Development of a Methodology for Flight Data Reproduction in a Simulation/Visualization Software

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para o Carlitos, a Clarita e Sandrinha.

"Get your education, don't forget from whence you came."

Lin-Manuel Miranda, *Hamilton*

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Resumo

A segurança operacional é um pilar da aviação. De modo a garantir que as aeronaves são operadas com um nível desejável de segurança e que o risco é reduzido a um nível aceitável, os operadores têm um Sistema da Gestão da Segurança Operacional (SMS, *Safety Management System*) dedicado à gestão das estruturas, responsabilidades, políticas e procedimentos necessários. A monitorização de dados de voo (FDM, *Flight Data Monitoring*) enquadra-se no SMS de um operador.

O FDM é normalmente realizado com recurso à análise gráfica e estatística, mas animações de dados de voo, que consistem na representação dos dados num formato visual dinâmico, podem também ser poderosas ferramentas de FDM. O objetivo desta tese é desenvolver uma ferramenta de animação de dados de voo baseada no simulador X-Plane para ser usada na Portugália.

As animações são alimentadas com dados do Gravador de Acesso Rápido (QAR, *Quick Access Recorder*) a bordo da aeronave. Os parâmetros são submetidos a um processo de conversão que cria um ficheiro formatado de acordo com as especificações do X-Plane. Depois, correm-se as animações no software de simulação, permitindo uma análise completa e imersiva dos eventos.

Concluiu-se que estas animações reproduzem os dados como esperado, apesar de o X-Plane apresentar algumas limitações em termos de introdução de dados, que resultam em inconsistências ou simplificações. Não obstante, as animações mostraram-se úteis na análise de eventos, fornecendo um meio rápido, eficiente e dinâmico para representar os dados de voo.

Palavras-chave: Monitorização de Dados de Voo, Gravador de Acesso Rápido, *X-Plane*, animação de dados de voo.

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Abstract

Safety is a pillar of aviation. To ensure that aircraft are operated with a desirable level of safety and the risk is reduced to an acceptable level, operators have a Safety Management System (SMS) dedicated to managing the necessary structures, responsibilities, policies and procedures. Flight Data Monitoring (FDM) falls within an operator's SMS.

FDM usually relies on graphical and statistical analysis, but flight data animation, consisting of the representation of the flight data in a dynamic visual format, can also be a powerful FDM tool. The objective of this thesis is to develop a flight data animation tool based on X-Plane to be used at Portugália.

The animations are fed with data from the airborne Quick Access Recorder (QAR). The parameters undergo a conversion process that creates a file formatted according to X-Plane's specifications. Then, the animations are run on the simulation software, allowing for a thorough and immersive analysis of the events.

It was found that these animations reproduce the flight data as expected, although X-Plane presents some limitations in terms of data input, which result in inconsistencies or simplifications. Nevertheless, the animations proved useful in the analysis of events, as they provide a fast, efficient and dynamic medium to represent the flight data.

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Glossary

A/T	Auto-Throttle
AGS	Analysis Ground Station
ALoSP	Acceptable Level of Safety Performance
ARINC	Aeronautical Radio, Incorporated
ARL	Aeronautical Research Laboratory
ASCB-D	Avionics Standard Communications Bus, Version D
BI	Business Intelligence
CDI	Course Deviation Indication
CSV	Comma-Separated Values
CVR	Cockpit Voice Recorder
DFDR	Digital Flight Data Recorder
DME	Distance Measuring Equipment
DME	*Direção de Manutenção e Engenharia*
DVDR	Digital Voice Data Recorder
EASA	European Union Aviation Safety Agency
EBT	Evidence-Based Training
EGT	Exhaust Gas Temperature
EICAS	Engine Indicating and Crew Alerting System
EPR	Engine Pressure Ratio
EU-OPS	European Union regulations for the operation of commercial air transport
EUROCAE	European Organisation for Civil Aviation Equipment
FAF	Final Approach Fix
FDAU	Flight Data Acquisition Unit
FDA	Flight Data Analysis
FDM	Flight Data Monitoring
FDR	Flight Data Recorder
FDX	Flight Data Exchange
FD	Flight Director

FMU	Flight Memory Unit
FOQA	Flight Operational Quality Assurance
GAIN	Global Aviation Information Network
GPWS	Ground Proximity Warning System
GS	Glide Slope
HDG	Heading
HUD	Head-Up Display
I/O	Input/Output
IAS	Indicated Airspeed
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
ISA	International Standard Atmosphere
ITT	Interstage Turbine Temperature
ITU	International Telecommunication Union
JAR-OPS	Joint Aviation Requirement for the operation of commercial air transport
KMZ	Keyhole Markup language Zipped
LAN	Local Area Network
LNAV	Lateral Navigation
LOC	Localizer
MAU	Modular Avionics Unit
MFD	Multi-Function Display
MLS	Microwave Landing System
MSL	Mean Sea Level
MTOW	Maximum Takeoff Weight
NAVAID	Navigational Aid
NDB	Non-Directional Beacon
OBS	Omni Bearing Selector
PCMCIA	Personal Computer Memory Card International Association
PFD	Primary Flight Display
QAR	Quick Access Recorder
RPM	Revolutions per minute
SARPs	Standards and Recommended Practices
SAT	Static Air Temperature
SID	Standard Instrument Departure
SMS	Safety Management System
SOP	Standards and Operating Practices

STAR	Standard Arrival Route
TCAS	Traffic Collision Avoidance System
TO/GA	Take-off/Go Around
TOT	Turbine Outlet Temperature
ULB	Underwater Locator Beacon
UTC	Coordinated Universal Time
VNAV	Vertical Navigation
VOR	Very High Frequency Omnidirectional Range

Chapter 1

Introduction

This chapter defines the motivation that drives this thesis work, introducing the topics that will be discussed in later chapters, their relevance in the context of this work and their legal framework. Then, the objectives of the thesis are listed and the thesis outline is presented.

1.1   Motivation

In a world where consumers and companies demand shorter transportation times and, consequently, faster and more efficient means of transportation, the aviation industry has plenty of opportunities to grow and thrive. However, the success of the operation of an airline depends not only on its economical outcome, but also on making sure it is done in the safest way possible. In fact, flight safety is one of the pillars of an airline's operation. As such, since the early days of aviation, international and local authorities have enforced laws, requirements and standards that regulate flight operations and ensure their safety. As a result, aviation is nowadays one of the safest means of transportation with an accident rate per million departures of 2.9 [1] and a fatal accident rate per million flights of 0.11 [2], regarding commercial operations in 2019.

The International Civil Aviation Organization (ICAO) defines safety in *Annex 19 to the Convention on International Civil Aviation* as "the state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level" [3]. In order to make sure that level is met, ICAO also stipulates, in *Annex 6*, that operators should implement a flight data analysis program as a part of their safety management system (SMS) if their aircraft have a certificated take-off mass in excess of 27 000 kg [4]. The objectives of an SMS are the identification of safety hazards and the implementation of adequate measures that guarantee the desired safety performance. To assist operators in implementing flight data analysis programs, ICAO has also developed the *Manual on Flight Data Analysis Programmes (FDAP)*, which describes how an

effective FDAP should be established to help airlines achieve the required safety levels [5].

In Europe, the standards defined in JAR-OPS 1 that regulate the operation of aircraft have been transposed into European law, originating the EU-OPS 1, published in the *Official Journal of the European Union* in 2008. The EU-OPS 1.037 defines and requires the establishment and maintenance of a flight safety program, including a flight data monitoring (FDM) program in accordance with ICAO Annex 6 [6]. In the United States, in 2004, the Federal Aviation Administration (FAA) issued the Advisory Circular 120-82 to provide guidance on the development of Flight Operational Quality Assurance (FOQA) programs, which are analogous to the FDM programs in use in Europe, although not mandatory [7].

The safety department of air operators is responsible for the analysis of events and occurrences in daily activities that concern the safety of their operation. This department works towards the detection of risks and the implementation of adequate measures to mitigate them. Under the aforementioned legislation and documentation, airlines throughout the world have been implementing flight data monitoring programs, with the purpose of achieving higher levels of safety in their operations. These FDM programs employ quick access recorders (QAR) to retrieve hundreds of aircraft performance parameters and provide easy and quick access to the data. The proper contextualization and interpretation of this information are fundamental to a profitable FDM program, but also pose a challenge to safety departments.

Flight data can be represented in a variety of different formats, particularly time-series graphs and cockpit and aircraft simulations [5]. On the one hand, time-series graphs are useful in the representation of the evolution of data over a period of time and are advantageous to the numerical estimation and prediction of trends and future data [8]. Nevertheless, they usually do not allow the visualization of the interactions between different sets of parameters and are generally harder to interpret without a context. On the other hand, modern flight simulating software that allows the input of external data may prove to be useful in the visualization of QAR data, because it allows the reconstruction of a flight. This way, every event, warning and instrument reading can be reproduced and interpreted in its context.

This type of technology can be used not only by the safety department of airlines for data monitoring purposes, but also by their training department to acquaint pilots with both typical and atypical operations and also in crew debriefings to review events during flights and the crew's response to them.

1.2   Objectives

The objective of this thesis is to develop a methodology that allows the QAR data to be imported into a flight simulation software, within the scope of the flight data monitoring program employed by Portugália's safety department. The final product should be a program that receives QAR data, rearranges it into a readable file by the flight simulator and inputs that file into the simulation software to allow the reconstruction and visualization of flight data in virtual reality. In the end, the resulting program should

be tested and validated with both simulated and real flight data.

In order to develop the desired product and achieve the main goal of this dissertation, the development process follows the steps listed below:

1. Evaluation the QAR data frame, with the purpose of determining and extracting the relevant data to be imported into the simulation.

2. Analysis of the requirements of the simulation software regarding the input of flight data and the structure of the file containing that data.

3. Development of a methodology that routinely converts the QAR data into a readable format by the simulation software and loads it into the program to run the flight simulation.

4. Validation of the developed process using test cases, with data from actual flights performed by the airline.

1.3   Literature Review

The research developed in the course of this thesis work is heavily supported by the regulations and recommendations issued by aviation authorities, such as ICAO and the European Aviation Safety Agency (EASA).

At the time of writing, ICAO has produced nineteen Annexes to the *Convention on International Civil Aviation*, with the purpose of facilitating the development of standards to be adopted by air operators worldwide. Each Annex concerns a particular aspect of civil aviation. The two most relevant Annexes for the development of this work are *Annex 6 - Operation of Aircraft* and *Annex 19 - Safety Management*. The former has been written with the aim of defining criteria for efficient and safe operations. It covers a wide range of aspects of an operation, from equipment and documents to maintenance and flight crew. The concepts of Safety Management System and Flight Data Analysis (FDA) are also first introduced in *Annex 6*, but are further developed in *Annex 19*. In particular, the latter integrates information and recommendations from existing annexes regarding safety management systems and the activities it comprises, namely the collection, analysis and protection of safety data. As such, this information serves as the foundation for the development of this thesis work.

ICAO also produces manuals, which include further explanations of the standards and recommended practices (SARPs) presented in the Annexes and establish methodologies that can be adopted by operators in order to implement the SARPs. The *Safety Management Manual* and the *Manual on Flight Data Analysis Programmes (FDAP)* are of particular interest within the scope of this work, because they present strategies to implement effective SMS and FDM programs, respectively. These two manuals are important in the definition of the framework that supports the developed work. Furthermore, the

Manual of Evidence-based Training is also relevant, since it provides information on how to implement an Evidence-based Training system, which can benefit from the flight data reproduction resulting from this thesis.

Another important regulatory document is the EU-OPS 1, in which the European Commission establishes the requirements and procedures applicable to commercial air operations in member states of the European Union. Particularly, EU-OPS 1.037 defines how a flight safety program, including flight data monitoring, should be established in order to prevent accidents and incidents.

The activities developed by the Safety Department at Portugália are guided by procedures. For the development of this thesis work, the procedures *P-DS-06 - Flight Data Monitoring Procedure* and *P-DS-11 - Processing and analysis of QAR files* are especially important, since this thesis work is being developed within the scope of the Safety Department's FDM activities and the data to be used is acquired by the QAR. The former provides information on the collection of flight data, to its analysis and resulting actions, whereas the latter establishes the necessary steps to obtain the flight data from the raw QAR files.

Other documents used at Portugália that support FDM activities that also play an important role in this work include the avionics manual for the Embraer 190 and 195, the *QAR Database Specification*, which presents all the available flight parameters provided by the QAR, and the Analysis Ground Station manuals, which is the FDM software employed at Portugália. These documents support the choice and analysis of the flight parameters to be used in the conversion and reproduction of flight data.

1.4   Thesis Outline

Chapter 2 Background presents the historical and technical aspects that serve as the framework for this thesis. In this chapter, flight data monitoring and safety management systems are addressed, as well as the technology employed for flight data collection and analysis.

Chapter 3 Data Frame Analysis and Conversion is dedicated to explaining the analysis of the two data frames implicated in the development of this thesis work and the entire conversion process from the QAR to the flight animations.

Chapter 4 Flight Data Reproduction Analysis presents the resulting product of the conversion process within the simulation software, X-Plane. The animations are analyzed from various perspectives and their characteristics, advantages and drawbacks are presented.

Chapter 5 Conclusions addresses the main conclusions drawn from this thesis work and establishes the future work that can be done using it as a starting point.

Chapter 2

Background

As demonstrated in Chapter 1, the aviation industry has revealed a growing concern with the safety of its operations, translated by the multitude of regulations and recommendations that authorities all over the world have enforced. Consequently, the flight data analysis techniques used within the scope of the operations of the safety departments in airlines have evolved. The historical and technical background on the development of flight animation and reconstruction software is addressed in this chapter.

Since this work was developed within the scope of the activity of Portugália Airlines, section 2.1 introduces a brief history of the airline and their fleet.

Section 2.2 presents an historical overview on the evolution of flight data recording and analysis programs and, particularly, their use of flight animation to achieve the desired safety goals.

In Section 2.3, the regulatory aspects fo Flight Data Analysis Programs (FDAP) are addressed, namely the integration of these programs within the Safety Management System of an airline, their objectives and equipment and the methodologies of data processing currently in use.

In Section 2.4, some current solutions on the market regarding flight data analysis are presented and a comparative study between them is conducted.

The history and technical aspects of flight data recording systems are discussed in Section 2.5, where the Flight Data Recorder (FDR) and QAR airborne systems are analyzed. The data flow within an aircraft is also examined.

The, Section 2.6, presents the systems used by the Safety Department at Portugália for FDM purposes, namely the *Analysis Ground Station* (AGS) program and Google Earth. Then, *X-Plane 11*, the simulation software used in the development of this thesis work, is introduced and its relevant characteristics are detailed.

Finally, Section 2.8 concerns Evidence-based training, a new paradigm that employs operational

data to improve training and assessment of crews.

2.1 Portugália Airlines

Founded in 1988, Portugália started operating domestic flights in Portugal in 1990. Two years later, it began international operations, and grew steadily as it conquered its place as a regional airline in the European market. By 2000, Portugália counted with a fleet of 14 aircraft - six Fokker 100 and eight Embraer 145. In 2007, the airline was integrated into Grupo TAP, operating in close connection with TAP. In 2016, the fleet was completely renovated and now consists of nine Embraer 190 LR and four Embraer 195 AR. Currently, Portugália operates under the commercial name TAP Express and provides services in the regional domain of the operations of Grupo TAP [9].

The main characteristics and some general dimensions of the two aircraft models operated by Portugália are summarized in Table 2.1. Figure 2.1 shows an image of each of the two aircraft.

Table 2.1: Characteristics of the aircraft in Portugália's fleet.

	E190 LR	E195 AR
Sources	[10–12]	[10, 11, 13]
Number of aircraft	9	4
Length [m]	36.24	38.67
Wingspan [m]	28.72	28.72
Height [m]	10.55	10.55
Maximum Takeoff Weight (MTOW) [kg]	50 300	52 290
Maximum fuel capacity [ℓ]	16 029	16 029
Cruise speed [km/h]	871	871
Range [km]	4 445	4 260
Service Ceiling [km]	12 500	12 500
Number of passengers	106	118
Maximum payload [kg]	12 900	13 900

(a) Embraer 190 LR [11].

(b) Embraer 195 AR [11].

Figure 2.1: Aircraft operated by Portugália.

The E190 and the E195 are part of the E-jets family, by Embraer, which also includes the E170 and the E175. They are single-aisle narrow-body jets, carry around 70 to 150 passengers, depending on the model, and are mainly used in regional operations. The E-jets come in a standard version, but two additional variations are offered for each model: the LR (Long Range) and the AR (Advanced Range).

In general, the standard versions have the smallest weights and the AR are the heaviest. Nevertheless, the AR can fly larger distances and their maximum payload is bigger than that of the LR and standard versions.

Regarding the two models operated by Portugália, Table 2.1 evidences that the E195 is somewhat longer and heavier than the E190. This small difference in size allows the aircraft to accommodate more passengers and increase the maximum payload. However, the E190 can fly longer distances than the E195. In any case, the two models are similar, in terms of specifications and are both fit for the operations performed by Portugália.

At Portugália, flight data monitoring activities fall within the responsibility of the safety department. To do so, they employ dedicated tools and systems that record, store and help analyze the data. The next sections set the framework for flight data monitoring and, in Section 2.6, the two tools currently in use at Portugália are presented, was well as X-Plane, which will also start to be used at the safety department for flight data analysis.

2.2 Historical Remarks

The need to record and analyze flight data arose during the first decades of aviation. However, the first prototypes and early designs of flight data recorders appeared only during World War II and it was not until the 1950s that the first generation of crash-survivable FDRs was introduced [14]. In the 1960s, aviation authorities all over the world started demanding both FDRs and Cockpit Voice Recorders (CVR) to be fitted to commercial aircraft, with the purpose of aiding in accident investigation [15, 16]. Specifically, ICAO Annex 6 regulates the use and operation of flight recorders according to the type of aircraft and the date of its certificate of airworthiness and also stipulates which parameters should be registered by the FDR [4]. The architecture and use of FDRs are further discussed in Subsection 2.5.1.

Nowadays, it is generally accepted that flight recorders are crucial to determining the cause of an accident or incident. Nonetheless, flight data can also be a major contribution to prevent those incidents. During the 1970s, new flight data recorders independent from the crash recorders were developed with the goal of monitoring parameter exceedances. One of the earliest uses of this technology was the certification of CAT III autolanding operations for the Caravelle in France and the Trident in the United Kingdom. Later on, Air France and British Airways implemented their own flight data monitoring programs, although it would take decades for these programs to become widely adopted by airlines all around the world, mainly due to reservations regarding data security, confidentiality and misuse [17]. Throughout the years, these concerns have been addressed by authorities. For instance, ICAO establishes an appropriate approach to ensure FDA data protection in the *Manual on Flight Data Analysis Programmes (FDAP)* [5].

As previously stated, early FDAPs consisted of the detection and analysis of parameter exceedances,

or, in other words, the evaluation of parameters to guarantee their compliance with acceptable limits at all times. Eventually, the analysis techniques evolved to accommodate for larger amounts of data and trend identification and, more recently, new software has been developed to allow the full reconstruction of a flight using animations and data from flight recorders.

One of the first uses of flight data animation dates back to the 1980s, during the Delta Air Lines flight 191 trial [18]. The simulations were crucial to determine the causes of the accident, that took place in 1985 - an encounter of the aircraft with a microburst-induced wind shear and the inability of the crew to properly deal with such circumstances [19]. At the time, forty different flight parameters retrieved from the FDR, audio data from the CVR, ground radar images, weather information and accounts from other pilots were fundamental to reconstruct the last moments of flight 191 [20]. A still image from the resulting animation is reproduced in Figure 2.2.

Figure 2.2: Still image from the flight animation used in the Delta 191 trial [21].

Evidently, the Delta 191 animation is simplistic and primitive, whereas modern software allows for life-like simulations that provide realistic graphical representations of the flight data, using hundreds of recorded parameters. The current flight data animation tools available on the market are discussed in Section 2.4.

2.3 Flight Data Analysis Programs

As stated in section 1.1, ICAO *Annex 6* establishes that a flight data analysis program must be instituted as a part of an operator's safety management system (SMS), if their aircraft have a maximum certificated take-off mass over 27 000 kg [4]. The structure of an SMS and the characteristics of FDM programs are addressed in this section.

