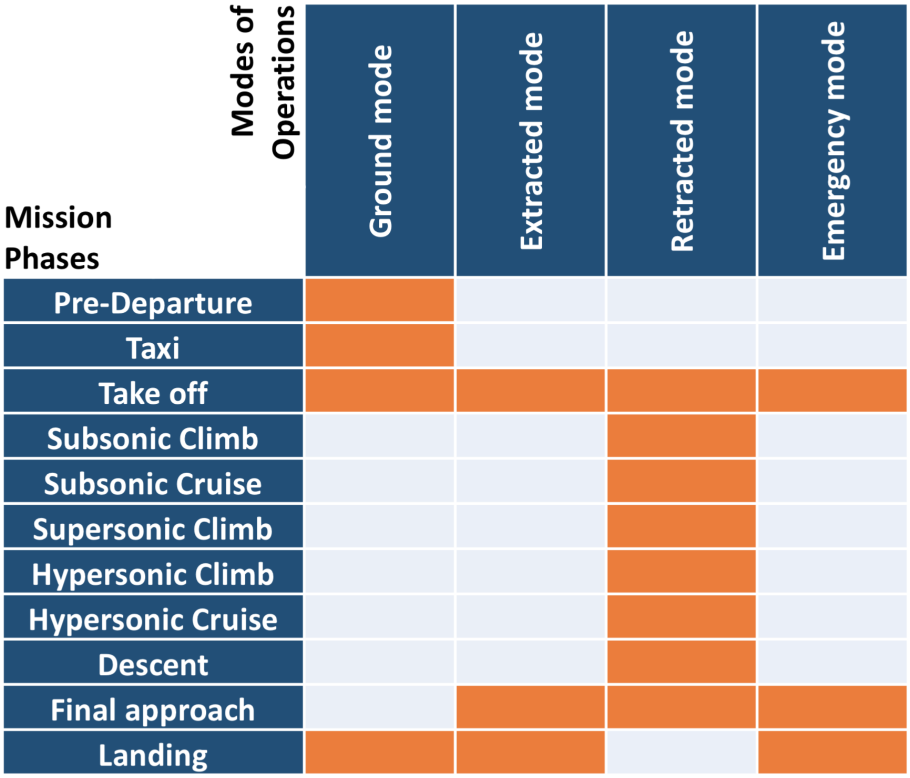


Figure 5.10. Landing Gear Phases/Modes Matrix.

Anther important issue that emerges from the contents of this Chapter is the synergy between the TEMS, the TPS, the ECLSS and the Propellant Subsystem. In fact, It is possible to note that the those subsystems are strictly related one to each other in terms of modes of operations definition for energy management and thermal protection purposes. This last aspect will be further investigated in Chapter 7 in terms of operations and subsystems' interfaces.

Chapter 6

Identification of Possible Out of Nominal Scenarios

This Chapter aims at defining and describing possible operational scenarios of the STRATOFLY MR3 mission identified as consequences of critical events and out of nominal situations. The meaning of *operational scenario* and the role of *out of nominal scenarios* definition in the ConOps analysis have already been discussed in Chapter 3.

In the first part of the Chapter, an overview on the general failures that may occur during the mission will be given taking into account the overall system. The failures consequences and the related definition of possible out of nominal scenarios, however, will be discussed taking into account the only propulsive subsystem. Thus, it is important to note that the out of nominal scenarios identified in this Thesis do not cover all the possible operational scenarios, but a part of them related mainly to critical events that can occur in relation to the propulsive subsystem.

The reason why the attention has been focused on the propulsive subsystem lies on the fact that it is the main subsystem involved in the mission trajectory simulation and assessment, and therefore the first one to be taken into account for a preliminary out of nominal scenarios analysis.

The out of nominal scenario identification and classification performed in this Chapter represents an important input for the simulation of some out of nominal scenarios that will be discussed in Chapter 9.

As it will be better explained in Section 6.4, the method with which the possible out of nominal scenarios have been identified consists on the definition of critical events related consequences to be multiplied by the different phases in which they can occur for the operational scenarios definition.

Some examples of out of nominal scenarios will be given in Section 6.5.

6.1 Possible Failures and Critical Events

The identification of the hazards and the possible critical events that can occur during the mission is an important analysis for many purposes. In the system design phase it permits, first of all, to include in the design of the different subsystems a series of elements and design techniques aimed at mitigating the risk, e.g. redundancies and appropriate safety factors, associated to possible failures and critical events. However, speaking about the ConOps analysis, therefore for the purposes of this Thesis, the identification of possible failures and critical events represents the starting point for the definition of possible operational procedures and possible out of nominal scenarios.

Also if, later in this Chapter, the attention will be focused on the propulsive subsystems, this Section is aimed at giving an overview of the possible failures and critical events that can occur to the overall system. Thus, a general summary of the potential critical events and possible failures that can occur in the different phases of the mission is provided in the following Table (Table 6.1).

Phase ID	Phases	Possible failures and/or catastrophic events
PH 1	Pre-Departure	• Avionics or Electric subsystem malfunction • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity
PH 2	Taxi	• Propulsive subsystem related failure • Avionics or Electric subsystem malfunction • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Phase ID	Phases	Possible failures and/or catastrophic events
PH 3	Take off	• Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Failure to retract of the Landing gear • Cabin pressurization related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity
PH 4	Subsonic Climb	• Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Unexpected cabin depressurization, ECS/E-CLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Phase ID	Phases	Possible failures and/or catastrophic events
PH 5	Subsonic Cruise	• Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Unexpected cabin depressurization, ECS/E-CLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity
PH 6	Supersonic Climb	• Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Unexpected cabin depressurization, ECS/E-CLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Phase ID	Phases	Possible failures and/or catastrophic events
PH 7	Hypersonic Climb	• Thermal Protection Subsystem related failure • Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Unexpected cabin depressurization, ECS/ECLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity
PH 8	Hypersonic Cruise	• Thermal Protection Subsystem related failure • Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Unexpected cabin depressurization, ECS/ECLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Phase ID	Phases	Possible failures and/or catastrophic events
PH 9	Descent	• Thermal Protection Subsystem related failure • Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Unexpected cabin depressurization, ECS/ECLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity
PH 10	Final approach	• Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Failure to rectivate the engines, or other propulsion related failure • Unexpected cabin depressurization, ECS/ECLSS related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Phase ID	Phases	Possible failures and/or catastrophic events
PH 11	Landing	• Failure to extract of the Landing gear • Loss of control, FCS related failure • Avionics or Electric subsystem malfunction • Propulsive subsystem related failure • Other subsystem failure • Unpredicted explosion • Detected fire or predicted explosion • Loss of structural integrity

Table 6.1: Possible failures and catastrophic events for the different mission phases.

Once the the possible critical events have been identified, the procedure to derive the associated operational scenarios consists on the definition of certain consequences to the different failures that can occur to the different subsystems in the different mission phases. Generally, two high level scenarios can be considered after a failure occurs: the system can deal with the specific failure thanks to design arrangements and the mission can be taken forward; or the specific failure compromises the mission that consequently has to be aborted. An additional scenario, that is not an option but instead must be avoided, is related to a catastrophic event after a failure occurs.

From the next Section, those concepts will be further developed for the propulsive subsystem related failures for the definition of possible out of nominal scenarios.

6.2 Propulsive Subsystem Failure related Consequences

The STRATOFLY MR3 propulsive subsystem, described in Chapter 2, is composed of the ATR engines and the DMR engine. The generic category of failures that can occur to this subsystem are:

- Minor failure to the propulsive subsystem that not compromise the engines integrity

- One or more engines are shut-off while the propulsive subsystem is working as ATR
- The engine is shut-off while the propulsive subsystem is working as DMR

The most top level consequences after a failure occurs to the propulsive subsystem are two: the mission can be taken forward; the mission must be aborted. In the case of mission abortion, moreover, there are two different cases on the basis of if the vehicle is still controllable or not, thus considering also the case in which the mission can continue, the propulsive subsystem failures related consequences result to be three in total:

1. The mission can be taken forward
2. The mission must be aborted and the vehicle is controllable
3. The mission must be aborted but the vehicle is uncontrollable

For the definition of possible out of nominal scenarios associated to possible critical events, it is not enough to define the failures related consequences but it is necessary to define a certain numbers of options associated to the different consequences. Figure 6.1 graphically shows what can happen after a failure occurs and how the different options are associated to the aforementioned failures related consequences. The six different options are briefly listed and described in Table 6.2.

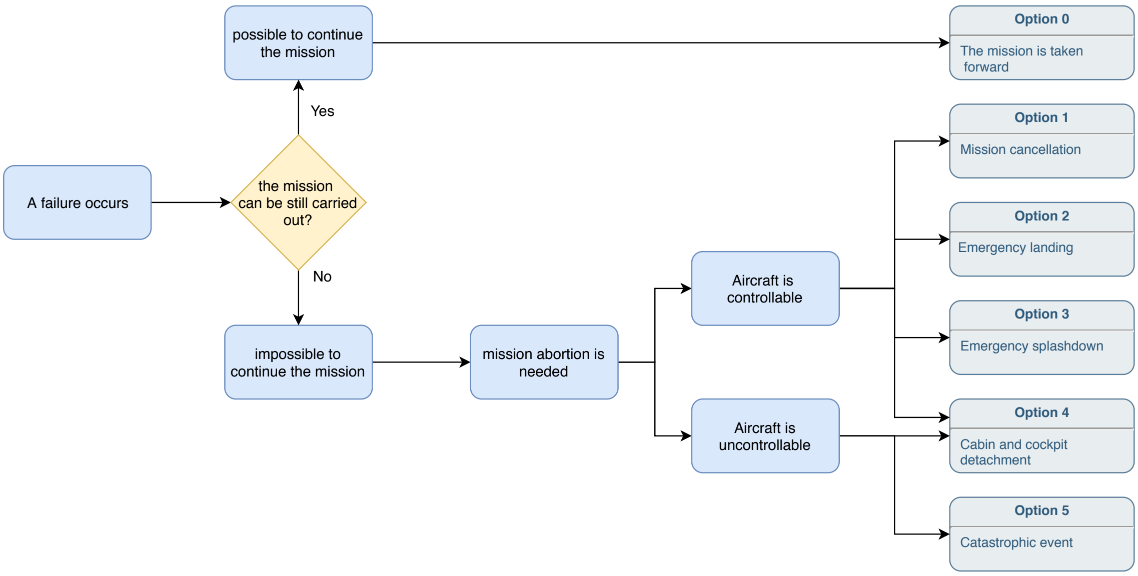


Figure 6.1. Propulsive Subsystem Failure related Consequences.

Option ID	**Option name**	**Description**
OP 0	Mission is taken forward	The mission can continue despite the failure occurred.
OP 1	Mission cancellation	The aircraft is stopped on ground and the take-off is cancelled.
OP 2	Emergency landing	An emergency landing on an appropriate landing runway is performed, fuel dumping before the landing is also performed if needed.
OP 3	Emergency splashdown	An emergency water-landing is performed, fuel dumping before the landing is also performed if needed.
OP 4	Cabin and cockpit detachment	The cabin and cockpit are detached from the main structure and are landed on water or ground through a parachute system. While falling down from high altitudes, cabin and cockpit shall be able to slow down and resist the high heat flow.
OP 5	Catastrophic event	A catastrophic event is inevitable if a failure occurs since since the aircraft has just performed take-off and/or is flying at a critical low altitude on which fuel dumping before an emergency landing is not possible.

Table 6.2. Operational options after a failure to the propulsive subsystem occurs.

The *emergency landing* and *splashdown* options are typically considered as mission abortion options for the major part of civil passengers aircraft. The *cabin and cockpit detachment* option, however, is being only recently considered [15] and has never been utilised as mission abortion option for the current civil aviation aircrafts.

Modern concepts of cabin escape and cabin detachment systems that have been investigated for high speed flight and space applications are related to detachable cabin capable of perform an atmospheric reentry and resist the consequent high heat flow [24]. Therefore, an eventual cabin detachable system for the STRATOFLY MR3 application should have similar characteristics, also if the feasibility of such kind of mission abortion option has still to be assessed since there are severa issues to be faced, for example the design complication itself as well as environmental and safety aspects related to the aircraft structure falling on ground after cabin detachment with probably the tanks still full of liquid hydrogen.

At this point of the discussion, all the option are just considered in order of theoretically define different out of nominal scenarios. Another step, however, has still to be done before the out of nominal operational scenarios definition and it consists on the association of the different options to the different phases of the mission, as it will be better explained in the next Section.

A graphical representation of the different options described in Table 6.2 will be given in Section 6.5 where some out of nominal scenarios examples will be discussed.

6.3 Mission Phases Clusterization

In order to identify the out of nominal operational scenarios, the different options available on the basis of the kind of failure that occurs have to be associated with the different mission phases potentially related to a certain critical event. However, the scenario associated to a critical event can be the same for different phases of the mission, therefore the eleven STARTOFLY MR3 mission phases have been grouped into six different clusters on the basis of the similarities of the possible consequences of a failure occurred to the propulsive subsystem.

The six phases' clusters are listed in Table 6.3, where it is possible to see the mission phases included in each cluster and a description of the cluster itself for a better understanding of the reason why the cluster has been defined. A graphical description of the phases clusterization is given in Figure 6.2.

Once the phases' clusters have been defined, by associating those to the different failures consequences' options it is possible to identify possible out of nominal scenarios that will be discussed in the next Section. The phases clusterization allows a lighter analysis that leads to define the out of nominal operational scenarios, otherwise redundant for similar mission phases in which a failure occurs. For example, considering the Cluster 1, it is possible to understand the reason why this cluster has been defined by thinking about the fact that the consequences of a failure occurring while the aircraft is still on ground are the same if the aircraft is parked on ground, is moving towards the take off runway or is performing the take off at a speed lower than the decision velocity. In those situation, in fact, the aircraft can be stopped, if it was moving before, or can remain stopped on ground and the mission can just

Cluster ID	Cluster Name	Phases	Description
CL 1	Mission Start	PH1, PH2, PH3	The aircraft is still stopped on ground or it is performing take-off running at a speed lower than the decision velocity.
CL 2	Early Ascent	PH3, PH4	The aircraft is performing take-off or is reaching higher altitudes just after take-off, but it is flying at critical low altitudes on which an emergency landing and fuel dumping are not possible after failure occurs.
CL 3	Subsonic Ascent and Cruise	PH4, PH5	The aircraft reaches increases flight altitude and performs subsonic cruise, during those phases the aircraft is flying above land and sonic boom is not yet allowed.
CL 4	High-speed Ascent and Cruise	PH6, PH7, PH8	The aircraft is flying above the sea at supersonic or hypersonic speed.
CL 5	Reentry	PH9, PH10	The aircraft is decreasing the flight altitude performing atmospheric reentry and approaching to landing.
CL 6	Landing	PH11	The aircraft is performing landing

Table 6.3. Phases Clusterization and Clusters description.

be canceled after a failure to the propulsive subsystem occurs.

The reason why the other clusters have ben defined can be understood by making similar argumentations of the one just discussed above.

6.4 Possible Out of Nominal Scenarios

The possible out of nominal scenarios have been identified by considering the combination of the five failure consequences options defined in Section 6.2 and the mission phases clusters defined in Section 6.3. Thus, considering six options and six clusters,

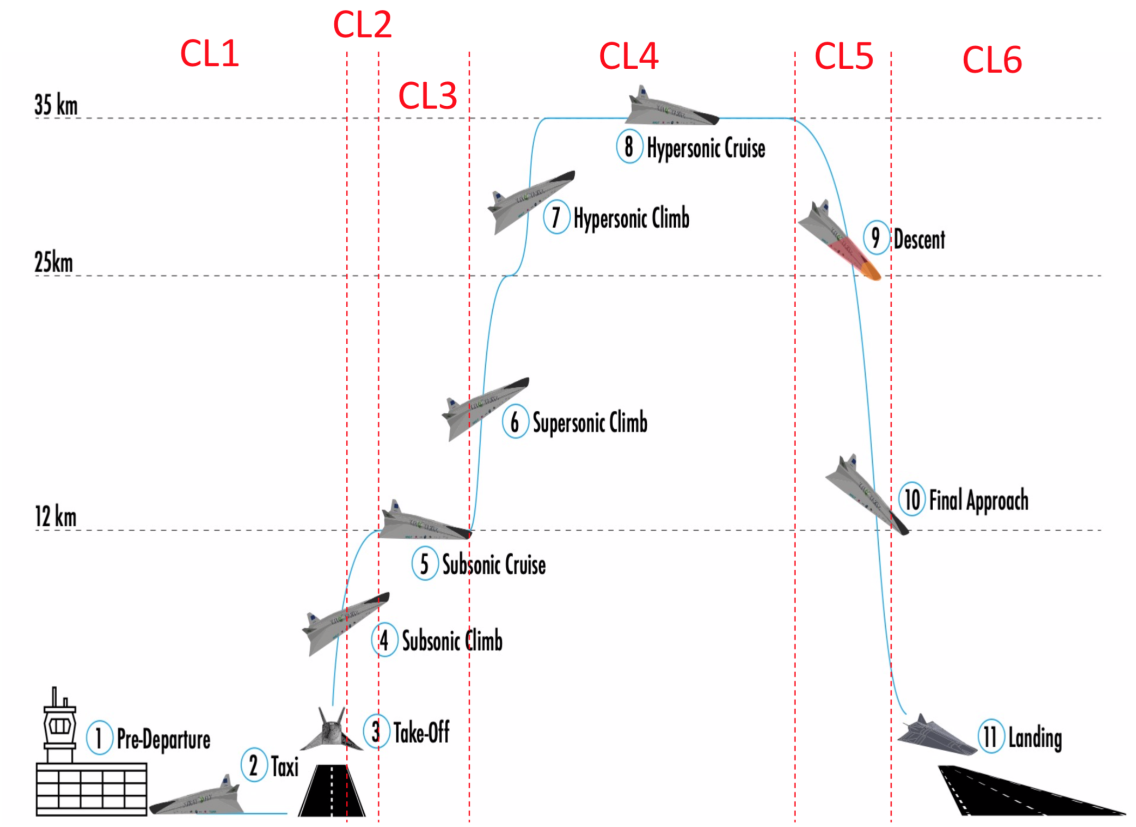


Figure 6.2. Graphical description of phases clusterization.

the total number of out of nominal scenarios should be equal to 6x6 = 36. However, not all the 36 scenarios make sense to be considered as possible real operational scenarios. For a better understanding of the previous statement, examples of out of nominal scenarios that make no sense to be considered can be an emergency landing when the aircraft is still parked on ground or a mission cancellation when the aircraft is flying above the ocean. Thus, considering the scenarios that make no sense, the number of the possible out of nominal scenarios goes down to 23 out of 36.

A list of all the possible out of nominal scenarios associated to a propulsive subsystem related failure is provided in Figure 6.3. The out of nominal scenarios are identified by an ID that goes from 1 to 23. The rows of the table represented in Figure 6.3 related to the scenarios that make no sense contain the string "//" rather than the scenario's ID.

Mission Phases	Phase Clusters	Possible Failures	Failure Consequences	Options	Scenario ID
PH 1: Pre-Departure PH 2: Taxi PH 3: Take-Off	CL1: Mission Start	• Minor Propulsive System related failure that does not compromise the mission • Propulsive System related failure that compromises the mission • Predicted explosion or fire at the Parking Area/Runway • Unpredicted explosion at the Parking Area/Runway	Mission can be taken forward	OP 0: Mission continues	1
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	2
				OP 2: Emergency Landing	//
				OP 3: Emergency Splashdown	//
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	//
				OP 5: Catastrophic Event	3
PH 3: Take-Off PH 4: Subsonic Climb	CL2: Early Ascent	• Minor Propulsive System related failure that does not compromise the mission • One or more ATR engines are shut down • Predicted explosion or fire during flight • Unpredicted explosion during flight	Mission can be taken forward	OP 0: Mission continues	4
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	//
				OP 2: Emergency Landing	5
				OP 3: Emergency Splashdown	//
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	//
				OP 5: Catastrophic Event	6
PH 4: Subsonic Climb PH 5: Subsonic Cruise	CL3: Subsonic Ascent and Cruise	• Minor Propulsive System related failure that does not compromise the mission • One or more ATR engines are shut down • Predicted explosion or fire during flight • Unpredicted explosion during flight	Mission can be taken forward	OP 0: Mission continues	7
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	//
				OP 2: Emergency Landing	8
				OP 3: Emergency Splashdown	9
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	//
				OP 5: Catastrophic Event	10
PH 6: Supersonic Climb PH 7: Hypersonic Climb PH 8: Hypersonic Cruise	CL4: High-speed Ascent and Cruise	• Minor Propulsive System related failure that does not compromise the mission • One or more ATR engines, or the DMR engine, are shut down • Predicted explosion or fire during flight • Unpredicted explosion during flight	Mission can be taken forward	OP 0: Mission continues	11
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	//
				OP 2: Emergency Landing	12
				OP 3: Emergency Splashdown	13
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	14
				OP 5: Catastrophic Event	15
PH 9: Descent PH 10: Final Approach	CL5: Reentry	• Minor Propulsive System related failure that does not compromise the mission • One or more ATR engines miss to reactivate after descent • One or more ATR engines are shut down during final approach • Predicted explosion or fire during flight • Unpredicted explosion during flight	Mission can be taken forward	OP 0: Mission continues	16
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	//
				OP 2: Emergency Landing	17
				OP 3: Emergency Splashdown	18
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	19
				OP 5: Catastrophic Event	20
PH 11: Landing	CL6: Landing	• Minor Propulsive System related failure that does not compromise the landing • One or more ATR engines are shut down • Predicted explosion or fire during flight • Unpredicted explosion during flight	Mission can be taken forward	OP 0: Mission continues	21
			Mission Abortion - Controllable aircraft	OP 1: Mission Cancellation	//
				OP 2: Emergency Landing	22
				OP 3: Emergency Splashdown	//
			Mission Abortion - Uncontrollable aircraft	OP 4: Cabin Detachment	//
				OP 5: Catastrophic Event	23

Figure 6.3. Possible out of nominal scenarios related to propulsive subsystem failures.

6.5 Examples of Out of Nominal Scenarios

This Section is aimed to provide useful examples that helps to understand the criteria with which the out of nominal scenarios have been identified.

Five different out of nominal operational scenarios, each of them related to a different mission abortion option, will be illustrated and described in the following. In particular, those are:

- *Scenario 2*: Take-off abortion and mission cancellation
- *Scenario 6*: Catastrophic event soon after take-off
- *Scenario 8*: Emergency landing after the Subsonic Cruise
- *Scenario 13*: Emergency Splashdown after the Supersonic Climb
- *Scenario 14*: Cabin and cockpit detachment during Hypersonic Cruise

From now on, when referring to a phases cluster or to a mission abortion option, the ID of the cluster or the option will be used in the for *CL i* and *OP j*, where $i = 1, ...,6$ and $j = 1, ...,5$.

In the Figures 6.4 - 6.5 - 6.6 - 6.7 - 6.8, aimed at illustrating the different examples of out of nominal scenarios, the light blue lines are related to the portion of nominal trajectory before the failure to the propulsive subsystem occurs while the red lines describe the out of nominal phases after the failure occurs.

6.5.1 Scenario 2: Mission Cancellation

A failure to the propulsive subsystem occurs when the aircraft is still on ground when performing Take-off at a speed lower than the decision velocity. Thus, the take-off can be safely interrupted and the Mission can be canceled, therefore the aircraft remains on ground and the passengers are evacuated. This scenario has been identified by putting together CL1 and OP 1.

The Scenario 2 is illustrated in Figure 6.4.

The situation illustrated in the Scenario 2 is the same of all the mission phases included in the CL1. The mission, in fact, can be canceled whenever the aircraft is still on ground, therefore also during Pre-departure and Taxi phases.

6.5.2 Scenario 6: Catastrophic event

This scenario is associated to the meeting of CL 2 and OP 5. A failure to the propulsive subsystem occurs soon after take-off or during the early Subsonic climb phase. In this case the altitude is not sufficient for performing fuel dumping and

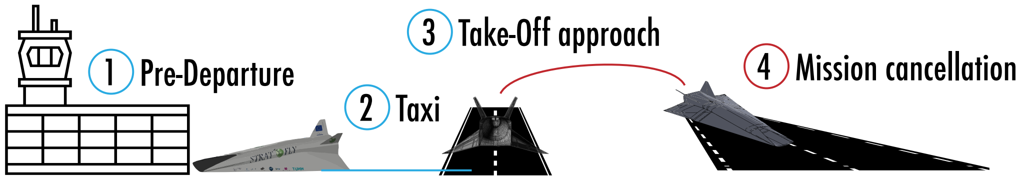


Figure 6.4. Scenario 2: Take-off abortion and Mission cancellation.

for performing appropriate landing manoeuvres, therefore the aircraft can do nothing but fall on ground with the tanks still full of fuel and a catastrophic event is inevitable.

The Scenario 6 is illustrated in Figure 6.5.

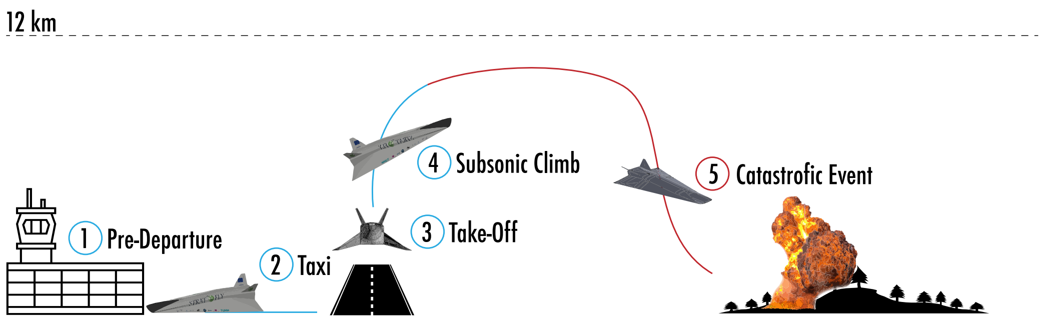


Figure 6.5. Scenario 6: Catastrophic event soon after take-off.

This scenario represents one of the most critical out of nominal situations and must be avoided by considering appropriate risk mitigation strategies to be further assessed with in the STRATOFLY MR3 project.

Generally, a catastrophic event may occur in all the clusters if a failure occurred to the propulsive subsystem is such that the aircraft results to be uncontrollable and emergency landing manoeuvres are impossible to be performed. In this case, the only available option to safe passenger life is the OP 4 related to the cabin and cockpit detachment. OP 4, however, is impossible to be performed during the CL 2 and so this is a confirmation of the fact that the Scenario 6 has to be properly assessed for the high risk related.

6.5.3 Scenario 8: Emergency Landing

This scenario is associated to the meeting of CL 3 and OP 2. A failure to the propulsive subsystem occurs when the altitude is relatively high and the aircraft is still flying over land. In this case fuel dumping and appropriate landing manoeuvres are possible, therefore the aircraft can perform an emergency landing in a runway that is reachable despite the failure. However, fuel dumping is possible if not against eventual social and environmental constraints related to the liquid hydrogen falling on ground. Thus, it is necessary to analyse an eventual trade off between environmental or social issues and the fuel dumping needed to avoid a possible catastrophic event.

The Scenario 8 is illustrated in Figure 6.6.

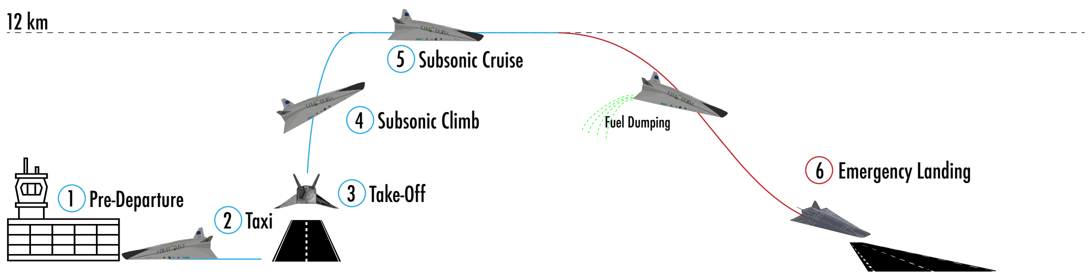


Figure 6.6. Scenario 8: Emergency landing after the Subsonic Cruise.

6.5.4 Scenario 13: Emergency Splashdown

This scenario is associated to the meeting of CL 4 and OP 3. A failure to the propulsive subsystem occurs when the aircraft is flying over sea. In this case the aircraft can perform an emergency splashdown, eventually after having performed fuel dumping if deemed necessary.

The Scenario 13 is illustrated in Figure 6.7.

The definition of the Senario 13 and of all the other scenarios associated to the emergency splash down option is of extreme importance for the design of the STRATOFLY MR3 vehicle that shall be eventually able to perform such kind of landing in the sea and shall be able to float in the water.

6.5.5 Scenario 14: Cabin and Cockpit Detachment

This scenario is associated to the meeting of CL 4 and OP 4. If a failure to the propulsive subsystem occurs when the aircraft is flying at sufficient altitude for

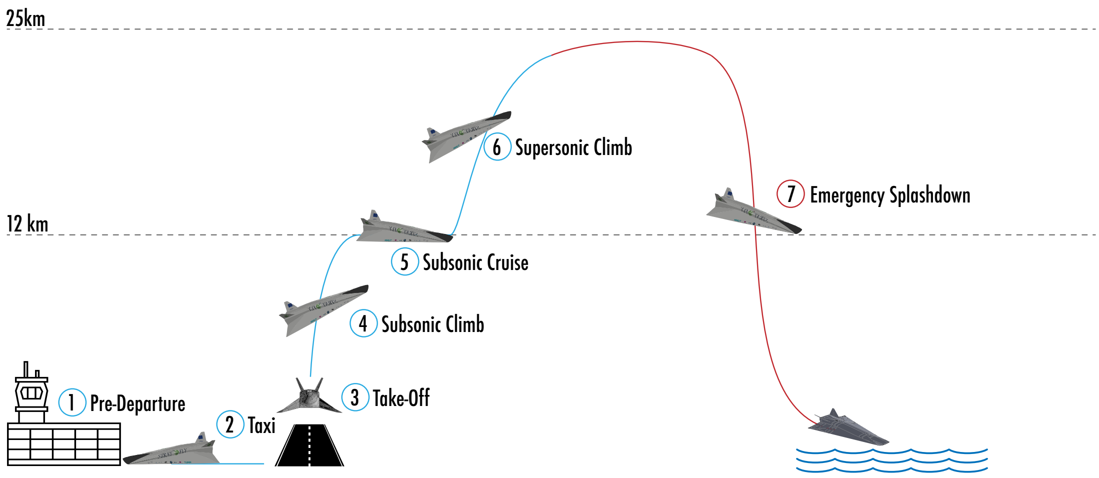


Figure 6.7. Scenario 13: Emergency Splashdown after the Supersonic Climb.

allowing cabin detachment, crew and passengers can be evacuated and parachuted on ground (or sea). The feasibility of such kind of system should be evaluated in terms of technical difficulties and possible problems related to the aircraft structure falling on ground, eventually over inhabited land.

Figure 6.8 represents the the Scenario 15 in which cabin and cockpit detachment is performed after a failure occurs during the hypersonic cruise. In this case, the cabin shall resist the high external heat flow during the atmospheric reentry and therefore the STRATOFLY MR3 cabin, if detachable, must be properly designed.

6.6 Considerations

The above discussion about out of nominal scenarios identification and classification represents a basis for further assessment and analysis about the actual capabilities of the system to deal with out of nominal conditions. The feasibility of the operational procedures developed qualitatively in this Chapter, in fact, has to be further assessed by taking into account the specific type of failure, how much engines are involved in the failure, the available propulsive performances after failure as well as the specific flight condition and environment.