2.3.1 Safety Management System

A safety management system is, according to *Annex 19*, a "systematic approach to managing safety, including the necessary organizational structures, accountability, responsibilities, policies and procedures" [3]. Essentially, an SMS provides the tools for operators to work on continuously bettering their safety performance, while mitigating risks and hazards and, therefore, preventing accidents and incidents. This safety performance is measured by the Acceptable Level of Safety Performance (ALoSP), which is established by the State authorities for the civil aviation operators to achieve and is defined in therms of safety performance targets and safety performance indicators. The former is the planned value that should be achieved over a given period of time, whereas the latter is a data-based parameter used for assessing safety performance. The methods used in an SMS to achieve its goals include the identification of hazards, the continuous collection and analysis of flight data and the evaluation of safety risks [22].

In order to help states implement adequate and effective safety programs, ICAO has issued the *Document 9859 - Safety Management Manual* (SMM), which provides a basis for the establishment of safety management systems in accordance with *Annex 19*. The SMS framework, as described in both of these documents, comprises four components:

1. **Safety policy and objectives:** Safety management can only be effective in an adequate environment, so this component ensures the commitment of all affected parties to safety, particularly senior management. It defines the supporting organizational structure, the key safety personnel, and the objectives of the SMS. This component is crucial to develop and encourage the desired safety culture.

2. **Safety risk management:** Every operation has associated risks. The goal of this component is to guide service providers in managing the safety risks and identifying potential hazards that can arise at any point of the operation. The process of safety risk management therefore includes hazard identification, safety risk assessment and safety risk mitigation. For a successful safety risk management it is crucial that service providers fully understand the systems and the environments in which they operate.

3. **Safety assurance:** It is imperative that an SMS ensures effective safety risk control. This component defines the set of processes that assess and determine if the SMS is performing according to requirements. If the SMS deviates from the expected performance, new safety risks can emerge or go undetected. Therefore, service providers must define the set of actions to be taken in order to respond to any issues in the SMS that may impact the the safety of their operations. Additionally, operators must continuously work towards the maintenance and improvement of the effectiveness of their safety management system.

4. **Safety promotion:** This component ensures that a positive safety culture is encouraged and

cultivated throughout all levels of an organization. Safety promotion presupposes not only the technical competence of all involved parties, improved through training and education, but also information-sharing and clear two-way communication, that enables everyone in the organization to offer constructive feedback.

Within a safety management system, there are two main hazard identification methodologies: reactive, which uses information from past events like accidents or incidents to identify the hazards that played a part in that event, and proactive, in which data from regular operations or low-risk events is analyzed to determine whether an hazard could contribute to a potential accident or incident [22]. One of the sources of information for proactive hazard identification is the flight data analysis program implemented within a service provider's SMS.

2.3.2   Objectives of FDM

Flight data analysis (FDA), also known as flight data monitoring (FDM) or flight operations quality assurance (FOQA), is described by ICAO in *Annex 6* as a process in which flight data is analyzed with the sole purpose of enhancing the safety of flight operations [4]. A flight data analysis program must be non-punitive and provide the means to periodically collect and analyze flight data in order to yield information that can be used for improvement in crew performance, training, maintenance and even air traffic control purposes. According to the *Manual on Flight Data Analysis Programmes*, the objectives of FDM are the following [5]:

- determine standard and non-standard behavior in operations and anomalies in aircraft performance, including hazard identification, which falls within the *safety risk management* component of SMS;

- identify trends in flight data and conduct predictive analysis;

- aid in event investigation, by comparing the flight data with standard behavior and determining whether it is an isolated event or a systematic issue;

- suggest adjustments in operations and monitor the efficacy of the applied changes;

- support crew training through Evidence-based Training (EBT) [23];

- enhance the economical efficiency of operations, due to the optimization of fuel consumption and the cutback in avoidable maintenance and repairs.

2.3.3   FDM equipment

In order to implement an effective FDAP, an operator must employ the proper devices to record, download, process and store the data. On board the aircraft, there are recording systems that contin-

uously capture and store hundreds of flight parameters. The best-known recorder is the FDR, used in accident investigation, but its recording duration, recorded flight parameters and ease of access to the data may be insufficient for FDM purposes. As a consequence, non-crash recorders such as the QAR are employed by operators to retrieve the necessary flight data for analysis. These recorders supply additional recording capacity in terms of duration, number of parameters and increased sampling rate. They also provide an easy access to the data, through USB or memory cards. Newer QAR systems eliminate this need of physically moving the data from the aircraft to the ground station by sending it through secure wireless connections, either when the aircraft is airborne or when it is close to the gate. Afterwards, the data uploaded into the ground-based system is analyzed using specialized software that processes and manipulates the information to help identify abnormal events, perform routine measurements, detect exceedances, and support continuing airworthiness functions [5].

2.3.4 Data protection

Although the main goal of FDAPs is to improve safety in a non-punitive manner, there have been misgivings regarding liability and data security. ICAO addresses these issues in chapter 3 of the *Manual on Flight Data Analysis Programmes*, where it is stated that FDA data protection is "a common interest of the State, the operator and the flight crews". The manual also provides strategies to improve data security, such as ensuring that only selected personnel can access the data and the de-identification of flight data files. Concerning these issues, the European law EU-OPS 1.037 establishes that the FDM program of an operator must be non-punitive and "contain adequate safeguards to protect the source(s) of the data" [6]. At Portugália, any one with access to safety data must sign a confidentiality agreement that prevents the unauthorized use and disclosure of the data, in accordance with the applicable national and European regulations.

2.3.5 Data analysis methods

Within the scope of FDM activities, several methods are used to process and analyze the data. These methods can be categorized into two groups: time series methods and flight data animation. The characteristics, benefits and drawbacks of each group are now discussed.

Analysis through time series methods

Flight data can be condensed in time series data, to which traditional statistical and analytical methods are applied to extract the relevant information for FDM analysis. Kumar et al. (2016) defines time series as a set of data points uniformly spaced in time that are systematically measured at successive times. Furthermore, Zhang and Zhang (2017) details a set of processes that can be used in time series analysis for flight data, including preprocessing, similarity search, trend prediction and data mining.

Exceedance detection is one of the most significant advantages of time series analysis, since it involves evaluating whether the aircraft deviated from normal operational limits. Another important benefit of numerical analysis methods is the fact that they allow the verification of compatibility and congruence between different parameters [15]. For example, if the elevator is deflected upwards, it is expected that the pitch angle increases. Moreover, time series analysis is particularly useful for comparing data from eventful flights with data from routine operations, which exposes outliers from normal operations [25]. It also allows the identification of trends and the use of predictive analytics to estimate future data. This can prove useful for defining standards in operations, continuing airworthiness functions and the early flagging of aircraft for maintenance due to the identification of problems in its systems [5]. Finally, these methods are also convenient to objectively and quantitatively evaluate an operation.

However, there are some drawbacks and shortcomings to time series analysis. Exceedance detection on its own may not be sufficient to explain events and detect potential hazards. A thorough integrated analysis using data from several parameters and sources is usually required to fully assess an exceedance, the causes led to it and the further effects it had in the operation. In addition, it is usually hard to comprehend relationships between large sets of data with the sole use of graphs and statistical analysis. Moreover, the graphical representation of flight data is often impractical for pilots, because it does not capture the sensory impressions that they experience in flight.

Some of these disadvantages are overcome using flight data animation methods, which are now described.

Analysis through flight data animation

In the last decades, flight data animation, which consists of the representation of data retrieved from operations in a visual medium, has gained relevance as an analysis tool. Animations reproduce the data just like it happens in flight and as accurately as possible. They were first used for accident investigation [21], but, nowadays, animations are used on a daily basis at airlines for FDM, training and crew debriefing purposes.

One of the biggest advantages of animations is that they are a powerful platform to integrate large amounts of data from various sources - CVR audio, ground features, FDR/QAR data, weather information - in a single medium, which provides a better understanding of the relationships between the factors that affect an operation. Animations also help contextualize events, and make it easy to understand what crews experience in flight, in terms of communications, warnings, instrument readings and many other events that take place during flights, often simultaneously [15, 21]. Moreover, these methods have the ability to show the flight from several different points of view - instrument panels, pilot inputs, external view of the aircraft - all using the same software [26]. Outside of the scope of FDM procedures, animations can also be an asset for other activities:

- Training of crews: animations are useful in supporting Evidence-based Training, mainly for the

familiarization of airports and procedures [15, 21].

- Crew debriefings: animations help crews see everything they did during a flight, as well as other factors and events they may have missed [21]. In fact, they are much easier for crews to understand than time series graphs, due to their nature being so similar to what crews experience in flight.

- Accident and incident investigation: not only are animations convenient for investigators to evaluate the causes that led to certain events [15], but they are also a practical way to present them to management [21].

On the downside, the software used for animations is usually more expensive and demands more computational power than the software used for analytical methods. Additionally, the metrics provided by animations are not as accurate and objective as time series methods and, therefore, are not useful in trend identification and numerical analysis. Lastly, animations require considerable data preprocessing due to formatting and errors in datasets, which is often more challenging than in time series analysis.

As demonstrated, both time series analysis and flight data animation have relevant advantages and downsides. Ideally, they can be used together for a more complete analysis and to meet the various needs of the operator. However, this is more expensive, time-consuming and demanding in terms of human and computational resources. Ultimately, the choice of methods for flight data analysis depends on the operator, the goals they intended to achieve with such methods and their resources.

2.4   Current Solutions on the Market

Up to this moment, several companies have developed and launched flight data monitoring solutions. This section briefly describes some of the most relevant tools currently on the market, both for numerical analysis and flight data animation.

The Global Aviation Information Network (GAIN) is a platform proposed in 1996 by the FAA for the cooperation between the aviation industry and the government to support and improve safety in operations, with the aim of helping "the aviation community reach the goal of zero accidents" [27]. In 2004, GAIN conducted the *Second Survey of Analytical Processes and Requirements for Airline Flight Safety Management*, which was answered by 50 airlines from all over the world, with fleets ranging "from under 10 aircraft to over 400" [26]. One of the questions addressed in this survey was the use of analytical methods and tools in the activities of the safety departments of the respondents, including for FDM purposes. The survey revealed that, at the time, about two thirds of the airlines that took the survey used at least one tool for FDM. Nowadays, FDM is mandatory for airlines operating under EASA jurisdiction, under the aforementioned conditions, and in the USA, where FOQA is voluntary, the FAA lists 57 participants as of February 2021 [28]. These statistics indicate an increased interest in FDM, which promotes the growth of the FDM tool market.

In 2003, GAIN created the *Guide to Methods & Tools for Airline Flight Safety Analysis*, a report that catalogs and describes existing tools for safety analysis, with the purpose of aiding airlines in the choice and incorporation of these tools in their activities [29]. Chapter 4 of this guide is focused on the tools used for FDM purposes and it covers 16 FDM tools available at that time. Nowadays, some of the tools listed in the guide are obsolete. The following list describes some FDM tools analyzed in the guide, including tools currently used in the aviation industry, but also tools that pioneered FDM activities.

- **Aircraft Flight Analysis and Safety Explorer (AirFASE)**: launched in 2004, this tool resulted of the joint effort of Airbus and Teledyne Controls [30]. It supports FDM activities in compliance with EASA, FAA, CAA and ICAO regulations and is equipped with automatic data processing and analysis, as well as data management and security functions. AirFASE features three interrelated types of data analysis methods: investigation tools that present data in numerical and graphical formats, animation tools that replicate the flight in a 3D environment and display the instrument panel and flight path, and reporting tools that generate customized and automatic statistic and event reports [31].

- **Aviation Performance Measuring System (APMS)**: the APMS was developed by NASA Ames Research Center and was launched in 1993 [32]. It was focused on the statistical analysis and interpretation of flight data, not only for exceedance detection purposes but also for the identification of potential hazards before they resulted in incidents or accidents. Even though it does not seem to be updated and in use anymore [33], the APMS provided the basic infrastructure for FAA's Aviation Safety Information Analysis and Sharing (ASIAS) program in use today [34].

- **British Airways Safety Information System (BASIS)**: BASIS was a modular system developed during the 1990s for British Airways' own use, although it eventually became the "most popular safety management tool", with over 150 external organizations also using it [29]. It featured several data analysis modules, each with a specific purpose, including the programs that had originally been developed for the validation of autoland capabilities [35]. These modules allowed the display of flight data in numerical and graphical formats, event analysis, exceedance detection, trend identification, flight animation and even included a remote viewer, to allow managers to view data even when they were away from the office.

- **Cassiopée Analysis Ground Station (AGS)**: developed by the French company Safran Electronics & Defense, AGS is a data management system used for flight data analysis. This software features a detailed statistical and event analysis interface, as well as an integrated reporting tool that produces automatic analysis and reports of the available flight data. AGS can be integrated with other tools. For instance, it is possible to connect AGS to CEFA FAS, which is described later on, to produce 3D flight animations [36].

- **Cockpit Emulator for Flight Analysis (CEFA)**: CEFA provides the Flight Animation System (FAS) tool, which uses FDM data to create 3D animations for analysis and investigation purposes [37]. They also carry the Aviation Mobile Services (AMS) tool. It uses the FAS technology to provide

crews with a cloud-based app that allows pilots to replay their flights on demand [38]. Alongside the 3D animation, CEFA FAS also shows navigation charts overlaid with the flight path, the instrument panel adapted to the aircraft type and data plots.

At the moment, APMS and BASIS have been discontinued or their use is not as widespread as it once was. However, they show that back in the 1990s there was already a need among airlines for comprehensive FDM tools that allowed safety officers to mine flight data to improve the safety of operations. In contrast, AirFASE, AGS and CEFA are still widely used by air operators, being some of the best-known FDM tools on the market. In the last decades, given the increased interest in FDM by regulators and operators worldwide, new tools have emerged on the market to respond to the specific needs of their users. Table 2.2 presents a non-exhaustive list of some of the FDM tools available on the market as of 2021, besides the ones already presented.

Table 2.2: FDM tools names and service providers.

	Tool Name	Developer	Sources
1	Flight Data Connect	L3Harris	[39, 40]
2	Sky Analyst FDM	Scaled Analytics	[41]
3	PGS Vision System PGS Analysis System PGS 3D Replay System	Flight Data Vision	[42–44]
4	LUCH	Flight Data Technologies	[45, 46]
5	Skytrac Flight Data Monitoring	Skytrac	[47]
6	Aerosight Flight Data Monitoring	Aerosight	[48]
7	Safety Insight	General Electric	[49, 50]
8	FDM360	FlightDataPeople	[51, 52]
9	EnVision	Appareo	[53]
10	Solutions for Aircraft data Replay and Analysis (SARA)	ERGOSS	[54]
11	NLR Flight Data Monitoring	Royal Netherlands Aerospace Center (NLR[1])	[55]
12	Aerobytes Flight Data Monitoring	Aerobytes	[56]

As FDM solutions, these tools share common traits to ensure an adequate service to operators. A comparative study with the mentioned tools was conducted to evaluate the features that characterize current FDM tools on the market. The characteristics assessed for each solution are as follows:

- Supports different kinds of fleet: the tool can be used by airlines and/or corporate operators and/or helicopter operators. It supports fleets with various sizes and types of aircraft and is scalable.

- Integrates with other tools on the market: the tool can be paired with other solutions used by the operator, for example by feeding them data, to provide a wider range of services.

- Easy data transfer from QAR/FDR: the data transfer between the recording systems and the analysis system is either automatic or simplified, not requiring complex and time-consuming strategies.

[1]Dutch: *Nationaal Lucht- en Ruimtevaartlaboratorium*

- Graphical and numerical analysis: the tool allows the representation of flight data in graphical form, showing the evolution of parameters through time. Trend estimation, future data prediction and statistical analysis are also facilitated.

- Flight animations: the solution is equipped with software that allows the 2D or 3D reconstruction and replay of flights.

- Report generation: personalized or standardized reports are issued, either automatically and/or on demand, showing detailed safety information retrieved from the flight data.

- Event and exceedance detection: safety officers can establish the normal or average values of flight parameters, as well as acceptable limits. Using that information, the tool can determine whether an event or exceedance occurred and warn the users accordingly.

- Platform: software can be hosted in house, making use of the hardware and human resources available at the customer's facilities. In contrast, it can be web-based, where data is stored and manipulated on the cloud and is available anywhere with an internet connection.

The results of the study are summarized in Table 2.3. The ticks (✓) indicate that the feature is available for the tool, the **x** symbol designates a feature that is not included in the solution and the dashes (**-**) signify that not enough information was found to draw plausible conclusions. In the *Platform* row, the symbol **W** indicates that a tool is web-based and **H** designates an in-house tool. An overall discussion of the findings is now presented.

Table 2.3: Characteristics of some FDM tools available on the market.

Tool	1	2	3	4	5	6	7	8	9	10	11	12
Supports different kinds of fleet	✓	-	✓	✓	✓	-	✓	✓	✓	-	✓	✓
Integrates with other tools on the market	-	-	-	-	✓	✓	✓	✓	-	✓	-	-
Easy data transfer from QAR/FDR	✓	-	✓	✓	-	✓	✓	✓	✓	-	✓	-
Graphical and numerical analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Flight animations	✓	x	✓	✓	✓	✓	x	✓	x	x	x	✓
Report generation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
Event and exceedance detection	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
Platform	W	W	H	W, H	W	W	W	W	W	W	-	W, H

Firstly, all the FDM tools considered are equipped with graphical and statistical analysis and trend identification methods, as well as event and exceedance detection techniques. Report generation, either manual or automatic, is also a common feature among the mentioned tools. Additionally, most tools are able to support different kinds of operators - airlines, helicopter and corporate operators being the clients mentioned - and are also able to accommodate fleets with different sizes and aircraft types.

One common trend among the analyzed tools is the easy data transfer from QAR/FDR to the software, because the latter is prepared to receive and manage raw flight data. Some of the sources also indicated that their tools can be easily integrated with other software used by operators to further their flight data analysis activities. Finally, many of the examined tools reported including software that allowed them to reproduce 2D and 3D replays of the flights, which can be an important asset to contextualize large amounts of data in a simple user-friendly way.

All of these activities are supported by sophisticated technology incorporated into the tools. For instance, all analyzed solutions but two are web based or offer that option. This means that the platform upon which the tools run and perform their activities is online, which promotes seamless software updates, facilitates IT support and reduces costs in terms of hardware, since these platforms can be accessed from a regular computer, smartphone or tablet and do not require dedicated servers running them. For example, SARA by ERGOSS and Sky Analyst are both hosted on Microsoft Azure [41, 54], a highly secure cloud solution that can be accessed anywhere with an internet connection. Some service providers, such as Flight Data Technologies [46] and Aerobytes [56], offer their products in both web-based and in-house platforms, allowing their clients to choose the solution that best serves their needs.

The integration of FDM tools with modern data management processes, like Business Intelligence and Big Data, is also improving FDM practices. Business Intelligence (BI) encompasses all the processes and strategies used for the collection, analysis and sharing of business data with the purpose of helping managers make the right decisions [57]. Therefore, FDM fully fits inside the definition of Business Intelligence, as the information retrieved from flight data can support a wide variety of activities inside an operator, from maintenance, to training, to safety. Big Data is another field that can be deeply advantageous to FDM. On the one hand, current QAR systems are able to record hundreds of parameters for several hours at a time, which by itself generates massive amounts of data. On the other hand, the integration of data from several flights performed by different operators in a single platform, like the one proposed by IATA's Flight Data Exchange (FDX) program, also presupposes the storage and analysis of enormous amounts of data. The use of Big Data techniques can help manage and generate value from flight data more efficiently. Of the studied tools, SARA and L3Harris' Flight Data Connect stand out for taking this into consideration. The former was designed with both Business Intelligence and Big Data in mind [54] and the latter is able to feed directly into IATA's FDX program [39].

Lastly, these tools evidence the tendency for software to become more web based, which provides the means to access data anytime, anywhere and reduces costs in terms of hardware and IT support, but also raises questions and reservations regarding data security. These concerns have been addressed by developers, who employ highly secure solutions to ensure data protection. Moreover, many current solutions ship with several tools included and are fully customizable, simplifying the setup of an FDM system, because operators only have to invest in one solution to acquire all the tools they need to perform their FDM activities.

2.5   Flight Data Collection

In this chapter, the collection of flight data in an aircraft is discussed. Firstly, the Flight Data Recorder is described, followed by the analysis of the Quick Access Recorder. Then, the data flow within an aircraft is examined.

2.5.1   Flight Data Recorder

When an accident involving an aircraft occurs, the attention turns immediately to the black box. This is the colloquial term used to describe the combination of the Cockpit Voice Recorder (CVR) and the Flight Data Recorder (FDR) installed in an aircraft. In some aircraft, these two units can be combined into a single recorder. For instance, the Embraer E-jets family employs a combined recorder called Digital Voice Data Recorder (DVDR) [58].