The feasibility of an emergency landing, for example, depends on the actual distance between the point of failure and an eventual available airport, as well as on the actual capabilities of the system to reach the specific emergency airport after failure.

However, it is not possible to take into account all the specific mission routes and to evaluate the consequence of all the failures that can occur at each point of

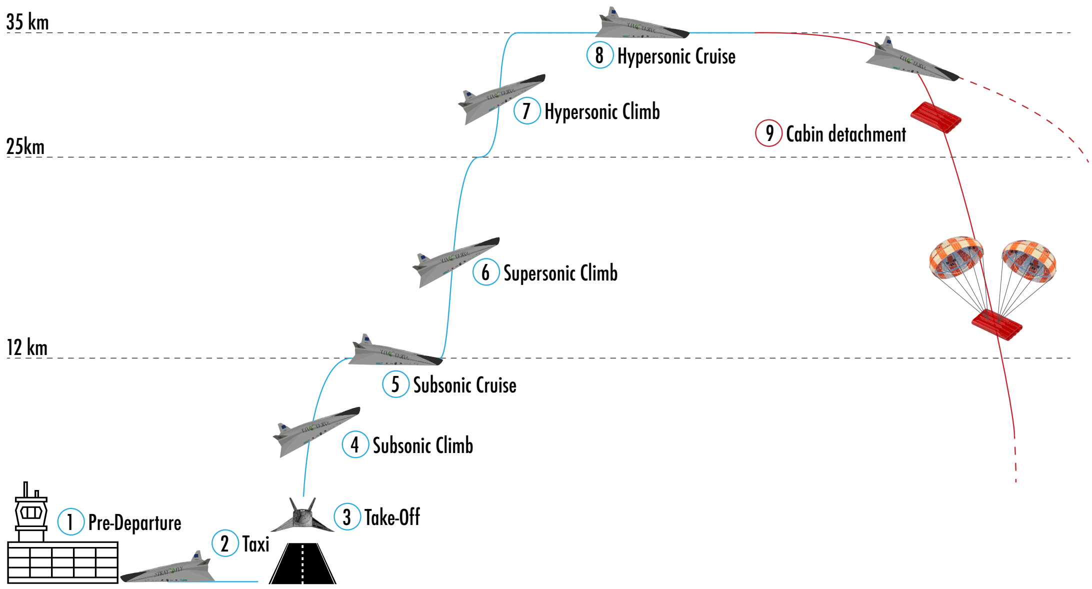


Figure 6.8. Scenario 14: Cabin and cockpit detachment during Hypersonic Cruise.

trajectory. It is, instead, necessary to develop major knowledge about the capability of the system to react to a critical event and to achieve general results to be used to predict the consequence of a certain failure and the best mission abortion option to be performed.

This type of analysis was performed as work of this Thesis and it is discussed in Chapter 9 where the out of nominal scenarios assessment was performed via the ASTOS trajectory simulation software, by considering as input the scenarios identification and classification discussed in the present Chapter.

In order to give a taste of the simulations results, it is possible to state that the situation in which all the 6 ATR engines are unavailable after failure must be avoided since too much risky, while the situation can be always managed with only one out of 6 ATR engines available after failure. Furthermore, if a failure occurs to the DMR propulsion unit during hypersonic climb or cruise, the aircraft can perform an emergency descent and an eventual emergency landing or emergency splashdown can be after performed by reactivating the ATR unit, assumed to be not affected by the failure. The only limitation, in this case, on the flyable distance before to reach an eventual emergency airport or strategic point for emergency splashdown is represented by the available mass of propellant on board after failure.

Another consideration to be done about the contents of this Chapter regards the cabin and cockpit detachment mission abortion option. Despite this option has been considered for out of nominal scenarios identification and classification, in fact, further assessments, based mainly on simulations, have demonstrated that this option is never necessary when considering failures affecting the performances of the propulsive subsystem. In this case, in fact, an emergency landing or emergency splashdown can be always performed as mission abortion option when the aircraft is flying at high altitudes. The cabin detachment might be necessary to avoid an inevitable catastrophic event, but the problem is that such kind of event is more probable if a failure occurs at low altitudes, for example soon after take off or early subsonic climb, in which the cabin detachment cannot be performed, resulting as an un-necessary option to be considered.

If other kind of failures, affecting not only the propulsion performances but also related to potential fire or explosion, are considered, then the cabin and cockpit detachment option can be re-evaluated. Anyway, technically speaking it would be easier to design subsystems and components with proper levels of reliability in such a way to avoid potential fire and explosion, than to design a cabin and cockpit detachment system for a hypersonic cruiser.

However, only failures affecting propulsion performances, and not potential explosions, have been considered for simulation purposes and out of nominal scenarios assessment as discussed in Chapter 9.

Chapter 7

Logical Decomposition of Operations

Part of the ConOps analysis consists on the description of the functions and functions correlation that the system shall perform at different levels from an operational point of view. This activity is addressed as logical decomposition of operations, that in this Chapter means Functional Flow Block Diagrams (FFBDs) analysis.

The FFBDs analysis has been already presented from a theoretical perspective in Chapter 3. Aims of the present Chapter is to describe and discuss the FFBDs analysis performed for the STRATOFLY MR3 mission as part of the original work of this Thesis.

The rules and methodology implemented in this Chapter are described in Section 7.1, while the other sections are intended to describe the FFBDs analysis at different levels. In particular, three different level of functions have been investigated: top level in Section 7.2, second level in Section 7.3 and third level in Section 7.4.

Moreover, Section 7.5 gives further explanation about the functions related to the synergy among the TEMS, TPS, ECLSS and propellant subsystem in terms of subsystems interfaces and common operations.

The contents of this Chapter does not only describe a heuristic and qualitative analysis, but also the operational procedures here developed and discussed are of extreme importance for modelling the nominal and out-of-nominal scenarios that have been simulated via ASTOS software as it will be discussed in Chapters 8 and 9.

7.1 Method

The methodology, symbology and conventions implemented for the FFBDs analysis performed in this Chapter have been provided by U.S. Air Force [38] and are described hereafter.

A functional flow block diagram consists of different blocks connected by simple arrows or logical connectors. Each diagram is related to a specific level of operations and each block within a diagram is related to a specific function. Function blocks are shown as a solid box with two separated regions for the identification number and the title. The number is contained in a "banner" on top of the box while the title is shown in the major portion under the banner. Each function is identified by a unique number, that has nothing to do with the sequence in which the functions may be performed. Moreover, the different functions are connected through a logical, not chronological, order, if then the functions respect a time sequence this shall be seen as a coincidence and not a rule.

The function number is given in the format "F$x.y.-.z$" where x, y and z are numbers. The last number, z in this case, stems for the function ID, while the previous numbers stem for the level of function decomposition. The longer is the function identification number, the more detailed is the level of decomposition for the specific function.

For example, F1, F2 and F3 are top level functions while F3 can be decomposed in F3.1, F3.2 and F3.3 that are second level functions. The function number helps at identifying the specific function when represented in different diagrams. Only the title, in fact, would not be enough and could lead to confusion.

Each diagram is introduced with on top the respective level and the title of the function that is being decomposed in the diagram. The input and output higher level functions are also represented in the diagram as dotted boxes outside the diagram boundaries.

Three type of logical connectors have been considered for to describe functions relationships: *"AND"*, *"OR"* and *"XOR"*, where "OR" is the conventional inclusive or, while the "XOR" represents an exclusive or. The connectors are represented as small circles with certain inputs and outputs. The following rules and conventions are considered:

- All the functions connected as input to an "AND" - originated as outputs from an "AND" - shall be performed before the functions following the "AND" are performed - after the functions preceding the "AND" are performed.
- One or more function connected as input to an "OR" - originated as output from an "OR" - shall be performed before the functions following the "OR" are performed - after the functions preceding the "OR" are performed.
- One and only one function connected as input to an "XOR" - originated as output from an "XOR" - shall be performed before the functions following the "XOR" are performed - after the functions preceding the "XOR" are performed.

Once the basis for the understanding of the FFBDs analysis have been put, the FFBDs at different levels are described in the following sections.

7.2 Top Level

The top level functions to be accomplished in the STRATOFLY MR3 mission are basically related to the capabilities of the system to perform the mission itself or to perform contingency operations to face out-of-nominal conditions. The top level FFBD is therefore represented in Figure 7.1.

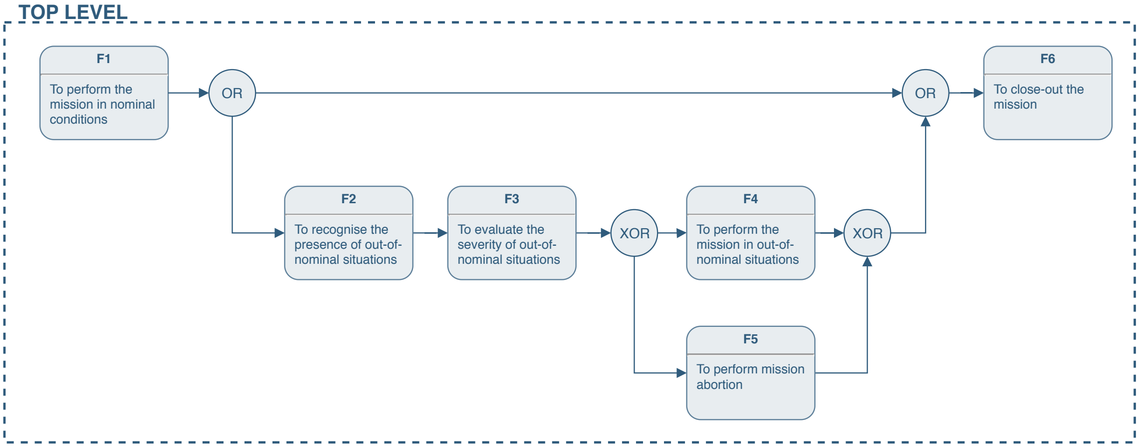


Figure 7.1. Top Level FFBD.

The diagram consists of 6 different functions organised in two main branches divided by an “OR” connector and respectively related to nominal and out of nominal conditions. The first function, addressed as F1, includes all the operations to be performed during the DRM, it represents in fact the capability of the system to perform the mission in nominal conditions. If critical events do not happen during the mission, after the aircraft lands on ground the mission can be definitely closed (function F6), if otherwise an out of nominal situation requires contingency operations, the mission can be closed only after the risk has been evaluated and proper mitigation actions have been performed, taking also into account a possible mission abortion.

It is important to note that the different functions are not organised in chronological order, but they are connected by logical sequences. The function to recognise the presence of out of nominal situations (F2), in fact, can be performed during each moment of the mission and not in a specific time, and so logically it is connected via an “OR” to F1 related to the function of the system to operate nominally.

After the risk related to an out of nominal situation has been evaluated, two different functions, connected by an exclusive “XOR”, are possible on the basis of the evaluation result: to continue the mission or to perform mission abortion.

In the next Section, two of the top level functions, F1 and F5, respectively related to the DRM or to mission abortion, will be decomposed in a second level FFBD.

7.3 Second Level

The second level of decomposition has been developed for two important top level functions: F1 related to the capability of the system to perform the mission in nominal conditions, and F5 related to the capability of the system to perform mission abortion after a critical event has been recognised and the mission has been evaluated impossible to be taken forward.

7.3.1 Nominal Conditions

To perform the mission in nominal condition mens actually to perform the design reference mission (DRM) as expected, therefore F1 is nothing else than the logical sequence of mission phases. Hence, Figure 7.2 shows the second level FFBD related to F1. The DRM has been already described in Chapter 4, it is directly refined and described under an operational point of view in the respective FFBD.

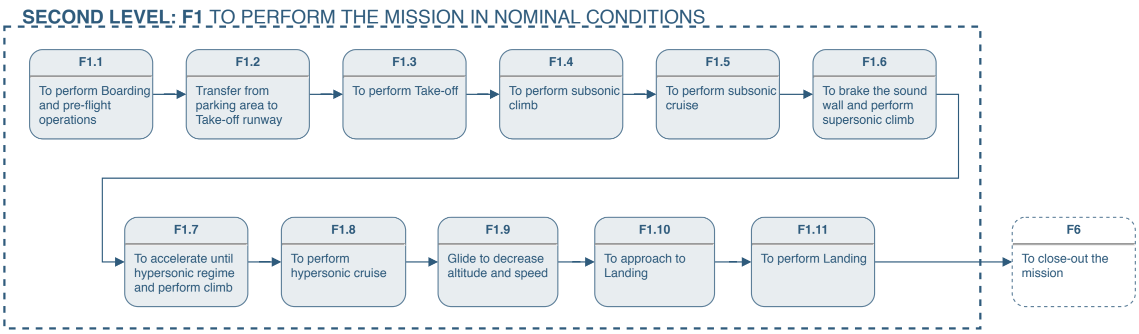


Figure 7.2. Second Level FFBD. F1: To perform the mission in nominal conditions.

F1, indeed, is decomposed in 11 different functions related each to one of the 11 mission phases. After all the functions, from take off to landing, have been fulfilled, the mission can be closed-out as it is represented by the arrow that connects F1.11 to the dotted F6.

7.3.2 Out of Nominal Conditions

The top level FFBD represented in Figure 7.1 shows how the consequences of function F3 (To evaluate the severity of out-of-nominal situations) can be duplex: to take forward the mission (F4) or, to be intended as exclusive "or", to abort the mission (F5). This Section is aimed at describing what inside the function F5, therefore what can happen is a mission abortion is needed. The second level FFBD related to the decomposition of F5 is shown in Figure 7.3.

The F5 related FFBD consists basically in the five mission abortion options, already discussed in Chapter 6, that can be read in the diagram within a list limited

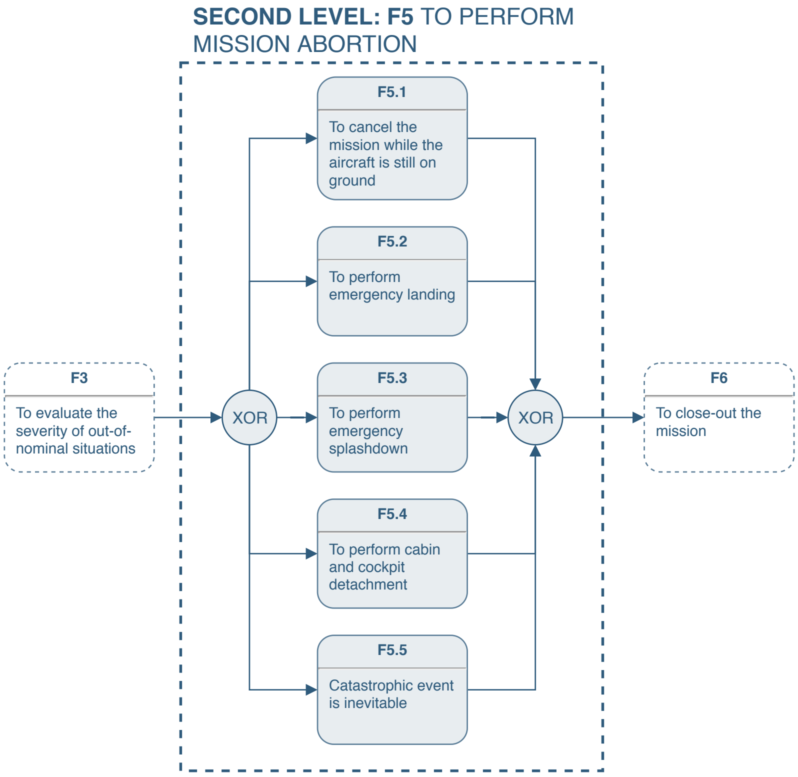


Figure 7.3. Second Level FFBD. F1: To perform mission abortion.

by "XOR" connectors. If one option is performed, in fact, no other options can be taken forward.

It is important to note that the mission abortion function is not to be intended to happen at a specific time of the mission, but it can be deemed necessary at any mission phase on the basis of which out of nominal scenarios can happen in the specific phase. Information about the possible out of nominal scenarios are given in Figure 6.3 in Chapter 6.

The input and output functions, represented as dotted boxes in the FFBD in Figure 7.3, are respectively F3 and F6. The mission abortion in fact is a logical consequence of the evaluation of the risk related to a certain out of nominal event, while the logical consequence of mission abortion is to close-out the mission, also if eventually in the sea or at an emergency arrival airport different from the expected one for the nominal mission.

The simulation and assessment of some out of nominal scenarios related to mission abortion will be discussed in Chapter 9.

7.4 Third Level

In this Section, some of the functions represented in the F1 related second level FFBD (see Figure 7.2) have been decomposed in third level FFBDs. Those functions are basically related to some mission phases, in particular the third level FFBDs described in this Section are:

- *F1.3*: To perform Take-off (Section 7.4.1)
- *F1.7*: To accelerate until hypersonic regime and perform climb (Section 7.4.2)
- *F1.9*: Glide to decrease altitude and speed (Section 7.4.3)
- *F1.10*: To approach to Landing (Section 7.4.4)
- *F1.11*: To perform Landing (Section 7.4.4)

The reason why those 5 mission phases have been chosen above others is duplex and depends on the specific phase:

1. F1.3 and F1.11, respectively related to take-off and landing, have been decomposed since those are not only the first and last phase of the mission, but also they are very important phases in terms of operational procedures. Furthermore, to decompose those phases from an operational perspective is of extreme importance for their modelling activity performed via ASTOS software in Chapter 8.
2. F1.7, F1.9 and F1.10 have been investigated and decomposed under an operational point of view since they are unprecedented mission phases never performed in previous conventional civil aviation missions. Therefore, the related FFBDs helps to understand the operational characteristics of supersonic to hypersonic transition and consequent climb as well as un-propelled descent and consequent engines reactivation before final approach and landing.

Further comments must be given to the fact that sometimes in the third level FFBDs it can be found an "OR" connector towards the higher level function F6 (To recognise the presence of out-of-nominal situations). This "OR" logical connector is intended to describe the capability of the system to recognise eventual critical events and the presence of possible failures. However, since this capability shall be implemented by the system during any phase of the mission, the aforementioned "OR" connector should be located in all the nodes of the FFBDs diagram. For simplicity and clarity, however, it has been chosen to locate the operational function to recognise possible failures only once for each FFBD, about at the beginning of the diagram. It is then up to the reader to take this aspect into account.

The third level FFBDs are therefore described and discussed in the following Sections.

7.4.1 Take Off

The STRATOFLY MR3 take off should be not much different, speaking about operational procedures, from the one of a conventional aircraft. The difference, however, between a conventional take off and the one of a hypersonic vehicle depends mainly on the aerodynamics characteristics related to the waverider configuration, what can happen, in fact, is that STRATOFLY MR3 requires higher speed to perform take-off. This aspect, however, will be better discussed in the take-off simulation described in Chapter 8.

This Section aims at describing the third level FFBD related to F1.3 (To perform take-off), that has been decomposed in sub-functions related to take off phases and operations. According to Kwasiborska A. et al. [17], the take off can be generally composed of three phases: take-off run, lift-off, and take-off climb. More interesting from an operational perspective is the take off further segmentation in six phases, or segments, that are respectively:

1. To begin the take off run.
2. To reach the decision velocity (V_1).
3. To reach the rotation velocity (V_R).
4. To perform lift-off.
5. To perform take off climbing until reaching the safe speed V_2 and the screen height h_S.
6. To continue Take off climb performing undercarriage retraction and eventual aerodynamic configuration changes.

The aforementioned take off phases can be extended to the STRATOFLY MR3 case as it is shown in the FFBD represented in Figure 7.4.

Although many information about conventional take off characteristics and parameters definition can be found in literature [7][9][17], for the purposes of this Thesis a simplified definition of the relevant take off related parameters is given in the following:

- The decision-making velocity V_1 is defined as the minimum velocity above which the take off run cannot be interrupted and the take off must be taken forward.
- The rotation velocity V_R is defined as the minimum velocity that allows attitude rotation before performing lift off.
- The safe velocity V_2 is defined as the minimum velocity to be reached during take off climb in order to close-out the take off.

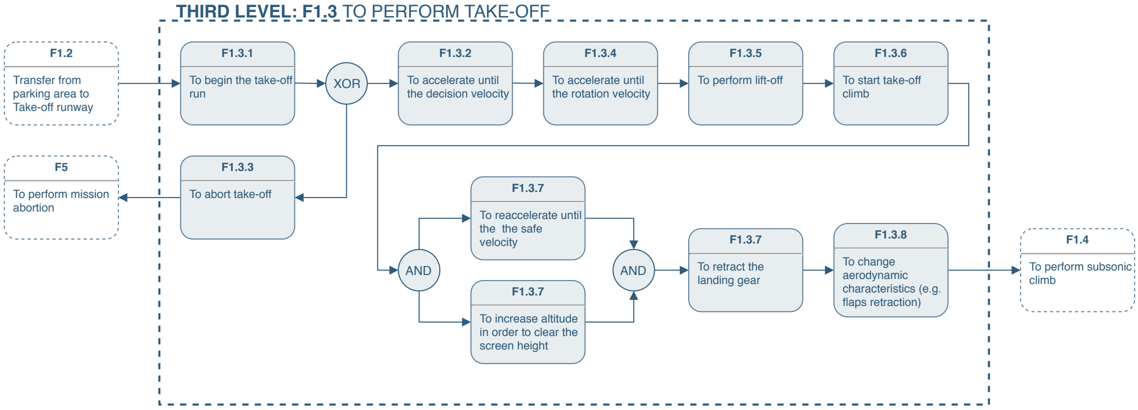


Figure 7.4. Third Level FFBD. F1.3: To perform take-off.

- The screen height, or virtual obstacle height, h_S is defined as the minimum altitude to be reached during take off climb in order to close-out the take off.

According to the EASA standard CS 25 for large aeroplanes [7] (CS 25.111), a screen height equal to $h_S = 35\,ft$ $(11\,m)$ above the take-off surface has been considered for simulation purposes as it will be discussed in Chapter 8.

By focusing again the attention on the take off related FFBD represented in Figure 7.4, it is possible to see that after the function F1.3.1, therefore after the beginning of the take off run, an exclusive "XOR" logical connector gives the possibility to consider F1.3.3 and therefore the higher level function F5 (to perform mission abortion) as F1.3.1 consequence. This is intended to describe the possibility to interrupt take off run and cancel the mission if a critical event is recognised to happen before the decision-making velocity V_1. If a failure occurs above V_1 the take off must be taken forward and eventual mission abortion operations shall be implemented after the virtual obstacle height has been reached.

The take off related FFBD described in this Section has helped the modelling of the take off trajectory simulation via ASTOS performed in Chapter 8.

7.4.2 High Speed Climb

A conventional civil passenger aircraft has never flown at hypersonic speed and, as innovative element, the supersonic to hypersonic regime transition is one of the most interesting aspects to be investigated under an operational point of view for the STRATOFLY mission. The third level FFBD represented in Figure 7.5 describes the logical decomposition of operations related to the mission segment between the supersonic climb and the reaching of hypersonic cruise starting conditions.

Hence, the supersonic climb ends when the aircraft reaches a speed of Mach about $M = 4-5$ and an altitude of about 25 km, then the active propulsion unit is

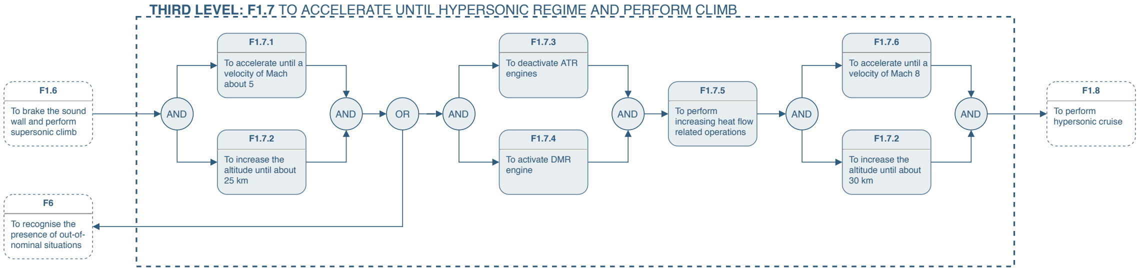


Figure 7.5. Third Level FFBD. F1.7: To accelerate until hypersonic regime and perform climb.

switched from ATR to DMR and the hypersonic cruise is performed until an altitude of about 30 km and a speed of M=8 are reached.

Further comments must be given about function F1.7.5: To perform increasing heat flow related operations. This function is intended to describe a series of operations to be performed when the external heat flow is sufficiently high to allow LH2 boil-off inside the tanks for the synergy among TEMS, TPS, ECLSS and propellant subsystem. This aspect has been partially addressed in Chapters 2 and 5, and will be further discussed in the present Chapter in Section 7.5.

After the hypersonic climb is completed, the hypersonic cruise, in which the major distance is covered, follows. At the end of the hypersonic cruise, the Descent phase is performed as it is described in the next Section.

7.4.3 Descent

The hypersonic cruise following phase is designed to be an unpropelled descent in which the aircraft decreases flight altitude and speed. Since this phase is not a common one for conventional civil passenger aircrafts, it has been further investigated under an operational perspective as it is shown in the third level FFBD represented in Figure 7.6.

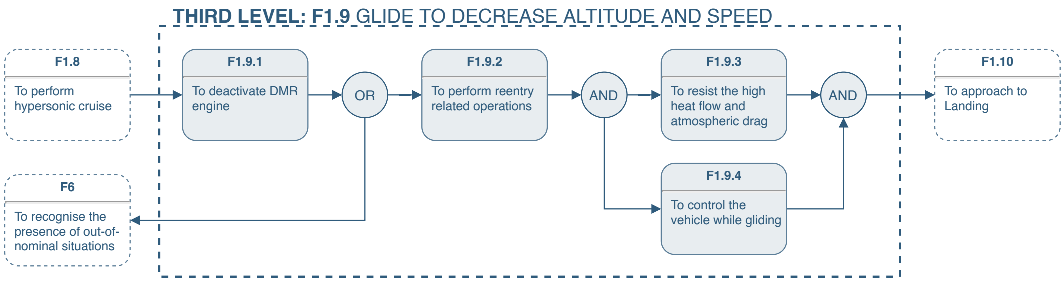


Figure 7.6. Third Level FFBD. F1.9: Glide to decrease altitude and speed.

From an operational point of view, function F1.9 (Glide to decrease altitude and speed) can be decomposed in four third level functions organised as in the respective FFBD. The first function to be accomplished to start the descent phase is to deactivate the propulsion plant, this means that the LH2 boil off generated by the external heat flow cannot be utilized for engine feeding purposes and therefore the subsystems synergy based on high temperature management shall change way of working as intended to be described by function F1.9.2 and as better discussed in Section 7.5.

Other third level functions are related to the capability of the system to manage the descent phase, therefore to control the aircraft while descending and to deal with high temperature and high drag in order to permit the correct decreasing of flight speed and altitude.

The descent phase is followed by the final approach, described in terms of FFBD in the next Section.

7.4.4 Final Approach and Landing

The third level FFBD analysis has been also performed for functions F1.10 and F1.11 respectively related to final approach and landing.

The final approach related FFBD, represented in Figure 7.7, shows the sequence of functions and operational phases that shall be accomplished from when the engines are reactivated to when the landing zone is finally reached.

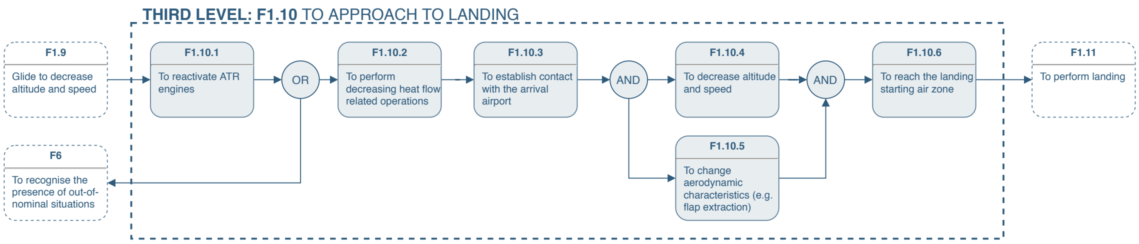


Figure 7.7. Third Level FFBD. F1.10: To approach to landing.

The function F1.10.2 (To perform decreasing heat flow related operations) has to be considered as related to the TEMS, TPS, ECLSS and propellant subsystems synergy that will be better discussed in Section 7.5.

An important function to be performed during the final approach is to establish contact with the arrival airport (F1.10.3) as soon as possible before landing. Other functions are to prepare the aircraft for landing in terms of possible aerodynamic configuration changes e.g. flaps extraction and to decrease altitude and speed in order to allow the following landing phase, represented in terms of FFBD in Figure 7.8.

The STRATOFLY MR3 landing operational procedures can be derived from the ones of a conventional aircraft. Some differences, however, between a conventional

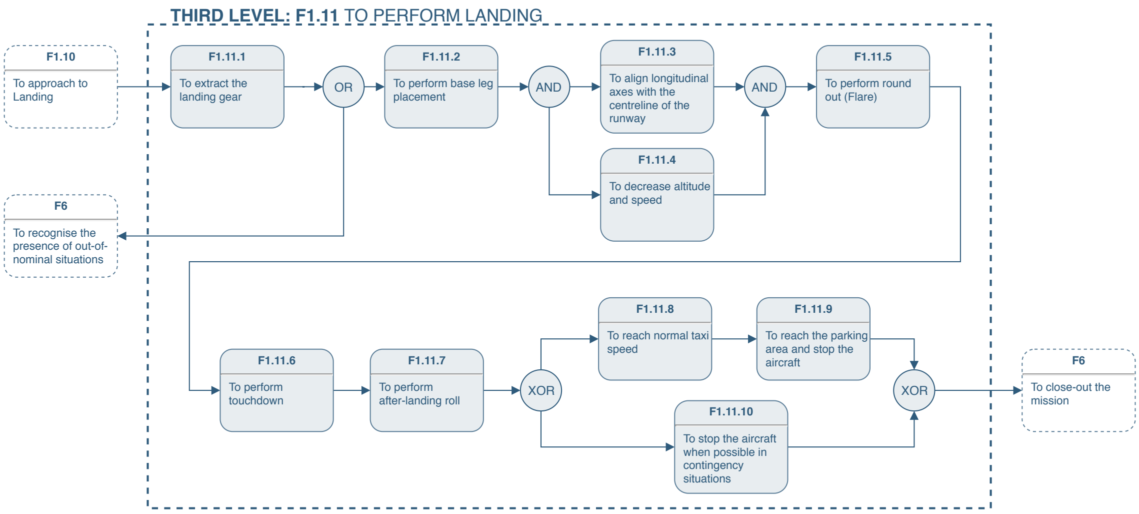


Figure 7.8. Third Level FFBD. F1.11: To perform landing.

civil aircraft and a hypersonic vehicle landings lie on the different aerodynamic configuration that can lead to higher landing speed in the hypersonic cruiser case. A description of the STRATOFLY MR3 landing including details about physical parameters and relevant characteristics will be given in Chapter 8. However, in the following the landing operational phases described by the FFBD in Figure 7.8 will be better explained and discussed.

According to the Federal Aviation Administration (FAA) [8], the landing can be generally divided into five phases:

1. To perform a correct *base leg* placement in terms of altitude and distance from which to start landing
2. To align longitudinal axes with the centreline of the runway and to decrease altitude and speed
3. To perform round out (*Flare*)
4. To perform touchdown
5. To perform after-landing run

In addition to the aforementioned five segments, two more operations have been considered to be included in the third level landing FFBD:

- The landing gear retraction (F1.11.1) to be performed as starting operation prior to landing.

- To brake until taxi speed after touchdown and to reach the parking area. In the case of out of nominal situations (e.g. excessive speed or uncontrollable aircraft) it could be necessary to stop the aircraft when possible prior to reach the parking area. This is described by the two branches divided by an exclusive "XOR" logical connector in the bottom right corner of the FFBD represented in Figure 7.8.

At the end of the landing phase, the mission can be finally closed-out as it is described by the higher level function F6 described as dotted box outside the third level landing related FFBD boundaries.

As already done for the take off, also for the landing phase a screen height, or virtual obstacle height, h_S must be defined as the minimum height to be reached before to start the round out and the touchdown. According to the EASA standard CS 25 for large aeroplanes [7] (CS 25.125), a landing screen height equal to $h_S = 50\,ft$ $(15\,m)$ above the landing surface has been considered for simulation purposes as it will be discussed in Chapter 8.

7.5 Synergy among TEMS, TPS, ECLSS and Propellant Subsystem

The cooperation and the integration of functions among TEMS, TPS, ECLSS and propellant subsystem is based on the high-temperature and high heat loads that affect the aeroshell during high speed flight. The synergy among those subsystems have been partially described in Chapter 2 in terms of subsystems design and in Chapter 5 in terms of modes of operations.

This Section is aimed at providing a further explanation about the high-temperature related subsystems synergy from an operational point of view. In some of the third level FFBDs described above in this Chapter, there are three blocks representing subsystems synergy related functions in different flight conditions. Those functions are listed in the following:

- *F1.7.5*: To perform increasing heat flow related operations (see Figure 7.5)
- *F1.9.2*: To perform reentry related operations (see Figure 7.6)
- *F1.10.2*: To perform decreasing heat flow related operations (see Figure 7.8)

A description of the different functions follows. In order to better understand the following discussion, however, the reader shall take into account the subsystems description provided in Chapter 2 and the modes of operations definition given in Chapter 5.

F1.7.5: To perform increasing heat flow related operations

This function is intended to describe the operational procedure related to the increasing heat flux when the aircraft increases its speed from early supersonic to high supersonic-hypersonic regime. In this case the high external temperature and the high heat load penetrating the aeroshell allow LH2 boil off inside tanks and the cooperation among the different subsystems is possible. Hence, the following operations happens:

- The TEMS and the TPS switch from *Low heat flow mode* to *High heat flow mode*.
- The propellant subsystem *Thermal mode* is activated in addition to the already active *Feeding mode*.
- The ECLSS gains advantage from TEMS related operations.

F1.9.2: To perform reentry related operations

Prior to perform the Descent phase at the end of hypersonic cruise, the engines are deactivated and the propellant subsystem shall not anymore feed the propulsion plant. The synergy among the subsystems led by the TEMS is still possible with the only difference that only gaseous H2 is exploited for cooling purposes, while liquid hydrogen is not pumped to the combustion chamber. This means that the following operations shall be performed:

- The TEMS and the TPS pass from *High heat flow mode* to *Reentry mode*.
- The propellant subsystem *Feeding mode* is deactivated and only the *Thermal mode* remains active.
- The ECLSS gains advantage from TEMS related operations.

F1.11.2: To perform decreasing heat flow related operations

At the end of the descent phase the engines are reactivated when the aircraft flies at subsonic speed to perform final approach. The external temperature decreases and the TEMS related subsystems synergy change way of working. In particular, the following operations shall be performed:

- The TEMS and the TPS switch from *Reentry mode* to *Low heat flow mode*.
- The propellant subsystem *Feeding mode* is reactivated while the *Thermal mode* is deactivated.

In order to better understand what happens during the cooperation among the different subsystems under the control of the TEMS, a sketched illustration is provided by Fernandez V. and Steelant J. and represented in Figure 7.9.

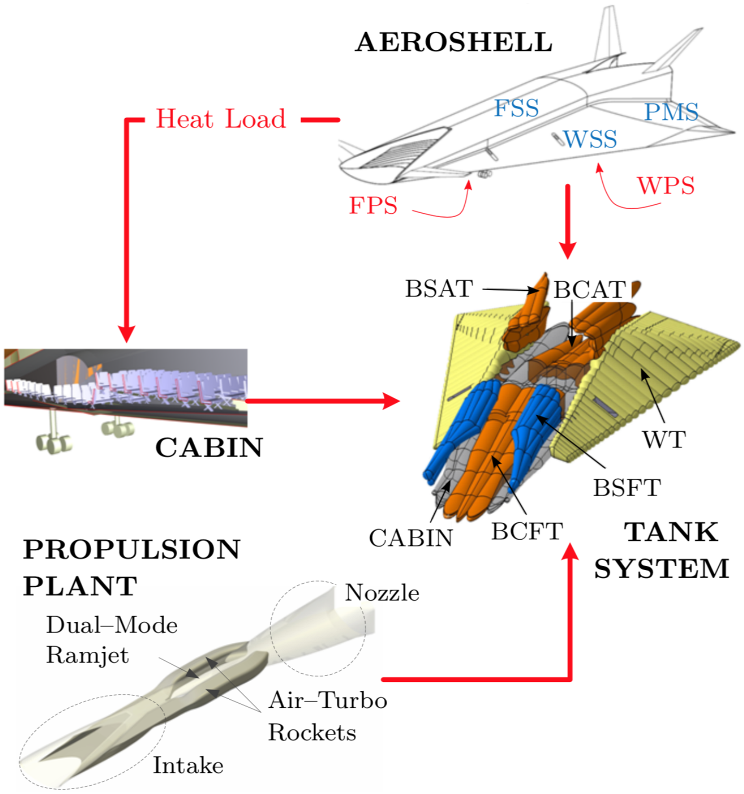


Figure 7.9. Illustration of the cooperation among TEMS, TPS, ECLSS, propellant subsystem and propulsion plant.

A further explanation of TEMS related subsystems synergy operations is provided by the N-squared diagram represented in Figure 7.10. As the FFBDs analysis, N2 diagrams analysis represents a useful logical decomposition tool. The theory under the N2 analysis has been already discussed in Chapter 3.

Three type of subsystems interfaces have been considered: Mechanical (M), Thermal (T) and Supplied Service (SS). The SS interface is intended to describe the role of the TEMS in managing and controlling the high-temperature related operations in cooperation with TPS, ECLSS, propellant subsystem and also propulsion plant. A double arrows link has been, however, considered between TEMS and TPS and between TEMS and propellant subsystem. Reason of that lies on the fact hat TPS and propellant subsystem not only receive input from the TEMS, but also actively work with the TEMS providing respectively the aerodynamic heating for LH2 boil

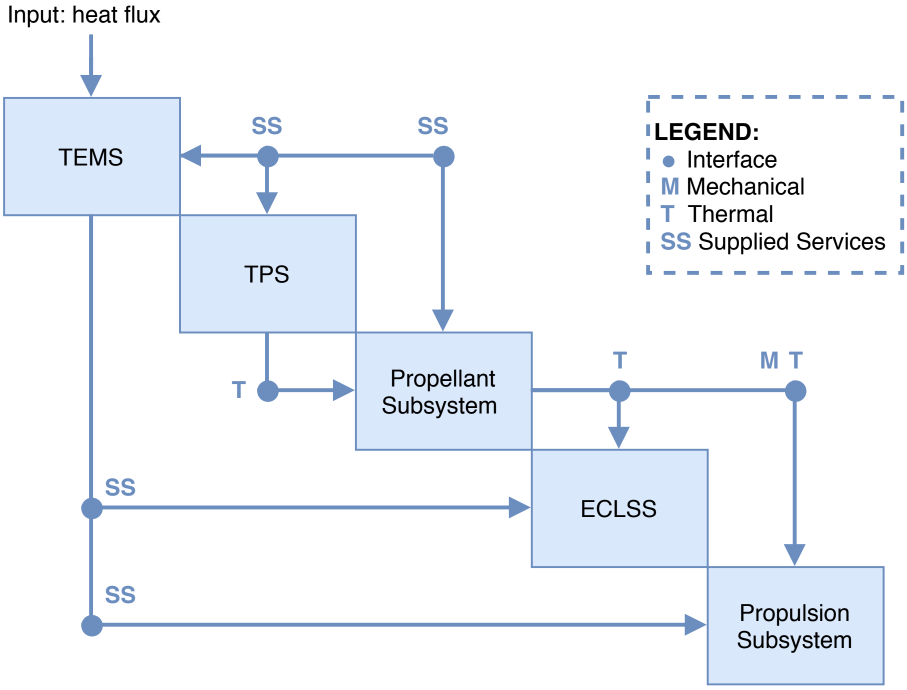


Figure 7.10. TEMS operations related N2 diagram.

off and the gaseous H2 for cooling purposes. The interface between TPS and the tanks is also represented by the thermal link between the two subsystems.

Moreover, the propellant subsystem is linked by a thermal interface with the ECLSS aimed at describing the passenger cabin cooling functions of the gaseous H2 produced after boil off.

The propellant subsystem is also linked with the propulsion plant by a duplex Thermal and Mechanical interface. The thermal interface is intended to describe the gaseous H2 propulsion plant cooling functions, while the mechanical interface describes the liquid hydrogen feeding from the tanks to the propulsion plant.

Chapter 8

Nominal Scenario Simulation and Assessment

The STRATOFLY MR3 design reference mission (DRM) trajectory simulation has been performed as part of the purposes of this Thesis.

Aim of this Chapter is to provide a description of the STRATOFLY MR3 DRM simulation and assessment in terms of details on the scenario modelling and achieved results. The DRM has been already discussed from a theoretical point of view in Chapter 4. However, the specific mission trajectory simulated in the present Chapter is referred to an antipodal routes characterized by departure from Brussels Airport (BRU) in Europe and arrival to Sydney Airport (SYD) in Australia. The BRU-SYD route has been chosen since it is the reference trajectory already assessed within the previous LAPCAT II project [18] and considered to be one of the best long-haul trajectories for the exploitation of hypersonic transport technologies.

The *ASTOS*® 9 Software, developed by Astos Solutions GmbH [1], has been used as simulation tool. The aero-database and the propulsion-database implemented as input for the scenario modelling have been fully described in Chapter 2, respectively in Sections 2.3.1 and 2.3.2. Furthermore, the scenario modelling activity gains relevant knowledge from the modes of operations definition, concerning in particular the propulsion subsystem, described in Chapter 5 and the logical decomposition of operations described in Chapter 7.

An overview on this Chapter contents follows:

- Relevant information about ASTOS characteristics and methodology implemented for the STRATOFLY MR3 design reference mission simulation are given in Section 8.1.
- The scenario modelling and dynamics configuration is described in Section 8.2.
- The simulation results are provided and discussed in Section 8.3.

Finally, a comparison between two STRATOFLY MR3 trajectory options as well as between the STRATOFLY MR3 and the LAPCAT MR2 trajectory simulation are provided in Section 8.4.

8.1 ASTOS Software and Methodology

ASTOS is an object-oriented software designed for aerospace applications' trajectory simulation and optimization. Although the software has been mainly developed for space applications such as launchers, satellites and re-entry vehicles trajectories simulation, it can be used with proper considerations also for atmospheric flight applications. Since STRATOFLY MR3 is not a conventional aircraft and for some aspects, such as the high speed cruise at high altitudes and the atmospheric reentry, it can be considered as a space-like vehicle and ASTOS reveals to be a very useful tool for the trajectory simulation and optimization of such kind of aircraft.

In this Chapter, however, only trajectory simulation has been performed, while an eventual optimization in which the software can find the optimal pattern of control parameters, respecting certain constraints and maximizing certain cost functions, goes beyond the purposes of this Thesis and can instead represent a further assessment to be performed within the STRATOFLY project.

ASTOS provides a full features Graphical User Interface (GUI) where the problem can be formulated and the simulation results can be plotted and assessed. The problem formulation consists on the scenario modelling in terms of environment and atmosphere as well as vehicle characteristics such as mass, dimensions, aerodynamics and propulsion properties. Moreover, the scenario formulation includes the definition of initial conditions as well as boundary conditions among the different mission phases.

An important set of input for trajectory simulation consists on the aerodynamic database and the propulsion database. As it has been fully explained in Chapter 2, the databases are provided in tabular form where the input variables are expressed as a function of other independent variables on the basis of the specific characteristics to be evaluated. For a better clarity and understanding of this Chapter's contents, some aspects of the aerodynamic and propulsion databases are taken up and reported in the following:

- The drag coefficient C_D is provided as a function of flight Mach number in a range from M=0.3 up to M=8, each at angle of attacks of $AoA = -2^o, 0^o$ and 2^o and different dynamic pressures.
- The lift coefficient C_L is provided as a function of flight Mach number in a range from M=0.3 up to M=8, each at angle of attacks of $AoA = -2^o, 0^o$ and 2^o.

- The ATR net thrust and the related fuel massflow are given as a function of altitude, Mach number and equivalence ratio. In particular, altitudes from 0 km up to 26 km, Mach numbers from M=0.01 up to M=4.5, each at ER=0, ER=0.5 and ER=1, have been considered.

- The DMR net thrust and the related fuel massflow are given as a function of altitude, Mach number, angle of attack and equivalence ratio. In particular, altitudes from 18 km up to 40 km, Mach numbers from M=4 up to M=8, each at AoA=$-2^o; 0^o; -2^o$ and ER=$0; 0.5; 1$, have been considered.

While altitude, Mach number and dynamic pressure depend on the specific flight condition, ASTOS allows the user to set desired control laws for some parameters among which the angle of attack and the equivalence ratio. Hence, the control carried out on the vehicle attitude and the throttle setting has been of extreme importance for the correct scenario formulation and trajectory definition. Beyond the work needed for the scenario modelling, in fact, a lot of effort has been put and lot of iterations have been performed in finding the correct pattern of control parameters and the correct tuning of the control laws.

It is important to note that to control the AoA means that a user-defined attitude is enforced to the aircraft and eventual torques due to aerodynamic or propulsive forces do not have any effect on the vehicle attitude. Thus, ASTOS ignores the rotational dynamics of the vehicle when a direct control on attitude is carried out. Therefore, the vehicle is considered as a point in space coincident with its centre of mass and the vehicle dynamic denotes a 3 DOF dynamics taking into account only the translational equations and not the rotational ones. As a consequence, information about the CoM and the CoP positions during flight, the moments of inertia and the deflection of the aerodynamic surfaces are useless since these are related to the rotational dynamics of the vehicle. Those information, however, can be derived from the trajectory simulation and evaluated during the whole mission, in this case the simulation could represent an input for further assessments.

The CoP position and aerodynamic surfaces deflection, indeed, can be derived from the flight condition knowing the vehicle attitude and aerodynamic characteristics. Moreover, the CoM position and inertia moments variation law can be derived by integrating information about the fuel consumption and residual propellant mass during mission with the tanks' emptying law, the CoM variation depends in fact on the propellant mass distribution.

The aforementioned analysis on aerodynamic surfaces deflection and CoM position, however, goes beyond the purposes of this Thesis and could represent a further assessment to be performed within the STRATOFLY project by taking advantage from the trajectory simulation described in the next sections.

8.2 Trajectory Simulation

The STRATOFLY MR3 design reference mission scenario, related to the BRU-SYD route, was modelled in ASTOS by using the software's GUI already described in the previous Section.

For the simulation, the *US Standard 76* atmosphere contained in ASTOS was implemented since it well reflects atmospheric data for the vehicle's operative range of altitude. Furthermore, no cross winds, hydrosphere and magnetic field effects were assumed.

The STRATOFLY MR3 vehicle model consists on the main core plus two actuators:

- The core composed of vehicle structure, including payload and tanks weight, and propellant
- The ATR actuator
- The DMR actuator

Both the actuators are fed by the same tanks.

Despite the ATR unit is composed of 6 different engines, it was modelled as a unique engine characterized by a net thrust that is the sum of the contribution of all 6 engines. This choice, however, is justified by the fact that exhaust gas produced by the engines is injected into the same nozzle. Since the ATR is modelled as a unique actuator, it is important to note that the throttle setting can have a duplex interpretation: it can be referred to all the engines or it can be intended as indicators of the fact that no all the engines are active. For example, a throttle equal to $1/6 = 0.16$ can mean that the overall engines performance is six-fold lower than the maximum, or it can be intended as only one engine out of six is active. In fact, the net thrust does not change in the two cases.

The above discussion about ATR modelling, does not apply to the DMR propulsion unit since it is composed of only one engine. Thus, the throttle setting has the only consequence of describing the engine performances in terms of ratio of effective net thrust to maximum available net thrust. The situation in which the DMR engine is deactivated can be be simulated by setting the throttle equal to zero.

The total vehicle mass is set equal to 400 tons. As a first step, a structural mass equal to 218.75 tons and 181.25 tons of propellant were considered since this mass distribution is the same as used for the LAPCAT MR2 trajectory simulation [18]. However, since the STRATOFLY MR3 reference mission is slightly different from the LAPCAT MR2 one, in terms of propelled final approach and landing instead of unpropelled descent, the total fuel consumption will be higher than 181.25 in the STRATOFLY MR3 case. This means that the propellant mass was iteratively adjusted in order to guarantee enough fuel to complete the mission. For the purposes of this Thesis, the total vehicle mass was always kept equal to 400 tons, a higher propellant mass, therefore, means a lower structural mass to be considered. This choice is justified by the fact that the structural mass of the STRATOFLY MR3 vehicle has still not be well defined and the trajectory simulation assessment performed in this Thesis in terms of fuel consumption and necessary propellant mass could lead to further analysis on the vehicle mass budget.

Another input for the scenario modelling is represented by the aerodynamic as well as propulsion characteristics expressed in form of databases as already discussed in Section 8.1.

The mission phases modelling was based on the design reference mission already described in Chapter 4. From the original 11 phases, the pre departure and taxi phases were not considered for simulation purposes, assuming that the mission starts with take-off. Hence, the 9 mission phases are listed in the following:

1. Take-off
2. Subsonic Climb
3. Subsonic Cruise
4. Supersonic Climb
5. Hypersonic Climb
6. Hypersonic Cruise
7. Descent
8. Final Approach
9. Landing

The departure airport is Brussels while the landing takes place in Sydney. During hypersonic cruise the aircraft shall fly above the Bering Strait, between Siberia and Alaska, in order to avoid high-noise flight over inhabited land. Table 8.1 provides the departure and arrival airports as well as Bering Strait geographical coordinates as considered in ASTOS for trajectory simulation purposes.

	Latitude	**Longitude**
Brussels Airport (BRU)	$50^o54'$ N	$4^o29'$ E
Sydney Airport (SYD)	$33^o56'$ S	$151^o10'$ E
Bering Strait	$66^o00'$ N	$169^o03'$ W to $168^o00'$ W

Table 8.1. Airports and Bering Strait geographical coordinates.

Furthermore, two different trajectory options, concerning in particular the Descent and Final Approach phases, have been considered and simulated. A description of the two different options follows:

- **Option A**:*Overland Final Approach.* At the end of the Descent phase the engines are reactivated when the aircraft is flying over inhabited land and the entire Final Approach phase is performed overland before landing in Sidney.
- **Option B**:*Oversea Final Approach.* At the end of the Descent phase the engines are reactivated when the aircraft is flying oversea near Australian coast. The major part of the Final Approach phase takes place oversea, where the aircraft performs proper manoeuvres with the aim to adjust the trajectory in order to correctly reach the arrival airport in Sidney.

The next subsections are intended to describe the mission phases modelling and dynamics configuration. Where not explicitly stated, the phases configuration settings have to be intended as similar for the two trajectory options. If different settings for the two different trajectory options have been considered for a specific mission phase, in fact, this will be clearly specified.

Relevant information for the mission phases modelling have been gained from the logical decomposition of operations performed in Chapter 7.

8.2.1 Take Off

The take off from Brussels airport was assumed to start at about the rotation and lift off phases with initial velocity of $160\,m/s$ ($M = 0.47$). The acceleration on the runway, in fact, cannot be simulated in ASTOS due to the fact that the surface constraint is not recognised and a lower take off velocity can lead to nonsense negative altitudes at the beginning of take off, for this reason a high speed was considered for assuring lift off.

Other important initial state settings are:

- Zero kilometer altitude
- Zero degree initial flightpath angle
- Initial heading equal to -26.6^o

The slightly west initial heading was iteratively assumed in order to assure subsonic cruise between England and Scandinavia as well as to assure Bering Strait passage during hypersonic cruise without previous lateral maneuvers.

Initial angle of attack equal to 2.5^o, anyway within a range between 0^o and 2.5^o during the whole take off, and maximum throttle were also assumed.

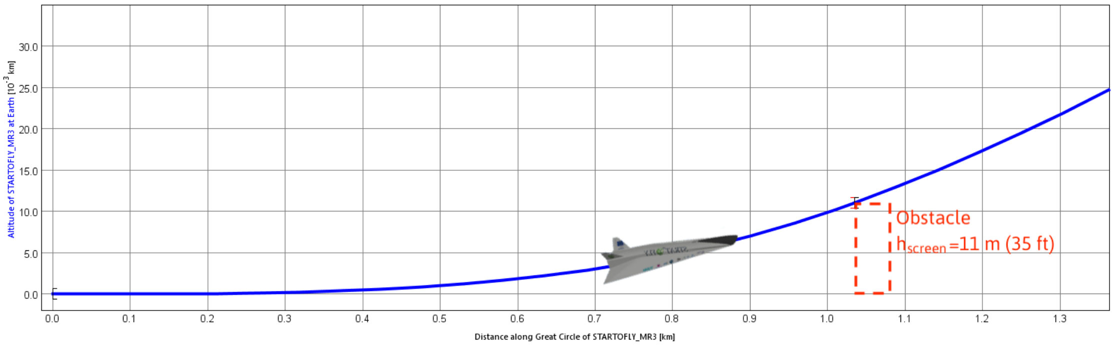


Figure 8.1. Take off trajectory.

The take off trajectory, intended as flight altitude *vs.* great circle distance, is represented in Figure 8.1.

The take off phase end condition was assumed to be related to flight altitude. The take off ends when the aircraft reaches an altitude equal or greater than the screen height, or virtual obstacle height, assumed equal to 11 meter above the take-off surface on the basis of the EASA standard CS 25 [7] as already discussed in Chapter 7 Section 7.4.1.

8.2.2 Subsonic Climb

The subsonic climb starts soon after take off when the flightpath angle is about equal to 6^o, whilst the phase ends when the aircraft reaches an altitude equal or greater than the subsonic cruise altitude of 12 km. The flightpath angle is never higher than 15^o during the whole phase and it is about equal to zero at the end of the phase before starting subsonic cruise.

During subsonic climb the vehicle accelerates until a velocity of Mach 0.95, assumed to be the subsonic cruise flight speed. The angle of attack varies within a range between -2^o and 2^o.

The throttle is assumed to be constant and equal to 0.32. This value has been iteratively found in order to avoid excessive steep climb and to assure a subsonic speed during the whole phase.

8.2.3 Subsonic Cruise

The subsonic cruise happens at an altitude of about 12 km, anyway between 12km and 13km, and Mach 0.95 flight speed. The flightpath angle as well as the angle of attack are about zero during the whole phase. The throttle is constant and equal to 0.32.

The subsonic cruise leg is needed in order to reach the proper distance from inhabited land before to break the sound barrier. Hence, a *target distance* from departure airport equal to 400 km was assumed as phase end condition.

8.2.4 Supersonic Climb

The supersonic climb starts with a throttle acceleration allowing subsonic to supersonic transition and positive flightpath angles. The throttle, indeed, follows a control law for which it goes from 0.32 up to 1.0.

The angle of attack remains within the range of -1^o; 1^o and the flightpath angle is never higher than 6^o.

The supersonic climb phase end condition was assumed to be related to flight Mach number. In particular, the phase ends when the Mach number is equal or greater than M=4. Moreover, the altitude results to be about 24 km at the end of the phase.

8.2.5 Hypersonic Climb

According to the operational procedure developed in Chapter 7 Section 7.4.2, the hypersonic climb starts with the deactivation of the ATR propulsion unit and the activation of the DMR engine.

The throttle was set equal to 0.74 and the angle of attack slightly negative during the whole phase. Those controls in throttle and attitude have been iteratively found in order to avoid undesired phugoid mode dynamic instability that can easily happen without the proper pattern of control parameters.

As a result, the flightpath angle is quite low and about equal to 1^o, anyway the rate of climb is similar to the previous supersonic climb phase thanks to the higher flight speed.

The hypersonic climb phase end condition was assumed to be related to flight Mach number. In particular, the phase ends when the Mach number is equal or greater than M=8, assumed to be the hypersonic cruise velocity. Moreover, at the end of the phase the altitude results to be about 30 km end the flightpath angle about 0^o.

8.2.6 Hypersonic Cruise

The hypersonic cruise is the phase during which the major distance is covered. The cruise happens at about 30 km - 35 km altitude and a constant Mach 8 flight speed. The flightpath angle is about zero during the whole phase, whilst the angle of attack is kept equal to $AoA = -0.442^o$, that revealed to be the optimum value to minimize long period phugoid oscillations that can happen during the hypersonic cruise.

While cruise is taken forward, however, the propellant mass, therefore the overall vehicle mass, decreases due to fuel consumption. As a consequence the flight altitude slightly increases due to the small excess of lift with respect to vehicle's weight. Therefore, higher flight altitude means lower atmospheric density and so lower drag as well as lower available net thrust. For the same throttle setting, however, the net thrust decrease is more significant if compared with the aerodynamic drag one, with the consequence of a small deceleration that can affect flight speed. For this reason, the throttle control law linearly increases throttle setting from 0.49 to 0.51 during the hypersonic cruise in order to assure constant flight Mach number of M=8.

The hypersonic cruise has been divided into two different legs: cruise to Bering Strait and cruise to Sydney. This split is justified by the fact that soon after Bering Strait passage some lateral maneuvers might be necessary on the basis of the desired point to be reached at the end of the cruise. Different lateral maneuvers, in fact, were considered for the two mission trajectory options as it will be better explained in Section 8.3.

The hypersonic cruise end condition, to be intended as "cruise to Sydney" leg end condition, was assumed to be related to a certain *target distance* from the departure airport. However, two different end conditions have been applied for the two different mission trajectory options:

- *Option A*: A target distance equal or greater than 15262 km was assumed as hypersonic cruise phase end condition.
- *Option B*: A target distance equal or greater than 15370 km was assumed as hypersonic cruise phase end condition.

Both the hypersonic cruise phase end condition values have been found iteratively.

8.2.7 Descent

According to the operational procedure developed in Chapter 7 Section 7.4.3, the descent phase starts with the deactivation of the propulsion plant. The descent, indeed, can be seen as an unpropelled gliding during which the flight altitude decreases and the flight Mach number decreases, until reaching subsonic speed, due to atmospheric drag induced deceleration.

The DMR engine deactivation is simulated by setting throttle to zero. The angle of attack remains equal to the one of previous phase. The flightpath angle is negative and never higher than 8^o in absolute terms.

The descent phase end condition was assumed to be related to flight altitude. However, two different end conditions have been applied for the two different mission trajectory options:

- *Option A*: A flight altitude equal or lower than 5 km was assumed as descent phase end condition.

- *Option B*: A flight altitude equal or lower than 12 km was assumed as descent phase end condition.

Both the descent phase end condition values have been found iteratively.

8.2.8 Final Approach

According to the operational procedure developed in Chapter 7 Section 7.4.4, the descent phase starts with the reactivation of the ATR propulsion unit. The initial speed is already subsonic and proper throttle setting was aimed at permitting a small excess of aerodynamic drag over the net thrust in order to allow deceleration and negative flightpath angles for decreasing flight altitude. The flight path angle, however, is higher if compared with the descent phase one and anyway it is never higher than 3^o in absolute terms. The angle of attack is set equal to -0.4^o.

Two different throttle settings have been considered for the two mission trajectory options:

- *Option A*: A constant throttle of 0.07 was assumed for the final approach phase.
- *Option B*: A throttle equal to 0.1 was assumed between flight altitude from 12 km down to 6 km, the throttle then decreases linearly to 0.07 at 5 km altitude and remains constant before landing.

The difference in throttle setting between the two trajectory options lies on the major distance to be covered and the lateral maneuver to be performed in the Option B (Oversea Final Approach) case.

The final approach phase end condition was assumed to be related to flight altitude. In particular, the phase ends when the flight altitude is equal or lower than the landing related height screen, or virtual obstacle height.

8.2.9 Landing

The landing starts when the flight altitude decreases until the screen height, or virtual obstacle height, assumed equal to 15 meters on the basis of the EASA standard CS 25 [7] as already discussed in Chapter 7 Section 7.4.4. The landing trajectory, intended as flight altitude *vs.* great circle distance, is represented in Figure 8.2.

The throttle is set constant and equal to final value from previous phase. The landing maneuver consists on a pitch up during which AoA increases linearly from final previous phase value to $AoA = 2^o$.

The landing phase end condition was assumed to be related to flightpath angle. The landing ends, in fact, when the flightpath angle increases until zero degree, in such a way to simulate the touchdown to Sidney airport's runway, that results to

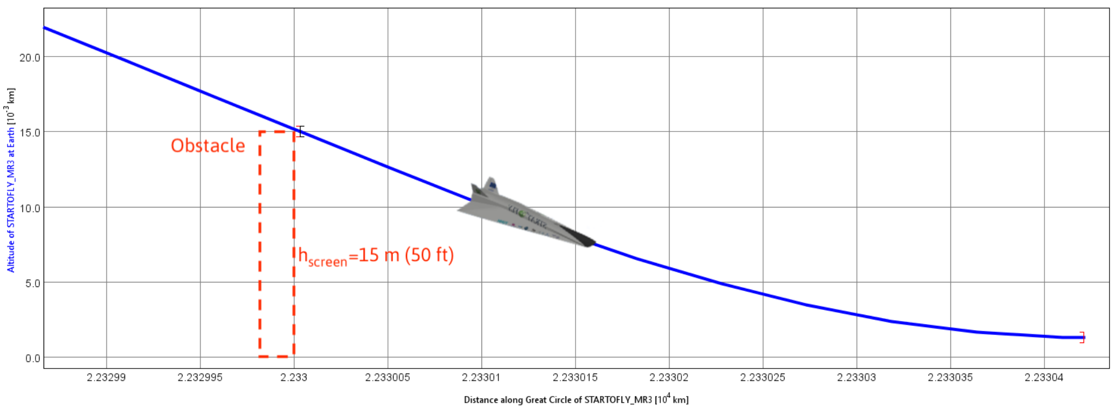


Figure 8.2. Landing trajectory.

happen, as it is possible to see in Figure 8.2, at an altitude of about 1 meter above the landing surface.

Moreover, the landing velocity results to be about 160 m/s, therefore similar to the one that has been assumed for take off.

8.3 Simulation Results

The results of the STRATOFLY MR3 design reference mission trajectory simulation are provided in this Section in form of figures and one summary table (Table 8.2).

Before starting with the presentation and explanation of the simulation results, a view on the STRATOFLY MR3 vehicle while performing the mission is given in Figure 8.3. The Figure was obtained thanks to the *Astroview* tool implemented in ASTOS that visually represents the mission simulation.

However, the main simulation results for both trajectory options A and B are given in the following:

- **Option A**: *Overland Final Approach*. The total mission duration is 3h18m and overall 203.2 tons of fuel have been consumed.

- **Option B**: *Oversea Final Approach*. The total mission duration is 3h35m and overall 210.9 tons of fuel have been consumed.

Major details about trajectory options A and B simulation results are given in the following subsections, while a comparison between them is provided in Section 8.4.