History of the FDR

Since the early days of aviation, there has been a need to record and interpret data from flights. One of the earliest and most notable flight data recording devices is the NACA V-g recorder. It dates back to World War II and it was fitted into transport and bomber aircraft with the purpose of measuring operational loads [15, 59]. In the mid-1950s, following a series of airline crashes, investigators started to realize the usefulness of data recording for investigations and the first crash-survivable recorders were proposed. One of these recorders was idealized by Dr. David Warren, a scientist at the Aeronautical Research Laboratory (ARL), in Australia, who participated in the investigations regarding the crash of the world's first jet airliner, the de Havilland DH.106 Comet, in the early 1950s. He suggested that having a device recording what had happened in the final moments of the flight would have been a piece of evidence "of inestimable value" [60, 61]. Dr. Warren elaborated on this idea in his 1954 document *Mechanical Engineering Technical Memorandum 142 - A device for assisting investigation into aircraft accidents*, where he suggested how a crash-survivable audio recorder can be built and installed to aid in accident investigation. He proposed that a small magnetic wire recorder, capable of recording up to 2 minutes of audio from the cockpit, was installed "in all major aircraft, especially those in early stages of development" [61].

At first, Dr. Warren's invention did not spark much interest. However, in 1958, with the support of ARL, he completed the first prototype black box, which continuously stored up to 4 hours of audio and signals from the main aircraft controllers and instruments [62]. This device, called Flight Memory Unit (FMU), attracted the attention of the UK Air Registration Board, and it was a matter of years until the CVR and the FDR started becoming mandatory in civil aircraft. Australia, the USA and the UK were among the first countries to implement such rulings, between the late 1950s and the early 1970s [59].

FDR Technology

Throughout the years, different technologies have been employed to record flight data. One of the earliest technologies was the oscillographic foil recorder, which used a set of mechanical needles that engraved data in a metal foil. Another similar method employed photographic film and light beams to register the data. The information came from sensors independent from the cockpit instruments, which raised problems regarding the calibration and reliability of the FDR sensors [15, 63]. Besides, these recorders were only able to register five or six specific parameters and the interpretation of the data was very time consuming. These two methods were discontinued by ICAO on *Annex 6* [4].

Magnetic tape recorders were later introduced, allowing the recording of not only flight parameters, but also audio. In the 1970s, second-generation Digital Flight Data Recorders (DFDR) were launched, in response to the need to record more parameters. This led to the creation of the Flight Data Acquisition Unit (FDAU), a system that receives both analog and digital information from several sources in an aircraft and directs it to data recorders, through well-defined data frames. At this point, FDRs could save up 18 parameters for up 25 hours and tape CVRs had enough capacity to store 4 audio channels with a duration of 30 minutes each [14]. In *Annex 6*, ICAO determined the discontinuation of magnetic tapes FDRs by 1 January 2016 [4].

In the late 1980s, solid-state technology, which employs stacked memory chips, was introduced in flight recorders. This represented a significant revolution, since it provided larger recording and storage capacities, better data quality and reliability, greater crash survivability and fewer maintenance concerns, because it does not involve moving parts. In addition, solid-state FDRs are capable of recording up to two hours of audio and have four times the capacity of magnetic tape DFDRs [14, 63].

Parameter Recording Requirements

In Chapter 6 of *Annex 6*, ICAO defines four types of FDRs - Type I, Type IA, Type II and Type IIA -, depending on the number of parameters they must record and the minimum duration of the recordings. The Annex also establishes which type of FDR should be fitted into an aircraft, according to the date of its certificate of airworthiness and its mass.

The most demanding recorders are the Type IA FDRs, which shall store at least the 78 parameters defined in Appendix 9 of the same document, with a recording duration of least 25 hours. The parameters that shall be recorded are related to all aspects of a flight and are divided into the following categories: flight path and speed, attitude, engine power, configuration and operation [4]. In addition, the sampling intervals, accuracy and resolution for each parameter are also defined to ensure adequate data quality.

Lastly, FDRs and CVRs operate on the endless-loop principle, meaning that the most recent data is written over the oldest data.

Survivability

Accident and incident investigations are highly dependent on the retrieval of the recorders. Therefore, it is essential that the data is adequately protected so it may survive the crash without suffering significant damages, which led to the definition of survivability standards for FDRs.

The European Organisation for Civil Aviation Equipment (EUROCAE) handles the standardization of airborne and ground equipment in the aviation industry [64]. Their document *EUROCAE ED-112, Minimum Operational Performance Specification (MOPS) for Crash Protected Airborne Recorder Systems* establishes the performance requirements for crash recorders, including the conditions the FDR must withstand and which are now presented [14, 65, 66].

- **High intensity fire**: 1100 °C for 1 hour.

- **Low intensity fire**: 260 °C for 10 hours.

- **Impact shock**: 3400 g for 6.5 ms.

- **Static crush**: 5000 lb for 5 minutes.

- **Deep sea pressure**: 20 000 ft for 30 days.

- **Penetration force**: 500 lb, dropped from 10 ft.

Additionally, crash recorders are also equipped with an Underwater Locator Beacon (ULB). This device is automatically activated once the aircraft is immersed in water to aid in the identification of its location, emitting an acoustic signal at 37.5 kHz that can be detected by dedicated receivers. Current regulations establish that the ULBs attached to flight recorders should transmit signals for 90 days since their activation [67].

2.5.2   Quick Access Recorder

The origins of the Quick Access Recorder (QAR) date back to the 1960s, when it was first employed in the Hawker-Siddeley 121 Trident for the development of the world's first autoland system, by Hawker-Siddeley and Smiths Aviation [59].

Like the FDR, the QAR is a device used to record and store data from several parameters in a flight. However, the QAR has four significant differences when compared with the FDR:

- the QAR is not meant to be crash-survivable and is not mandatory;

- the QAR usually records substantially more parameters than the FDR, sometimes more than 2000;

- while the FDR only stores data from the last 25 hours of operation, the QAR can store data from periods of time of more than 30 days [59];

- data access is simplified, eliminating the need for frequent downloads of the data stored in the FDR before it is overwritten with new data.

The large storage capacity of the QAR and its ease of access to the data make it an ideal device for FDM purposes.

Similarly to the FDR, different data recording media have been employed by QARs. Originally, tape was used to record the information, offering between 10 hours of recording at 64 words per second to 20 hours at 256 words per second. Then, optical disks began to be used, providing higher data transfer rates than tape. However, these two technologies are no longer used in QARs. Instead, solid-state memory, implemented through integrated circuits, is currently employed. One of the most relevant systems is the Personal Computer Memory Card International Association (PCMCIA) card, a reliable and compact medium whose storage currently surpasses that of the optical disks. Another solution that can be found on the market is the mini QAR, which copies the data provided to the FDR, reducing the frequency at which the data must be downloaded from the crash recorder. The mini QAR is practical due to its small size and easy implementation, but it has the disadvantage of being limited to the parameters recorded by the FDR. QARs can also be equipped with a wireless antenna, which allows the transmission of data through the Internet, either automatically when the aircraft is in the gate or on demand. However, this solution still raises questions regarding data security and interference with mobile phones [68].

2.5.3 Data flow

The transmission of data in an aircraft from the sensors to the recorders is done through specific data buses, which depend on the manufacturer. A general architecture of the data flow system in an aircraft is represented in Figure 2.3.
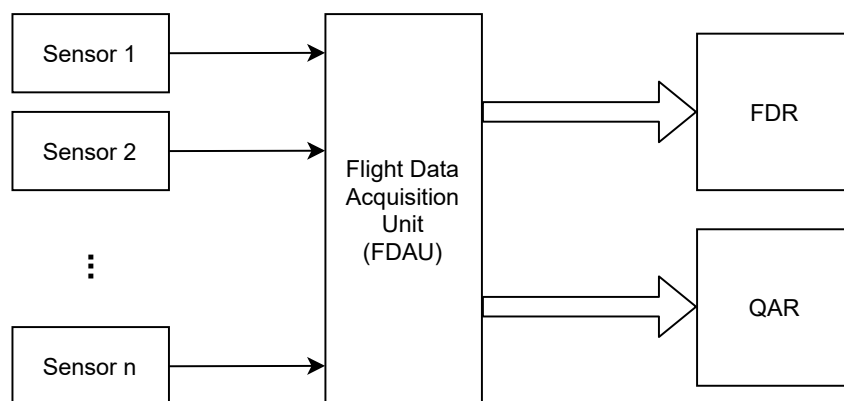

Figure 2.3: Data flow within an aircraft (adapted from [69]).

Data is acquired through sensors, devices that measure flight parameters and transmit the information to the Flight Data Acquisition Unit (FDAU), which is capable of collecting both analog and digital data. In the FDAU, data is processed and analog parameters are sampled into digital values. Then, the

21

FDAU conveys the respective data to the FDR and the QAR through standardized data frames.

The specific details of this architecture vary with the aircraft's manufacturer. Figure 2.4 represents the flight data flow in the aircraft belonging to the Embraer E-jets family. In these aircraft, the connection between system components is done through the system network buses, which consist of the Honeywell Avionics Standard Communications Bus, Version D (ASCB-D) and a Local Area Network (LAN). The former provides a connection along the entire aircraft between several components, consisting of 4 redundant buses, whereas the latter is nonredundant and is intended to support maintenance and the software-loading interface for the system [58]. The aircraft are also equipped with three Modular Avionics Units (MAU), which integrate and house up to 24 avionics modules, with various functions. The communication between the MAUs and other aircraft systems is done through the system network buses, namely the ASCB-D bus. All three MAUs feature data input and output (I/O) modules, which fulfill the role of the FDAU in these aircraft. To communicate with the DVDR and the QAR, two types of data buses using Aeronautical Radio, Incorporated (ARINC) standards are used: the ARINC 717 and the ARINC 429. These standards define the data frames that carry the messages through avionics data buses. The Custom I/O module in the MAU 3 feeds the necessary flight data to the DVDR through the ARINC 717 data bus and a copy of this information is transmitted to the QAR. Similarly, the Generic I/O module in the MAU 3 sends additional flight data to the QAR through ARINC 429 data buses. In the QAR, flight data is stored in a PCMCIA card working in continuous mode, that is, when the memory is full, the oldest data is overwritten with the new data [70].
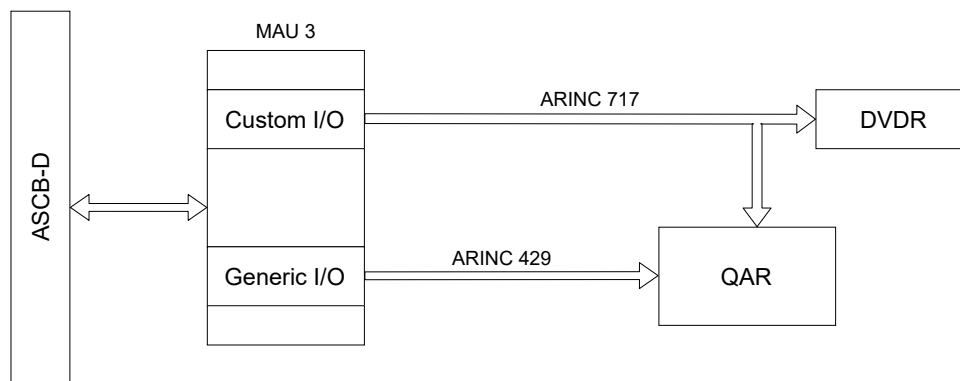
Figure 2.4: Data flow within the E-jets family aircraft (adapted from [70]).

2.6 Flight Data Monitoring at Portugália

At Portugália, FDM is performed by the Safety Department, where flight data is gathered and analyzed and safety reports are issued. If deemed necessary, remedial actions at various levels may be issued, in order to improve the safety of operations, and the implementation and results of such actions are also monitored by the department. The FDM procedure is guided by the document *P-DS-06 - Flight Data Monitoring Procedure* [71], developed by the Safety Department, which details all the rules and steps that constitute the FDM program at Portugália.

The flight data from an aircraft is recorded by the QAR and stored in a PCMCIA card. To ensure that no data is lost, at least once every four days Portugália's Maintenance and Engineering Department (DME, *Direção de Manutenção e Engenharia*) collects the memory card installed in an aircraft's QAR, replaces it with a new one and loads the data to AMOS Web-drive, a file repository where the raw binary QAR files are stored. The Safety Department then accesses these files, downloads them and loads them into AGS, where the data is processed and converted into engineering units [71, 72]. Data from the FDR is not routinely accessed and analyzed by the Safety Department, but may be used in case the QAR data is unavailable.

As previously introduced in Section 2.4, Cassiopée Analysis Ground Station (AGS) is a data management system used for flight data analysis. The binary QAR files are uploaded into AGS, which splits the data into individual flights, computes statistics and the relevant information about each flight, scans the data for events and exceedances and then adequately stores all the data. Then, one can choose a flight from the database, analyze and compare the time evolution of its parameters and view associated events.

Although AGS is the main FDM tool employed at Portugália, the team also uses Google Earth to visualize the path and the profile of a flight superimposed with the globe. AGS offers the option to export the geographical data from a flight as a Keyhole Markup language Zipped (KMZ) file, which can be uploaded into Google Earth to show the trajectory described by an aircraft. In addition, labels and text can be shown in specific locations to identify events, sequential positions can be connected to create a path and portions of the path can be highlighted. These features are used to analyze, for instance, taxiway routes, Standard Instrument Departures (SID) and Standard Arrival Routes (STAR) operations, the position where the aircraft captured the localizer (LOC) signal, whether the glide path was correctly followed, go-around procedures and noise events. Google Earth is also helpful when analyzing the location where certain events, like Traffic Collision Avoidance System (TCAS) and Ground Proximity Warning System (GPWS) warnings, took place in the airspace, as it helps contextualize them within the surrounding space.

The conclusions drawn from the analysis of the flight data are an important tool to improve safety in Portugália's operations. Every quarter, the FDM Expert Panel meets to present and discuss the exceedances and events detected, as well as the evolution of event statistics and tendencies related to any aspect of the operation. Additionally, crews may be contacted to provide feedback regarding an exceedance if the Safety Manager deems it necessary. Captains also receive quarterly reports that summarize the exceedances they have been involved in. Furthermore, if FDM analysis reveals that a structural limitation was exceeded, the Safety Department informs the Maintenance and Engineering Department with the purpose of assessing whether structural damage occurred. Finally, remedial actions may be suggested and monitored by the Safety Department to correct situations that may pose a safety risk. The goal of all these actions is always the improvement of safety and not the punishment of anyone involved.

2.7 X-Plane 11 as an FDM tool

Although the FDM procedures currently in use at Portugália are already thorough and effective, the introduction of an animation software to aid in data analysis was proposed, since this method can provide new perspectives on the evolution of the data and the occurrence of events. As such, X-Plane 11 was chosen as the platform to reproduce and animate the flight data recovered from the recorders. Its main characteristics and features that led to this choice are now described.

X-Plane is a flight simulation tool, developed by Laminar Research. The first edition of the software was released in 1995 and the latest version, X-Plane 11, was officially released in 2017. This software is currently one of the best-known flight simulation tools on the market. Its main characteristics that differentiate it from its competitors are as follows:

- **Customization utilities and extensibility**: the X-Plane installation ships with *Plane Maker*, a tool that allows the design of custom aircraft to use in the simulator, and *WorldEditor*, which is used to edit and create custom airports and scenery. Additionally, users can download and install more content and add-ons to expand, customize and improve their experience with the simulator.

- **High-resolution scenery**: the simulator makes the flying experience as realistic and thorough as possible, by including scenery that covers the Earth from $74°$ north to $60°$ south and replicating over 34,000 airports all over the world [73].

- **Aerodynamic forces computation**: the simulator implements blade element theory, in order to compute the aerodynamic forces that act on an aircraft. Essentially, the simulator breaks it down into small elements and calculates the forces that act on each element. Other simulators usually refer to lookup tables and stability derivatives, in order to determine the performance of an aircraft in flight, which are frequently gross estimations and oversimplifications of how an airplane flies. Conversely, blade element theory provides a much more accurate and robust calculation of an aircraft's performance, by accounting for its geometry [74].

These characteristics make X-Plane 11 a highly reliable, accurate and complete simulator, as well as an adequate choice for the development of this project. Not only does it allow the use of a customized aircraft model corresponding to the ones operated by Portugália, it also provides a wide library of airports that covers the company's operations and simulates flights as similar to real life as possible, which is an important asset in simulations used for flight data analysis. Furthermore, X-Plane also offers the option to save and replay flights. In particular, it is possible to load data from a flight data recorder and recreate the flight of an aircraft, provided that data is organized in a format that can be read and processed by X-Plane. This feature is especially relevant for the development of this thesis work, thereby motivating the choice of X-Plane 11 as the simulation platform for the animation of the flight data.

X-Plane is also a certified software to be used in crew training with specific hardware [75].

2.8   Evidence-based training

As stated before, flight data analysis can be used to support the training of crews through evidence-based training, or EBT for short. ICAO defines evidence-based training as the "training and assessment that is characterized by developing and assessing the overall capability of a trainee across a range of competencies rather than by measuring the performance of individual events or maneuvers" [76]. Traditional training relies heavily on the repetition of scenarios, so that crews are proficient and know how to mitigate risks if they ever find themselves in such a situation. However, it is impossible to foresee all risks and dangerous situations that can occur, but, ideally, crews should be equipped with the necessary tools and competences to deal with any situation that may arise. This is the principle from which EBT was born.

One of the greatest advantages of EBT is that it can be adapted to the needs of an operator. With this purpose, data is collected from various sources to identify potential safety weaknesses and the training is customized to address them. Some of the most relevant data sources are as follows, according do ICAO [76]:

- Data from FDM activities: risks identified by the Safety Department can be used to adjust training with the purpose of helping crews be more effective and efficient in their mitigation.

- Information regarding specific aspects of the operation, like airports, weather and fleet for instance.

- Data from crew training, to identify what aspects of training need to be further addressed and improved.

- World fleet data from other operators with a similar fleet and/or operations.

Finally, EBT is built around a framework of competencies that cover all the "technical and non-technical knowledge, skills and attitudes" [76] necessary to ensure the safest and most efficient commercial air transport operation possible. The training is focused on the simultaneous development of these competences to prepare crews to respond to any situation. Operators can define their own competency system, but ICAO has established a baseline framework that comprises the following competencies:

- **Application of procedures**: using the appropriate instructions and applicable regulations and knowledge to adequately operate the aircraft.

- **Communication**: having effective verbal and written communication skills, ensuring the correct exchange of information.

- **Aircraft flight path management, automation**: controlling the aircraft in flight, using the adequate automation systems and guidance.

- **Aircraft flight path management, manual control**: controlling the aircraft in flight, using the appropriate manual control systems and guidance.

- **Leadership and teamwork**: encouraging a healthy work environment where the team works towards the same goals.

- **Problem solving and decision making**: identifying the necessary steps to solve problems, putting them into practice and making decisions in a timely manner using the adequate processes.

- **Situation awareness**: being aware of all the aspects that concern the flight and anticipating any events that could disturb the operation.

- **Workload management**: managing and monitoring the available resources in order to plan and schedule tasks in the most efficient way possible.

- **Knowledge**: demonstrating the applicable knowledge about the system and its limitations, procedures, regulations and the operation environment, showing interest in learning and being able to apply the knowledge and to choose the most adequate information sources.

Chapter 3

Data Frame Analysis and Conversion

On the previous chapter, X-Plane, AGS and the FDM procedure used at Portugália were introduced. Since the X-Plane FDR simulations are fed with data from AGS, this chapter addresses the analysis of the data frames on both sides and the conversion from one to another. The data flow from an aircraft's QAR to X-Plane is represented in Figure 3.1. It shows that the data fed to AGS by the QAR can be exported as a comma-separated values (CSV) file, which then undergoes data conversion to create the FDR file that will eventually be uploaded into X-Plane to run the simulations.
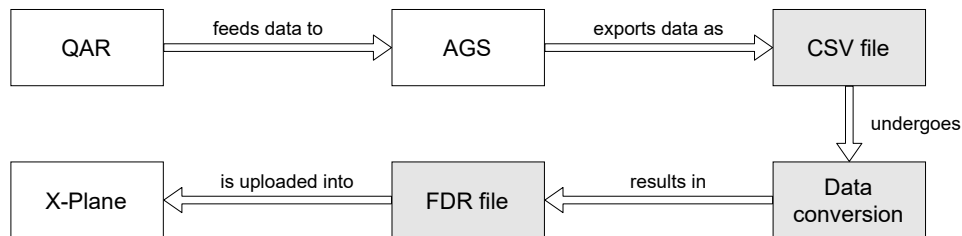
Figure 3.1: Data flow from the QAR to X-Plane.