A description, supported by figures, about the simulation of common mission phases between the two trajectory options follows. The two-dimensional flight trajectory related to the first four phases of the mission is provided in Figure 8.4. In particular, the Figure shows the take off from Brussels airport, the subsonic climb

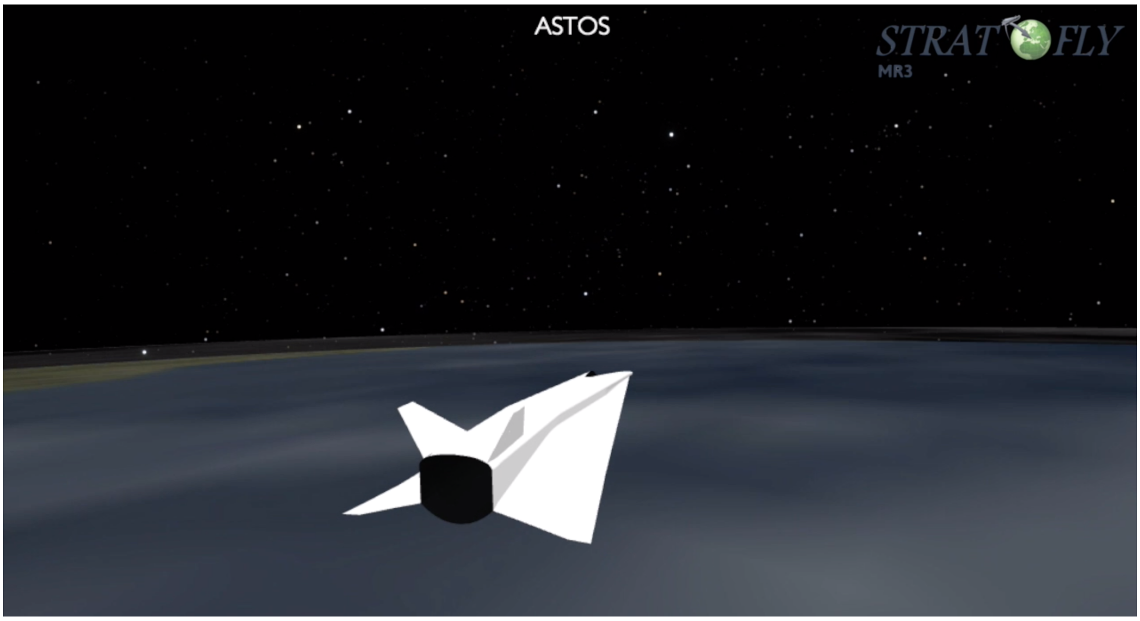


Figure 8.3. Illustration of the STRATOFLY MR3 vehicle during mission obtained thanks to the *Astroview* tool implemented in ASTOS.

and subsonic cruise between England and Norway, and finally the further acceleration related to supersonic climb. The boundaries between the different mission phases are described by small bars that can be seen in the Figure. Furthermore, the color line represents the flight altitude.

The above discussed mission part is also described in Figure 8.5 by a three-dimensional view looking in western direction. The subsonic cruise can be clearly seen in Figure as a plateau between subsonic and supersonic climbs. The beginning of the hypersonic climb can be also seen in Figure 8.5. In this case, color line describes the flight Mach number.

The subsonic cruise leg is necessary in order to avoid supersonic flight close to inhabited land as current regulations require [43]. As it is possible to see in Figure 8.6, showing the density population in the 2D map together with the ascent trajectory, the sound barrier is broken only at the end of the subsonic cruise when the aircraft is flying far enough from populated zones. The flight Mach number in Figure 8.6 is described by line contours.

Figure 8.7 provides a trajectory detail related to Bering Strait passage during hypersonic cruise. The color line describing the flight altitude is always red since the hypersonic cruise happens at about a constant 30 km altitude.

Soon after having passed the Bering Strait, the aircraft can perform proper lateral maneuvers on the basis of the desired point to be reached at the end of high-speed cruise and descent. This aspect is better analysed in the next subsections, in which, moreover, the rest of the mission trajectory simulation is described by giving

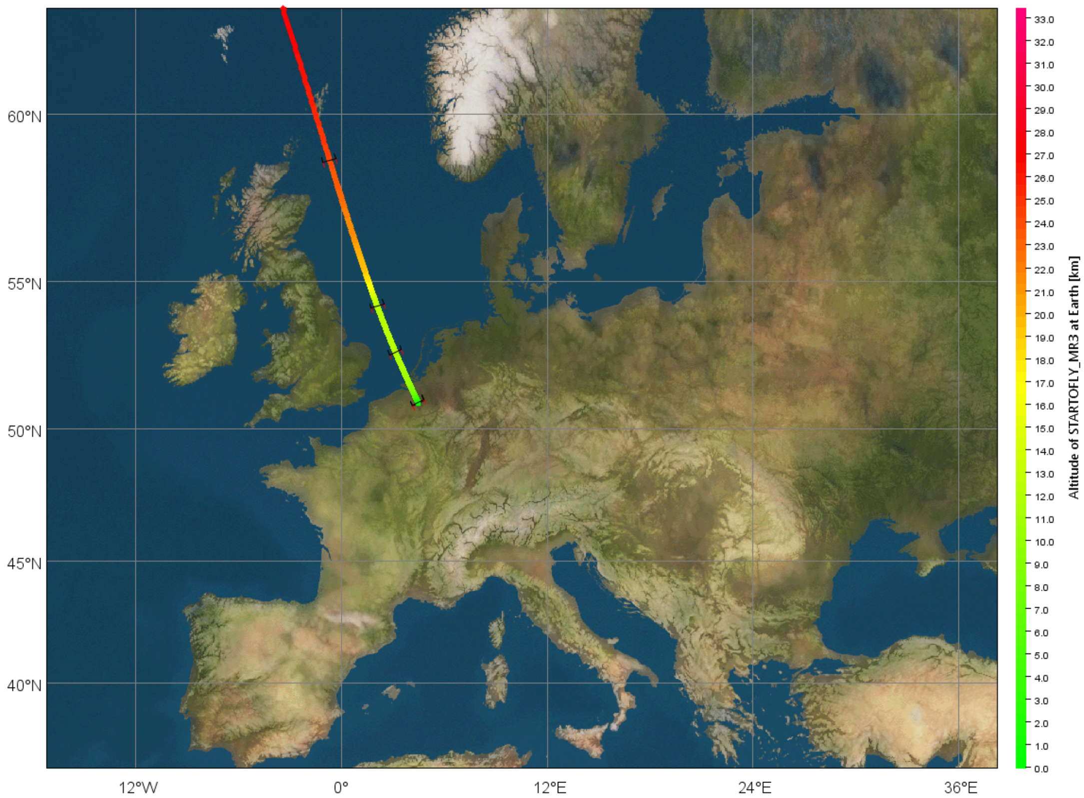


Figure 8.4. Take off from Brussels Airport and Climb between England and Norway 2D trajectory.

attention to the two trajectory options separately.

8.3.1 Option A: Overland Final Approach

In the case of mission trajectory option A, a right turn characterized by a bank angle of 2^o held for 300 seconds is performed soon after Bering Strait passage in order to align flight trajectory with Sidney airport to be reached at the end of the mission without other lateral maneuvers.

The complete mission trajectory is described by the satellite view represented in Figure 8.8, where the line contours describe flight Mach number.

A detail on descent as well as final approach and landing in Sidney is provided in Figure 8.9, representing both the 2D and the 3D flight trajectory. As it is possible to see in Figure, no lateral maneuvers are performed prior to landing. Moreover, the engines reactivation at the end of the descent can be seen in the 3D map as a change of descent steepness during final approach.

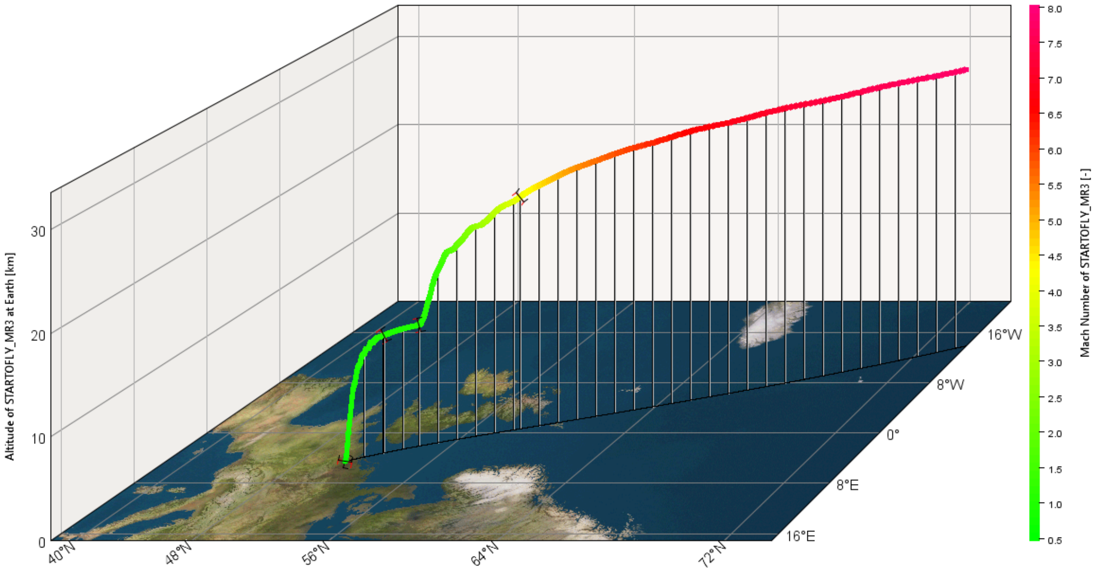


Figure 8.5. Take off from Brussels Airport and Climb between England and Norway. 3D view looking in western direction.

	Duration [s]		Fuel Consumption [tons]	
Mission Phases	**Option A**	**Option B**	**Option A**	**Option B**
Take off	5.0	5.0	0.7	0.7
Subsonic Climb	795.0	795.0	18.1	18.1
Subsonic Cruise	656.5	656.5	9.9	9.9
Supersonic Climb	914.5	914.5	25.2	25.2
Hypersonic Climb	1008.1	1008.1	39.7	39.7
Hypersonic Cruise	5606.8	5579.7	102.7	102.3
Descent	1935.3	1691.9	0.0	0.0
Final approach	1010.1	2286.2	7.0	15.1
Landing	9.5	9.5	0.1	0.1
Total Mission	11940 3h18m	12940 3h35m	203.2	210.9

Table 8.2. Mission phases Duration and Fuel Consumption

Relevant information about the overall mission trajectory in terms of flight altitude and flight Mach number profiles during mission can be found by looking in Figure 8.10, that represents a good summary of everything already mentioned

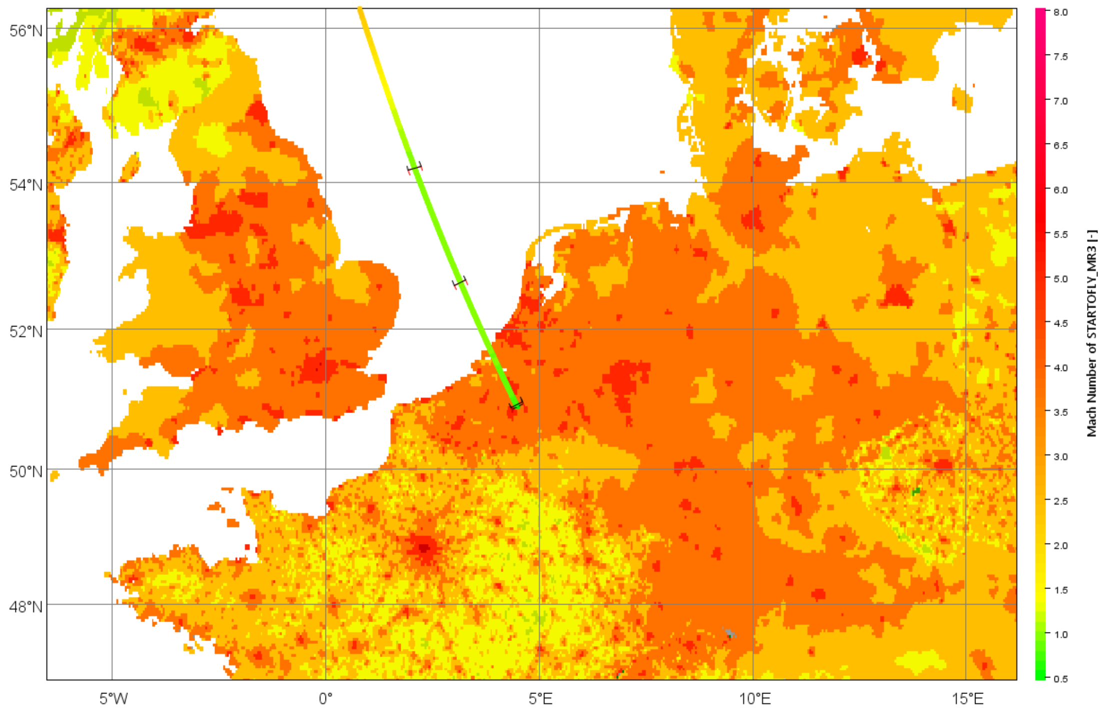


Figure 8.6. Take off from Brussels Airport and Climb between England and Norway trajectory in 2D map showing density population.

about mission modelling and simulation. Again, the boundaries between the different phases are described by the small bars in Figure.

Relevant information about fuel consumption and propellant mass profiles during mission can be found in Figure 8.11. Here it is possible to see the propellant consumed during the different mission phases as well as the instantaneous fuel consumption for both the ATR propulsion unit and the DMR engine. The unpropelled descent phase is underlined in Figure 8.11 by a constant propellant mass during time and zero fuel consumption. Moreover, it can be seen that the propellant mass decreases linearly during the cruise phases, and the most fuel consuming mission phase is, as expected, the hypersonic cruise.

The analytical assessment performed in Chapter 5 about propulsive subsystem level modes of operations has been of extreme importance for the trajectory simulation modelling described in the present Chapter, in particular for the throttle control settings during the different phases of the mission. A comparison between the analytical assessment performed in Chapter 5 and the actual simulation results can be performed by looking at, respectively, Figure 5.2 and Figure 8.11.

Relevant knowledge about the fuel mass flow during mission can be also gained by looking at Figure 8.11. In particular, both the ATR mass flow, described by the

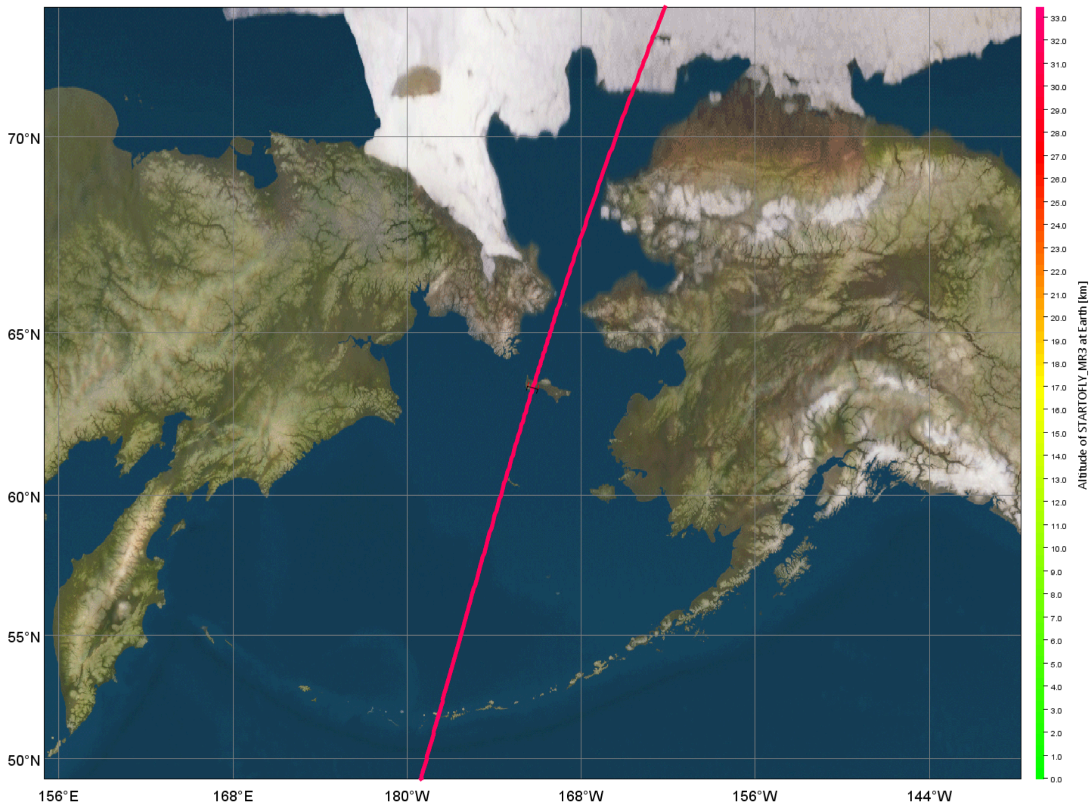


Figure 8.7. Bering Strait passage during Hypersonic Cruise.

red line, and the DMR, described by the green line, are never higher than 50 kg/s during the whole mission. However, further analysis showed that higher mass flow values of about 150 kg/s can be reached at take off if maximum throttle is considered. According to what already mentioned when the propulsive database was described in Chapter 2 Section 2.3.2, the mass flow ratio, therefore the fuel consumption, decreases when altitude and Mach number decrease, therefore the take off, in which both the altitude and the Mach number are initially zero, is the most fuel consuming mission phase in terms of instantaneous mass flow.

8.3.2 Option B: Oversea Final Approach

The complete mission trajectory, in the case of B trajectory option, is described by the satellite view represented in Figure 8.12, where the line contours describe flight Mach number.

Differently from the A trajectory option case, in this case no lateral maneuvers are performed soon after Bering Strait passage. As a result, the aircraft arrives

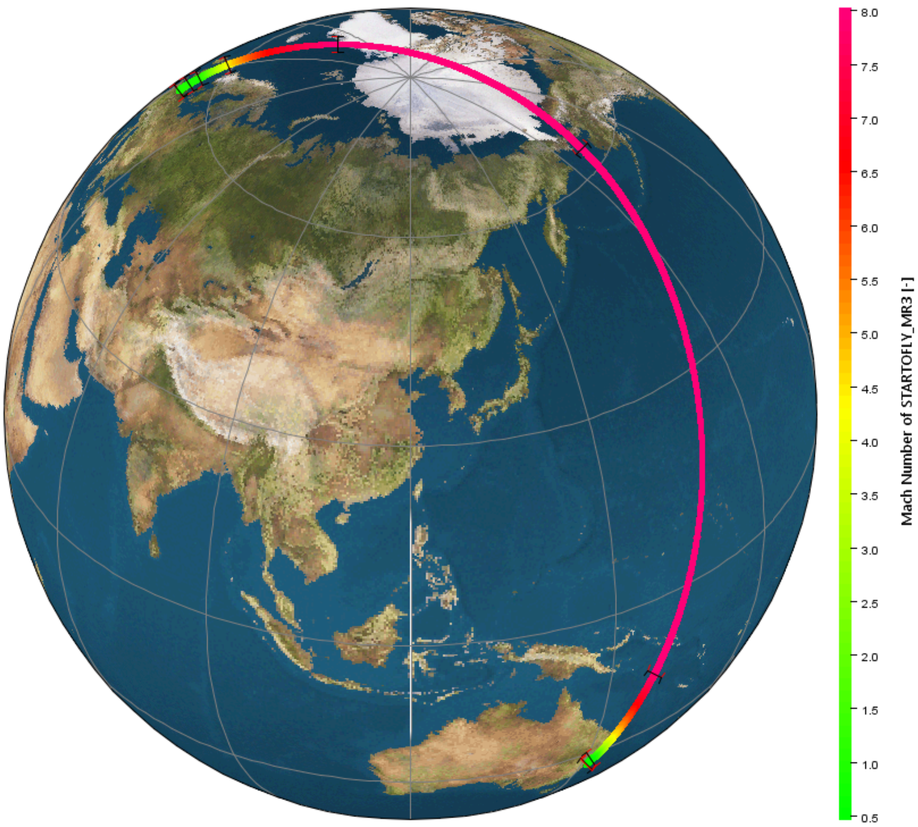


Figure 8.8. View on complete trajectory in the case of overland final approach (Option A).

slightly East with respect to Australian coast at the end of hypersonic cruise and descent, and further lateral maneuvers are therefore needed prior to reach the arrival airport. This situation is well described by Figure 8.13, showing the 2D and 3D flight trajectory before landing in Sidney. The final approach can be divided into two legs: the first one is aimed at performing proper lateral maneuver to align flight trajectory with the arrival airport and reducing distance, whilst the second leg represents the actual final approach prior to landing. The right turn performed during the first final approach leg is characterized by a bank angle equal to 4^o held for 215 seconds. In this case the final approach phase is longer if compared with the option A case, resulting in major phase duration and fuel consumption as it possible to note by looking in Figures 8.14 and 8.15, representing respectively the flight altitude and flight Mach number profiles during mission and the fuel consumption and propellant mass during mission.

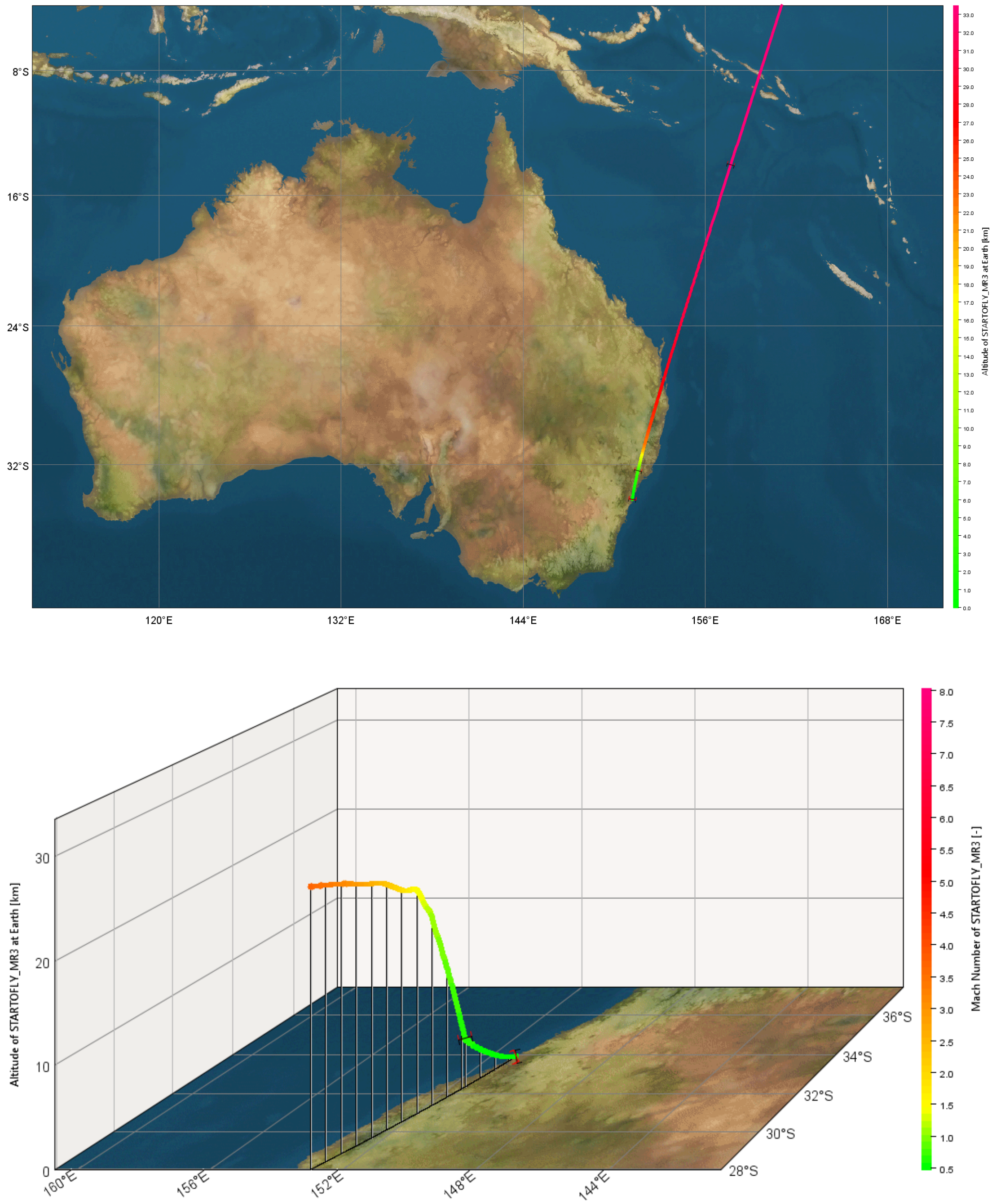


Figure 8.9. Final part of trajectory and Landing to Sydney Airport in the case of overland final approach (Option A). 2D map (top) - 3D view looking in southern direction (bottom).

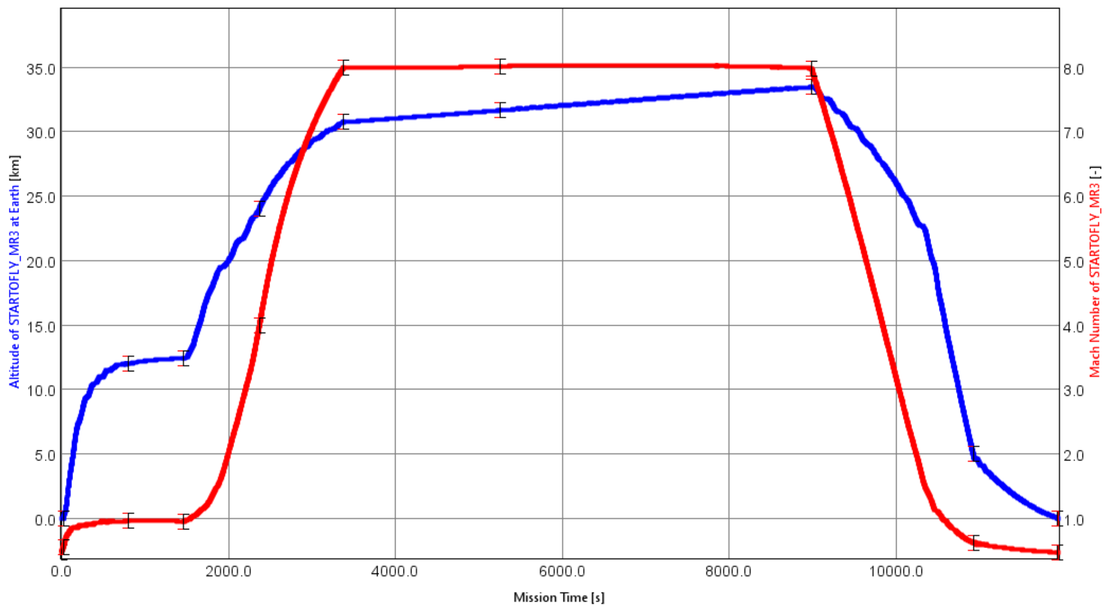


Figure 8.10. Flight Altitude and Flight Mach Number *vs.* Mission Time in the case of overland final approach (Option A).

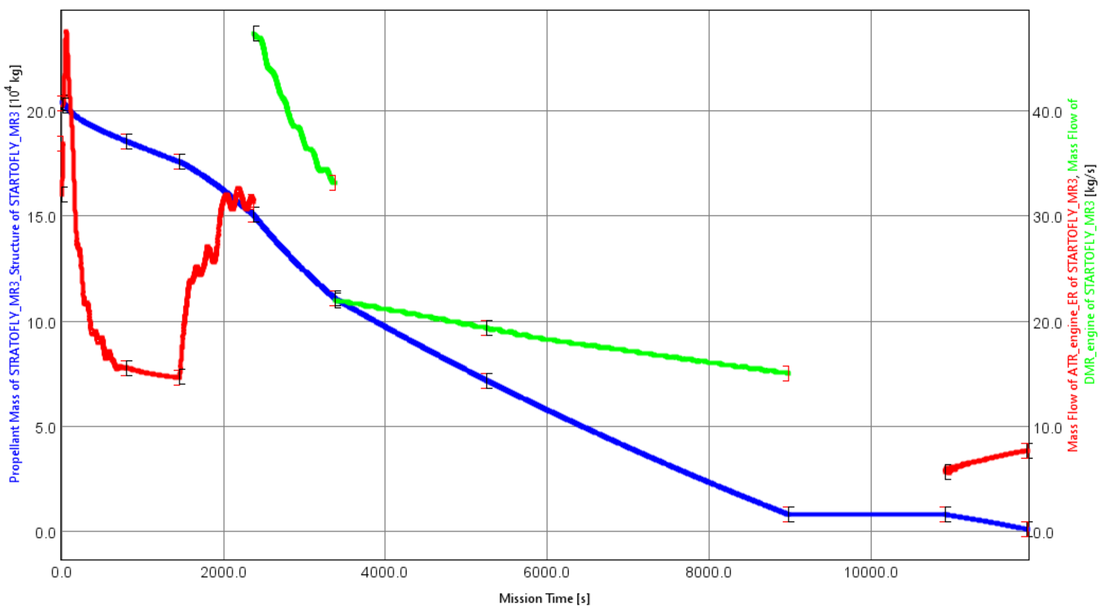


Figure 8.11. Fuel mass and fuel massflow *vs.* Mission Time in the case of overland final approach (Option A).

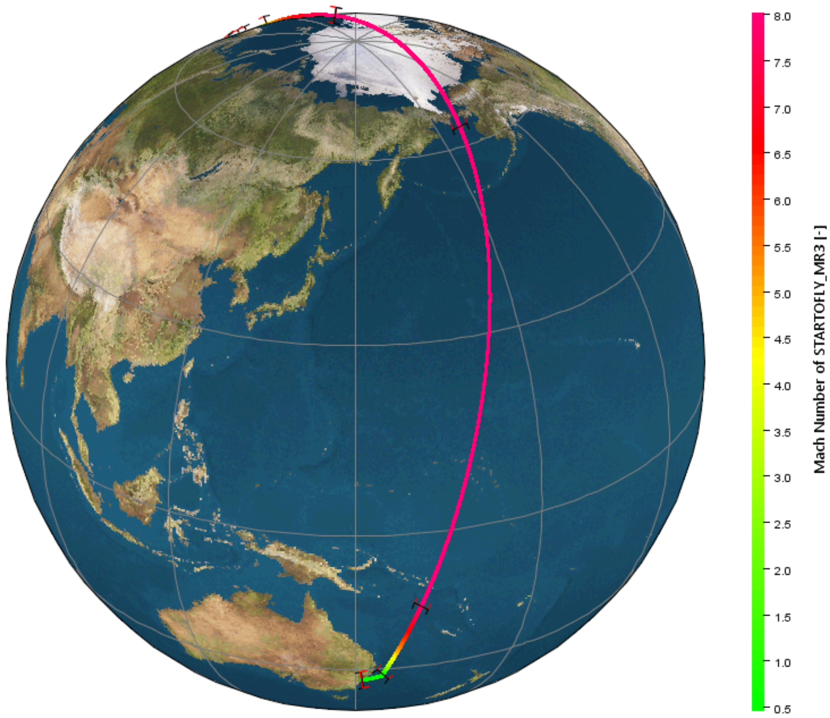


Figure 8.12. View on complete trajectory in the case of oversea final approach (Option B).

8.4 Considerations and Discussion

On the basis of the discussion taken forward in this Chapter about the STRATOFLY MR3 design reference mission simulation performed via *ASTOS®* 9 Software, the BRU-SYD route has revealed to be in principally feasible, given the vehicle layout as well as aerodynamics and propulsion performances as modelled in ASTOS.

Two mission trajectory options, related respectively to an *Overland* and an *Oversea* Final Approach, have been considered and simulated. In the first case the travel time from Brussels to Sydney resulted in 3h18m, whilst in the second case the travel time was longer and equal to 3h35m. However, a more detailed comparison between the two trajectory options is given in Section 8.4.1.

Nevertheless, further assessment shall be carried out about the effective total vehicle weight at take off and the the total mass of propellant loadable on board. In fact, an overall propellant consumption during the whole mission of about 200-210 tons of fuel, on the basis of the specific trajectory option, resulted from the simulation. This amount of fuel, however, is higher than the 181 tons calculated

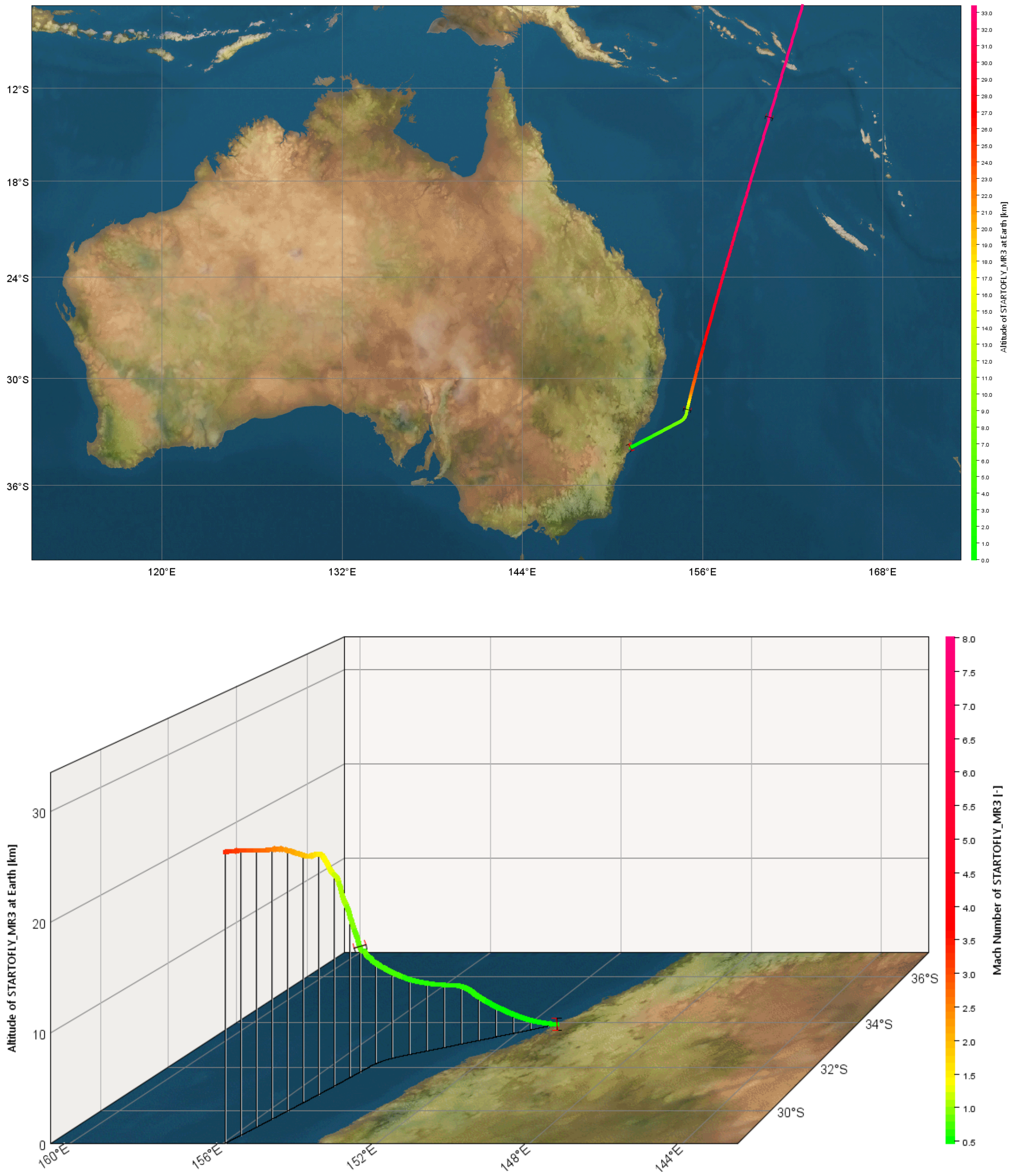


Figure 8.13. Final part of trajectory and Landing to Sydney Airport in the case of oversea final approach (Option B). 2D map (top) - 3D view looking in southern direction (bottom).

within the previous LAPCAT II project in the case of the LAPCAT MR2 vehicle for the same BRU-SYD route [18]. More details about a comparison between the

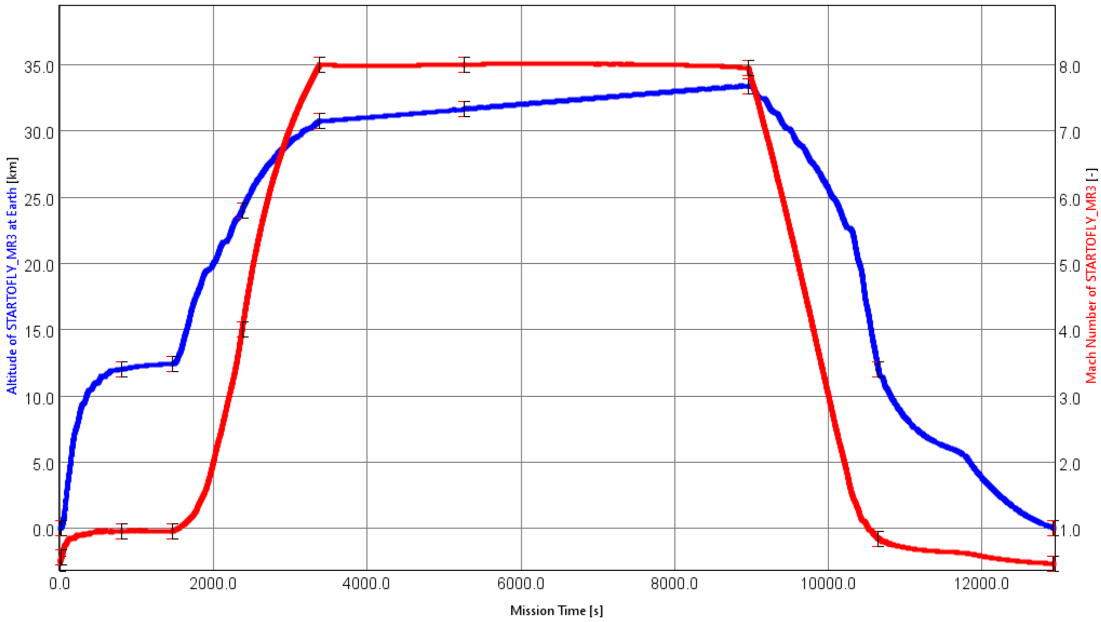


Figure 8.14. Flight Altitude and Flight Mach Number *vs.* Mission Time in the case of oversea final approach (Option B).

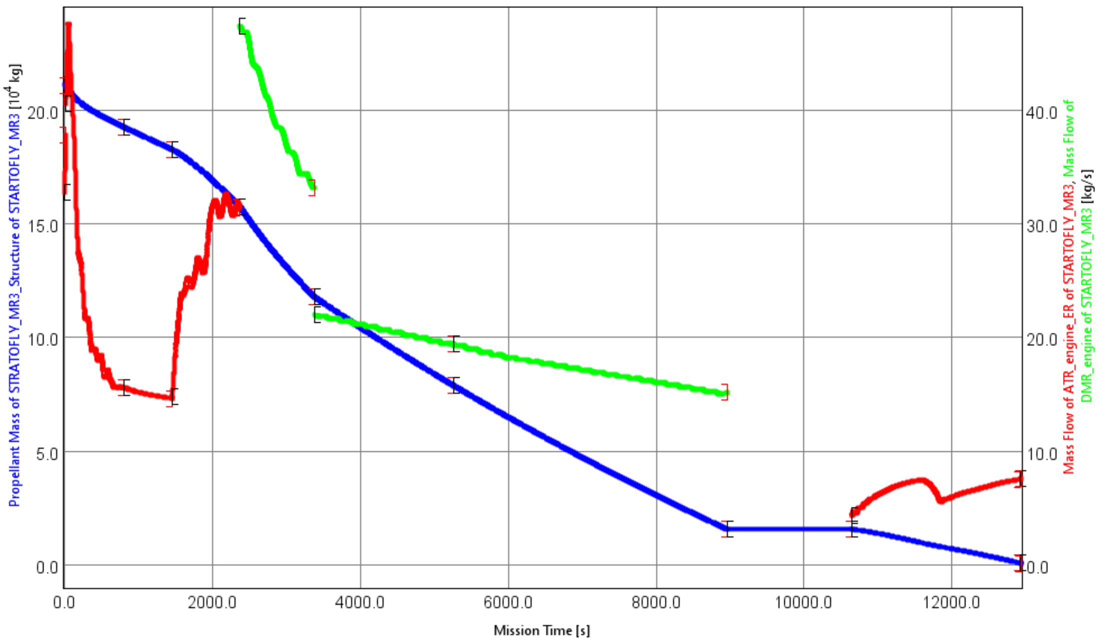


Figure 8.15. Fuel mass and fuel massflow *vs.* Mission Time in the case of oversea final approach (Option B).

STRATOFLY MR3 and LAPCAT MR2 trajectories simulations are provided in Section 8.4.2.

8.4.1 Comparison between two Trajectory Options

The STRATOFLY MR3 Brussels-Sydney reference mission simulation was performed taking into account two trajectory options, addressed as A and B, that have been fully described in Section 8.2 in terms of trajectory modelling and in Section 8.3 in terms of simulation results.

A comparison among the two trajectory options can be performed by looking at Table 8.2 where the key trajectory data have been summarised.

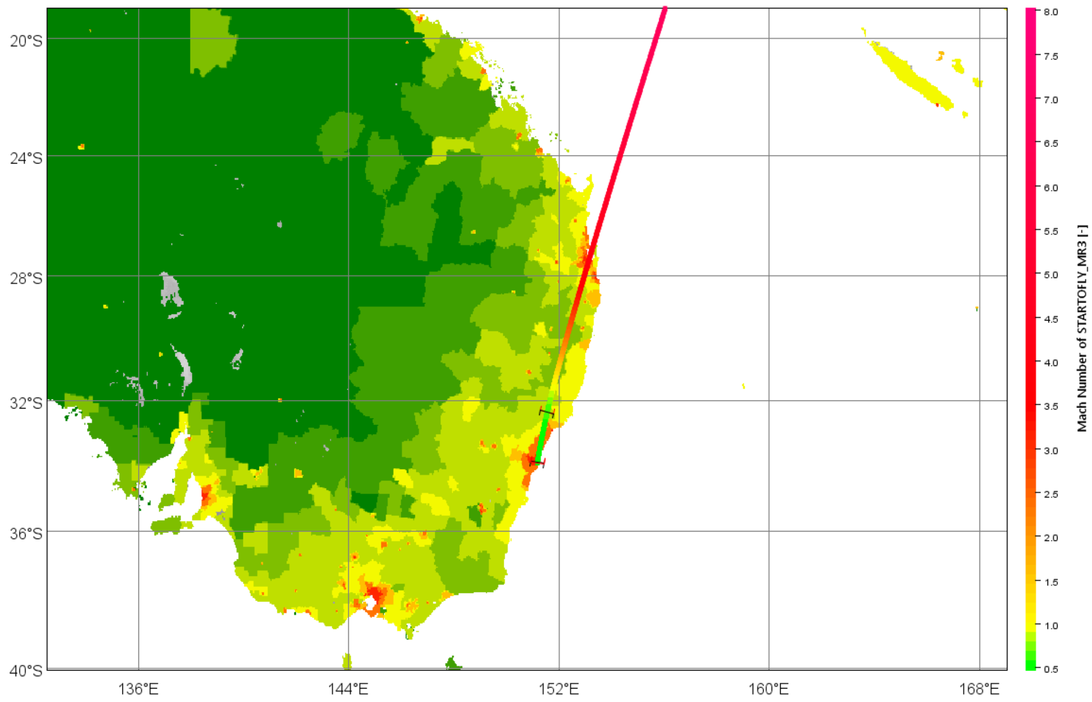
The main differences between the two trajectory options lie on the total travel time and the overall fuel consumption. In fact, trajectory option B, related to an oversea final approach, is 17 minutes longer and 7 tons more fuel consuming than trajectory option A. The major time needed to complete the mission in the trajectory option B case might be not a problem since 3h35m of flight to reach Sidney from Brussels is still an outstanding results for a civil passenger aircraft, whilst the major fuel consumption represents a possible problem in terms of mass budget, since more fuel on board at take off means potentially less mass available for other subsystems and payload (passenger).

It might seems like there are no reasons why option B shall be chosen as reference trajectory above option A, but the true is that there is one important reason why this should be done that lies on current regulations about supersonic flight [43]. As already mentioned for subsonic cruise that is needed prior to supersonic ascent, in fact, supersonic flight above inhabited land must be avoided. However, looking at option A related trajectory, the aircraft performs part of the descent at supersonic speed over inhabited land prior to perform the final approach, going in this way against current regulations. Mission trajectory option B, instead, is related to a descent performed far from the Australian coast, for then to perform an oversea final approach, leading in this way to a major fulfilling of the current regulations in the field of supersonic transport. This concept is well described by Figure 8.16, showing the final approach and landing to Sidney trajectory in a density population map for both options A and B cases, in which it is possible to see the flight Mach number described by the trajectory line contours.

Nevertheless, it is not the purpose of this Thesis to judge which one of the two mission trajectory options is the best, but instead it is to give an overview on simulation results and to put the basis of a more detailed evaluation to be performed by taking into account the maximum fuel effectively loadable on board as well as environmental, social and legal factors.

As a result of this analysis, it can be said that if enough fuel, in particular 210.9 tons, can be carried on board of STRATOFLY MR3, then mission trajectory option

B is better than option A. If instead, as probable, there is a more strict constraint on the maximum propellant mass loadable on board, the mission trajectory option A shall be chosen above option B as good trade off between vehicle capabilities and current regulations.



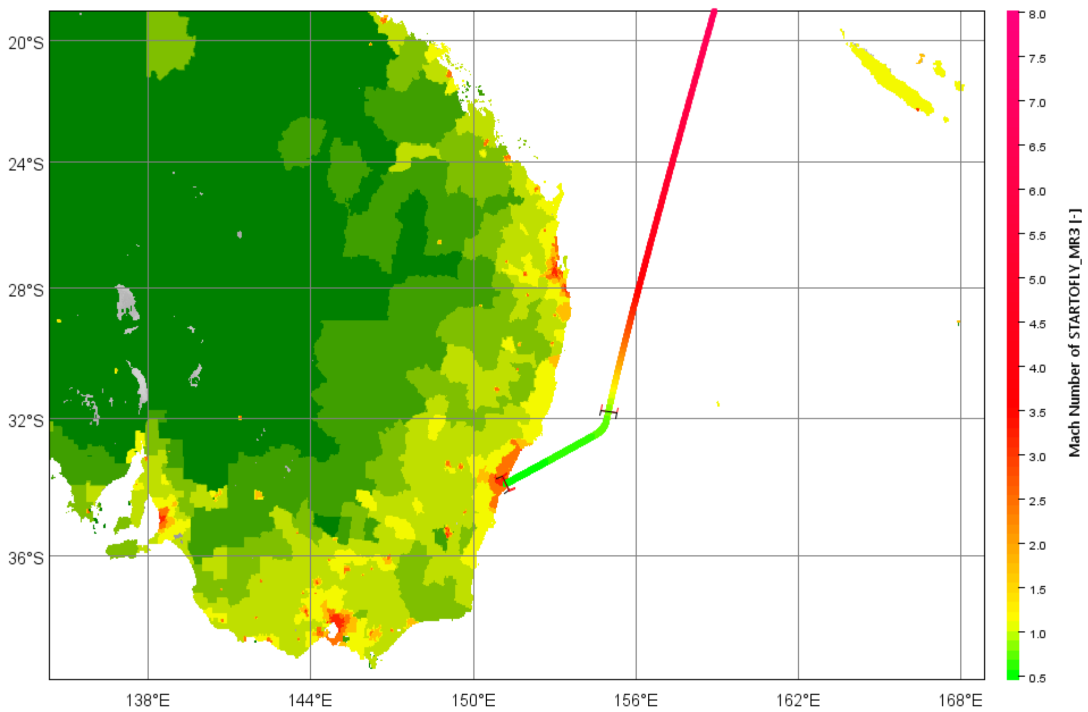


Figure 8.16. Final part of trajectory and landing to Sydney Airport in a density population map for both trajectories options A (top) and B (bottom).

8.4.2 Comparison between Trajectory Simulation performed for two different Vehicles

This Section is aimed at giving an overview on relevant differences, as well as possible causes of those differences, between the BRU-SYD mission trajectory simulations for the STRATOFLY MR3 and the LAPCAT MR2.

As already described in Chapter 4, the LAPCAT MR2 reference mission has been simulated and optimized via ASTOS software by ESA [18], leading to a total travel time of 2h55m and an overall fuel consumption of 181 tons for the Brussels-Sydney route.

As a result of the STRATOFLY MR3 design reference mission simulation performed via ASTOS software in this Thesis and described in the present Chapter, the total travel time is 3h18m and the overall fuel consumption is 203.2 tons, considering option A case, for the same Brussels-Sidney route.

Since the two vehicles have similar geometrical characteristics, and similar aerodynamic and propulsion databases have been implemented in the two cases, the causes of the differences related to reference trajectory simulation results have to be searched elsewhere.

As a result of a careful analysis about the reference mission scenario modelling and the simulation results, the reason why the trajectory simulation results are different for the two vehicles is triplex. In order of importance:

1. The propelled final approach and landing phases were not included in the LAPCAT MR2 reference trajectory, for which the unpropelled descent phase is the last one of the mission. As a consequence, about 10 tons of fuel and 16 minutes of travel time are spared with respect to the STRATOFLY MR3 reference mission, that in fact includes propelled final approach and landing after the unpropelled descent phase.

2. The subsonic cruise leg, in the case of LAPCAT MR2 trajectory, has been shortened to 240 km instead of the 400 km considered for the STRATOFLY MR3 trajectory. A shorter subsonic cruise phase, in fact, leads to a fuel saving of about 4 tons and to about 6 minutes less of flight time.

3. The LAPCAT MR2 reference trajectory was not only simulated, but also optimized by taking also into account the minimization of fuel consumption as cost function. Since an optimization was not performed in the STRATOFLY MR3 reference trajectory case, the optimal solution in terms of control parameters sizing during mission was not calculated by ASTOS software but only assumed by the user. As a consequence, the fuel consumption and travel time are slightly different between the case of optimized and not optimized trajectory.

By integrating all the information provided in the list above, it is possible to understand the reason under the difference in terms of 23 minutes of travel time and 22 tons of fuel consumption between the LAPCAT MR2 and the STRATOFLY MR3 reference trajectory simulations.

Once the causes of this difference have been assessed, it is possible to understand how the overall fuel consumption can be reduced if deemed necessary after a mass budget and maximum propellant mass assessment. This, in fact, can be done by shortening the subsonic cruise leg as well as the final approach phase. To shorten the final approach means to reduce the flight altitude at which the engines are re-activated soon after the unpropelled descent phase.

Further analysis and simulations showed that a complete elimination of the subsonic cruise leg as well as a reduction of flight altitude at which the final approach starts could lead to a reduction in fuel consumption up to about 15 tons, that represents a non-negligible fuel saving and a benefit in terms of mass budget. This, however, goes against current regulations about supersonic flight over inhabited land, and, as a consequence, a trade off between regulations and system mass budget shall be performed in order to assess the amount of fuel to be carried on board at take off.

Chapter 9

Out of Nominal Scenarios Simulation and Assessment

This Chapter is aimed at providing a description of the work performed in this Thesis about the simulation and assessment of some out of nominal scenarios related to possible critical events that can occur during the STRATOFLY MR3 mission.

The reference mission trajectory that has been considered for the purposes of this Chapter is the Brussels-Sydney route, already described in Chapter 8 in terms of nominal scenario simulation. Nevertheless, in the different scenarios discussed in the present Chapter, the mission trajectory remains the same as the design reference mission only until a critical event occurs, for then to change on the basis of the specific situation to be assessed. As a result, for all the scenarios simulated in this Chapter, the take off takes place, as expected, in Brussels airport, whilst the landing is never performed in Sydney airport since a certain out of nominal condition always shows up prior to complete the mission.

The out of nominal scenarios simulation has been performed by using the *ASTOS*® 9 Software, developed by Astos Solutions GmbH [1], and already described in Chapter 8 in terms of software capabilities and graphical user interface (GUI).

The content of this Chapter gains relevant knowledge from the out of nominal scenarios identification and classification performed in Chapter 6 from a theoretical point of view, by taking into account, in particular, propulsive subsystem related critical events. The propulsive subsystem, in fact, is the major subsystem involved in the trajectory definition, and, as a matter of fact, the only one simulated in ASTOS as important input for trajectory simulation.

The propulsion performances, as well as the aerodynamic characteristics, of the STRATOFLY MR3 vehicle are implemented in ASTOS in form of tabular databases already fully described in Chapter 2, respectively in Sections 2.3.1 and 2.3.2.

Furthermore, the logical decomposition of operations performed in Chapter 7 gives also some input for the out of nominal scenarios simulation and assessment described in the next sections.

An overview on this Chapter contents follows:

- Relevant information about the methodology implemented for the STRATOFLY MR3 out of nominal scenarios simulation are given in Section 9.1.
- Some out of nominal scenarios simulation related to failures that can occur to the air turbo rocket (ATR) propulsion unit is described in Section 9.2.
- Some out of nominal scenarios simulation related to failures that can occur to the dual mode ramjet (DMR) propulsion unit is described in Section 9.3.

Finally, eventual considerations on this Chapter contents are provided in Section 9.4.

9.1 Methodology

All the information provided in Chapter 8, in particular in Section 8.1 about ASTOS software capabilities and in Section 8.2 about trajectory simulation modelling, are also valid for the purposes of the present Chapter and will not be taken up again.

Nevertheless, what is important to underline and explain is the methodology with which the failures occurring to the propulsive subsystem have been simulated via ASTOS software.

As already described in Chapter 8, the propulsive performances in terms of net thrust can be controlled by the user by setting a certain throttle, defined as the ratio of effective net thrust to maximum available net thrust, and therefore included between 0 and 1. The maximum available net thrust, however, depends on several independent variables as described by the propulsion database. The control carried out on the throttle setting represents the basis on which the propulsive subsystem related failure is simulated. Major details about ATR and DMR failure simulation follow:

- The ATR propulsion unit is composed of 6 engines. Thus, the contribution of a single engine on the total available net thrust is equal to $1/6 = 0.16$. Hence, the failure of one engine can be simulated by subtracting 0.16 from the throttle setting. As a consequence, the number of active engines when a certain throttle is set can be found by dividing the throttle by 0.16 and approximating then by excess. For example, the situation in which 2 out of 6 engines are active can be simulated in ASTOS by setting the throttle equal to $2 \cdot 0.16 = 0.32$ or eventually some other number between 0.16 and 0.32.
- The DMR propulsion unit is composed of a unique engine. Therefore, any throttle greater than zero has the only role to describe engine performance. An eventual DMR failure, involving the overall engine performances, can be

simulated by setting the throttle equal to zero, with the consequence of zero net thrust.

The methodology and the logical process on the basis of the formulation of an out of nominal scenario consists, generally, on the following steps:

1. Departure from Brussels airport
2. Nominal trajectory until the failure point
3. Failure simulation based on throttle setting
4. Emergency maneuver aimed at performing emergency landing or emergency splashdown
5. Out of nominal trajectory prior to reach the emergency landing airport or the sea point for splashdown
6. Emergency landing or emergency splashdown

The different out of nominal scenarios that are simulated in this Chapter, will be classified on the basis of the scenarios classification performed in Chapter 6. In particular, a list of the propulsive subsystem related failure scenarios, and respective scenario IDs, is provided in Table 6.3.

The main purpose of he simulation activity performed in this Chapter is to assess and understand the minimum set of engines needed to face critical events and certain out of nominal situations, as well as to evaluate the feasibility of certain operational procedures aimed at performing mission abortion as much as safe as possible.

From the 23 out of nominal scenarios listed in Table 6.3, only some of them have been selected to be simulated in order to maximize the knowledge gained from simulation results by minimizing the number of scenarios actually simulated.

It is important to underline that one out of nominal scenario listed in Table 6.3 can be related to more than one scenario that can be simulated. For example, an emergency landing during *Subsonic Ascent and Cruise* (Scenario 8) can be related to several scenarios on the basis of the specific point of the mission at which the failure occurs and of the different airports in which the emergency landing can be performed.

An overview on the out of nominal scenarios simulated and assessed in this Chapter follows.

ATR related Failure Scenarios (Section 9.2):

- *Scenario 6*: Catastrophic event after an ATR failure occurs during subsonic climb
- *Scenario 5*: Emergency landing to departure airport soon after take off

- *Scenario 8*: Emergency landing to departure airport after an ATR failure occurs during subsonic climb
- *Scenario 8*: Emergency landing to Norwich Airport (UK) after an ATR failure occurs during subsonic cruise

DMR related Failure Scenarios (Section 9.2):

- *Scenario 12*: Emergency Landing to Sapporo New Chitose Airport, Japan, after a failure occurs during hypersonic cruise
- *Scenario 13*: Emergency Splashdown near to Tokyo, Japan, after a failure occurs during hypersonic cruise
- *Scenario 12*: Emergency Landing to Honolulu Airport, Hawaii, after a failure occurs during hypersonic cruise

The geographical coordinates of the airports considered for the purposes of this Chapter are given in Table 9.1.

	Latitude	**Longitude**
Brussels Airport (BRU)	$50^o54'$ N	$4^o29'$ E
Norwich Airport (NWI)	$52^o40'$ N	$1^o16'$ E
Sapporo New Chitose Airport (CTS)	$42^o46'$ N	$141^o41'$ E
Tokyo Haneda Airport (HND)	$35^o33'$ N	$139^o46'$ E
Honolulu Airport (HNL)	$21^o19'$ N	$157^o55'$ W

Table 9.1. Airports Coordinates.

9.2 ATR related Failure Scenarios

The ATR propulsion unit powers the vehicle during subsonic and early supersonic phases, in particular the ATR engines work from Mach number M=0 up to M=4. Possible failures occurring to the ATR during the mission could affect one or more of the 6 engines of which it is composed. The engines failure simulation method has already been described in Section 9.1.

Four different out of nominal scenarios related to ATR failure have been simulated and described in this Section with the aim to understand the possible consequences of such critical event on the basis of the number of engines affected by the failure as well as the flight conditions in terms of flight altitude and specific point of the mission in which the failure occurs.

As a first step, it is possible to state that the only two situations that shall be simulated are:

- 5 out of 6 engines are inoperative: only one engine is available
- All engines are inoperative: no engines are available

The reason why does not make any sense to simulate different situations lies on the fact that during the nominal trajectory the throttle is always equal or lower than 0.32 (2 engines active) except for the take off and the supersonic climb. Thus, given that the failure occurs only after take off is completed, it is possible to state that the mission can be performed with only two engines prior to supersonic climb. Therefore, when simulating an ATR failure that can occur during subsonic ascent and subsonic cruise, it make sense to consider the possibilities mentioned above related to 5 or 6 engines getting unavailable since only 2 engines are needed to power the aircraft during those phases in nominal conditions.

However, it shall be noted the importance of redundancy related to the fact that 6 engines are available in nominal conditions. Hence, if one engine fails, the missing performances are redistributed among the other available engines the desired performances of the ATR unit are restored. This represents another confirmation of the fact that only the cases of 5 engines or 6 engines failed shall be considered for out of nominal scenarios simulation purposes.

In the following, four out of nominal scenarios related to ATR failure will be described. In particular, Section 9.2.1 shows how a catastrophic event is inevitable if a failure affecting all the 6 engines occurs during early subsonic climb, whilst Section 9.2.2 shows a successful emergency landing to the departure airport when a failure affecting 5 out of 6 engines occurs in two different situations: soon after take off and during subsonic climb.

Finally, in Section 9.2.3 the case of no engines available after failure will be again taken up considering a failure occurring during subsonic cruise when the aircraft is flying at 12 km altitude. In this case, it will be shown how an unpropelled descent and emergency landing to eventual close and available airports, such as, for example, Norwich Airport in England, is possible and conceptually feasible.

9.2.1 No Engines Available after Failure

The out of nominal scenario simulation described in this subsection is aimed at proving that a failure affecting the whole ATR propulsion unit could represents an important critical event, also with catastrophic consequences, if it occurs soon after take off or during subsonic climb.

The scenario hereafter described, and represented in Figure 9.1, has been classified, according with Table 6.3, as Scenario 6: Catastrophic event as a consequence of a failure occurring during early subsonic ascent.

In Figure 9.1, as well as in the other figures describing out of nominal scenarios in the following subsections, the failure point is represented through an orange "X", whilst a scaled illustration of the STRATOFLY MR3 vehicle is intended to underline the direction of travel.

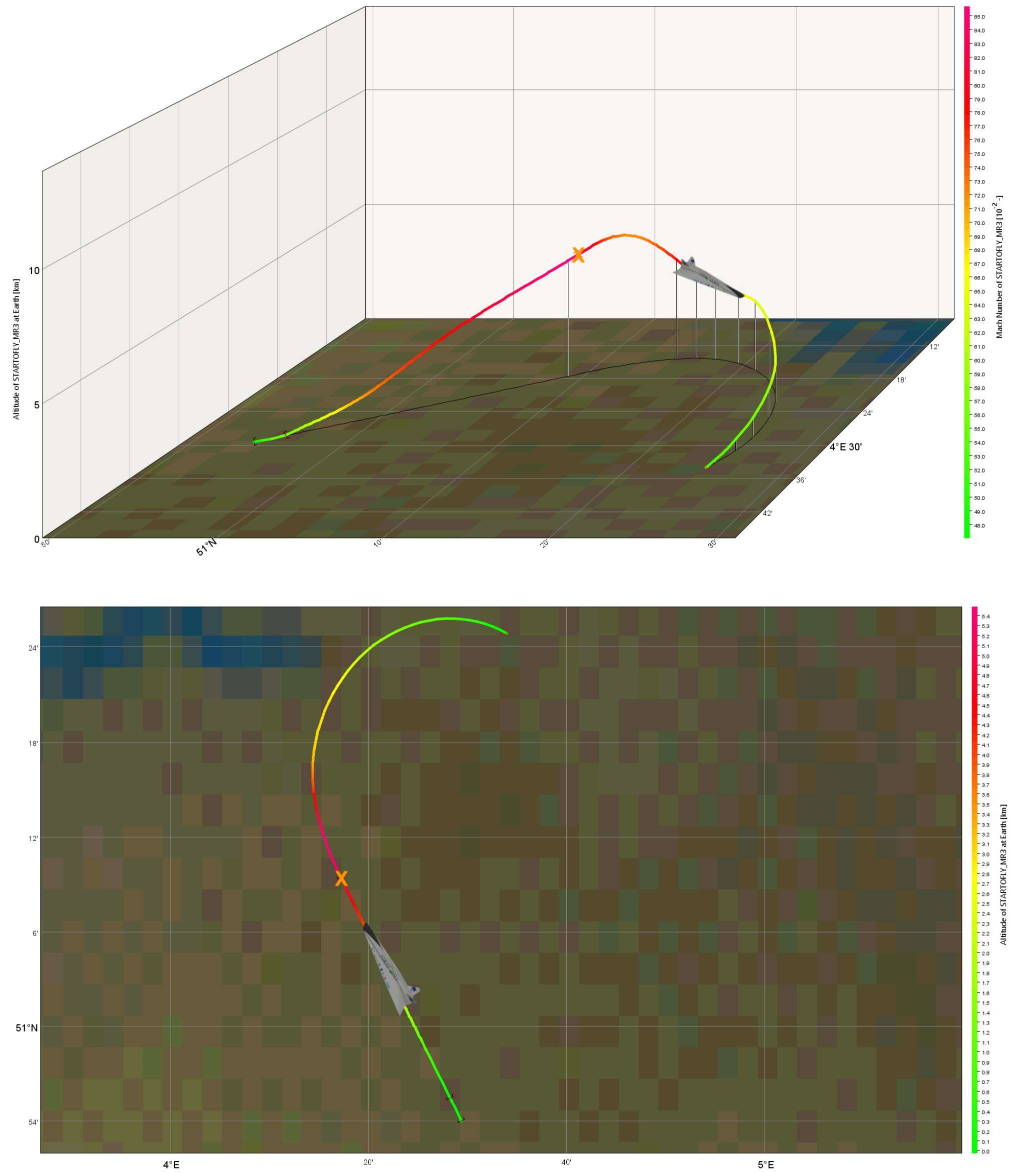


Figure 9.1. Scenario 6: Catastrophic event after an ATR failure affecting all the 6 engines occurs during early subsonic climb. (top) 3D view looking in western direction - (bottom) 2D map.