This chapter is focused on the three gray blocks in the previous schematic. Section 3.1 introduces the structure of the data in the AGS output files. Then, in Section 3.2, the FDR file structure to be used by X-Plane is explored. The conversion of the data from one data frame to another is explained in Section 3.3. Finally, in order to make the process user-friendly, a Graphical User Interface (GUI) was designed to support the application and is presented in Section 3.4.

3.1 Analysis of the AGS data frame

As seen in the previous chapter, the flight data from an aircraft is recorded by the QAR and stored in a PCMCIA card. These files are then sent to the Safety Department where they are downloaded and loaded into AGS, which process data and converts it into engineering units [71, 72].

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In AGS, one can access any flight in the database, analyze statistics and events, and visualize the evolution of any parameter recorded by the QAR. Since over 2000 parameters are recorded every flight, it is necessary to choose which ones to analyze. AGS provides the option to define a parameter list and, when a flight is opened using it, only the parameters included in the list are shown. It is also possible to export the data from the parameters that are being analyzed into a CSV file, a feature that is employed in the development of this work. The period of the parameters written on CSV file can also be defined and, for this work, a period of 0.125 s, corresponding to a sampling rate of 8 Hz, was chosen. Below, in Figure 3.2, is presented an example CSV file exported from AGS, like the ones meant to be used with the developed program. Notice, however, that some data was omitted to fit the page and that this is only a sample of what the actual CSV files look like, as they have hundreds of thousands of rows due to the length of the flights and their corresponding QAR recordings.

```
SAT_PIL,SAT_COP,SAT_FDC_CL,LONPC,LONP1,LONG_FMS,LATPC,LATP1,LAT_FMS,ALT_QNH,ALT_GEOM,RALT,(...),DATE_R
,,,,,,,,,,,-0.9,,,,,,,,,,,-0.61111,,,,,,,,,,,0.0000,,,,,,,,,,,,-20.6,,,,,,,,,,,,,,,,,,(...),,7.8,,0,,,,,,,
,,,,,,,,,,,,,0.63,0.00,,11.92,,,,0.00,-0.60493,-0.53,-0.4,,,,,,,,,,,,,,,,,,,-20.5,,,,(...),36.42188,,,,
32.3027,38.8340,,,,,,,,,,,,,,,,,,,,,-0.60356,,,,,,,,0,,0.0000,,,,,,,,,,,,,,,,,,,,,1,,,,(...),,,,,,,,,,,,,,
,,,,,11.2002201,,,,,,,,0.63,0.03,,,,-0.03,,,-0.60493,-0.53,,,,0.0,,,,0.00,,,0.00,10.28,(...),,,,,,,,,,,,,,
,,,,,,,,,,,,,,,,,,,,,-0.60493,,,,,,,,,,,0.0000,,,,,,,,,,,,-20.6,,,,,,,,,,,,,,,,,,,,,,-0.5665,(...),,,,,,
,,,,,,,,,,,,,0.66,0.00,11.98,,,,-0.07,,-0.60150,-0.53,-0.4,,,,,,,,,,,,,,,,,,0.00,0.00,,-20.4,(...),,,,,,,
,,28.75,,,,,,,,,,,,,,,,,,-0.59944,,,93.7,,0.0,,,,0,,0.0000,,,,,,,1,,,,,,,,,,,,112.50,,,,226.0,(...),,,,,
,,,11.2002,,,0.0000,,,-27570.5,,,-0.8,0.66,0.00,,,0.03,,,,,-0.59944,-0.53,,,,,,(...),123,00:00:00,23/08/20
,,,,,,,,,,,,-1.4,,,,,,,,,,-0.60631,,,,,,,,,,,0.0000,,,,,,,,,,,,-20.6,,,,,,,,,,,,,,,,,,,,,,-0.5527,(...),,,
,,,,,,,,,,,,,0.66,0.03,,11.92,,,,0.00,-0.60905,-0.53,-0.4,,,,,,,,,,,,,,,,,,,(...),40.84375,36.50000,,,,
32.3086,38.8477,,,,,,,,,,,,,,,,,,,,,,,-0.60905,,,,,,,,0,,0.0000,,,,,,,,,,,,,,,,,,,,,2,,(...),,,,,,,,,,,,,,,,
,,,,,,,,,,,,,0.63,0.00,,,,-0.03,,,-0.60768,-0.53,,,,0.0,,,,0.00,,,,0.00,,,10.28,,,,,(...)0,,,,,,,,,,,,,,
,,,,,,,,,,,,,,,,,,,,,,-0.60356,,,,,,,,,,,0.0000,,,,,,,,,,,,-20.6,,,,,,,,,,,,,,,,,,,,,,-0.5527,(...),,,,,,
,,,,,,,,,,,,,0.66,0.00,11.98,,,,-0.07,,-0.60493,-0.53,-0.4,,,,,,,,,,,,,,,,,,0.00,,-20.6,(...),,,,,,,,,,,,
,,28.75,,,,,,,,,,,,,,,,,,-0.60837,,,93.7,,0.0,,,,0,,0.0000,,,,,,,1,,,,,,,,,,,,112.50,(...),200,,,,,,,,,
,,,11.2002,,,0.0000,,,-27570.5,,,-0.4,0.63,-0.04,,,0.03,,,,-0.60837,-0.53,,,,,(...),123,00:00:00,23/08/20
```

Figure 3.2: Example of a CSV file exported from AGS containing the QAR data to be used in the animations.

Additionally, it is also possible to define the exported files' name. Users can choose an entirely custom name for their files or take advantage of AGS's function that creates a structured filename based on an aircraft's registration number, flight number, date and time, which uniquely identifies a flight. An example of the resulting format is shown in Figure 3.3, where the four parts that constitute the name are highlighted and identified. In this example, the flight TAP879A was performed by the aircraft whose registration number is CS-TPT, on 20 August 2021, at 10:16:52. This format was adopted in the development of this work, as the information it bears is fundamental to fill some of the fields present in the FDR file structure.

Figure 3.3: Format of the CSV files' name.

Taking these features into consideration, the first step of the work was to evaluate the data recorded by the QAR and available in AGS. For the purpose of this work, the way the parameters are transmitted through ARINC data buses and recorded by the QAR is not particularly relevant. In fact, since AGS automatically processes the QAR files, it is only necessary to know the meaning behind the values presented and exported from AGS, in order to choose the adequate parameters to convert the data into the FDR format. With this goal in mind, the documents *Parameter Report* [77] and the *QAR Database Specification* [70] manual were consulted and the main findings are presented below.

- Each parameter is identified by a unique mnemonic related to the type of information it stores. For instance, flap deflection can be found under the parameter FLAP and information about the selected heading is stored in the parameter HEAD_SEL.

- Although it is not a standard practice, the captain and the first officer can choose different settings on their instruments, like the autopilot modes and the barometric pressure dialed into the altimeter, for example. This information is available for both sides of the cockpit under different parameters.

- Both the units and the meaning of positive and negative values are well defined for each parameter, when relevant. For instance, in the case of movable control surfaces, it is important to know whether a positive deflection angle indicates if the surface moves up or down.

- Some parameters also have upper and/or lower limits, which are also defined in the aforementioned documents. As an example, the selected heading given by HEAD_SEL can only take values between 0° and 360°.

- Some data is discrete and the corresponding parameters take values from a finite set of options. In AGS, the possible values of a parameter are represented by integer numbers and each number has a specific meaning within that parameter. For example, the parameters LAT_MOD_ACT31 and VERT_MOD_ACT31 record the information about the engaged autopilot modes and can take any integer value from 0 to 32. The meaning behind each possible value is defined to ensure the correct interpretation of the data.

- The parameters recorded by the QAR are sampled at 0.25 Hz, 0.5 Hz, 1 Hz, 2 Hz, 4 Hz or 8 Hz. This information is specified for each parameter and is an important factor when choosing the period of the data written in the FDR file.

- As seen in Section 2.5.3, the parameters are fed to the QAR through two data buses: ARINC 429 and ARINC 717. The bus source of each parameter can also be found in the QAR data frame.

3.2   Analysis of the X-Plane FDR data frame

As previously stated, X-Plane is capable of loading data from real flights and replay them in a simulation. The flight data input file format is called Flight Data Recorder and its file extension is .fdr.

X-Plane FDR files are plain text files, but they are structured in a specific way, which allows the simulator to properly identify to which parameter each value refers. The organization of these files is described in X-Plane's *Knowledge Base* [78] and is presented below.

There are several different fields allowed in an FDR file. The first word of each line is a four-letter code that identifies the type of information conveyed by that line of the file. A list of line identifiers, their description and example lines are now introduced.

- **COMM**: used to introduce a comment. These lines are ignored by the simulator, since they do not contain actual data to be used by the simulator.

  `COMM, Hello, this is a comment!`

- **ACFT**: describes which aircraft should be used in the simulation, indicating the directory path where the aircraft files are stored, inside de X-Plane folder in the disk.

  `ACFT, Aircraft/Extra Aircraft/Embraer E195 v2.5 - TAP/E195.acf,`

- **TAIL**: defines the tail number of the aircraft and must come immediately after the `ACFT` line.

  `TAIL, CSTPT,`

- **TIME**: indicates Coordinated Universal Time (UTC or ZULU) at the start of the flight.

  `TIME, 08:36:15,`

- **DATE**: indicates the date of the flight.

  `DATE, 01/01/20,`

- **PRES**: specifies the pressure at sea level during the flight, in inches of mercury (inHg).

  `PRES, 29.92,`

- **TEMP**: denotes the temperature at sea level during the flight, in degrees Fahrenheit (° F).

  `TEMP, 70,`

- **WIND**: indicates the direction in degrees true and the true speed in knots (kt) of the wind during the flight, separated by a comma.

  `WIND, 230, 16,`

- **CALI**: used to calibrate the scenery, this field provides the actual takeoff or landing coordinates - longitude, latitude and altitude in feet (ft).

  `CALI, -118.34, 34.57, 456,`

- **WARN**: indicates the time when a warning sound should be played and the directory path to the `.wav` file inside the X-Plane folder.

```
WARN, 10, Resources/sounds/alert/1000ft.WAV,
```

- **TEXT**: the simulator is equipped a speech synthesis software able to read text and convert it into audio. This field defines the text to be read and the time instant when it should be played.

```
TEXT, 10, Hello world.,
```

- **MARK**: indicates the time stamp at which a text marker should appear in the time slider.

```
MARK, 15, I am a text marker at 15 seconds.,
```

- **EVNT**: specifies when the flight path should be highlighted and for how long.

```
EVNT, 20, 10,
```

- **DATA**: these fields contain the actual flight data to be reproduced by the simulator, with each DATA line corresponding to a time instant. They hold a total of 79 parameters in a structured fashion, although some of them appear more than once for multi-engine aircraft. A total of 118 values are written in each DATA line. All data is numeric and the values are separated by commas. If the original QAR data does not include a particular parameter, the fields must be populated with a dummy value, such as 0. The parameters and their units are listed in Table A.1 in Appendix A, in the order they must appear in the DATA fields.

```
DATA, 1, 5, -0.9, ..., 10, 0.0,
```

Every single line must end with a comma, except DATA and COMM lines, and they can appear in any order, with the exception of the TAIL line, that must come after the ACFT line. The lines PRES, TEMP and WIND represent an oversimplification of what happens in a real flight, because sea-level pressure, sea-level temperature and wind during the flight are all volatile parameters that can change instantaneously. This format does not account for those possible changes and instead considers these values constant.

At the beginning of the file, before any flight information, two additional lines are written. The first line either shows 'A' or 'I', referring to Apple or IBM carriage returns, respectively, ensuring the software properly manages the document. The second line must be '2', in reference to the version number of the FDR format.

An example FDR file is shown below, in Figure 3.4, some data omitted in the DATA lines to fit in the page.

```
A
2
ACFT, Aircraft/Extra Aircraft/Embraer E195 v2.5 - TAP/E195.acf,
TAIL, CSTPT,
DATE, 20/08/2021,
TIME, 10:16:52,
PRES, 29.92,
TEMP, 59,
WIND, 0,0,

DATA, 0, 17, -9.206, 38.65, 2685.0, 0, 0.05, -0.01, 0.0, -2.13, -0.62, 22, 161, -1053, (...), 0, 0,
DATA, 1, 17, -9.206, 38.651, 2668.0, 0, 0.0, -0.01, -0.0, -2.15, -0.78, 22, 162, -1046, (...), 0, 0,
DATA, 2, 17, -9.205, 38.652, 2653.0, 0, 0.01, -0.01, 0.0, -2.26, -1.01, 22, 163, -1029, (...), 0, 0,
DATA, 3, 17, -9.205, 38.652, 2638.0, 0, -0.08, -0.02, 0.02, -2.26, -0.61, 22, 162, -995, (...), 0, 0,
DATA, 4, 17, -9.204, 38.653, 2623.0, 0, -0.06, -0.02, -0.0, -2.03, -0.26, 22, 161, -943, (...), 0, 0,
DATA, 5, 17, -9.204, 38.654, 2608.0, 0, 0.02, -0.01, 0.0, -1.74, -0.1, 22, 160, -916, (...), 0, 0,
DATA, 6, 18, -9.204, 38.654, 2592.0, 1246, -0.02, 0.0, -0.0, -1.57, -0.04, 22, 159, -914, (...), 0, 0,
DATA, 7, 18, -9.203, 38.655, 2577.0, 2466, 0.01, 0.0, 0.02, -1.49, -0.24, 22, 159, -922, (...), 0, 0,
DATA, 8, 18, -9.203, 38.656, 2561.0, 2460, 0.16, -0.01, -0.01, -1.5, -0.44, 22, 160, -932, (...), 0, 0,
DATA, 9, 18, -9.203, 38.656, 2546.0, 2470, -0.09, -0.02, 0.01, -1.57, -0.15, 22, 160, -934, (...), 0, 0,
DATA, 10, 18, -9.202, 38.657, 2531.0, 2424, 0.03, -0.02, 0.02, -1.67, 0.22, 22, 161, -921, (...), 0, 0,
```

Figure 3.4: Example of an X-Plane FDR file containing the formatted data to be used in the animations.

3.3 Conversion of the AGS data to FDR format

In the two previous sections, the data frames on both the AGS and the X-Plane sides were described. This Section sets forth the process through which data is converted between the two formats. Firstly, the general conversion process is described and then the computation of each parameter to be written in the FDR file is detailed.

3.3.1 File conversion process

After analyzing the two implicated data frames, the next step is to determine which parameters of the AGS data correspond to the parameters in the FDR files. To do so, the *Parameter Report* [77], the *QAR Database Specification* [70] manual and the *AGS Method for Database Programming* [79] manual, which list all the available parameters provided by the QAR and AGS at Portugália, were used. The list of required parameters, available in X-Plane's *Knowledge Base* [78], was used in this step of the work, to navigate the numerous parameters in the QAR data frame. The AGS parameters chosen for each FDR entry are summarized in Table B.1, in Annex B.

After determining the correspondence between the parameters on both sides, the conversion algorithm was developed. Some of the parameters were similar in both data frames. However, most required some form of manipulation, namely unit conversion, nondimensionalization and comparison with other parameters. The conversion process was implemented in Python, due to the language's data manage-

ment and analysis capabilities. The algorithm is divided into three main parts: initializing the variables, converting the parameters and writing the FDR file.

Variable initialization consists of the creation of the variables that will store the data in the computer's memory. Each parameter that populates the `DATA` lines is stored in a list containing all its values from the beginning of the flight until its end, with a sampling rate of 8 Hz. Therefore, and for organization purposes, all variables are initialized before starting the conversion process.

Afterwards, the CSV file exported from AGS is opened and read using Python's *pandas* library, which includes a function that reads a CSV file and transforms the data into an organized table called DataFrame, similar to an Excel sheet, where each column corresponds to a parameter and each line to an instant in time. Sometimes, there may be errors that make a parameter's column in the DataFrame fully empty. Thus, all such columns in the DataFrame are dropped and deleted, so they do not interfere in the conversion process. Then, the length of the DataFrame is retrieved, informing of how many instants of time were recorded in that flight. Afterwards, the DataFrame containing all the data from AGS is used to extract the necessary information to fill the FDR file.

The title of the CSV file also provides information to build the FDR file. As shown in Section 3.1, the format of the CSV files' name is constant, so the conversion software can read it to extract information regarding the flight. Taking this into consideration, the registration number of the aircraft, the date and the hour of the flight included in the CSV name are respectively used to fill the `TAIL`, `DATE` and `TIME` fields in the FDR file. Additionally, the FDR file is named after the CSV file from which it is created, for coherence.

Regarding the `ACFT` line, which defines the path within the X-Plane folder for the aircraft model to be used in the simulation, an E-195 model developed by X-Crafts was downloaded, as well as Portugália's livery for the model. Therefore, this line shows the path for this model's files inside the X-Plane folder. Additionally, the `PRES`, `TEMP` and `WIND` lines are also included in the FDR file. However, because they take constant values throughout the entire flight, they do not faithfully represent what happens in a real flight, where wind and sea-level pressure and temperature are constantly varying in time and space. Had they been omitted, these parameters would take standard values, that is, 59 ° F for the temperature, 29.92 inHg for the pressure and 0 kt and 0° for the wind speed and direction, respectively. In the FDR file, the `TEMP` and `WIND` lines are set with those values, but the pressure at sea-level is defined differently, since it affects the altitude values shown on the altimeter. Because these simulations are meant to represent specific parts of a flight, the value in `PRES` was defined as equal to the barometric pressure dialed into the altimeter during that part of the flight. This way, the altitude shown on the altimeter during the replay is congruent with the altitude input in the FDR file.

For the `DATA` lines, each parameter requires a dedicated algorithm to be read from the DataFrame, processed and finally written in its corresponding variable. The rationale behind each value written in a `DATA` line is explained in the next section.

After all the parameters are computed and the variables are all set, the information is written in the FDR file, using Python's built-in file writing function, in the structured fashion described in Section 3.2. Although the CSV data is sampled at 8 Hz, the data in the FDR files is written with a sampling frequency of 1 Hz, to reduce continuity errors in the parameters with an original sample rate of less than 8 Hz.

3.3.2 Parameter calculation

The data that comes from the QAR is sampled at various rates and samples from different parameters can be acquired at different instants in time. This means that the data in the CSV file - and, consequently, in the DataFrame - looks similar to what is represented in Table 3.1. As the table shows, depending on the parameter's sampling rate, there may be empty spaces between every two measurements. Also, the time instant at which the first value is recorded varies with the parameter and is not necessarily at 0 s. Therefore, data must be adequately manipulated to account for these situations. The generic algorithm that reads the DataFrame columns and sets the variables with the data to be written on the FDR file is represented by the flowchart of Figure 3.5. In this figure, `aux_var` is a variable that is updated every time a new value is found when iterating a column, `ctrl_var` is used to determine whether the first value in the column has been found and `num_data` indicates the number of instants of time recorded in the CSV, which corresponds to the number of rows in the DataFrame.

Table 3.1: Example of an excerpt from a CSV file containing flight data exported from AGS.