A description of the scenario represented in Figure 9.1 is given in the following:

- The aircraft performs take off from departure airport in Brussels

- The subsonic climb phase is taken forward in nominal conditions until an altitude of 5 km is reached
- A failure to the ATR occurs at 5 km flight altitude. As a consequence, all the 6 engines are unavailable and no thrust can be generated
- Soon after failure, a right turn is performed in order to try an emergency landing to the departure airport
- The lateral maneuver cannot be properly completed and the aircraft can do nothing but fall on ground at a speed of about $180\,m/s$ and a flight path angle equal to -6^o

Now, considering the high speed and the steep descent angle with which the vehicle reaches the ground, and considering also that the area around the Brussels airport is highly populated and the vehicle's tanks are still full of LH2, then it is possible to assume that a catastrophic event happens.

Further analysis and simulations, performed by considering different flight altitudes at which the failure occurs, demonstrated how a catastrophic event is basically inevitable if such kind of failure, affecting the overall ATR performances, occurs at any point of the subsonic climb. If, however, there would be airports close enough to be reached by proper emergency maneuvers after such kind of failure occurs, the catastrophic event might be avoided as in the case of the emergency landing to Norwich airport, England, described in Section 9.2.3.

Another option that might be considered in order to avoid a catastrophic event is to perform fuel dumping soon after a failure affecting all the 6 ATR engines occurs. The fuel dumping, in fact, may be useful to reduce vehicle weight and to increase, as a consequence, the capability of the vehicle to fly major distance before falling on ground with the aim to reach an emergency arrival airport. Fuel dumping option, however, shall be further assessed taking into account not only technical feasibility and real advantages, but also social and environmental factors related to the LH2 falling over inhabited zones.

Nevertheless, it shall be said that the out of nominal scenario (Scenario 6), described in the present Section and represented in Figure 9.1, must be absolutely avoided by considering proper risk mitigation strategies. In fact, the first risk mitigation strategy implemented for avoiding such kind of catastrophic scenario is represented by the configuration of the ATR propulsion unit itself. The ATR, indeed, is composed of 6 engines that represents an important redundancy, since, with proper levels of reliability, it is unlikeable that all the 6 engines get failed at once and, also in the unfortunate case in which 5 out of 6 engines fail at once, only one engine available is enough to perform proper mission abortion and a safe emergency landing as it will be discussed in Section 9.2.2.

9.2.2 One Engine Available after Failure

The out of nominal scenarios simulation performed in ASTOS has led to the important result that a safe mission abortion and a safe emergency landing can be performed after a failure affecting the ATR in the case there is at least one available engine.

The two scenarios described in this Section, in fact, consist both on an emergency landing to the departure airport after an ATR failure affecting 5 out of 6 engine occurs. The two scenario differ only for the different mission instant at which the failure is simulated to happen.

The two out of nominal scenarios, including scenario ID based on Table 6.3 classification, are listed in the following:

- *Scenario 5*: Emergency landing to departure airport soon after take off
- *Scenario 8*: Emergency landing to departure airport after an ATR failure occurs during subsonic climb

A graphical description of Scenario 5 and Scenario 8 is given respectively in Figures 9.2 and 9.3. As said before, what changes between the two scenarios is only the flight altitude at which the failure occurs. In particular:

- *Scenario 5*: The failure affecting 5 out of 6 ATR engines occurs at 200 meter above the take off surface
- *Scenario 8*: The failure affecting 5 out of 6 ATR engines occurs at 7 kilometer altitude

A description of the two scenarios is given in the following:

- The aircraft performs take off from departure airport in Brussels
- The subsonic climb phase is taken forward in nominal conditions until a certain altitude
- A failure to the ATR occurs. As a consequence, 5 out of 6 engines are unavailable and a maximum throttle equal to $1/6 = 0.16$ can be provided
- Soon after failure, a lateral maneuver is performed in order to try an emergency landing to the departure airport
- The lateral maneuver can be successfully completed and the emergency landing can be performed

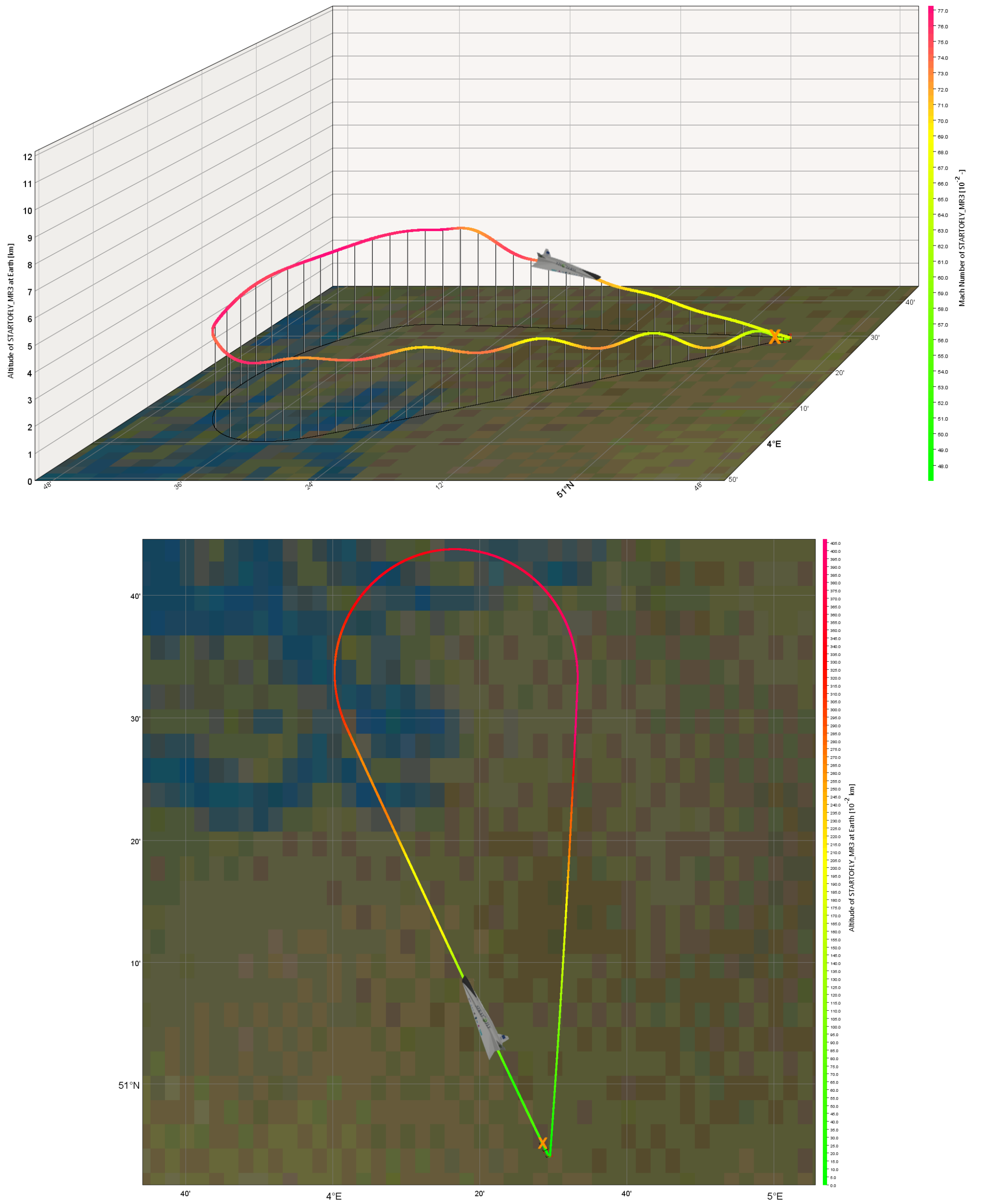


Figure 9.2. Scenario 5: Emergency landing to departure airport soon after take off as consequence of an ATR failure affecting 5 out of 6 engine. Only one ATR engine is available. (top) 3D view looking in eastern direction - (bottom) 2D map.

The simulation of the post-failure phases was performed according to the methodology described in Section 9.1. In particular the fact that only one engine is available after failure was simulated by assuming a throttle equal or smaller than $1/6 = 0.16$.

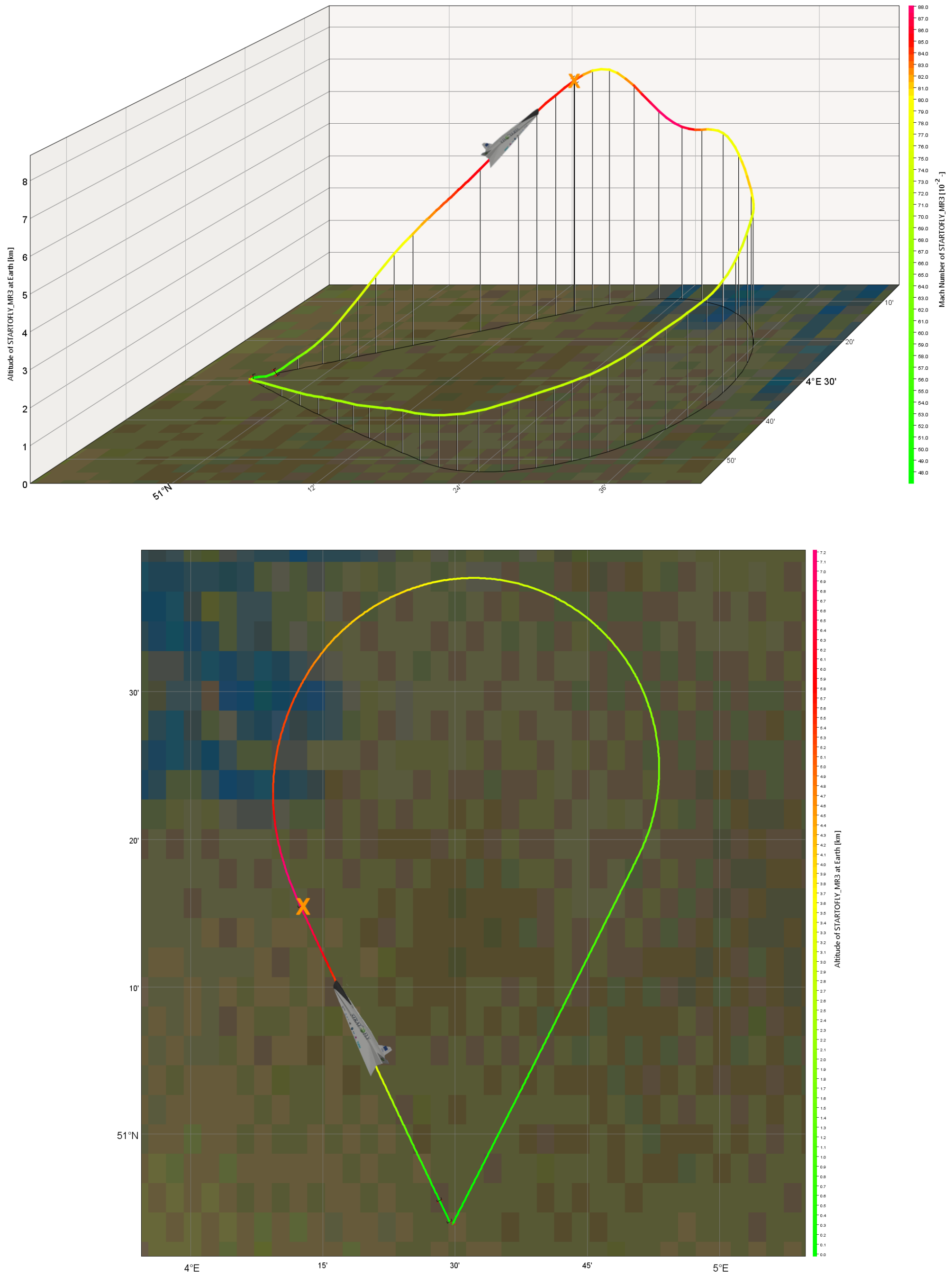


Figure 9.3. Scenario 8: Emergency landing to departure airport after an ATR failure occurs during subsonic cruise. As a consequence, only 1 out of 6 engines is available. (top) 3D view looking in western direction - (bottom) 2D map.

Since in both cases the landing happen exactly in the Brussels Airport, with flightpath angle about -3^o and flight speed similar to the one of take off, it can be assumed that the emergency landing is performed safely and the mission is correctly aborted without catastrophic consequences.

Considering, that this emergency landing can be performed both in the cases in which the failure happen soon after take off and un which the failure happen at higher altitudes, it can be stated that if one engine is available after failure an emergency landing can be performed at any mission phase.

Further simulations, moreover, demonstrated that also when the ATR is not operative, therefore during high supersonic-hypersonic phases, in out of nominal conditions the aircraft can decrease its flight altitude until reaching conditions at which the ATR can be reactivated, and, at this point, only one ATR engine is sufficient to perform emergency maneuver and eventually an emergency landing. This aspect will be further discussed in Section 9.3.

9.2.3 Emergency Landing to Norwich, UK

In this Section, the situation of zero available ATR engines after failure is again considered by providing a successful example of emergency landing to a reachable airport. In particular, the scenario hereafter described is related to an emergency landing to Norwich airport, England, after a failure affecting the overall performances of the ATR propulsion unit occurs during the subsonic cruise phase. The Norwich airport geographical coordinates are provided in Table 9.1.

The scenario is classified, according with Table 6.3, as Scenario 8: Emergency landing after an ATR failure occurs during subsonic ascent and cruise. It is important to underline that, also if this scenario is addressed with the same ID of the one described in the previous Section and represented in Figure 9.3, it doesn't mean that the two scenarios are the same, but it only means that they are related to the same mission abortion option and they occur during the same mission phases cluster (see Section 6.3).

Hence, the out of nominal scenario related to emergency landing in Norwich is represented in Figure 9.4 and described in the following:

- The aircraft performs take off from departure airport in Brussels
- The subsonic climb phase is taken forward in nominal conditions
- The subsonic cruise phase is taken forward in nominal conditions until a distance of 260 km from the departure airport
- A failure to the ATR occurs 260 km far from the departure airport. As a consequence, all the 6 engines are unavailable and no thrust can be generated

- Soon after failure, a left turn is performed in order to try an emergency landing to Norwich airport
- The lateral maneuver can be completed and the aircraft performs an emergency landing to Norwich airport at a speed of about $111\,m/s$ and a flight path angle of about -3^o

Looking at the arrival flight speed and flight path angle described above, it is possible to assume a safe emergency landing. Moreover, fuel dumping is not needed prior to landing.

Nevertheless, the out of nominal scenario just described above does not lead to an absolute result. Indeed, it is not true that an emergency landing can be always performed if an ATR failure affecting all the 6 engines occurs during subsonic cruise, but the feasibility of an emergency landing depends instead on the availability of on ground airports close enough to be reached from the point of trajectory at which the failure occurs. The case showed above, in fact, represent a fortunate and isolated case in which the mission can be safely aborted after failure for two main reasons:

1. The failure occurs at a point of the mission in which it is possible to reach an available emergency airport after an unpropelled approach.
2. The pilot is is good enough to perform the correct maneuver soon after failure. If, in fact, the pilot delays the decision to perform an approach maneuver to Norwich airport, the emergency landing cannot be properly completed and an emergency splashdown near England coast is instead probable.

The analysis performed in this Section, therefore, has the main purpose to show how the success of a mission abortion always depends on several factors, among which the kind of failure and the exact point of the mission at which failure occurs, and to put again attention on the importance of proper risk mitigation strategies aimed at avoiding a lost of the overall ATR performances after failure. As already discussed in Section 9.2.1, fortunately, the situation in which all the 6 ATR engines fail at once is unlikeable if proper reliability levels are assured.

Furthermore, as demonstrated in Section 9.2.2, only one engine is sufficient to perform a safe emergency landing also if longer distances have to be flown before to reach an available airport. Thus, it is relatively ok to have 5 out of six engines failed and unavailable, but it must be absolutely avoided the loss of the last engine needed to perform mission abortion safely, because, again, the safe emergency landing simulated in this Section represents a fortunate case not always repeatable.

9.3 DMR related Failure Scenarios

Since STRATOFLY MR3 is provided with two different propulsion units, it is necessary to treat them differently in order to study propulsive subsystem failure related

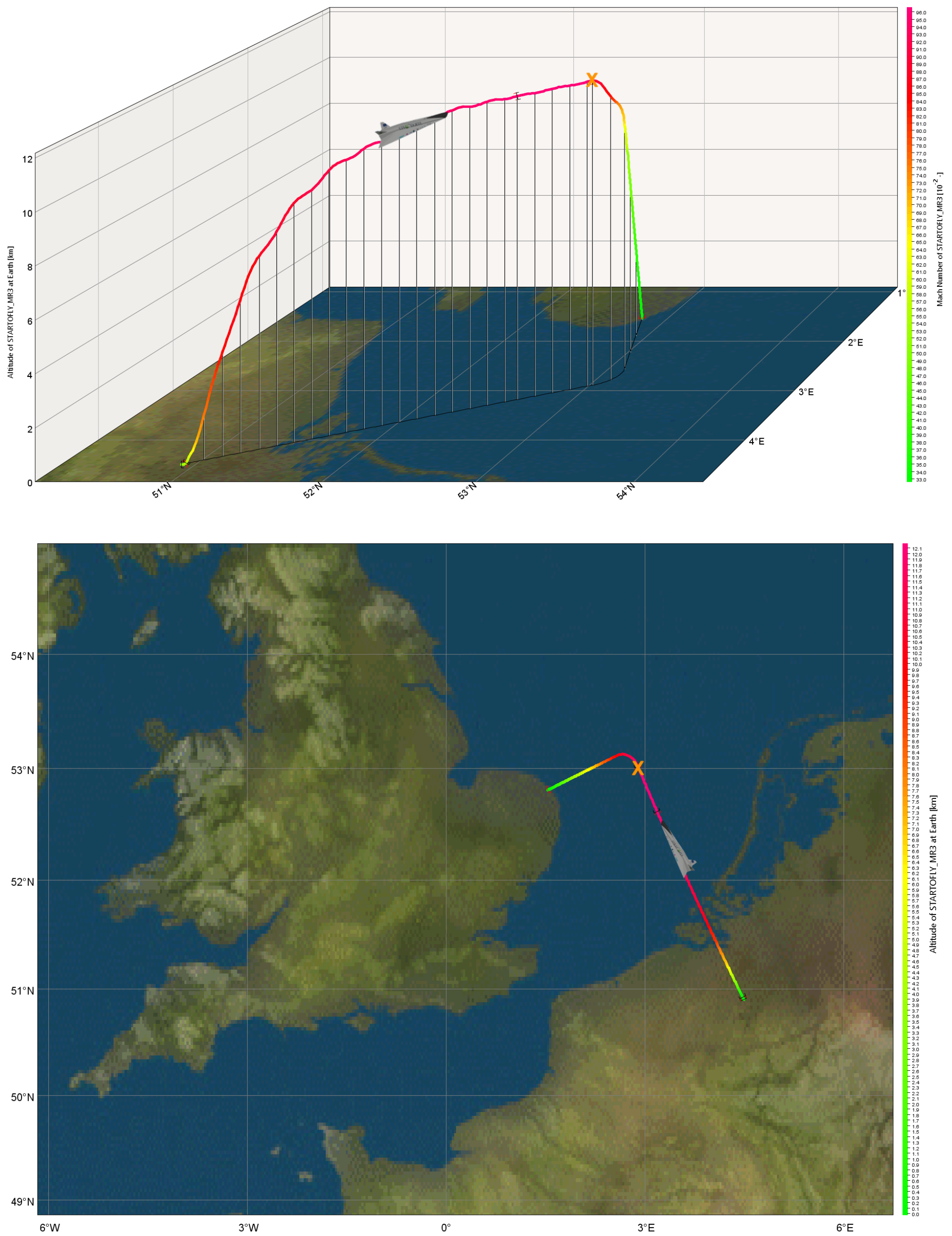


Figure 9.4. Scenario 8: Emergency landing to Norwich Airport (UK) after an ATR failure occurs during subsonic cruise. None of the ATR engines is available. (top) 3D view looking in western direction - (bottom) 2D map.

out of nominal scenarios. As already done for the ATR propulsion unit in Section

9.2, the present Section aims at describe some relevant out of nominal scenarios simulations related to possible failure affecting the dual mode ramjet (DMR) propulsion unit.

The DMR propulsion unit powers the vehicle during high supersonic and hypersonic mission phases, in particular the DMR engine works from Mach number M=4 up to M=8. As already discussed in Section 9.1, the DMR is composed of only one engine and it reduces the possible failure modes to be considered as input for the out of nominal scenarios definition. For the purposes of the scenarios simulation described in this Section, in fact, a DMR failure is assumed to have as consequence the loss of the overall engine performance, and this can be simulated by setting the throttle equal to zero at the time the failure is assumed to happen.

Another important assumption to be considered in order to understand the contents of the following discussion is that a failure to the DMR does not affect the ATR propulsion unit. Thus, if the DMR fails, the ATR can be still used in order to perform proper mission abortion maneuver, making it possible to reach eventual emergency airports or strategic splashdown points as far as allowed by the propellant on board after failure. However, it is important to remember that the ATR operates at lower altitudes and lower flight speeds with respect to the DMR, therefore, after a failure occurs to the DMR the flight altitude and the flight speed shall decrease before the ATR can be re-activated.

For clarity, the above discussed assumptions are taken up in the following:

1. A DMR related failure affects the overall engine performances. No thrust can be generated after failure.

2. A DMR related failure does not affect the ATR propulsion unit.

3. The only restriction to the flyable distance, using the ATR after a DMR failure, consists on the available fuel on board.

Nevertheless, it shall be said that the above listed assumptions represent a limitation on the total DMR related failure out of nominal scenarios hat can be defined. First of all, certain failures affecting the common intake or the nozzle of the propulsive subsystem can lead to a loss of performances of both the ATR and the DMR, therefore, according to assumption 2, a DMR failure has to be intended as affecting the DMR duct, making it possible the correct operation of the ATR. Moreover, it is not absolutely true that the only restriction on the flyable distance after DMR failure is represented by the propellant on board, in general, in fact, a DMR failure can affect the TEMS subsystem in terms of capability of the vehicle to deal with the high external heat loads when the aircraft decreases flight altitude and speed before to reactivate the ATR. This last aspect, however, needs further assessment to be performed from who of competence within the STRATOFLY project.

The out of nominal scenarios assessment performed hereafter, in fact, is focused on trajectory simulation with the aim to evaluate the feasibility of certain post-failure operational procedures by taking into account the propulsive subsystem capabilities. Once the vehicle geometrical and aerodynamic characteristics are defined, indeed, the propulsion unit performances and the available fuel on board, in fact, are the most important elements to be considered for trajectory definition, and as a matter of fact the propulsive one is the only subsystem that has been simulated in ASTOS.

The out of nominal scenarios simulation and assessment, described in the next subsections, aims not only at giving some scenarios isolated examples, but especially at finding general results that might be useful to develop major knowledge about the STRATOFLY MR3 capabilities to deal with out of nominal conditions that can occur in a generic mission, therefore beyond the only BRU-SYD route taken as reference trajectory.

The knowledge that shall be gained from the contents of the following subsections, in fact, is not only related to the specific numbers and scenarios examples, but instead the innovative contribution of the work about out of nominal scenarios assessment performed in this Thesis consists on the methodology and achieved results.

The method and the logic on the basis of the DMR failure related out of nominal scenarios simulation are described in Section 9.3.1. Moreover, three out of nominal scenario simulation examples are provided in Sections 9.3.2, 9.3.3 and 9.3.4 with the aim to demonstrate the methodology implemented and to open further discussions.

9.3.1 Flyable Distance after DMR Failure

On the basis of the DMR failure out of nominal scenarios simulation there are the three assumption discussed in the previous Section and taken up in the following:

1. A DMR related failure affects the overall engine performances. No thrust can be generated after failure.
2. A DMR related failure does not affect the ATR propulsion unit.
3. The only restriction to the flyable distance, using the ATR after a DMR failure, consists on the available fuel on board.

Thus, an analysis shall be performed with the aim to calculate the flyable distance after DMR failure as a function of the available fuel on board after failure. Moreover, given a specific reference trajectory, the propellant mass on board can be considered as a function of the mission time, therefore also the flyable distance after DMR failure can be evaluated as a function of the mission time at which the failure occurs.

The reference trajectory that was considered for the following analysis is the BRU-SYD Option A (Overland Final Approach) mission trajectory (See Chapter 8

Section 8.3.1). The total travel time is 3h18m and the overall fuel consumption is 203.2 tons. Hence, assuming a residual propellant mass of about 1 ton at landing in Sydney, the initial propellant mass at take off that has been considered for the following analysis is 204.25 tons.

Purpose of the analysis hereafter described is to evaluate the flyable distance as a function of mission time at which a failure affecting the DMR occurs. The failure was assumed to happen at some point of the hypersonic cruise, that represents the longest mission phase in terms of both time and distance covered, and during which, therefore, it is most probable that a failure to the DMR occurs.

From now on, when a *failure* is mentioned, it is implicitly referred to the DMR. The general failure related out of nominal scenario consists on the following steps:

1. Departure from Brussels airport
2. Nominal trajectory until the hypersonic cruise
3. A failure to the DMR occurs at some point of the hypersonic cruise
4. An emergency descent is performed as a consequence of failure
5. The ATR is reactivated as soon as a flight altitude of about 10 km is reached
6. An emergency subsonic cruise is performed in order to reach an airport for emergency landing or a strategic point for emergency splashdown
7. Final Approach and emergency landing or emergency splashdown are performed

The fact if an emergency landing or splashdown happens depends on the difference between the distance of an eventual emergency airport and the flyable distance after failure. If in fact, the airport can be reached, then an emergency landing can be performed, otherwise, if all the fuel is consumed before to reach the emergency airport, a splash down has to be performed.

The overall flyable distance after failure has to be intended as the contribution of all the post-failure phases, therefore descent, emergency subsonic cruise and final approach prior to emergency lending or splashdown.

As a first step, the flyable distance has been calculated in two different situations:

- A failure occurs at the beginning of hypersonic climb
- A failure occurs at the end of hypersonic climb

The two cases are described by the Flight Altitude and Flight Mach Number profiles represented in Figure 9.5, the point of failure is highlighted with an orange circle in the flight altitude profile for both the cases.

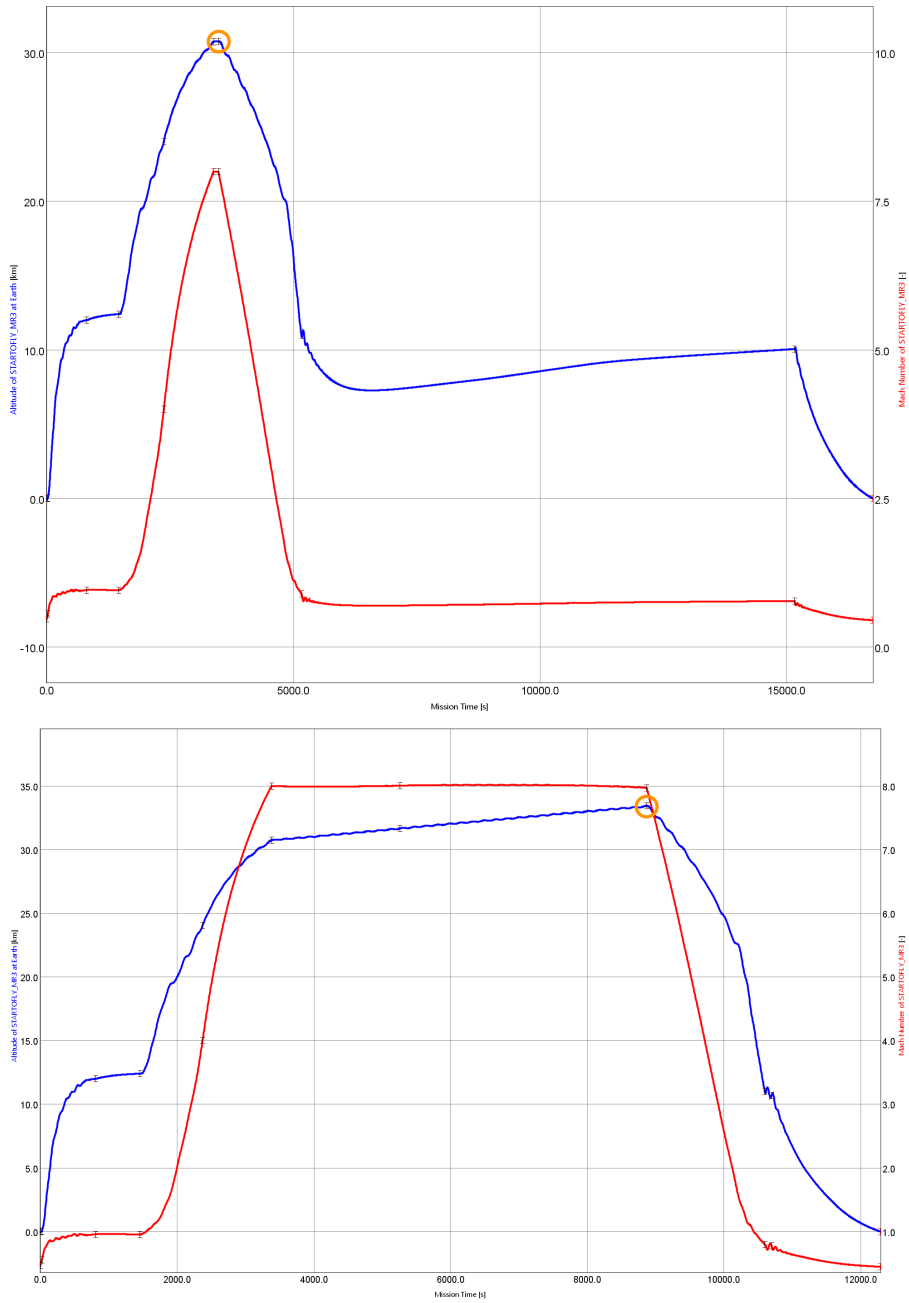


Figure 9.5. Flight Altitude and Flight Mach Number *vs.* Mission Time in the case of a DMR failure occurring (top) at the beginning of hypersonic cruise - (bottom) at the end of hypersonic cruise. The point of failure is highlighted with an orange circle.