Time (s)	PITCH_IRS_8HZ (°)	PITCH (°)	ROLL (°)	HEAD_T (°)
0	-0.61111			
0.125	-0.60493	-0.53	-0.4	
0.25	-0.60356			
0.375	-0.60493	-0.53		
0.5	-0.60493			
0.625	-0.60150	-0.53	-0.4	
0.75	-0.59944			93.7
0.875	-0.59944	-0.53		
1	-0.60631			
1.125	-0.60905	-0.53	-0.4	
1.25	-0.60905			
1.375	-0.60768	-0.53		
1.5	-0.60356			
1.625	-0.60493	-0.53	-0.4	
1.75	-0.60837			93.7

Since the CSV file is written with a sampling rate of 8 Hz, the variables containing the data to be written on the FDR file will also be sampled at 8 Hz, even if their corresponding parameters have lower sampling rates. In these cases, the empty spaces between two consecutive samples have to be replaced with some value, in order to set the variables correctly. This process corresponds to the section in the blue rectangle in Figure 3.5. The algorithm iterates through the selected DataFrame column and, at each
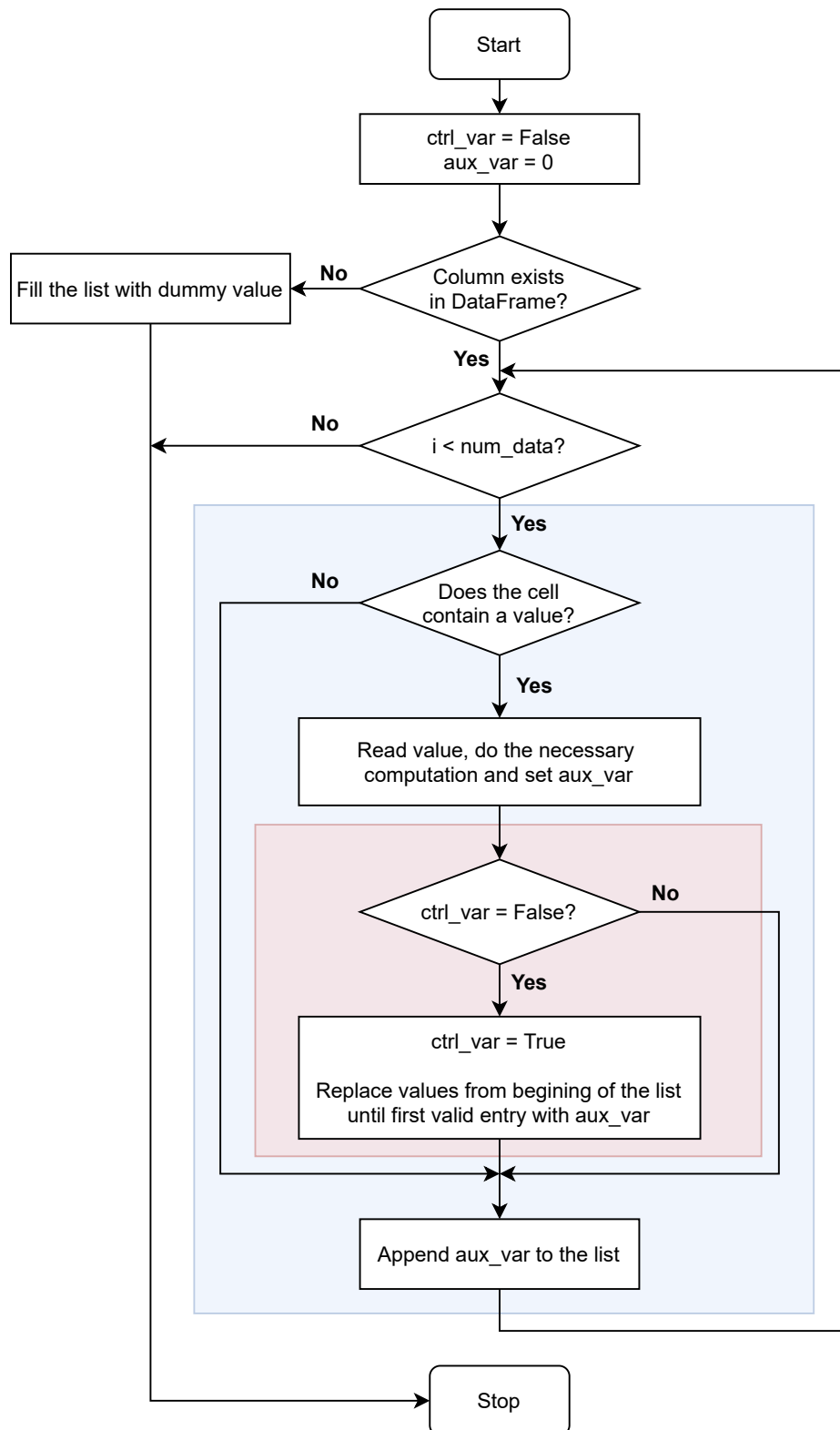
Figure 3.5: Flowchart of the algorithm that sets the variables with the parameters used to fill the FDR file.

time instant, if it finds a value, it uses it to compute the value that will be written in the FDR and saves the resulting value in an auxiliary variable (`aux_var`). If, on the other hand, the cell is empty, `aux_var` keeps its previous value. In either case, in every iteration the value of `aux_var` is appended to the end of the list, so that all lists have a length equal to `num_data`. This process goes on until the last recorded time instant is reached. An example application of this method is reproduced in Table 3.2, where it is shown that empty spaces in the original data are filled with the closest value to the left.

Table 3.2: Application of the method for filling empty spaces in data.

Original data	0.22		0.27		0.31		0.33		0.31
Resulting data	0.22	0.22	0.27	0.27	0.31	0.31	0.33	0.33	0.31

It was also pointed that the first measurement may not necessarily be recorded at 0 seconds, as it is shown in Table 3.1 in columns PITCH, ROLL and HEAD_T. The block in red in Figure 3.5 corresponds to the part of the algorithm where this situation is addressed. A previously stated, the variable `crtl_var` is a boolean that is initialized as False and receives the value True once the fist value in a column has been reached. Until then, the value 0 is appended to the list. As soon as the first value in the column is found, all the previous entries in the list are replaced with that value. An example of the application of this process is represented in Table 3.3. In this example, the first value was recorded at 0.75 s and its value is copied to all previous entries.

Table 3.3: Application of the method for filling the first entries in the data.

Time (s)	0	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1
Original data							28.75		
Resulting data	28.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75	28.75

The generic algorithm used to calculate all the parameters in the FDR file represented in Figure 3.5 was adapted to the requirements of each parameter. For instance, if there is no information available on the DataFrame regarding a specific parameter, its list is filled with a dummy value, usually 0. However, if more than one column in the DataFrame provides information for a parameter, the existence of that column is tested and the conversion algorithm is applied before resorting to filling the list with dummy values. This is done because, in an aircraft, more than one sensor may be measuring a parameter or the values may be conveyed through different data buses or they may be recorded at different sampling rates, originating several entries in the QAR that record information about the same parameter of the flight. Nevertheless, in some cases it is useful and more robust to use more than one available column to compute a parameter, in which case the ComboCalc function is called to merge all available data. This function verifies which columns are available and computes their average value in case more than one source of data is available.

Finally, the data that comes from the CSV file is discrete, but the parameters it represents can be either discrete or continuous. For example, the latitude and longitude of an aircraft are in fact continuous in time and space, but they are sampled when recorded by the QAR. When writing their values in the FDR, it was noted that there were continuity errors, introducing jumps in the position of the aircraft in the

simulations. This was due not only to the natural noise in readings but also to sensor resolution and the computation process previously described. To solve this problem, a Savitzky-Golay smoothing filter was applied to the continuous parameters, in order for the simulations to be smoother and more accurate. The Savitzky-Golay is a digital filter that fits subsets of adjacent points to a polynomial of a defined degree, using the least-squares method [80]. In this project, the data was smoothed using windows of 10 seconds and second-degree polynomials. It was found that these parameters smoothed the data in a satisfactory way, while also keeping it faithful to the unprocessed data that originated it.

The following paragraphs describe the specific computation of every parameter to be written in the FDR file.

Time

The time in seconds since the beginning of the recording is not directly given by the CSV file. However, because the sampling frequency of the data and the length of the DataFrame are known, it is possible to create an array indicating the elapsed time since the beginning of the flight at each instant. Therefore, since the CSV data is sampled at a rate of 8 Hz, time is represented by a float array, where each two consecutive entries are separated by 0.125 s.

Temperature of ambient air

To obtain the temperature of the ambient air near the airplane at its altitude, in degrees Celsius, three possible parameters that give the static air temperature (SAT) were chosen - SAT_PIL, SAT_COP and SAT_FDC_CL. The SAT is the undisturbed air temperature, that is, it does not account for the temperature induced by the aircraft's movement in air. Therefore, it corresponds to the ambient air at the current altitude. Since the chosen parameters already have the correct units, the values are directly copied to the FDR.

Longitude and latitude

The aircraft's longitude, in degrees, is directly read from the CSV file, where three different parameters provide this information, for redundancy: LONPC, LONP1 and LONG_FMS. However, the first one is preferred over the others, because it is sampled at a 1 Hz rate, whereas the other two have lower sampling rates. The minus signal is used to indicate longitudes to the West and the values are rounded to the third decimal place.

Similarly to the longitude, the latitude is given in degrees by three parameters - LATPC, LATP1 and LAT_FMS -, although the first one is preferred over the other two due to its higher sampling rate. The minus signal represents southern latitudes.

Altitude above mean sea level (MSL)

The distance of the aircraft to the mean sea level is impractical, if not impossible, to determine during flight. Instead, sensors measure the static pressure of the air surrounding the aircraft and, using the International Standard Atmosphere (ISA) model, the air data computer calculates the pressure altitude of an aircraft. Since the real atmosphere does not necessarily behave exactly like the ISA model, pilots adjust the pressure setting on the altimeter, to account for the local variations of MSL pressure. In particular, when taking off from an airport and until the local transition altitude, which depends on the airport, pilots use the local mean sea level pressure, or QNH, so that the altitudes shown are calculated relatively to that pressure setting. When using QNH, the altimeter reads the aerodrome's elevation when the aircraft in on the ground. This is also the case during the descent and landing phases of the flight, below the transition altitude of the arrival airport. Furthermore, above these transition altitudes, the altitude of the aircraft is measured relatively to the MSL considering that the atmosphere behaves like the ISA model. Therefore, pilots adjust the altimeter pressure setting to the standard value 1013.25 mb or 29.92 inHg, also known as QNE. This ensures that all aircraft flying in a given airspace employ the same altitude reference. There is also another altitude setting, the QFE, that makes the altimeter show the value 0 when the aircraft is on the ground, but, in civil aviation, the QNH is the pressure setting used below transition alitudes.

In order to compute the altitude of the aircraft in the animation, as well as the value shown in the altimeter, X-Plane FDR files include a field which defines the altitude above MSL at each instant. The pressure setting input in the altimeters and the mean sea level pressure defined in the PRES line are also contributing factors.

In the QAR data frame, the parameter ALT_QNH gives the altitude of the aircraft relative to the local QNH, the mean sea level pressure. Therefore, below transition altitudes, this parameter can be used to approximate the altitude above MSL, as required by X-Plane. Above transition altitudes, the same parameter provides the altitude relative to the standard pressure setting. This means that, around the transition, there is an oscillation in the altitude, due to the adjustment of the pressure setting. Since the pressure at the MSL becomes unknown as soon as the aircraft starts flying using standard pressure, it is not possible to know exactly the distance of the aircraft to the mean sea level. Considering these facts, the parameter ALT_QNH was chosen to populate the altitude fields in the X-Plane FDR file.

Radio altimeter altitude

The radio altimeter measures the altitude of the aircraft above the terrain directly below it, using the reflection of radio waves. Its readings are fundamental for the Ground Proximity Warning System and for category II and III precision approaches, where radio altimeter values are used to calculate the distance to the decision height defined for a particular approach [81]. Because there are two possible entries in the CSV, RALT and RALT_2, they are merged to compute the values used to populate the FDR file, unless only one of them is available.

Aileron position

The ailerons are control surfaces installed on the trailing edge of the wings that control the roll of the aircraft. In the FDR file, their deflection is given in ratio, from -1.0 to 1.0, with positive values indicating a roll to the right.

In the CSV file, the information regarding the deflection of the ailerons is given, in degrees, for the right-wing and the left-wing ailerons and can be found under the parameters AILR and AILL, respectively. Considering that positive values in these two parameters indicate that the corresponding aileron is deflected downwards, the following conclusions can be drawn:

- Positive ratio indicates a roll to the right, so the right aileron is deflected upwards (negative angle) and the left aileron is deflected downwards (positive angle).

- Negative ratio indicates a roll to the left, so the right aileron is deflected downwards (positive angle) and the left aileron is deflected upwards (negative angle).

In the case of the concerned aircraft, the deflection angle of the ailerons ranges from $-25°$ to $15°$. Therefore, they may not necessarily deflect symmetrically. However, from the observation of the graphs representing the movement of the ailerons during a flight, the deflection is symmetrical under normal operation. Thus, for the purpose of computing the aileron ratio, the deflection was limited to $-15°$ to $15°$. The ratio for each available side is calculated, dividing the values by $15°$, on the case of the left-side ailerons, or $-15°$, in the case of the right-side ailerons. Then, the average ratio is calculated taking into consideration the information from both sides of the aircraft. If there is data from only one of the sides, then its corresponding values are used by themselves to fill the FDR file.

Elevator position

The elevator is a control surface located on the horizontal stabilizer that controls the pitch of the aircraft. In the FDR file, the deflection of the elevator is given in ratio to its maximum value, from -1.0 to 1.0, where negative values indicate pitch down and positive values indicate pitch up.

In AGS, there are four parameters that indicate the deflection of the elevator, in degrees, one for each part that constitutes the surface: ELEV_LI for the inner left surface, ELEV_LO for the outer left, ELEV_RI for the inner right, and ELEV_RO for the outer right. In these parameters, the positive values indicate that the elevator is deflected downwards and the negative values indicate that it is deflected upwards. After analyzing the values of these four parameters, it was noted that their values are not necessarily equal, but are similar between one another. To determine the value to be written in the FDR file, the average deflection on each side of the elevator is computed. Then, the average between both sides is calculated, unless one of the sides does not have any information, in which case only the data from the existing side is used. Finally, these values are converted into a ratio to conform to the FDR format.

Associating -1.0 to 15°, 0.0 to 0° and 1.0 to −25°, which are the limits of the elevator's deflection, the ratios are calculated for each time instant and the final value is written in the FDR file.

Rudder position

The rudder is a control surface installed on the vertical stabilizer that controls the yaw of the aircraft. In the FDR file, this parameter defines the position of the rudder as a ratio to its maximum values, with negative values indicating rudder deflected to the left and positive values corresponding to a deflection to the right. However, X-Plane assumes that the rudder is a single surface, whereas, in reality, it can be split into smaller surfaces, with different deflection angles. In AGS, the information about the deflection of the rudder's lower and upper surfaces can be found under the parameters RUDD_LO and RUDD_UP, respectively. Therefore, the value written in FDR will be the average of the two parameters, if they are both available, or only one of them, otherwise. Since the defection angle of the rudder surfaces ranges from −31° to 31°, where the positive values indicate a deflection to the left, the angles are divided by −31° to obtain the values to be written on the FDR.

Pitch angle

The pitch angle is a result of the rotation of the aircraft around its lateral axis and is positive when the nose is pointing upwards. Similarly to previous parameters, the pitch is given by two possible entries from AGS - PITCH_IRS_8HZ and PITCH -, which are both used to calculate the final value if they are both available. They are recorded in the intended units and the sign convention is also similar, so no specific data manipulation is required to obtain the value to be written on the FDR file.

Roll angle

The roll angle corresponds to the rotation of the aircraft around its longitudinal axis and is positive when the aircraft turns right. There is only one parameter that provides information regarding this entry, ROLL, so it is directly copied into the FDR, because both the units and the sign convention of the CSV values are congruent with the specifications of X-Plane.

True heading

The true heading of the aircraft is measured relatively to the true North, in degrees, and is given in AGS by HEAD_T nad HEAD_TRUE. However, HEAD_T ranges from −180° to 180°, while HEAD_TRUE takes values from 0° to 360°. To fit with the FDR format, the values provided by HEAD_T are wrapped to the interval 0° to 360°. Finally, if the two possible parameters are available in the CSV, they are merged to compute the values written the FDR.

Indicated airspeed (IAS)

The indicated airspeed is the value shown in the airspeed indicator in the aircraft's instrument panel and corresponds to the difference between total and static pressure at each instant. In the AGS data frame, the parameters IAS and IAS_COP store the values shown in the captain's and the first officer's instruments, respectively, so these two parameters are used to compute the values to be written in the FDR file. If they are both available on the CSV, their arithmetic mean is calculated at each instant. Otherwise, only the available parameter is used to fill the corresponding entry in the FDR.

Indicated vertical speed

The indicated vertical speed is given in feet per minute and, in AGS, there are three parameters that provide this data: IVV_4s, sampled at 1 Hz, VSI_REC, sampled at 0.25 Hz, and VS_GGF1, sampled at 2 Hz. Therefore, the column that provides more data is VS_GGF1, so it is preferred over the other two. If is is unavailable, IVV_4s is used and, as a last option, VSI_REC can also be employed.

Sideslip angle

The angle between the aircraft's longitudinal axis and the direction of the airflow is the sideslip angle, being positive when the aircraft's nose points to the right. In AGS, two parameters provide this information: SIDESLIP_BEF, sampled at 4 Hz and SIDE_SLIP, sampled at 1 Hz. Therefore, when writing the FDR file, the former is preferred to the latter, for it is more detailed.

Turn and slip indicator angle

The turn and slip indicator shows whether the aircraft is performing a coordinated turn, in terms of slip angle and turn rate. In X-Plane, this is given by the deflection angle shown on the instrument, with positive angles indicating a right turn. However, because this parameter is not recorded by the QAR, it is not used in the FDR file, so its corresponding fields receive the value 0.

Mach number

The indicated Mach number is the ratio of the speed of the aircraft to the local speed of sound. In AGS, two parameters can be found that store this information: MACH and CK_MACH. If they are both available, their average is computed at each time instant. Otherwise, the available parameter is used to fill the FDR.

Angle of attack

The angle of attack is defined by the angle between the chord of the wing and the direction of the airflow. In AGS, there are two parameters that indicate the angle of attack, corresponding to two different

sensors installed on the aircraft: AOA_BD1 and AOA_BD3. If both parameters exist in the CSV file, then their average is computed at each instant and the value is written on the FDR file. However, if only one of the parameters is available, then its values are copied to the FDR file.

Stall Warning

A stall is characterized by a sudden loss of lift and occurs when an aircraft exceeds the critical angle of attack. Because it is an undesirable and dangerous situation, aircraft are equipped with stall warning systems, to warn the pilots about an impending stall. These frequently include an audible warning and a stick shaker, that shakes the control column.

This parameter indicates whether the stall warning is active, but, in the QAR data frame, there is no parameter that directly provides this information. There are, however, two parameters that give the instantaneous stall warning activation angle, that is, the angle of attack that, if exceeded, activates the stall warning: AOA_WA1 and AOA_WA3. If they are both available, their average value is computed at every instant. Otherwise, the available parameter is used. Then, for each time instant, this value is compared with the angle of attack previously computed and, if the warning activation angle is exceeded, the corresponding stall warning entry in the FDR file is set at 1. Otherwise, 0 is written on the FDR file.

Flap handle position

The position of the flaps is controlled by a handle on the cockpit. This parameter indicates the position of the handle as a ratio, from 0 (retracted) to 1 (extended). In the AGS data frame, there are two possible parameters that convey this information, although in different formats. The correspondence between the parameters and the value written on the FDR file is shown in Table 3.4.

- **FLAP_LVR**: this parameter takes 7 possible integer values, from 0 to 6. To transform them into a ratio, they are divided by their maximum value, 6.

- **FLAP_LEVER**: the information about the position of the flap lever is given by the powers of 2, from 1 to 64. Therefore, in order to obtain a ratio from these values, their binary logarithm is computed and the resulting number is divided by 6, which is the maximum possible value resulting from the previous operation.

Finally, because the two parameters convey exactly the same information, it is indifferent to use one or another and FLAP_LEVER is used only in case FLAP_LVR is not available. The obtained values are written on the FDR file.

Table 3.4: Correspondence between AGS parameters and the FDR values for the flap handle position.

FLAP_LVR	FLAP_LEVER	FDR
0	1	0.0
1	2	1/6
2	4	2/6
3	8	3/6
4	16	4/6
5	32	5/6
FULL	64	1.0

Flaps position

Flaps are high-lift devices mounted on the trailing edge of an aircraft's wings, which decrease the stalling speed of the wing when extended. In the aircraft operated by Portugália, their extension angle ranges from $0°$ to $37°$. However, in the FDR file the flap position is given in ratio, from 0 to 1. Therefore, the AGS data, found under the column FLAP, is divided by its maximum value, $37°$.

Slats position

Similarly to the flaps, the slats are high-lift devices, but they can be found on the leading edge of the the wings. They also allow the aircraft to operate at higher angles of attack without stalling, by reducing stall speed. In the E-jets, the angle of deployment of the slats ranges from $0°$ to $26°$. The information about the position of the slats is present in the FDR files in the form of a ratio. Therefore, the values from AGS are divided by $26°$, in order to obtain the ratio that is written on the FDR file.

Speed brakes

Normally used during the approach and after landing, speed brakes are movable panels that can be extended to increase drag and, therefore, reduce the speed of the aircraft.

In the FDR file, the deflection of the speed brakes is given as a ratio, from 0.0 (retracted) to 1.0 (extended). In AGS, the parameter SPD_BRK indicates whether the speed brakes are extended or not. If the panels are at least at 20% of full scale deflection, then SPD_BRK is set at 1. Otherwise, the speed brakes are considered to be closed and the parameter receives the value 0. Since this format corresponds to the one required by the FDR, the values of SPD_BRK are copied into the FDR file. However, if this parameter is not available there are three other possible parameters that store the deflection angle of the speed brakes: SPD_BRK1, SPD_BRK3 and SPD_BRK4. The angle can range between $-50°$ and $50°$, but only the positive values are considered. Associating the value 1.0 to $50°$ and 0.0 to $0°$, the values stored in these parameters are converted into a ratio, dividing them by $50°$.

Landing gear handle position

An aircraft's landing gear is responsible not only for providing support for the aircraft's weight, but also for enabling its movement on the ground. The landing gear can either be fixed or retractable. At Portugália, all the aircraft are equipped with retractable landing gears. The position of the gear is controlled by a handle in the cockpit and this parameter displays whether it is in the retracted or extended position, using the values 0 and 1, respectively.

In AGS, there are two parameters that convey this information: LDG_SELDW and LDG_SELUP. They have different configurations, meaning that their possible values have different meanings.

- **LDG_SELDW**: this parameter can take five values - 0 (not down), 1 (down), 2 (transit), 3 (down and locked) and 4 (unsafe). To convert the data into the desired format, if the value is 0, 2 or 4, the value 0 is written on the FDR file. Otherwise, if it is 1 or 3, then the landing gear is extended and the value 1 is written.

- **LDG_SELUP**: in contrast, this parameter only takes two values - 0 (not up) and 1 (up). Therefore, in the first case the value 1 is written and, in the second case, 0 is written on the FDR file.

Nose, left and right landing gear position

The landing gear of the aircraft operated by Portugália consists of two gears: the nose gear and the main gear, which, in turn, comprises the left and right landing gears. The information about the actual position of each of these three gears is given by the the parameters LDGNOS_POS, for the nose gear, LDGL_POS, for the left one, and LDGR_POS, for the right landing gear. These three columns have the same configuration, taking the values 0 (not computed), 1 (up and locked), 2 (in transit), 3 (down and locked) and 4 (abnormal). In X-Plane's FDR files, there are also three entries concerning the position of each part of the landing gear - nose, left and right -, where the value 1 indicates an extended gear and 0 corresponds to the retracted position. Thus, if the AGS parameter indicates 3, then the gear is down and the value 1 is written on the FDR file. In any other case, the gear is up and 0 is written.

Elevator trim angle

Control surfaces can be trimmed, that is, their position can be adjusted to balance aerodynamic forces, so that the aircraft is able to maintain a defined attitude without the need for control inputs, reducing the workload on the pilots.

In particular, the elevator can be trimmed to help control pitch. The FDR file includes the information about the elevator trim as a ratio from -1.0 to 1.0, with positive values indicating nose up. In AGS, the information regarding elevator trim is found under the parameter PITCH_TRM, which takes values from −14° to 3°, where positive values also imply nose up. Therefore, -1.0 is associated to −14°, 1.0 to 3°

and 0.0 to 0°. The negative values of PITCH_TRM are divided by 14°, the positive ones are divided by 3° and the results are written on the FDR file.

Navigation frequencies 1 and 2

Aircraft are equipped with radios, not only for communication but also for navigation purposes. In particular, the frequency band 108 MHz-117.975 MHz is allocated to aeronautical radio navigation and the band 117.975 MHz-137 MHz is reserved for communications [82]. Since aircraft are equipped with two receptors for navigation, one for the captain and one for the first officer, pilots can define two navigation frequencies - NAV 1 and NAV 2 -, corresponding to the navigational aids (NAVAID) used during the flight. Usually, the two receptors are set to the same frequency. Although only the frequency on the side of the pilot flying is used, the two frequencies are set for redundancy purposes, in case the main one fails.

In AGS, the frequencies are given by the parameters NAV_FRQ1 and NAV_FRQ2, in megahertz. However, in the FDR file, they must be written as a five-digit number with no decimal places. Therefore, the values read from the CSV are multiplied by 100 and, if necessary, zeros are added to the left of the resulting number to fill the 5 digits.

Navigation aid type 1 and 2

The information about the NAVAID being tracked on the two radio frequencies is also available on the FDR file. The entries can take 5 different values: 0 for none, 2 for non-directional beacon (NDB), 3 for very high frequency omnidirectional range (VOR), 5 for localizer (LOC), and 10 for Instrument Landing System (ILS). In AGS, the parameters NAV_SRC_P and NAV_SRC_C provide this information about the pilot's and the first officer's radio, respectively. However, their values differ from the X-Plane's standard. The relevant values in AGS are: 0 for none; 4, 5 and 6 for VOR/LOC 1, 2 and 3; and 7 and 8 for Microwave Landing System (MLS) 1 and 2. Therefore, given the available options, if the value on the CSV parameters is 4, 5 or 6, then 3 is written on the FDR file; if it is 7 or 8, the value 10 is chosen; in any other case, due to the lack of equivalent values on the AGS data, 0 is written on the FDR file.

Omni bearing selector (OBS) 1 and 2

The OBS is a knob associated to the course deviation indicator (CDI), that allows the pilot to choose a course to be followed by the aircraft. The FDR file receives the information about the heading selected on the captain's and the first officer's CDI. However, this information is not available on the QAR data for each CDI, so the parameter HEAD_SEL, which indicates the seleted heading is used for both entried in the FDR file.

DME 1 and 2 distance

The aircraft is equipped with two Distance Measuring Equipment (DME) receivers. In the FDR file, two parameters show the distance, in nautical miles, from the aircraft to the station associated with each receiver. In AGS, the columns DME_DIS1 and DME_DIS2 provide this exact information, which is copied to the FDR file at each time instant.

Localizer deflection 1 and 2

The ILS is a navigational aid used to provide guidance to aircraft during landing operations. The ILS uses two signals: the localizer for lateral guidance and the glide slope for vertical guidance. The information about the position of the aircraft relative to the signals of the ILS is given on the primary flight display (PFD), using dots.

In X-Plane, the localizer deflection ranges from -2.5 dots to 2.5 dots, with positive values indicating that the aircraft is to the right of the runway centerline. In AGS, the information is conveyed in a similar way, through the columns LOC_DEVC and LOC_DEVC2, for the captain's and the first officer's instruments. However, since they come in a scale form -5 to 5 dots, the AGS values are divided by 2 to fit in the FDR format.

CDI 1 and 2 flags

The CDI includes a small flag that indicates whether the aircraft is flying to or from the navigational aid to which it is associated at a given moment in time. In the FDR file, there are two entries, one for the captain's CDI and on for the first officer's. They can take the values 0 (deactivated), 1 (to) or 2 (from). However, there is no corresponding parameter on the QAR data, so, by omission, the two entries are kept at 0 throughout the whole flight.

Glide slope deflection 1 and 2

Similarly to the localizer defletion, the glide slope deflection is also given in dots, with a scale of -2.5 dots to 2.5 dots, with positive number indicating that the aircraft is above the desired path. The AGS data is found under the columns GLIDE_DEV_1_DOTS and GLIDE_DEV_2_DOTS, for each of the two PFD. In order for the data to be congruent with the FDR format, the AGS values are divided by two, since they can range from -5 to 5 dots.

Outer marker, Middle marker and Inner marker signals

According to the International Telecommunication Union (ITU), a marker beacon is defined as "a transmitter in the aeronautical radionavigation service which radiates vertically a distinctive pattern for providing position information to aircraft" [82]. The ILS employs marker beacons to aid in approaches.

Their signal is transmitted through a carrier wave at 75 MHz and there are usually three marker beacons, whose location and modulation frequencies are defined in the European Radio Navigation Plan [83] and are introduced next.

The outer marker is located at 7.2 km from the runway threshold. The carrier is modulated with a wave at 400 Hz and a visual blue signal and a characteristic aural signal are emitted in the cockpit.

The middle marker can be found at 1050±150 m from the runway threshold. It modulates the carrier wave with a signal at 1300 Hz and an amber visual signal and a specific sound are emitted in the cockpit.

Lastly, the inner marker is usually between 75 m to 450 m from the landing threshold, modulating the carrier with a wave at 3000 Hz. Similarly to the two previous markers, a characteristic aural sound can be heard in the cockpit and a white light is shown on the panel.

In the FDR file, the information about whether the aircraft is above each marker beacon is conveyed through three dedicated parameters, that indicate 1 when the aircraft is receiving a signal from their corresponding marker beacons or 0 otherwise. In AGS, the three columns OUT_MK, MID_MK, INR_MK use the same format to show that information, so their data is copied to the FDR file.

Flight Director (FD)

The flight director is a guidance system that shows the pilots the pitch and roll angles required at each instant to follow a defined trajectory, on the attitude indicator [84]. It does not control the aircraft, but, if the autopilot is engaged, it follows the indications of the flight director. The FDR file indicates whether the flight director is turned on or off using the values 1 and 0, respectively. In the CSV files, the state of the flight director is given in the same format by the columns FDEN_PB_PL and FDEN_PB_CP, corresponding to the captain's and the first officer's instruments. Then, if at least one of these signals indicates 1, this value is written on the FDR file and, otherwise, 0 is written.

FD pitch and roll angles

As previously stated, the flight director calculates and shows the pitch and roll angles required for the aircraft to follow the desired path. These two parameters are also shown in the FDR files, where the pitch command is given in degrees with positive indicating nose up and the roll command is also given in degrees with positive values indicating a turn to the right. The corresponding data can be retrieved from AGS through the columns FDPITCHCMD and FDROLLCMD, respectively, which employ the same units and standards to represent the angles. Therefore, the data is simply copied from the CSV to the FDR file.

Speed in knots or Mach

The speed being held by the autopilot can be provided in knots or in Mach number. At each time instant, if this parameter takes the value 1, then the autopilot is holding Mach, but, if its value is 0, the autopilot is using knots. In the CSV file, this information can be found under the parameter ASPD_TYPE, which uses the same standard as the FDR file: 1 for Mach and 0 for knots. Thus, the information is copied from the CSV to the FDR file.

Auto-throttle (A/T)

The auto-throttle is responsible for automatically adjusting the amount of thrust required during the flight, ensuring that the aircraft follows the intended trajectory and maintains the characteristics desired at each phase of the flight. This system allows for a more intelligent and efficient fuel consumption, while reducing the workload on the pilots [85].

In the FDR file, there is a parameter that indicates whether the auto-throttle is engaged, taking the value 1, or not, in which case it shows 0. In AGS, the entries AT_EGD and AT_ENG_MWS convey this information using this standard. Since there are two available sources, they are combined to obtain the value written in the FDR file. If at least one of them shows 1 at a given instant, then the value 1 is written. Otherwise, 0 is written.

Autopilot active lateral and vertical modes

Larger aircraft are equipped with automatic flight control systems, including an autopilot, flight director and, often, an auto-throttle. These systems have different modes of operation, for both vertical and lateral guidance, depending on the flight parameters being controlled. Modes can be armed or engaged. An armed mode is a state that will activated once the aircraft reaches that target, whereas an engaged or active mode sets the parameters that the autopilot is holding. These two parameters in the FDR file define the active lateral and vertical modes at each moment during the flight.

In X-Plane, lateral modes are wing-level (0), heading hold (1) and navigation using a localizer or another NAVAID (2), although the AGS data frame provides more options for the active lateral mode under the parameter LAT_MOD_ACT31. The correspondence between AGS and FDR parameters is shown in Table 3.5. All the options in AGS that do not have a direct association are set to 0 by default.

As for the vertical modes, X-Plane recognizes 7 different options: pitch (3), vertical speed (4), airspeed (5), airspeed with altitude armed (6), altitude hold (7), terrain-follow (8) and glide slope hold (9). In AGS, the parameter VERT_MOD_ACT31 provides the information regarding the engaged vertical mode, with more detail than the FDR file format. The correspondence between the FDR values and the AGS data is shown in Table 3.6. The AGS values that have no equivalent in the FDR format are set to 3.

Table 3.5: Correspondence between the AGS parameter and the FDR values for the active autopilot lateral mode.

FDR		LAT_MOD_ACT31		
0	Wing-level	0	NONE	None
		1	ALIGN	Align with runway centerline
		19	RLOUT	Roll out - maintain alignment with runway after landing
		20	ROLL	Maintain bank angle or level wings
1	Heading	14	HDG	Heading hold
		22	TRACK	Track hold
2	LOC and other NAVAIDs	6	BC	Back course mode
		15	LNAV	Lateral navigation guidance
		16	LOC	Localizer
		24	VOR	VOR

Table 3.6: Correspondence between the AGS parameter and the FDR values for the active autopilot vertical mode.

FDR		VERT_MOD_ACT31		
0	None	0	NONE	None
3	Pitch	3	APPV	Approach with vertical guidance
		7	D-ROT	De-rotation - commands nose pitch down on touchdown
		10	FPA	Flight Path Angle
		11	GA	Go Around
		21	TO	Takeoff
		27	WSHR	Windshear - provides flight path angle guidance
		28	VNAV	Vertical Navigation
		29	LVTO	Low visibility takeoff
4	Vertical speed	26	VS	Vertical speed
5	Airspeed	17	OVSP	Overspeed
6	Airspeed with altitude armed	9	FLCH	Flight Level Change
		30	VFLCH	VNAV Flight Level Change
7	Altitude hold	2	ALT	Altitude hold
		5	ASEL	Altitude selected
		31	VASEL	VNAV with altitude selected
8	Terrain-follow	8	FLARE	Flare - provides vertical guidance between glide slope and touchdown
9	Glideslope hold	12	GP	Glide Path
		13	GS	Glide Slope
		23	VNAV	Vertical Navigation
		28	VNAV & GS	VNAV with Glide slope

Autopilot lateral and vertical modes armed for capture

As previously stated, a mode can be armed on the autopilot, which means that it is ready to capture a signal and become active. In the FDR file, the armed modes are not explicitly written, like the active modes. Instead, the values 1 and 0 indicate whether there is an armed mode or not. This is valid for both the lateral and the vertical armed mode.

The armed lateral mode is given by the parameters LAT_MD_ARM_PIL and LAT_MD_ARM_COP in AGS. If the mode is 0, which corresponds to NONE, then no lateral mode is armed and 0 is written in the FDR file. If, on the other hand, any mode is armed, then 1 is written. Since there are two parameters providing this information, the second one is used only in case the first one is unavailable.

The process is similar for the armed vertical mode, but the AGS parameters are VER_MD_ARM_PIL and VER_MD_ARM_COP.

Back course mode

A back course mode approach is a non-precision approach that uses information from the localizer signal from the runway complementary to the one where the landing is being performed. Nowadays, modern ILS antennas are highly directional, so back course approaches are falling into disuse, because the antennas do not provide enough energy on the back lobe to support this operation. Since this approach is not performed by Portugália crews, the back course value is always kept at 0.

Autopilot speed, heading, vertical speed and altitude selection

The autopilot is used to automatically control the aircraft, without the need for constant manual input from the pilots. In particular, the autopilot is capable of holding speed, altitude, heading and vertical speed. These four parameters can be found in the FDR file.

The speed the autopilot must hold can be given in knots or in Mach number. At each instant in time, it is necessary to assess which type of speed is being considered, in accordance with the previous parameter that registered this information. The parameter IAS_SEL provides the selected speed in knots and MACH_SEL indicates the selected speed in Mach number. Therefore, at each instant, if the autopilot is holding speed in knots, the parameter IAS_SEL is used, and, if it is holding speed in Mach, MACH_SEL is used.

The magnetic heading selected for the autopilot is given by the parameter HEAD_SEL. Since it has the correct units and the values are limited to the interval from 0° to 360°, the dalues are directly copied to the FDR file.

The autopilot can also hold the vertical speed of the aircraft, which can be found in the CSV file under the parameters IVV_SEL_P, selected by the captain, and IVV_SEL_C, selected by the first officer, in feet per minute. These values are selected by the crew, thus the former is used when available and the latter is employed otherwise. Since the data in the CSV has the desired units, no other manipulation is required.

Finally, the parameter ALT_SEL gives the altitude held by the autopilot in feet, as required by the FDR format, so its values are directly copied to the file.

Barometric pressure dialed into the altimeter

Aircraft are equipped with a barometric altimeter, an instrument that indicates the altitude of the aircraft depending on the outside pressure. The altimeter is calibrated with a pressure setting, so it can show altitude relative to different reference points, namely above mean sea level, above ground level and above mean sea level in a standard atmosphere, which corresponds to the flight level.

In X-Plane's FDR file format, the pressure dialed into the altimeter is given in inches of mercury. In AGS, this information is available under the parameters ALT_CPT_INHG and ALT_FO_INHG, for the captain's and the first officer's altimeters, respectively, also in inches of mercury. Therefore, the values are copied into the FDR file without further manipulation. Since there are two possible parameters, the second one is used only when the first one is not available.

Decision height

In precision approaches or approaches with vertical guidance, the decision height is a defined height relative to the runway threshold at which the pilot must determine a missed approach if they are unable to establish the necessary visual reference to continue with the landing [86].

In the CSV, the decision height dialed by the captain is given by DH_SEL_P, while the one set by the first officer is recorded by DH_SEL_C. Because these parameters are selected by the crew and are not a measurement from an instrument, they are not merged to obtain the value to write in the FDR file. Instead, and considering the parameters are imported from the CSV in feet, if DH_SEL_P is available, it is used in the FDR file. Otherwise, DH_SEL_C is used.

Master caution

More complex aircraft are equipped with an annunciator panel, a set of lights that indicate the status of the various systems that constitute the aircraft. If a yellow light shows up on the panel, its corresponding system will need attention in the near future. Additionally, the Master Caution signal is turned on, showing a yellow light, until the pilot acknowledges the signal and presses its button. In the FDR file, the value 1 indicates that the Master Caution is on, whereas 0 indicates that it is turned off.

In the CSV, the columns MASTER_CAUT and MCAUTION contain information regarding the state of the Master Caution, in accordance with the FDR file format. Therefore, if at least one of the two parameters indicates that the master caution is on, the value 1 is written. Otherwise, 0 is written on the FDR file.

Master warning

Similarly, to the master caution, the aircraft is equipped with a master warning signal. If a system is in a critical state and requires immediate attention, a red light shows up on the annunciator panel and

the Master Warning signal, a red light and an aural signal, is turned on, until the pilot acknowledges it and presses the button.

The only parameter in AGS which indicates the state of the Master Warning is MWAR and it takes two possible values: 1, if it is on, and 0, if it is off. Since this is in accordance with the FDR format, the values of MWAR are directly copied to the FDR file.

Ground Proximity Warning

The Ground Proximity Warning System (GPWS) is installed in aircraft to detect and warn the crew about dangerous situations, including an imminent collision threat with the ground or other obstacles. When a dangerous situation is detected, the GPWS emits aural and visual warnings that not only identify the hazard, but also define a set of measures the pilots must adopt to correct the situation. In particular, the GPWS has seven alert modes, which are described below [58].

- **Mode 1 - Excessive descent rate:** this mode is triggered when the aircraft is descending with a rate above the limits defined by the GPWS system, which depend on the altitude above ground level. The situation is resolved by reducing the rate of descent to values below the alert limits.

- **Mode 2 - Excessive closure to terrain:** when the aircraft encounters a region where the radio altimeter values are rapidly decreasing, a mode 2 alert is issued to prevent a ground collision. This alert depends on the radio altitude and the rate at which the aircraft is approaching the terrain. It is resolved by pulling the nose of the aircraft up and increasing its altitude.

- **Mode 3 - Altitude loss after take-off:** this alert sounds to warn the crew if the aircraft loses altitude immediately after take-off or a go around. It stops once a positive rate of climb is established.

- **Mode 4 - Unsafe terrain clearance:** this mode is associated with an insufficient distance to the ground. It depends on the phase of the flight and the configuration of the aircraft, and the alert cleared once the aircraft has a safe distance to the ground or is adequately configured.

- **Mode 5 - Excessive deviation below glide slope:** if the aircraft significantly descends below the intended glide slope, the GPWS emits an alert. It is resolved by aligning again with the glide slope.

- **Mode 6 - Advisory callouts:** the callouts are announcements of certain altitudes out loud by the GPWS. The system is also triggered when the bank angle exceeds the flight envelope.

- **Mode 7 - Windshear alerting:** if the aircraft encounters windshear, this mode is triggered and sounds an alert, depending on the longitudinal and vertical components of the wind speed.

In AGS, the parameter GPWS_WARN has two possible values - 1, if the GPWS is emitting a warning, and 0, otherwise -, which is also the configuration employed by the FDR format, so the data in this parameter is directly copied to the FDR file.

The remaining parameters, described in the next paragraphs, refer to the performance of the aircraft's engines. X-Plane can simulate flights done by aircraft with up to four engines, so four entries must be written for each parameter, one per engine. If the aircraft is equipped with less than four engines, the excess entries are filled with 0. The aircraft operated at Portugália are equipped with two engines, so the entries corresponding to them are filled with data from the QAR, while the two remaining entries are filled with 0. Following standard engine numbering, engine number 1 is mounted on the left wing and engine number 2 is located on the right wing, from the perspective of the pilot looking forward.