The trajectory characteristics in terms of time of failure, distance covered before failure, available fuel, flyable distance and flyable time for both the cases listed above are reported in Table 9.2.

	Time of failure [s]	Covered distance before failure [km]	Available fuel [ton]	Flyable distance [km]	Flyable time [s]
Beginning of hypersonic cruise	3479	3130	108.6	4055	13267
End of hypersonic cruise	10072	16000	10	2360	3418

Table 9.2. After DMR failure flight characteristics at the beginning and at the end of hypersonic cruise.

As expected, the available fuel, and so the flyable distance, are smaller in the case the failure occurs at the end of the hypersonic cruise instead of at the beginning. Indeed, it can be stated that the mire is mission time at which a failure occurs, the smaller is the available fuel on board and the flyable distance.

Figure 9.6 shows the propellant mass on board as a function of the mission time. The fuel mass *vs.* mission time has been also described in Chapter 8 by Figure 8.11. As already mentioned in the case of Figure 8.11 and as it is also possible to see in Figure 9.6, the propellant mass decreases linearly during hypersonic cruise.

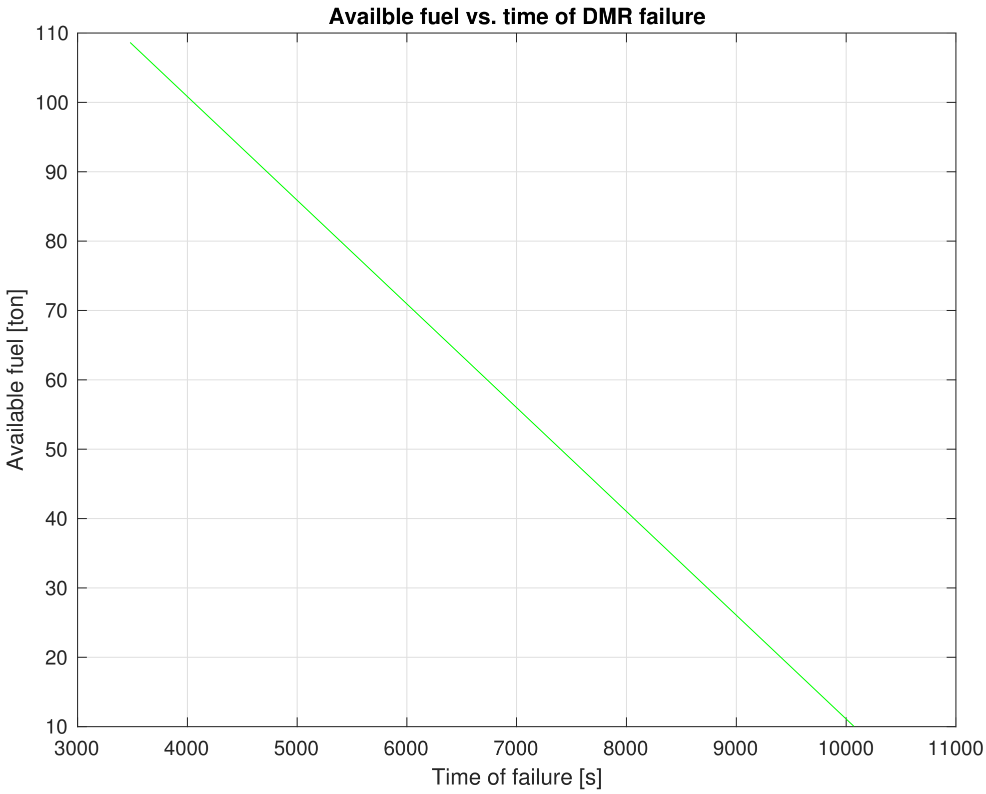


Figure 9.6. Available fuel after failure *vs.* time on which a DMR failure occurs.

Since the flyable distance after failure stems directly from the available fuel, it is possible to assume with good approximation that also the flyable distance, similarly to the propellant mass, decreases linearly vs. mission time at which a failure occurs during hypersonic cruise. Therefore, the flyable distance after failure *vs.* time on which a DMR failure occurs is represented in Figure 9.7.

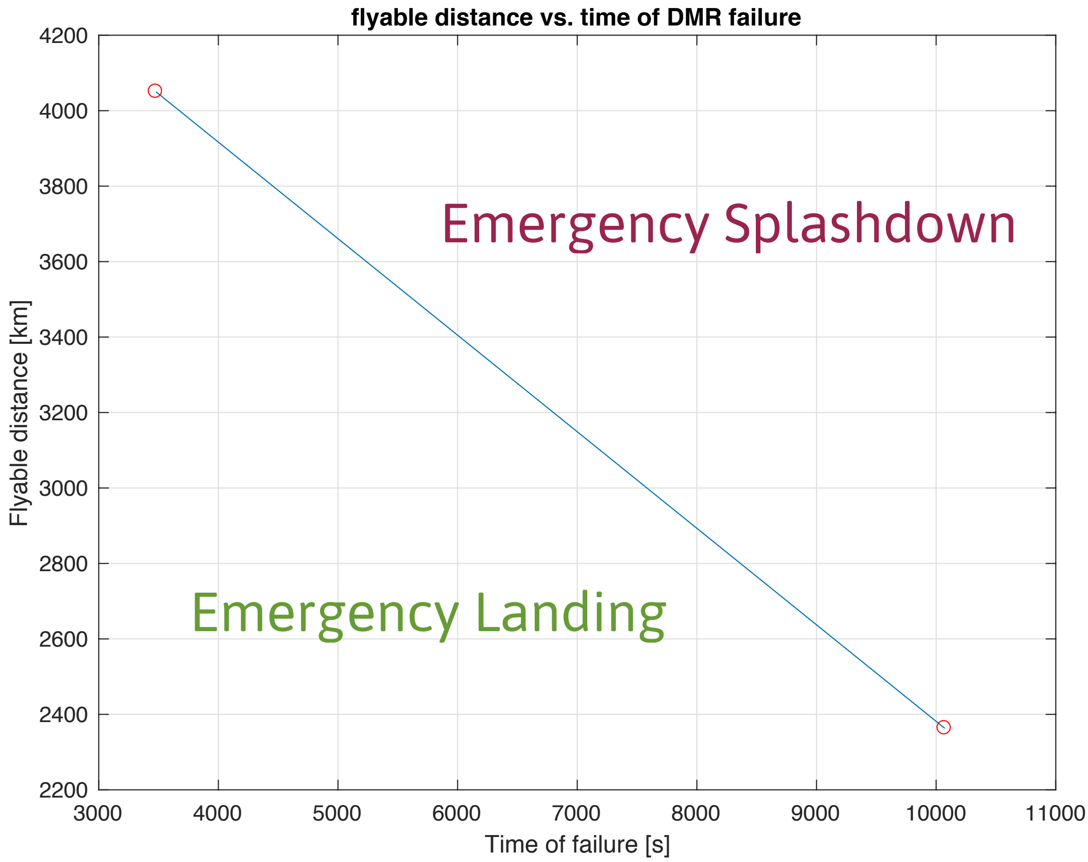


Figure 9.7. Flyable distance after failure *vs.* time on which a DMR failure occurs.

To put it differently, the flyable distance after failure is a function of the mission time at which the failure occurs according to the following equation:

$$d_{flyable} = d_{flyable_{t=0}} - \theta \cdot t_{mission} \tag{9.1}$$

Where:

- $d_{flyable}$ is the flyable distance after failure
- $d_{flyable_{t=0}} = 4940.2\,km$ is the intercept
- $t_{mission}$ is mission time at which the failure occurs

- $\theta = 0.2559\, km/s$ is the slope, representing the loss on flyable distance at each more second of mission at which the failure occurs

Other simulations performed by considering different mission time at which the failure occurs, demonstrated how actually the flyable distance as calculated in (9.1) and represented graphically in Figure 9.7 well reflects the simulation results. The flyable distance after failure at each simulation is calculated iteratively by considering the actual flight distance covered after failure until the vehicle touches the ground, after having performed descent, eventual subsonic cruise and final approach, without fuel on board.

Another important result of simulations is that post-failure phases, in which the ATR is used, were carried out by considering a throttle smaller than 0.16, leading at the conclusion that only one ATR engine is needed to perform mission abortion. Hence, in the very unfortunate case in which the DMR engine fails, and also 5 out of 6 ATR engines fail, the mission can be still safely aborted.

The above discussed analysis and the achieved results illustrated by (9.1) and Figure 9.7, lead to the important possibilities to predict, given a failure occurring at a certain mission time and given the distance to an eventual emergency airport, if an emergency landing can be performed, or if instead an emergency splashdown is necessary as mission abortion option. By comparing the flyable distance and the actual distance to a certain on ground airport, indeed, it can be said if the emergency landing can be performed or not.

Let us consider a circle in the map with radius equal to the flyable distance after failure and center coincident with the point of trajectory at which the failure occurs, all the airports included within the circle boundaries can be potentially reached by the vehicle in order to perform emergency landing. This concept is well described by Figure 9.8, showing a map representing all the airports close to the STRATOFLY MR3 trajectory during hypersonic cruise, as well as the trajectory itself and a series of circles related to the flyable distance after a failure occurs at a certain trajectory point. Figure 9.8, however, has to be intended as a qualitative representation since the circles dimensions can be not the same as calculated by (9.1).

It shall be noted that the flyable distance after failure also includes eventual flight distance covered for performing lateral maneuvers aimed to reach the emergency airport, therefore, the real flyable distance may be smaller or equal between the one described by (9.1) on the basis of the kind of lateral maneuver performed. It is improbable, for example, that the aircraft can reach an emergency airport that is behind the vehicle and exactly as far as the flyable distance: some propellant, in fact, is used for performing a 180^o turn with the consequence to decrease the effective flyable distance.

Let us focus the attention again to Figure 9.7 showing the flyable distance after failure as a function of the mission time at which the failure occurs, it can be seen that the graph is divided into two regions:

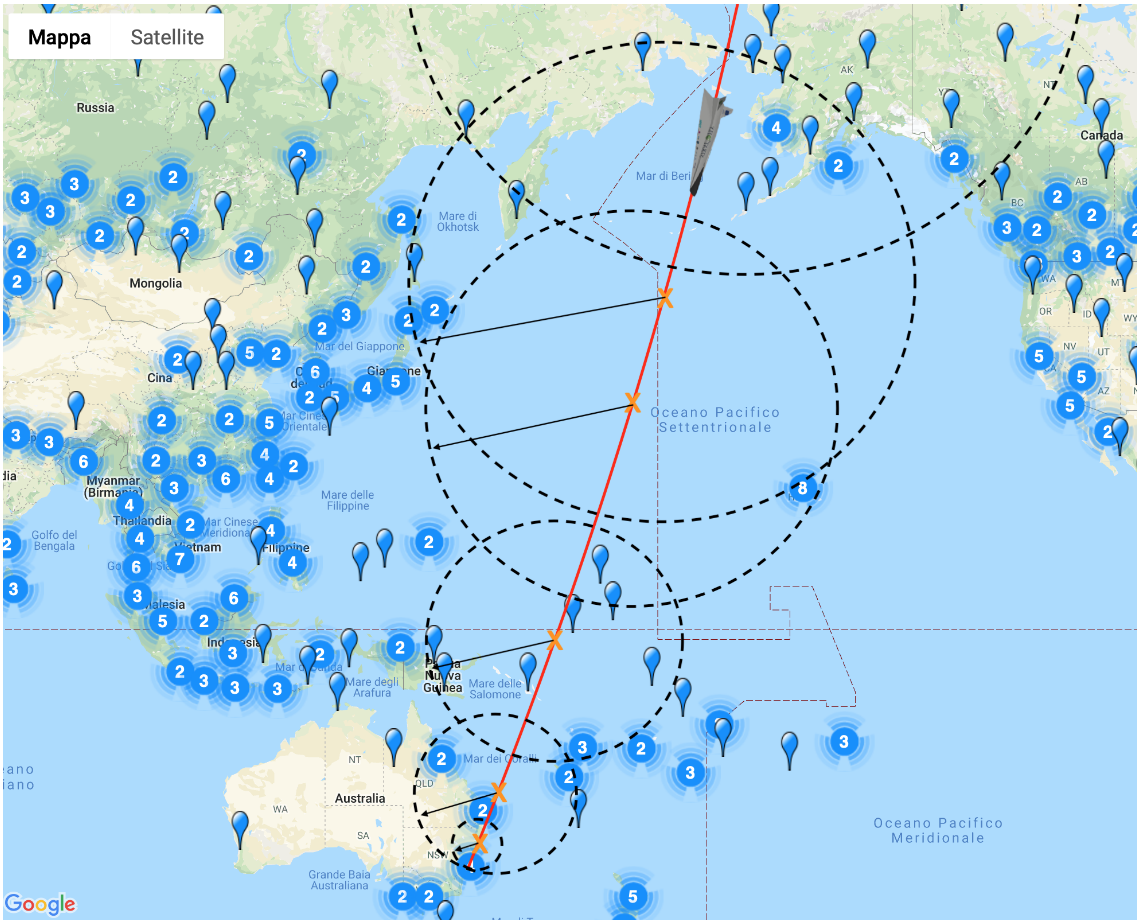


Figure 9.8. Map of airports close to STRATOFLY MR3 trajectory potentially reachable after a DMR failure. Qualitative illustration.

- Top right corner: Emergency Splashdown
- Bottom left corner: Emergency Landing

Those two regions are intended to describe the fact that, considering a failure occurring at a certain mission time and given an airport chosen by the pilot for performing emergency landing, if the distance from the failure point to the emergency airport is under the blue line, then it means that it is smaller than the flyable distance and an emergency landing can be performed. If, otherwise, the distance to the emergency airport is over the blue line, then it means that it is higher than the flyable distance and the emergency landing cannot be completed with the consequence of a splashdown at a certain distance from the coast of the country inn which the airport is.

As it will be better discussed in the following subsections, after a failure to the DMR occurs the pilot should always chose an emergency airport on which to perform emergency landing also in the case in which the airport cannot be reached. An eventual splashdown close to the coast of a certain country that the pilot wanted to reach in out of nominal conditions, is always better than a splashdown occurring in the middle of the pacific ocean in terms of facilitating search and rescue operations.

According to the out of nominal scenarios classification reported in Chapter 6 Figure 6.3, and considering a failure occurring during hypersonic cruise, the emergency landing is addressed as *Scenario 12*, while the emergency splashdown is addressed as *Scenario 13*.

In the next subsections, the simulation of the following specific out of nominal scenarios will be discussed:

- *Scenario 12*: Emergency Landing to Sapporo New Chitose Airport, Japan, after a failure occurs at 5832 s mission time (Section 9.3.2)
- *Scenario 13*: Emergency Splashdown near to Tokyo, Japan, after a failure occurs at at 6356 s mission time (Section 9.3.3)
- *Scenario 12*: Emergency Landing to Honolulu Airport, Hawaii, after a failure occurs at 6356 s mission time (Section 9.3.4)

The simulation of the above listed scenarios has the double aim to provide simple examples about the discussion carried out until now, as well as to open further discussions about relevant points. The last two scenarios in the list, indeed, will highlight the importance to chose the correct airport where to perform the emergency landing: for the same failure occurring at the same mission time, if the pilot choses to go to Tokyo Haneda Airport the vehicle can't reach the airport and it has to perform splashdown near Japanese coast, if otherwise the pilot choses to go to Honolulu Airport, then the emergency landing can be properly completed.

Further discussion, however, including graphical description of the different scenarios, will be taken forward in the respective subsections.

9.3.2 Emergency Landing to Sapporo New Chitose, Japan

A failure affecting the dual mode ramjet engine occurs at 5832 s after departure, when the aircraft is performing hypersonic cruise over the pacific ocean, slightly south of the Bering Strait. A reserve of 61.3 tons of fuel is still available on board and, according to (9.1), the flyable distance is about 3447 km.

At this point, the pilot shall chose an airport on which to perform an emergency landing. One of the closest airport results to be Sapporo New Chitose International Airport , Japan, of which the geographical coordinates are reported in Table 9.1.

The pilot, therefore, performs quickly a right turn in order to align flight trajectory with the emergency airport, then he reactivates the ATR engines when possible and drives the aircraft towards Sapporo hoping to have enough fuel on board to reach the airport, to perform emergency landing and save passengers life.

Figure 9.9 shows how the distance from the failure point to New Chitose Airport, represented as a green triangle in the graph, is located on the bottom with respect to the actually flyable distance at the same time of failure. Therefore, it can be stated that an emergency landing can be effectively taken forward with success.

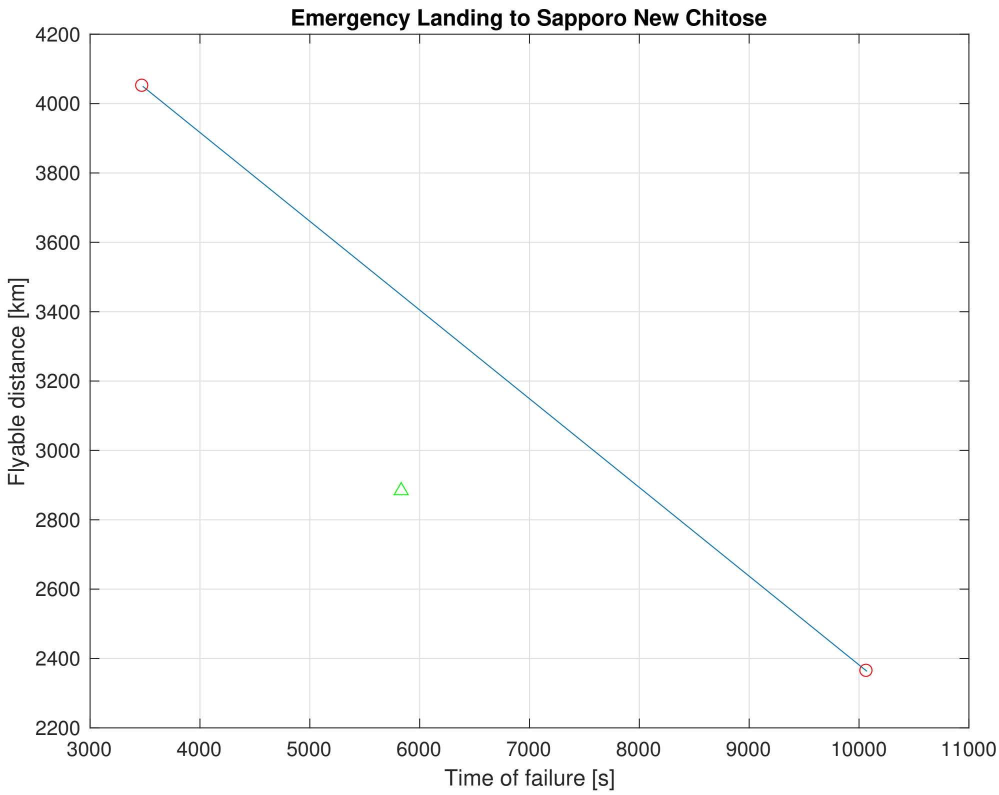


Figure 9.9. Flyable distance after failure *vs.* time on which a DMR failure occurs and distance from failure point to Sapporo New Chitose Airport (green triangle) at mission time $t = 5832\,s$.

The simulation, in fact, demonstrated how an emergency landing to New Chitose Airport is in principally feasible as illustrated in the following Figures. The point of failure is highlighted with an orange "X" in all the figures.

Figure 9.10 represents a complete view on the trajectory performed before and after failure. The line contours describe flight Mach number.

The 2D trajectory is represented in Figure 9.11, where it is possible to have a good view on the lateral maneuver performed prior to reach Sapporo New Chitose airport. The line contours describe flight altitude.

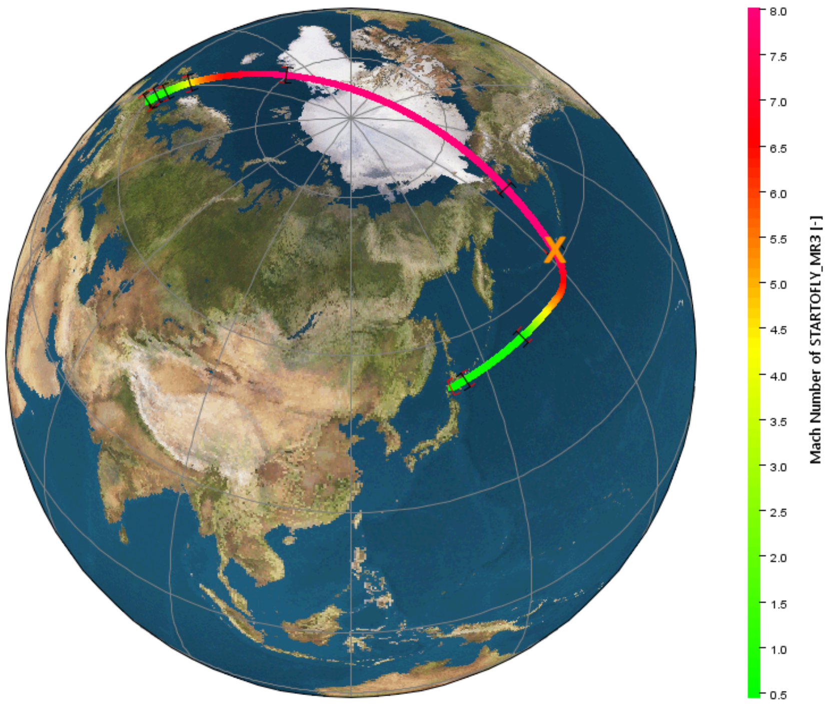


Figure 9.10. Satellite view on the Emergency Landing to Sapporo New Chitose Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 5832\,s$.

Additional information for the understanding of the scenario are provided by Figure 9.12, representing a 3D view on the emergency subsonic cruise, final approach and emergency landing in Sapporo looking in northern direction. The figure shows how the subsonic cruise is carried out at about constant altitude in order to cover distance before to reach the emergency airport.

This out of nominal scenario has demonstrated the validity of the analysis performed in Section 9.3.1 about flyable distance after DMR failure. Moreover, it is important to consider that the emergency landing is only possible when the pilot choses correctly an emergency airport and performs proper lateral maneuvers as soon as possible. Decision delay, in fact, can lead to the impossibility to reach an airport for emergency landing with the consequence of an emergency splashdown to be performed, this is the case of the out of nominal scenario described in the next section.

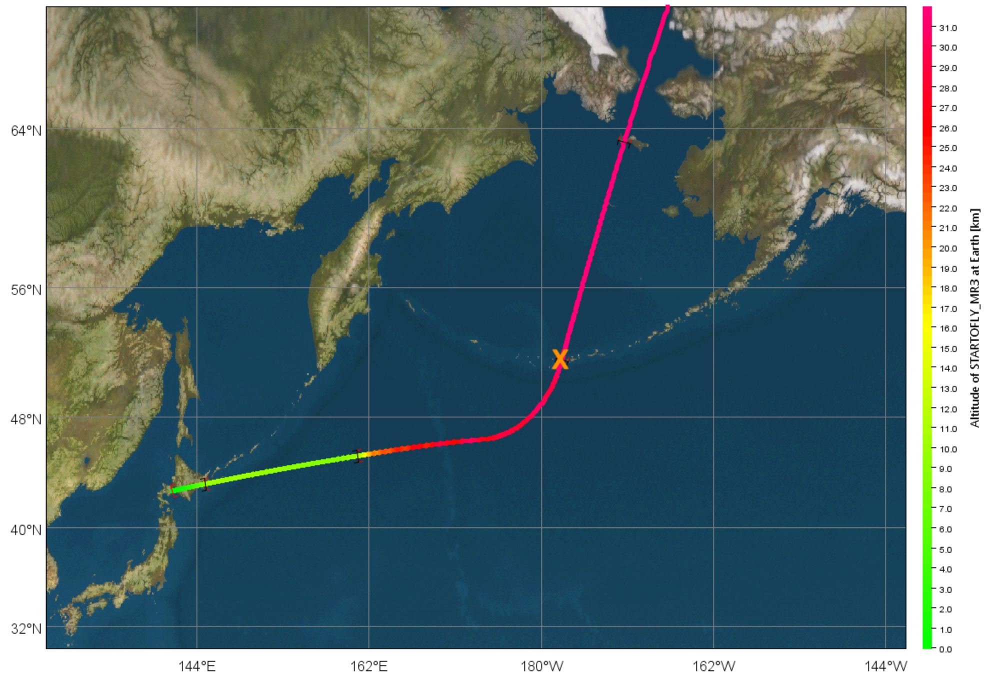


Figure 9.11. 2D trajectory of an Emergency Landing to Sapporo New Chitose Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 5832\,s$.

9.3.3 Emergency Splashdown near Tokyo

A failure affecting the dual mode ramjet engine occurs at $6356\,s$ after departure, when the aircraft is performing hypersonic cruise over the pacific ocean in the north hemisphere. A reserve of 53.3 tons of fuel is still available on board and, according to (9.1), the flyable distance is about 3314 km.

At this point, the pilot shall chose an airport on which to perform an emergency landing. The situation is not easy to be assessed since there are only airports at a distance greater than 3000 km. Two possibilities are Tokyo Haneda, Japan, 3390 km far, and Honolulu, Hawai, 3200 km far. The geographical coordinates of the two airports are reported in Table 9.1. For some reason, the pilot decides to perform a right turn soon after failure and to go to Tokyo Haneda.

The distance between failure point and Tokyo Haneda airport is illustrated graphically in Figure 9.13.

The pilot performs a right turn in order to align flight trajectory with the emergency airport, then he reactivates the ATR engines when possible and drives the aircraft towards Tokyo hoping to have enough fuel on board to reach the airport, to perform emergency landing and save passengers life.

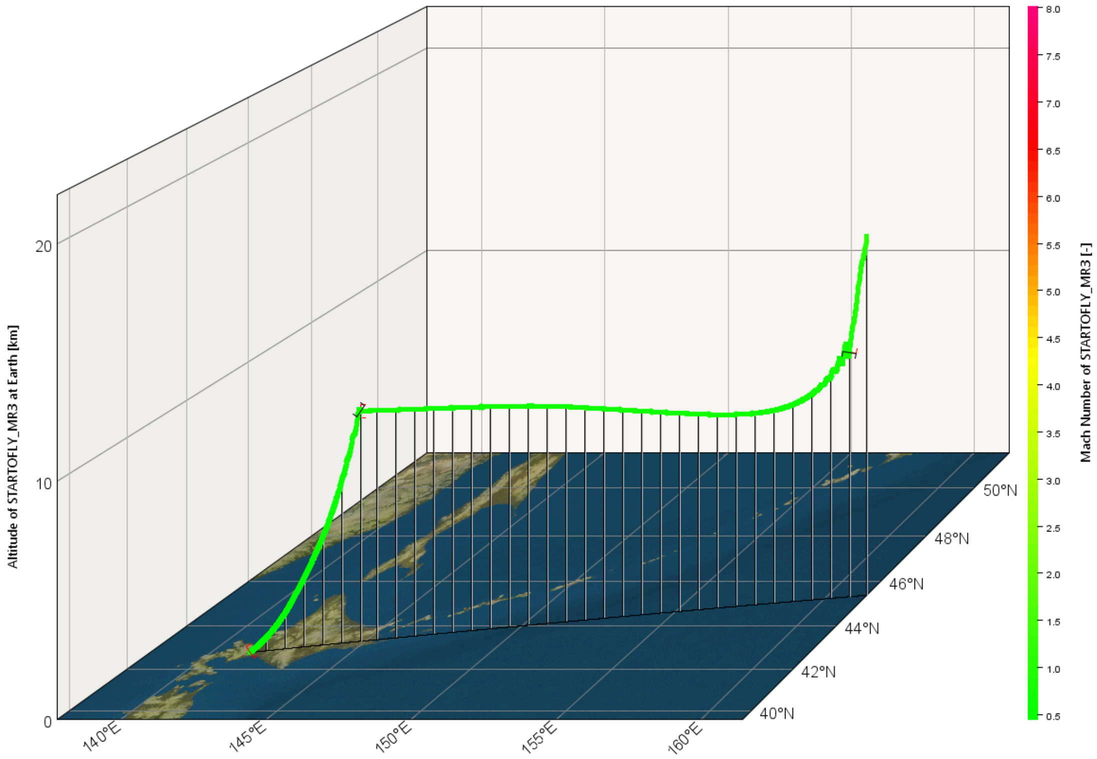


Figure 9.12. Emergency Landing to Sapporo New Chitose Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 5832\,s$. 3D view looking in northern direction.

Unfortunately for the pilot, Figure 9.14 shows how the distance from the failure point to Tokyo Haneda Airport, represented as a purple triangle in the graph, is located above the actually flyable distance at the same time of failure. Therefore, it can be stated that the emergency landing cannot be completed and, instead, an emergency splashdown near Japanese coast shall be performed.

The simulation, in fact, demonstrated what stated above as illustrated in the following Figures. The point of failure is highlighted with an orange "X" in all the figures.

Figure 9.15 represents a complete view on the trajectory performed before and after failure. The line contours describe flight Mach number.

The 2D trajectory is represented in Figure 9.16, where it is possible to have a good view on the lateral maneuver performed trying to reach Tokyo Haneda airport. The line contours describe flight altitude.

Additional information for the understanding of the scenario are provided by Figure 9.17, representing a 3D view on the emergency subsonic cruise, final approach and emergency splashdown looking in eastern direction.

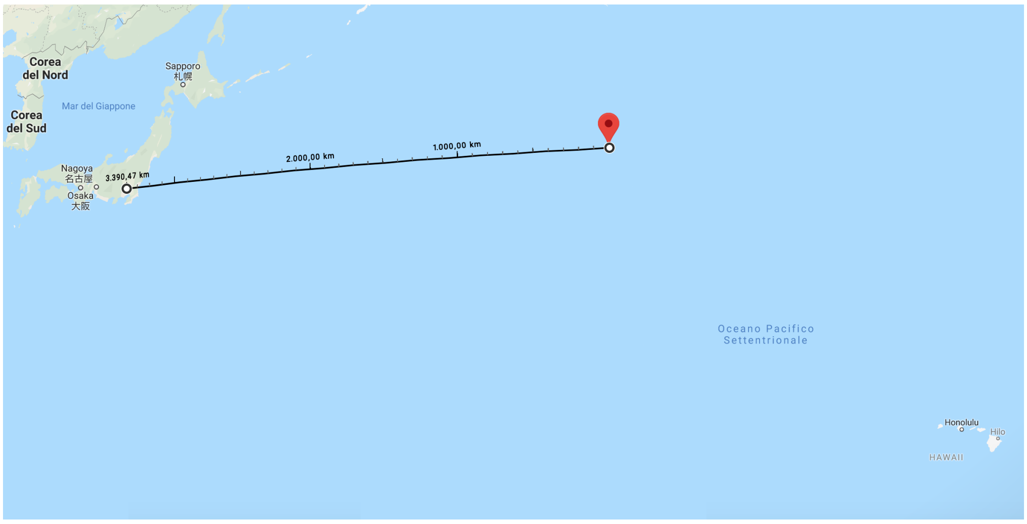


Figure 9.13. Illustration of distance from failure point to Tokyo Haneda Airport at mission time $t = 6356\,s$.

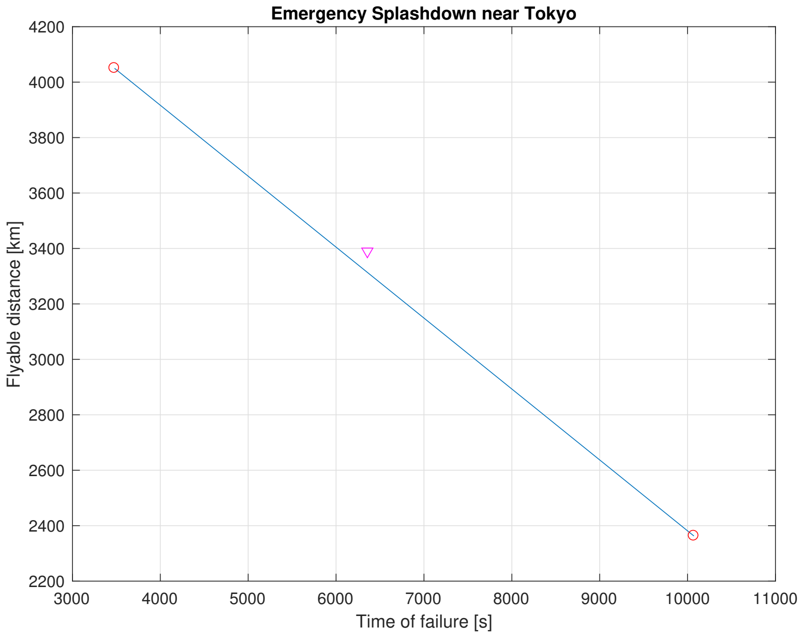


Figure 9.14. Flyable distance after failure *vs.* time on which a DMR failure occurs and distance from failure point to Tokyo Haneda Airport (purple triangle) at mission time $t = 6356\,s$.

Since, however, the splashdown happen close to Japanese coast, it is possible to assume that the safe and rescue operations can be taken forward without particular

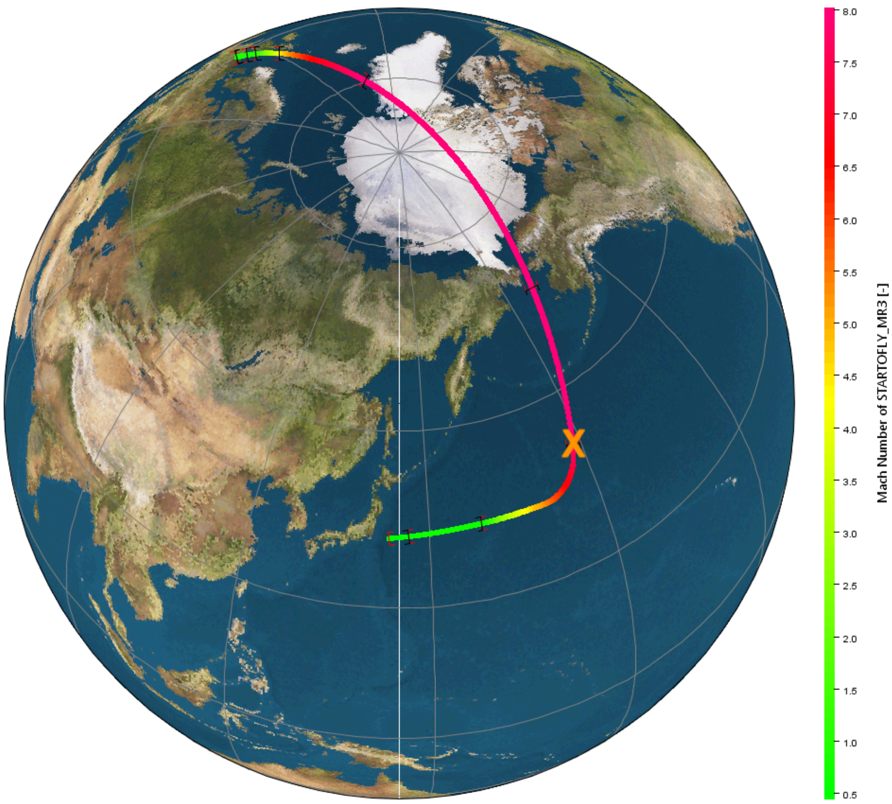


Figure 9.15. Satellite view on the Emergency Splashdown near Tokyo after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$.

problems. The fact that the pilot has decided to try to reach an emergency airport after failure, has led to the better safe and rescue operations organisations instead of the case in which the splashdown takes places in the middle of the Pacific Ocean. Therefore, the scenario simulated in this Section shows how it is alway convenient to try to reach an emergency airport, because, also if it cannot be reached, en eventual splashdown happens closer to land leading at easier safe and rescue operations.

Nevertheless, would have been the scenario consequences different if the pilot would have decided to fly towards Honolulu, instead of Tokyo, after failure? The answer is given in the next Section.

9.3.4 Emergency Landing to Honolulu, Hawaii

A failure affecting the dual mode ramjet engine occurs at $6356\,s$ after departure, when the aircraft is performing hypersonic cruise over the pacific ocean in the north

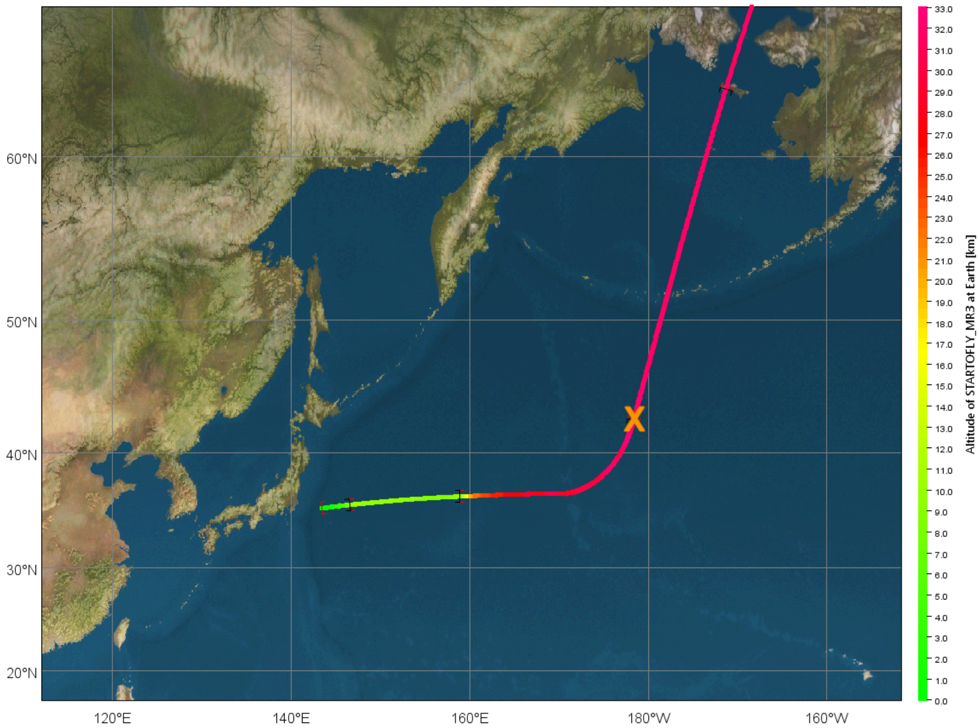


Figure 9.16. 2D trajectory of an the Emergency Splashdown near Tokyo after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$.

hemisphere. A reserve of 53.3 tons of fuel is still available on board and, according to (9.1), the flyable distance is about 3314 km.

At this point, the pilot shall chose an airport on which to perform an emergency landing. The situation is not easy to be assessed since there are only airports at a distance greater than 3000 km. Two possibilities are Tokyo Haneda, Japan, 3390 km far, and Honolulu, Hawai, 3200 km far. The geographical coordinates of the two airports are reported in Table 9.1. The pilot decides to perform a left turn soon after failure and to go to Honolulu in order to perform an emergency landing.

The distance between failure point and Honolulu airport is illustrated graphically in Figure 9.18.

The pilot performs a left turn in order to align flight trajectory with the emergency airport, then he reactivates the ATR engines when possible and drives the aircraft towards the Hawaii hoping to have enough fuel on board to reach the airport, to perform emergency landing and save passengers life.

The pilot decision to reach Honolulu instead of Tokyo reveals to be the best decision. In fact, Figure 9.19 shows how the distance from the failure point to Tokyo Haneda Airport, represented as a green triangle in the graph, is located under the

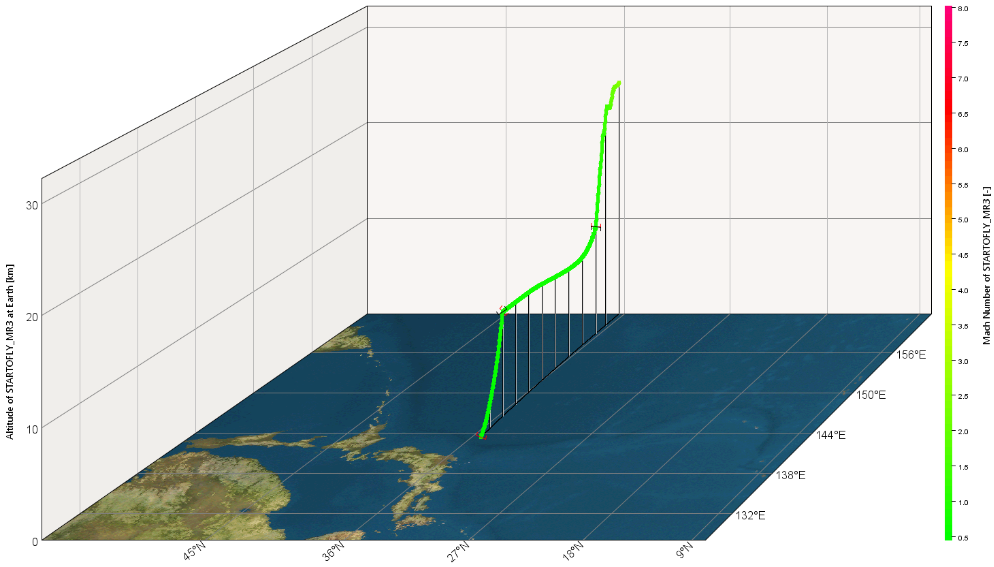


Figure 9.17. Emergency Splashdown near Tokyo after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$. 3D view looking in eastern direction.

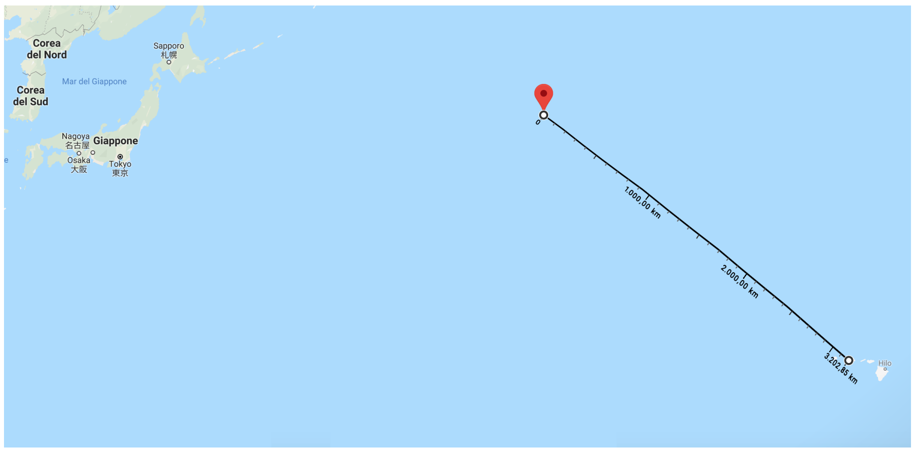


Figure 9.18. Illustration of distance from failure point to Honolulu Airport at mission time $t = 6356\,s$.

actually flyable distance at the same time of failure. Therefore, it can be stated that an emergency landing can be effectively taken forward with success.

The simulation, in fact, demonstrated how an emergency landing to Honolulu Airport is in principally feasible as illustrated in the following Figures. The point of failure is highlighted with an orange "X" in all the figures.

Figure 9.20 represents a complete view on the trajectory performed before and

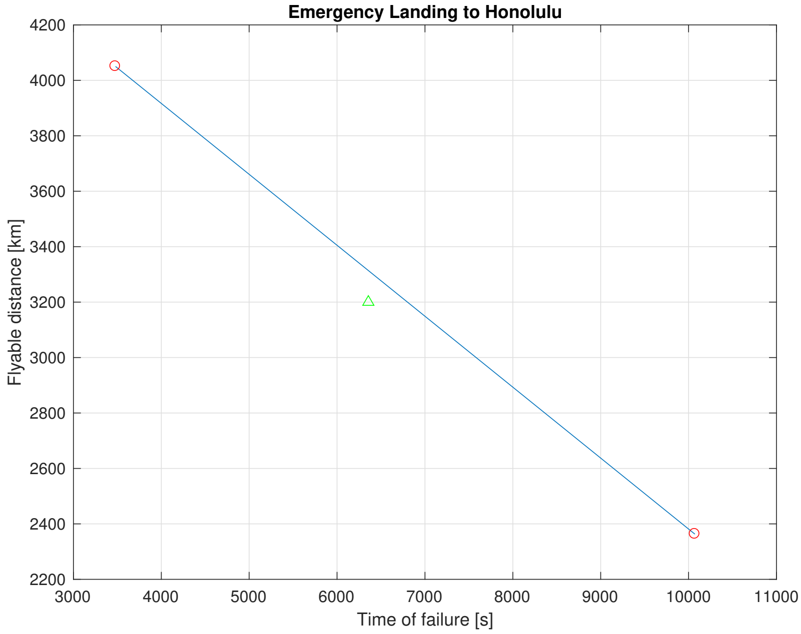


Figure 9.19. Flyable distance after failure *vs.* time on which a DMR failure occurs and distance from failure point to Honolulu Airport (green triangle) at mission time $t = 6356\,s$.

after failure. The line contours describe flight Mach number.

The 2D trajectory is represented in Figure 9.21, where it is possible to have a good view on the lateral maneuver performed prior to reach Honolulu airport. The line contours describe flight altitude.

Additional information for the understanding of the scenario are provided by Figure 9.22, representing a 3D view on the emergency subsonic cruise, final approach and emergency landing to Honolulu looking in eastern direction.

In addition to validate the flyable distance analysis performed in Section 9.3.1, the out of nominal scenario described in the present Section remarks again the importance for the pilot to take the right decision about what emergency airport to reach for performing emergency landing after a failure to the DMR occurs.

Nevertheless, the analysis performed in Section 9.3.1, and validated by the out of nominal scenarios simulations above described, about flyable distance after DMR failure, might represents a useful tool to decrease human factor in the decision of an emergency airport to be reached after failure. If, in fact, the reachable airports as a function of the mission time of failure are well defined at beginning of the mission for the overall trajectory, the pilot could gain advantage from such kind of knowledge in order to improve decision making.

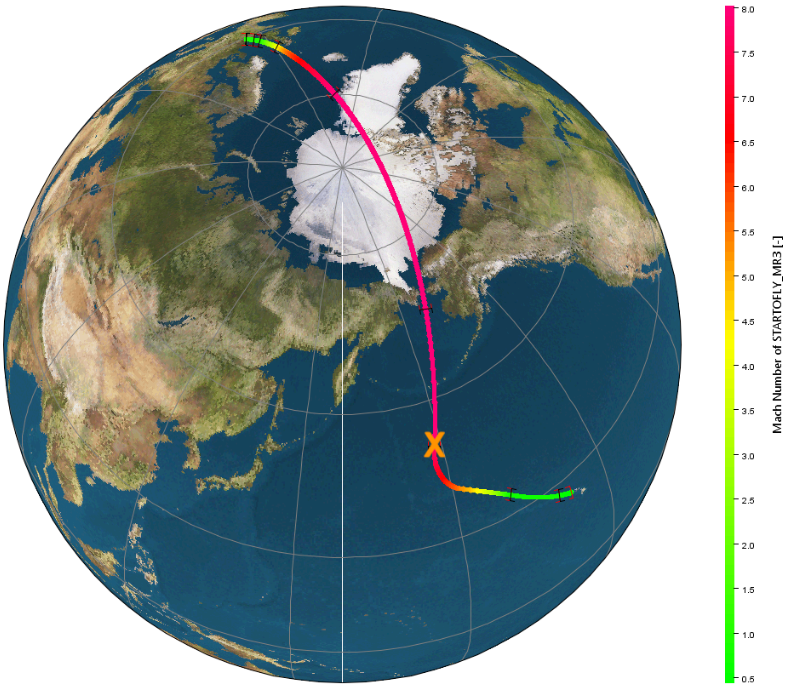


Figure 9.20. Satellite view on the Emergency Landing to Honolulu Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$.

9.4 Considerations and Discussion

In this Chapter several out of nominal scenarios have been considered and simulated via ASTOS software. The aim of those out of nominal scenarios simulation and assessment is not only about the presentation of some isolated examples that only apply to a specific mission and specific flight conditions, but instead the main contribution of the discussion carried out in this Chapter should be related to general results to be applied beyond the specific case.

In fact, it is not possible to take into account all the specific mission routes and to evaluate the consequence of all the failures that can occur at each point of trajectory. It is, instead, necessary to develop major knowledge about the capability of the system to react to a critical event and to achieve general results to be used to predict the consequence of a certain failure and the best mission abortion option to be performed.

With the purpose to summarise relevant points that emerge from the out of nominal scenarios simulation and assessment performed in this Chapter, the most important results are listed in the following by considering a generic perspective, and thus not applied to a specific case.

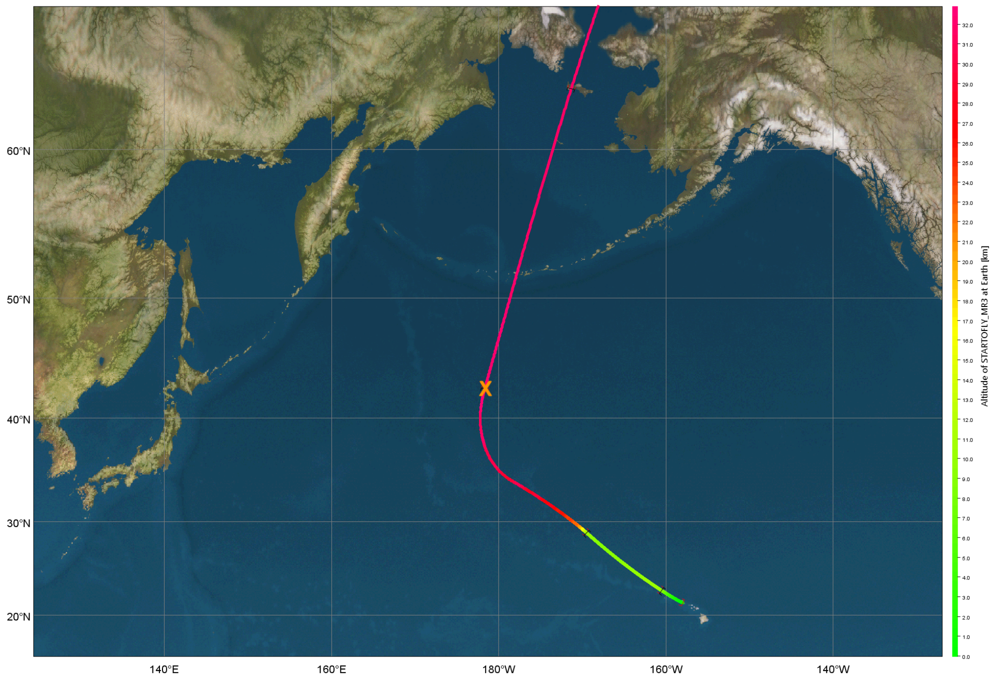


Figure 9.21. 2D trajectory of an Emergency Landing to Honolulu Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$.

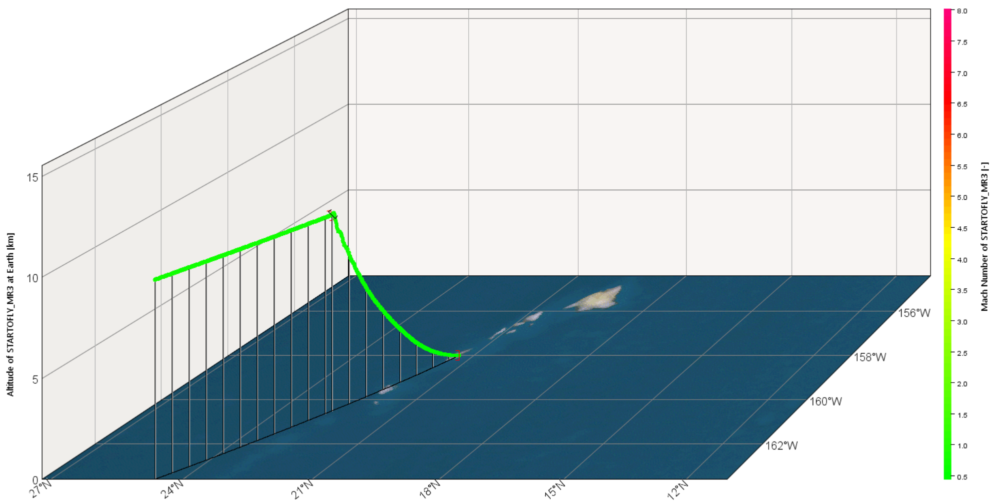


Figure 9.22. Emergency Landing to Honolulu Airport after a failure occurs during hypersonic cruise to the DMR at mission time $t = 6356\,s$. 3D view looking in eastern direction.

- A failure affecting the overall ATR performances, thus all the 6 engines, represents a critical event with potential catastrophic consequences. Hence, such kind of situation must be absolutely avoided by considering proper risk mitigation strategies, such as redundancies and high reliability levels. Moreover, this situation is more critical if occurs soon after take off or early subsonic climb. A catastrophic event might be avoided if reachable emergency airports are present and if fuel dumping is performed.
- The case of a failure affecting 5 out of 6 ATR engines, thus only one engine available after failure, is always manageable by the system. One engine, in fact, is enough to perform emergency subsonic cruise, final approach and landing, as far as allowed by the fuel on board after failure. Hence, if the failure occurs in the initial mission phases since there is, with high probability, enough fuel on board to reach an eventual emergency airport, whilst there might be more problems in performing an emergency landing if the failure occurs when the fuel reserve is limited, in this case an emergency splashdown can be performed.
- If a failure occurs to the DMR unit, therefore when the aircraft is flying at hypersonic speed, emergency descent, subsonic cruise, final approach and emergency landing or splashdown can be performed as mission abortion by considering the reactivation of the ATR engines, assumed to be not involved in the failure.
- The flyable distance after DMR failure depends on the available fuel on board after failure. The flyable distance can be calculated as a function of mission time at which the failure occurs. In particular, the flyable distance decreases linearly with mission time if a failure occurs during hypersonic cruise.
- Emergency landing can be performed if the distance between DMR failure point and emergency airport is smaller or equal than the flyable distance.
- Emergency splashdown shall be performed if the distance between DMR failure point and an eventual airport is greater than the flyable distance.
- It is always better to try to reach an airport for emergency landing after DMR failure, instead of performing emergency landing to the middle of the ocean. In fact, also if the emergency landing cannot be performed because of a lack of fuel, the eventual emergency splashdown is performed closer to land in order to make it easier to carry out search and rescue operations.

Another consideration to be done regards the cabin and cockpit detachment mission abortion option. Despite this option has been considered for out of nominal scenarios identification and classification performed in Chapter 6, the out of nominal scenarios simulation and assessment performed in the present Chapter have demonstrated that this option is never necessary when considering failures affecting the performances of the propulsive subsystem since an emergency landing or splashdown are always feasible if at least 1 ATR engine is available.

The cabin detachment might be necessary to avoid an inevitable catastrophic event, but the problem is that such kind of event is more probable to happen if a failure occurs at low altitudes, for example soon after take off or early subsonic climb, in which the cabin detachment cannot be performed because of a lack of space por parachuted descent and because of the vehicle structure falling on ground, resulting as an un-necessary option to be considered.

If other kind of failures, affecting not only the propulsion performances but also related to potential fire or explosion, are considered, then the cabin and cockpit detachment option can be re-evaluated. Anyway, technically speaking it would be easier to design subsystems and components with proper levels of reliability in such a way to avoid a complete loss of propulsion performances and potential fire and explosion, than to design a cabin and cockpit detachment system for a hypersonic cruiser.

However, the contribution of the work performed in this Thesis about out of nominal scenarios assessment is based on the assumption of considering propulsive subsystem related failure in terms of loss of propulsion performances. Other type of failure about other subsystems or related to potential fire and explosions were not considered and need further assessment to be carried out from who of competence within the STRATOFLY project.

Moreover, further analysis has to be performed about the flyable distance after DMR failure evaluation. In this Chapter, in fact, the flyable distance has been calculated (see Section 9.3.1) by taking into account the specific BRU-SYD trajectory. The specific equation parameters on the basis on which the flyable distance is evaluated may change on the basis of the actual hypersonic cruise duration and the propellant mass carried on board at take off. Anyway, the contribution of the results achieved by the analysis on flyable distance after failure carried out in this Chapter lies on the development of method and tools to be used to predict the capability of the system to reach or not an eventual emergency airport after a DMR failure occurs and to be applied, with proper consideration, for a generic STRATOFLY MR3 mission beyond the specific BRU-SYD case.

Conclusions and Discussion

As from June 2018, the EU funded STRATOFLY allowed several institutions across Europe to commonly build-up an established experience and know-how in the field of hypersonic civil transport. After one year of project activities, the STRATOFLY MR3 configuration as well as propulsive and aerodynamic characteristics were defined, and preliminary activities about environmental, social and economical aspects were taken forward as well. The internal configuration and the subsystem design, however, is still on going and further assessment about mass and power budgets have to be carried out.

At this stage of design of such kind of complex aerospace product, system engineering activities are of extreme importance both for the coordination of different design activities carried out by different participants as well as for further assessment on the operability of an innovative vehicle such as STRATOFLY MR3.

In the field of system engineering, this Thesis gives a contribution to the project in terms of Concept of Operations (ConOps) analysis and trajectory simulation. Among the different outcomes that were obtained and described in this document there are the conceptual Design Reference Mission, the modes of operations definition and the operability assessment of the different subsystems during the mission as well as the implementation of logical decomposition tools, such the FFBDs and N2 analysis for the development of certain operational procedures. The contents of the study, carried out by analytical approach, served as input for the reference mission modelling and simulation via the *ASTOS*® 9 Software.

Taking into account the reference Brussels-Sydney mission, two different trajectory options were considered and simulated on the basis of the different kind of final approach prior to landing in Sydney to be performed: Overland final approach (Option A) and Oversea final approach (Option B).

As a result, it was shown that the BRU-SYD mission as a representation of an antipodal flight is in principally feasible, given the available vehicle layout as well as the databases implemented for describing propulsion and aerodynamic performances.

Moreover, Overland final approach resulted to be the best option in terms of travel time and overall fuel consumption, the BRU-SYD trajectory was in fact completed in 3h18m and 203.2 tons of liquid hydrogen were consumed in total.

On the other hand, Option B resulted in 3h35m travel time and overall 210.9 tons of fuel consumption, also if it revealed to be more respectful than Option A towards current regulations about high-speed flight over inhabited land.

As a result of this analysis, in fact, it was found that a non-negligible part of fuel is used for avoiding supersonic flight near inhabited land, in particular to perform the subsonic cruise leg prior to carry out supersonic acceleration and to perform eventual final approach leg above the ocean after having completed the descent phase and consequent deceleration from hypersonic to subsonic speed far from populated zones.

Thus, a trade off between regulations about high-speed flight and system mass budget shall be performed in order to assess the amount of fuel to be carried on board at take off. It is true, in fact, that the elimination of the subsonic cruise leg as well as the shortening of the final approach leg could lead to a reduction in fuel consumption up to about 15 tons, that represents a non-negligible fuel saving and a benefit in terms of mass budget. However, this is impossible to be accepted in terms of current regulations and therefore the above mentioned trade off has to be carried out and noise reduction solutions shall be investigated as well.

As part of the work carried out in this Thesis, a study about critical events and out of nominal conditions was also performed and let to the identification and classification of out of nominal scenarios related to possible failures affecting the propulsive subsystem during the mission. Different mission abortion options were identified and some out of nominal scenarios were simulated and assessed via the *ASTOS*® 9 Software with the aim to develop major knowledge about the capability of the system to deal with out of nominal conditions and to react to possible critical events.

As a result of this analysis about out of nominal scenarios, it was shown that only one out of 6 Air Turbo Rocket (ATR) engines available after failure is sufficient for performing emergency maneuvers and eventual emergency landing or splashdown, whilst a total loss of propulsion performances, thus zero engines available after failure, shall be in any case avoided, by considering proper risk mitigation strategies, because of the potential catastrophic consequences.

Moreover, considering a failure affecting the Dual Mode Ramjet (DMR) during hypersonic cruise, and assuming that the ATR is not affected by the same failure, it was shown that mission abortion can be performed by considering an emergency descent, ATR reactivation, emergency subsonic cruise, final approach and emergency landing to an eventual airport or otherwise emergency splashdown. The only limitation of such kind of procedure is represented by the available fuel on board. It was shown that the propellant mass decreases linearly during hypersonic cruise and so does the potentially flyable distance after a failure to the DMR occurs. This result serves as tool to predict the capability of the vehicle to reach an emergency airport for landing in out of nominal conditions. By comparing, in fact, the flyable distance after failure and the distance between failure point and emergency airport, it is possible to understand if an emergency landing could actually carried out, or if, instead, the vehicle shall perform emergency splashdown because of a lack of available fuel.

The out of nominal scenarios assessment has also highlighted the importance of performing eventual splashdown as much as possible close to land for facilitating search and rescue operations, as well as the importance for the pilot to carry out emergency maneuvers as quick as possible and to make the best decision about the reachable emergency airport since an incorrect decision making and a delay in performing emergency maneuvers could lead to transform a possible emergency landing into a necessary emergency splashdown.

The tools developed and the results achieved in this Thesis could be used to enhance further developments and assessment to be carried out within the STRATOFLY project. First of all, the propellant mass needed for completing the reference mission was iteratively found by simulations and further assessment about mass budget and actual capabilities of the system to store a certain amount of fuel on board need to be carried out. With this purpose, this Thesis helps to understand which possible modification in trajectory could be implemented with the aim to reduce fuel consumption and related consequences from a regulatory point of view.

Furthermore, the feasibility of the mission abortion procedure after DMR failure developed in this Thesis has to be further assessed taking into account possible heat flux related problems. It might be possible, in fact, that a DMR failure also affects the capability of the Thermal and Energy Management Subsystem (TEMS) to deal with high external temperatures, leading in this way to an eventual overheating during the emergency descent phase. This is, however, only a hypothesis and further analysis from who of competence shall be carried out.

Further assessment is also needed for the identification of other out of nominal scenarios taking into account a wide range of possible failures and other critical events affecting all the subsystems. The out of nominal scenarios analysis performed in this Thesis, in fact, is limited to possible failures affecting the propulsive subsystem performances and it is more about trajectory consequences than to system and passenger state of health after failure. The tools and results described in this document, however, provide a preliminary overview on out of nominal scenarios and could be used as starting point for further studies about critical events and out of nominal flight conditions.

In conclusion, the project STRATOFLY shows how the development a hypersonic vehicle concept is not only a series of complex tasks, but also an interesting and fascinating challenge to be faced thanks to the cooperation of several engineers and researchers from different institutions as well as the sum of small contributions from students among which this Thesis is intended to fit.

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