Additionally, the FDR file has a fixed structure, so all the parameters have to be written. Therefore, although Portugália operates turbofan-powered aircraft, the parameters regarding propeller engines, which have no interest for the considered aircraft, have to be filled with 0 and written in the FDR file.

Throttle position

The throttle position indicates how much thrust the pilots are demanding from the engines. This entry shows the position of each throttle, relative to its maximum value. From AGS, the parameters TLA1 and TLA2, for engines number 1 and 2, respectively, are retrieved. However, since they come in degrees and take values between 0° and 83°, it is necessary to divide their values by 83°, so they become nondimensional as required by the FDR format.

Propeller RPM command and actual RPM

In aircraft equipped with propeller engines, like turboprops and piston engines, the pilot controls the engines' rotational speed. However, the actual revolutions per minute done by the propeller may not be exactly similar. These two parameters indicate the demanded and the actual rotational speed of the propellers. Nevertheless, the aircraft operated at Portugália use turbofan engines. Thus, these parameters are not relevant for the simulations and are filled with 0 throughout the entire flight.

Propeller pitch

The blades in a turboprop engine can rotate around their axis, changing the angle with the airflow around them, affecting their efficiency. However, like previous parameters, the propeller pitch is not used with turbofan engines, so its entries are entirely filled with 0.

N1 and N2

The aircraft used at Portugália are equipped with two turbofan engines. Each engine features two concentric spools - one high pressure and one low pressure -, each one made up of a compressor and a turbine connected through a shaft.

The low-pressure spool rotates at a lower speed than the high-pressure spool. Its rotational speed is translated by the parameter N1, which is represented as a percentage of a reference value defined

by the engine manufacturer. Similarly, the rotational speed of the high-pressure spool is represented by the parameter N2, also as a percentage of a reference value.

The QAR provides the values of N1 and N2 for each engine, through the parameters N11 and N21, for engine number 1, and N12 and N22, for engine number 2.

Engine Manifold Pressure

The engine manifold pressure is a parameter used in piston engines, defined as the pressure difference between the atmospheric air and the manifold entrance and it indicates the engine's power. Because it is only used for aircraft using piston engines, its fields are entirely populated with 0.

Engine Pressure Ratio (EPR)

The ratio between the pressure at the exit of the turbine and the pressure of the air at the entrance of the compressor is called engine pressure ratio. It provides information regarding the thrust produced by an engine. However, at Portugália the N1 is used as the thrust reference parameter, because it is preferred by the engine manufacturer's, General Electric, so the EPR is not provided by the QAR. Therefore, all its corresponding entries are filled with 0.

Engine torque

The engine torque indicates the load applied in the shaft connected to the rotating blades and produced by the engine movement. Since this parameter is only relevant for aircraft powered by turboprop engines, it is not filled with data from AGS.

Fuel flow

The fuel flow is defined by the mass of fuel supplied to each engine in a defined time period. The FDR file receives this parameter in pounds per hour (lb/h). The AGS provides the relevant information through the parameters FF1 and FF2, corresponding to engines 1 and 2, respectively, in kilograms per hour (kg/h). Therefore, it is necessary to perform a unit conversion, knowing that 1 kg is approximately 2.205 lb, for the values to be in accordance with FDR requirements.

Interstage Turbine Temperature (ITT)

The temperature of the exhaust gases between the high-pressure turbine and the low-pressure turbine is given by the interstage turbine temperature. The parameters ITT1 and ITT2 from AGS record the ITT of engines 1 and 2, in degrees Celsius, as required by X-Plane.

Exhaust Gas Temperature (EGT)

The exhaust gas temperature is also known as the turbine outlet temperature (TOT), because it measures the temperature of the gases that exit the turbine in a turbofan engine. In AGS, the two parameters CK_EGT1 and CK_EGT2 provide the information of the EGT in engines 1 and 2, respectively. These parameters are recorded in degrees Celsius, in line with the requirements of the FDR file.

Cylinder Head Temperature

This parameter corresponds to the temperature of the head of the cylinders integrated in a piston engine. Therefore, it is not relevant for the aircraft used at Portugália and its entries are filled with 0.

3.4   Graphical User Interface

With the purpose of making the developed tool more user-friendly and accessible, Graphical User Interface was designed, using Python's built-in Tkinter library.

Through the GUI, the users can choose the CSV file to be converted to FDR format, choose the time period of the flight they want to replay, see the resulting FDR file and launch X-Plane.

When the tool is launched, the window of Figure 3.6 shows up on the screen. In this window, the user can choose the file they want to convert, by clicking on the *Open* button. This launches a dialog window that allows the user to find the file to be converted, provided it is a CSV file.
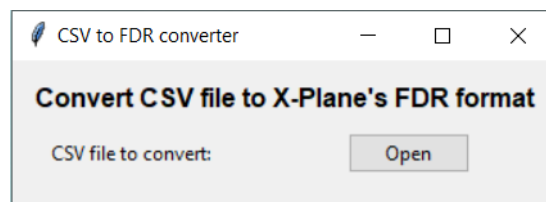

Figure 3.6: First screen of the GUI.

After choosing a valid file, the window expands and new elements show up. The path of the chosen CSV file is displayed, as well as two entry fields and a new button. The two fields allow the user to choose when they want the replay to start and end. These values are given in minutes, relative to the beginning of the recording. The button *Generate FDR* calls a function that performs a set of actions:

- Verifies that the chosen simulation start and end times are valid. The possible errors are discussed below.

- Reads the CSV file name and creates a new FDR file in X-Plane's folder in the computer, if the start and end times are valid. The FDR file's name is copied from the CSV file's name.

- Converts the simulation start and end times into indexes, knowing that the data is sampled at 8 Hz.

- Calls the `csvtofdr.py` script, which is responsible for performing the actual data conversion discussed in the previous sections. If the conversion returns any error, a dialog pops up on the screen informing the user.

- Creates the *Show FDR* and *Open X-Plane* buttons if the conversion was successful.
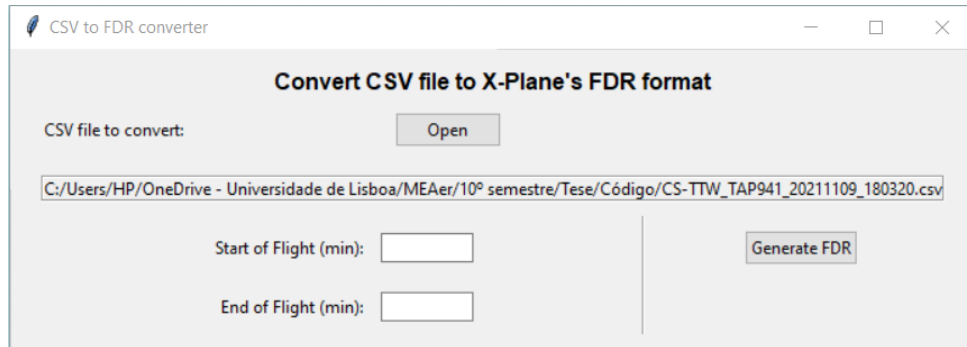
The resulting window is shown in Figure 3.7.

Figure 3.7: Second screen of the GUI.

As previously stated, the user may be interested in replaying only a small portion of the flight. To address this option, the tool asks the user to input the simulation start and end times. To prevent problems and ensure that the chosen values are valid, the input of these fields is tested and validated. Four different errors can arise during this stage, each one corresponding to an image in Figure 3.8. The user can input values as many times as needed until a valid set of values is found.

The first error occurs when the user inputs something that is not a number, like letters or other characters, or leaves at least one of the text boxes empty. When this happens, the error message shown in Figure 3.8(a) is displayed.

The second error happens when the user inputs a start time that exceeds the end time. In this case, the error of Figure 3.8(b) is shown.

The two chosen times have to be non-negative numbers. Therefore, if the user inputs a negative number in any of the spaces, the program warns them by presenting the error shown in Figure 3.8(c).
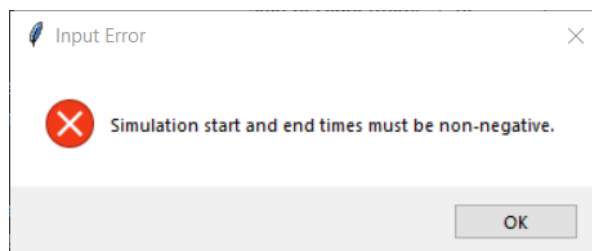
Finally, the program also verifies whether the simulation end time exceeds the end time of the data written in the CSV file. In case it does, the dialog window of Figure 3.8(d) pops up on the screen.
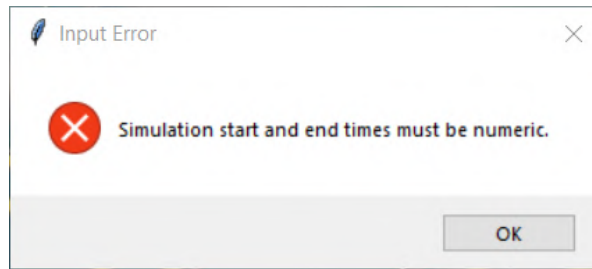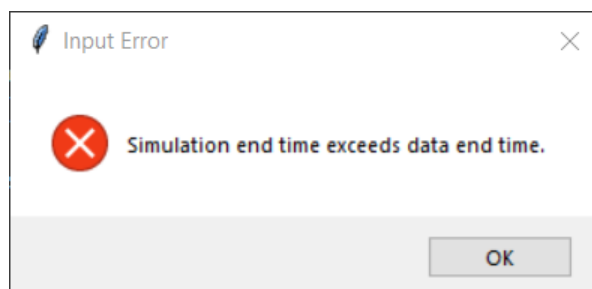
(a) Error about the input of non-numeric values in the simulation start and end times.
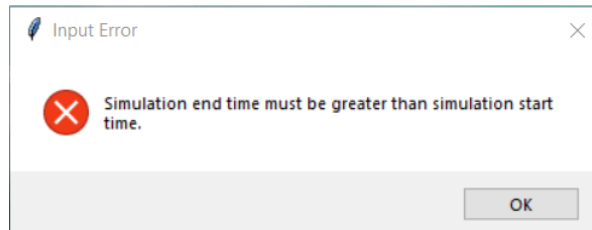
(b) Error about simulation start time having to be greater than simulation end time.

(c) Error about the input of negative numbers on simulation start and end times.

(d) Error about the end time exceeding the maximum data time.

Figure 3.8: Errors related to the validation of the animation start and end times.

After a successful file conversion, the user is presented with two new options, through the buttons *Show FDR* and *Open X-Plane*. The former opens the generated FDR file in the application with which its extension is associated, which depends on the computer system being used. The latter finds the path for the X-Plane 11 executable file in the computer and runs it. If an error arises during this process, the user is adequately warned through a dialog window. The screen showing these two buttons is presented in Figure 3.9.
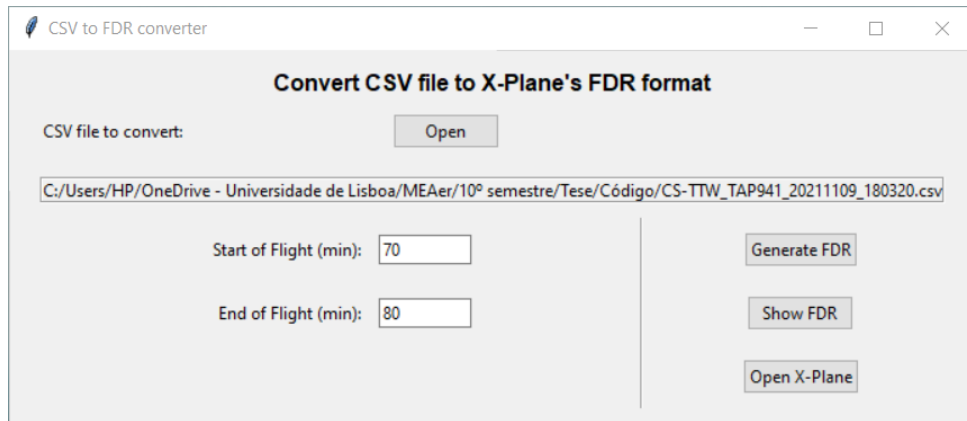
Figure 3.9: Third screen of the GUI.

Finally, the tool is encapsulated in a standalone executable file, so it can be used in any Windows system, without the need to access the code.

Chapter 4

Flight Data Reproduction Analysis

After the data conversion is performed and the resulting file is automatically saved to X-Plane's folder, the simulator can be launched to replay the flight. The main goal of this chapter is to discuss the features of the resulting animations, their capabilities and also their drawbacks and eventual inconsistencies with the data that originated them.

To view the replays, one must choose the option *Replay Flight* on the main menu of X-Plane and select the desired FDR file for replay from the list. Afterwards, the replay is loaded and can be viewed. An example of the first frame of an animation is shown in Figure 4.1.

Figure 4.1: First frame of an animation.

As seen in Figure 4.1, the animation starts with an inside view of the aircraft, on the left-hand side of the cockpit. The instrument panel and the Head-Up Display (HUD) can be seen, as well as a time bar, where the progress and speed of the animation can be controlled. The time since the beginning of the flight is also shown on the top right corner of the time bar and ranges between the two values input on the GUI during data conversion. The characteristics of the animations are now addressed.

4.1 Features and characteristics of the animations

In general, the animations resulting from the data conversion performed are faithful and coherent with the data provided, but there are some simplifications and omissions which are addressed in Secion 4.3.

The user can interact with the animations while they are running to show the desired information. To do so, the user can choose to visualize the flight from different points of view, read the instrument panel and even change the meteorology, when relevant. This section explores each of these aspects of the animations, how they can be accessed, their characteristics and advantages.

Views

One of the greatest features of flight data animation is that the aircraft can be viewed from several perspectives, both inside the cockpit and outside the aircraft. This provides information that would otherwise be difficult to visualize in its context and each view offers a unique point of of view of the flight, enabling the user to access information. X-Plane offers this option, making it possible to change the perspective during the animation as the user deems necessary.

The view from outside the aircraft is represented in Figure 4.2. Although no numerical data is observable in this view, it allows the user to visualize the position of the aircraft in the airspace, its surroundings, the ground below it and the movement of control surfaces. The user can also rotate the camera around the aircraft and adjust the zoom in order to see the flight from the desired point of view.
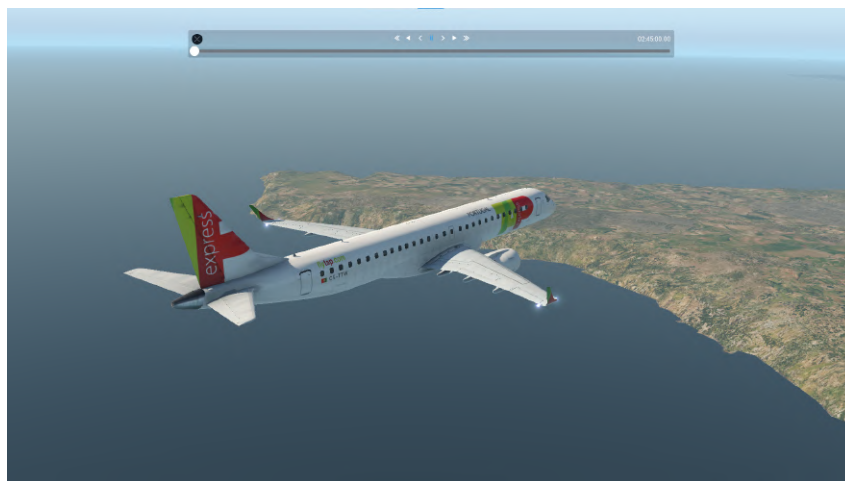

Figure 4.2: Outside view of the aircraft.

Figure 4.1 shows the view inside the cockpit with the HUD, but X-Plane also includes the option to disable the HUD. The resulting view is represented in Figure 4.3. Contrary to the view with the HUD, this one allows the user to look not only ahead, but also around the cockpit. It is also possible to zoom in and out in order to get a better view of the instruments.

Figure 4.3: Inside view of the cockpit without the HUD.

Another interesting feature provided by the chosen aircraft model is the fact that, in the inside view of the cockpit without the HUD, the Primary Flight Display (PFD), Multi-function Display (MFD) and the Engine Indicating and Crew Alerting System (EICAS) can be amplified as shown in figure 4.4.

Figure 4.4: Amplified instrument displays.

It is also possible to watch the animation from the point of view of the control tower, which is particularly useful during approach, landing and take-off operations. The user can control the camera direction and zoom to adapt the visualization to their needs. The view from the Lisbon control tower during a landing operation in runway 03 is shown in Figure 4.5.
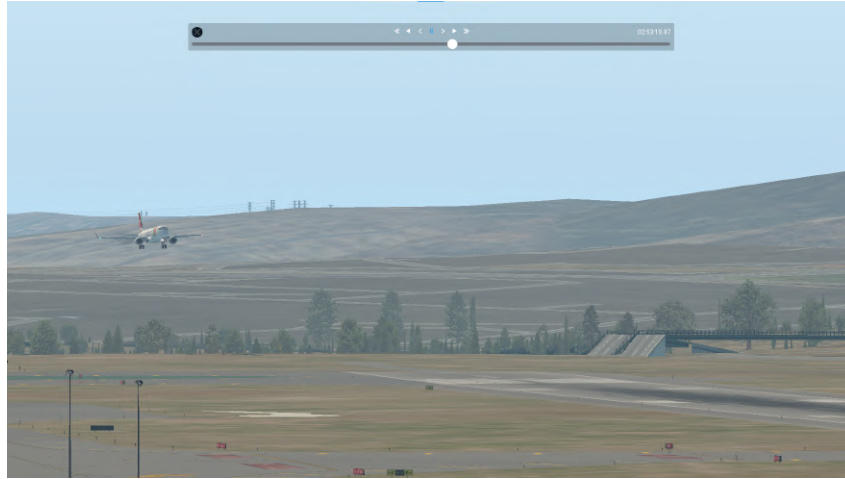
Figure 4.5: View from the control tower.

Instrument Panel

An important advantage of animations is that the instruments can be monitored, using the appropriate views. This provides an overview of the information provided by the instruments as a whole, which is not as easily obtained when analyzing graphs.

As seen in the previous subsection, the chosen aircraft model features the option to amplify three displays - the PFD, MFD and the EICAS -, which provide valuable information regarding aircraft performance. Some aircraft models in X-Plane allow the users to view the instrument panel in a second monitor connected to the computer. That is not the case with the chosen aircraft model, but the amplified displays serve the same purpose without requiring additional hardware.

However, being able to see the flight from different perspectives simultaneously - for instance, watching the aircraft from the outside while also monitoring the instruments - can sometimes prove useful. X-Plane requires one copy of the software for each different view. Nevertheless, some external applications - such as *Air Manager* [87], *Flight Sim Remote Panel* [88] or *XpRemotePanel* [89] - can be connected to X-Plane, allowing the user to customize an instrument panel and monitor it while running the animations.

Meteorology

Although this feature was not used in this work, it is worth mentioning that X-Plane offers a highly-customizable weather simulation. The user can choose from a set of predefined conditions or, alternatively, manually or automatically input the weather. It is possible to edit visibility, pressure at sea level, temperature and precipitation, as well as adding cloud and wind layers at various altitudes. Finally, the simulator is also able to read a custom METAR file, written with a specific structure, which automatically sets the weather as defined on the file.

4.2 Comparison of the animations with AGS and Google Earth analysis using test cases

The fourth objective of this thesis, as defined in Section 1.2, states that the animations must be validated using data from flights operated by Portugália. In this section, two events are analyzed, using data from two flights performed by the company: a go around and a localizer deviation.

4.2.1 Go Around

A Go Around is a maneuver performed when the crew decides not to continue an approach, when it is deemed not possible to continue the approach to a successful landing [90]. According to the company's Standards and Operating Practices (SOP), a go around must be performed under certain circumstances, such as an unstable approach, the obstruction of the runway or the absence of a landing clearance, among others. The SOP manual defines the sequence of actions to be taken during a go around.

The go around is initiated by pressing one of the TO/GA (Take-off/Go Around) buttons, which moves the thrust levers to TO/GA thrust and automatically sets the vertical and lateral modes GA and TRACK to perform the go around. Then, one notch of flaps is retracted and, after ensuring positive climb rate, the landing gear is retracted as well. Afterwards, the modes VNAV and LNAV are engaged, the flaps are cleaned and the new approach is performed. The go around procedure is reproduced in Figure 4.6, as shown on the company's SOP manual.
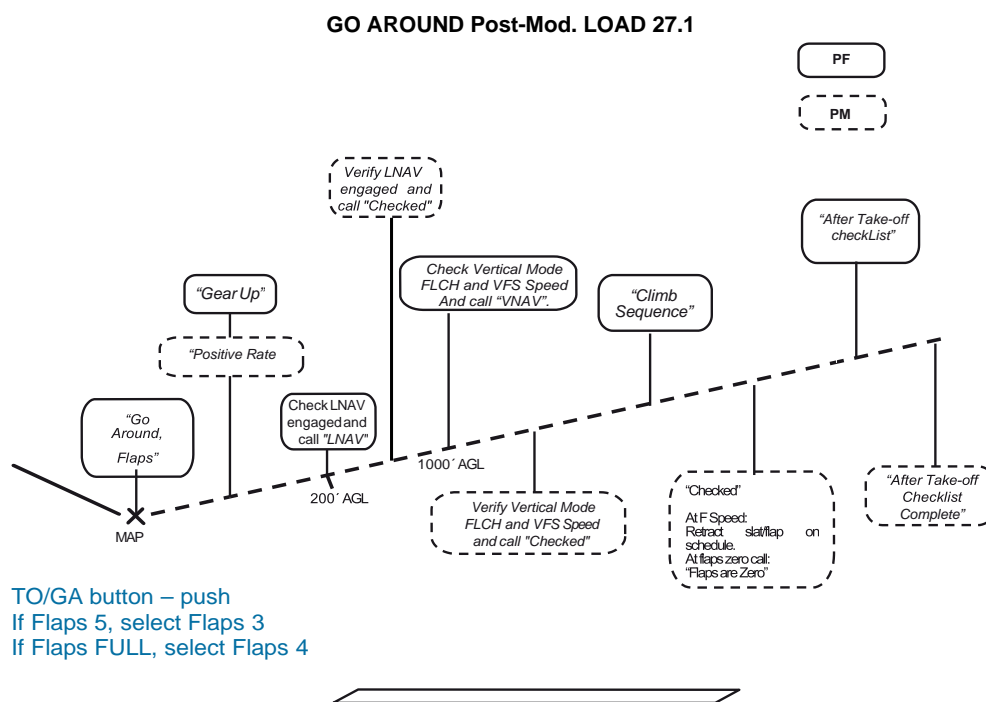

Figure 4.6: Go Around procedure [90].

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The go around that was chosen to analyze happened during an approach to runway 03 at Lisbon airport. The Air Traffic Control instructed the crew to discontinue the approach at around 200 ft above aerodrome level because another aircraft that had just landed was slow to exit the runway. As a result, the crew performed a go around according to the company's SOP and landed successfully after a few minutes. No exceedances were detected during these maneuvers and both approaches were stable.

The trajectory of the aircraft can be visualized in Google Earth using data exported from AGS. Figures 4.7 and 4.8 represent the path described by the aircraft during the two approaches and go around on a map, from the top and the side, respectively. This method allows the visualization of the position and altitude of the aicraft relatively to its surroundings.

Figure 4.7: Top view of a go around during the approach to Lisbon represented on Google Earth.
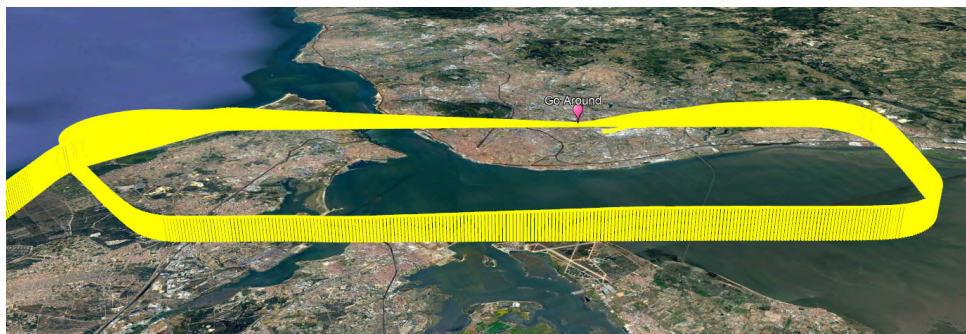

Figure 4.8: Side view of a go around during the approach to Lisbon represented on Google Earth.

In order to determine whether the go around was performed according to the procedures established on the SOP manual, the FDM analyst must observe the evolution of certain parameters around the time

of the go around. These parameters include the altitude, the status of the autopilot and auto-throttle, the indicated vertical speed, the engaged modes, the TO/GA button, the thrust, the landing gear and the flaps. As an example, some of these of these graphs - corresponding to the altitude QNH, the indicated vertical speed, the position of the flap lever and deflection of the flaps and slats, and the position of the landing gear and its lever during the two approaches and the go around studied in this section - are represented in Figures 4.9 to 4.12. In this specific event, the go around was fully performed according to the company's standards.
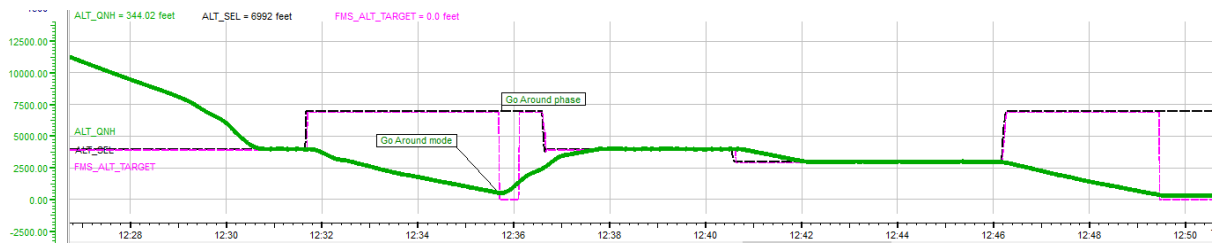

Figure 4.9: Graph of the altitude QNH during a go around in Lisbon represented in AGS.
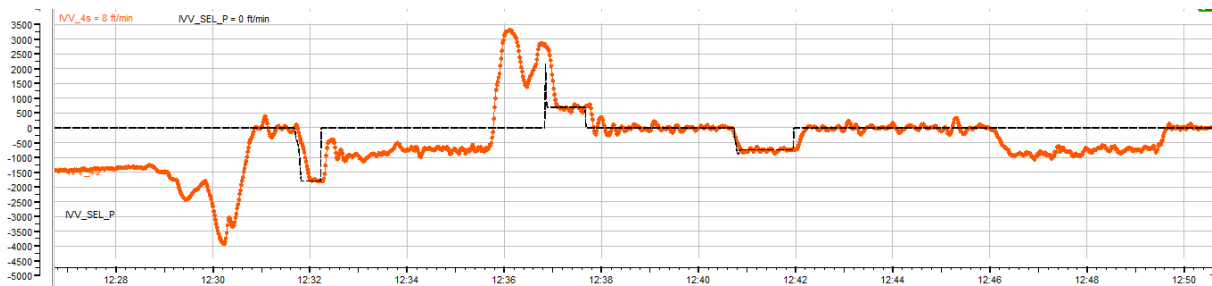

Figure 4.10: Graph of the indicated vertical speed during a go around in Lisbon represented in AGS.
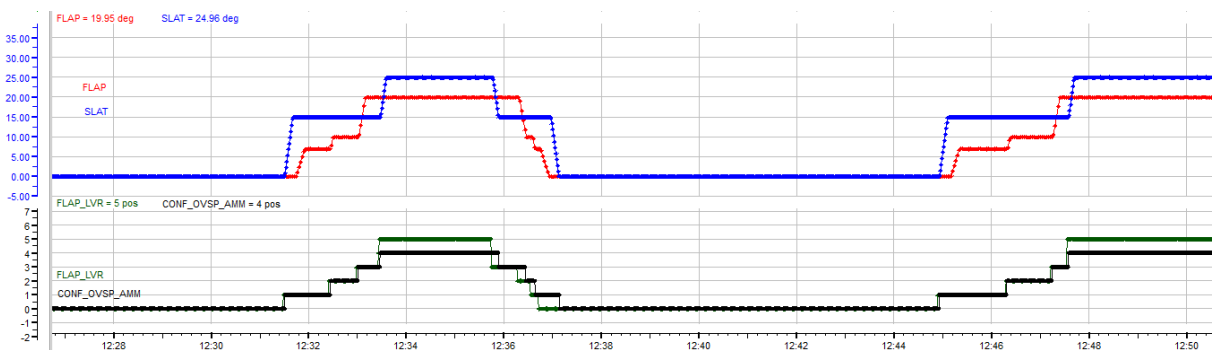

Figure 4.11: Graphs of the position of the flap lever and the deflection of the flaps and slats during a go around in Lisbon represented in AGS.
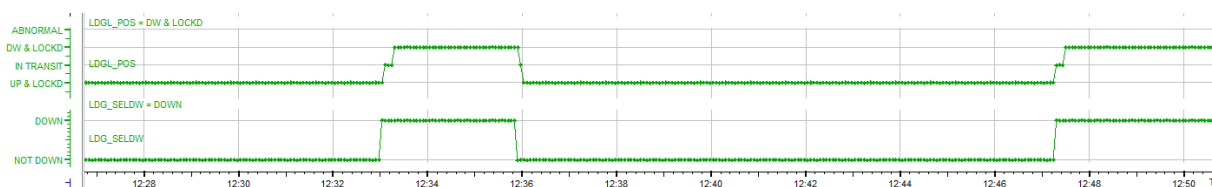

Figure 4.12: Graphs of the position of the landing gear and its lever during a go around in Lisbon represented in AGS.

The analysis performed so far can be complemented by the visualization of the event through an animation. It shows the exact location where each step of the two approaches and go around took

place, enabling a dynamic analysis of the sequence of events. Figures 4.13 through 4.16 illustrate some of these steps in the course of the go around.

During the first approach, the aircraft is fully configured to land, as shown in Figure 4.13, and the approach is stable according to the standard procedures at the company. Then, some meters before reaching the runway threshold, the go around is initiated. This instant corresponds to Figure 4.14. In this figure, the image on the right shows the instrument panel at the same time, which includes some useful data to analyze the go around. For instance, it indicates that the approach mode becomes armed and the rotational speed of the engines (N1) is increased to TO/GA values - around 80% - once the go around is initiated. As the aircraft starts climbing, the landing gear is retracted and the flaps are cleaned. These actions are displayed in Figure 4.15. Then, the aircraft describes the go around trajectory without any relevant event or irregularity and attempts a second approach to Lisbon airport. The moment when the aircraft is fully configured for landing is represented in Figure 4.16. This second approach is stable and culminates in a safe landing.

Figure 4.13: Beginning of the first approach before a go around in Lisbon.

(a) Outside view.

(b) Cockpit view.

Figure 4.14: Animation at the instant when the go around was initiated.

(a) Retraction of the landing gear.

(b) Retraction of the flaps.

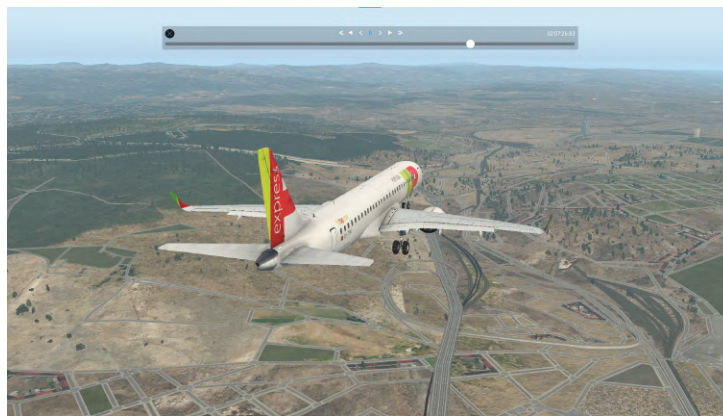Figure 4.15: Retraction of the landing gear and the flaps after initiating the go around.

Figure 4.16: Aircraft fully configured to land in Lisbon, after the go around.

4.2.2 Localizer deviation

As previously stated, the localizer is a system that provides lateral guidance relatively to the runway axis, during an approach. The deviation of the aircraft from it is shown on the instruments in dots. When the aircraft is aligned with the runway, the deviation equals 0 dots.

A localizer deviation occurs when the aircraft is not aligned with the runway during the approach. It can happen when the aircraft is capturing the signal from the LOC or after the signal capture if, for any reason, the aircraft deviates horizontally from the intended path. In the company's FDM program, localizer deviation events are currently only detected below 1000 ft above aerodrome level as an unstable approach precursor. An unstable approach occurs when, below 1000 ft above aerodrome level, at least one of the stabilized approach criteria is not met. The criteria are: the aircraft is configured to land; it is on the intended flight path; the flight path can be maintained performing only small corrections in heading and pitch; the speed is within defined limits; the rate of descent is lower than 1000 ft/min; the power setting is adequate; and the briefings and checklists have been concluded [91]. Regarding the fight path, the company's SOPs establish that the localizer should be within 1/2 dot, that is, the maximum acceptable deviation is 1/2 dot to either side of the beam.

The localizer deviation that is analyzed in this section happened during an ILS approach to runway 06 at Amsterdam Schiphol Airport, due to repeated disconnections of the LOC lateral mode, which resulted in deviations from the glide path. With the approach mode armed, the aircraft would capture the LOC signal but would soon start turning left, not following the correct glide path. This happened twice during the approach. Subsequent FDM analysis showed that the event culminated in a stable visual approach, because it was not possible to successfully conduct the initially cleared ILS approach. The occurrence was reported by the captain and the trajectory of the aircraft is represented in Figure 4.17.

Figure 4.17: Localizer deviation during the approach to Amsterdam represented on Google Earth.

In the analysis of this event, AGS is used with the purpose of determining the exact localizer deviation throughout the approach, the actual and selected heading, the active autopilot modes, the altitudes at which the events occurred and other relevant numerical data. The graphs corresponding to the altitude, the localizer deviation and the active and armed lateral modes are represented in Figures 4.18 to 4.20.
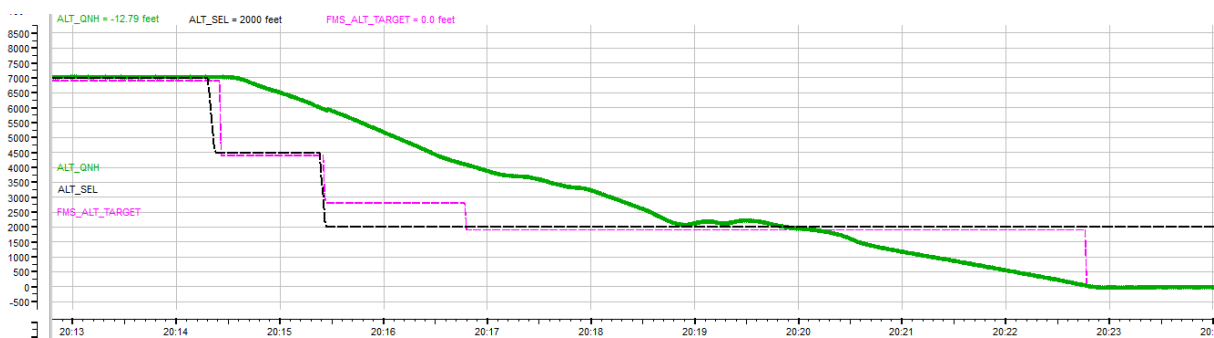

Figure 4.18: Graph of the altitude QNH during a localizer deviation in Amsterdam represented in AGS.
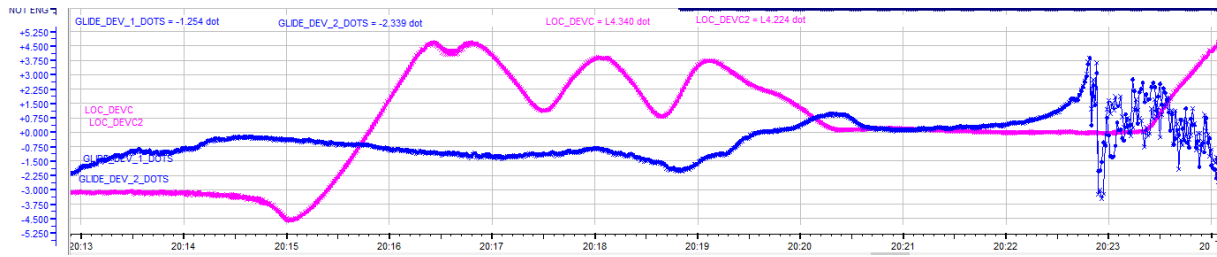
Figure 4.19: Graph of the ILS deviation in dots during a localizer deviation in Amsterdam represented in AGS - glideslope in blue and localizer in pink.
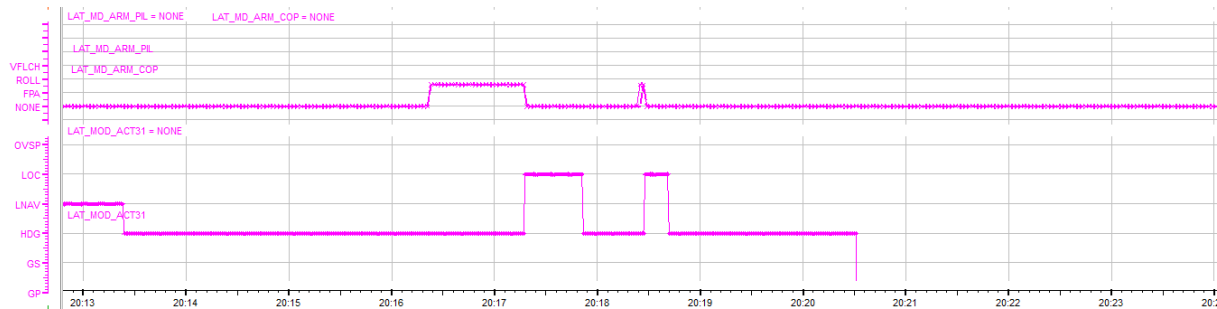
Figure 4.20: Graphs of the armed and active autopilot lateral modes during a localizer deviation in Amsterdam represented in AGS.

Although the graphs from AGS and the trajectory observed in Google Earth are enough to analyze this event, the analysis can benefit from an animation, because one can not only observe the evolution of the active and armed autopilot modes, but also the movement of the aircraft throughout the approach and landing. Some images from the animation of this event are reproduced in Figures 4.21 through 4.25.

(a) Cockpit view.

(b) Primary Flight Display.

Figure 4.21: Still image 1 from the animation of the localizer deviation in Amsterdam.

(a) Cockpit view.

(b) Primary Flight Display.

Figure 4.22: Still image 2 from the animation of the localizer deviation in Amsterdam.

(a) Cockpit view.

(b) Primary Flight Display.

Figure 4.23: Still image 3 from the animation of the localizer deviation in Amsterdam.

(a) Cockpit view.

(b) Primary Flight Display.

Figure 4.24: Still image 4 from the animation of the localizer deviation in Amsterdam.

(a) Cockpit view.

(b) Primary Flight Display.

Figure 4.25: Still image 5 from the animation of the localizer deviation in Amsterdam.

The animation shows that the approach is initiated with the HDG lateral mode active and the LOC and G/S armed (Figure 4.21). The autopilot and autothrottle are engaged, although the state of the autopilot is not visible in the animations, as there is no field regarding this parameter in the FDR file structure. As the aircraft approaches the glidepath from the left, the localizer signal is captured and the LOC mode is automatically engaged - represented by the green letters that read "NAV" -, but he aircraft starts turning left, deviating form the intended path (Figure 4.22). After a few seconds, the crew engages HDG once again and corrects the aircraft's trajectory (Figure 4.23). With the approach mode armed, the aircraft captures the LOC mode again, only to start turning left, deviating once again from the glidepath (Figure 4.24). Due to this misbehavior, the crew corrects the trajectory with the HDG mode active and then disengages the autopilot and flies a manual approach, which is performed safely (Figure 4.25). It is also worth mentioning that the artificial horizon does not follow the bank and pitch angles of the aircraft, because there is no information about this instrument on the FDR input file.

4.2.3 Comparing the three analysis methods

The two examples studied in the previous sections show that each one of the three analysis methods has its own advantages and they complement each other, as they represent the same data under different formats.

On the one hand, the graphical analysis done with AGS provides the most accurate and mathematical perspective, because numbers and data are directly accessed and analyzed using time-series graphs. This is the most adequate method to examine the evolution of each parameter throughout the flight. It is also particularly useful to analyze parameters that are usually not accessible by the crew and in providing the value of any parameter at any given instant in time. This method is also an important tool to establish the magnitude and duration of events and exceedances, which is fundamental in activities

such as determining whether a maintenance task is required. Graphical analysis is the preferred method to analyze events such as high speed approaches, high rates of climb and descent, and landing gear and flap exceedances, to name a few.

On the other hand, visual methods such as the geographical analysis supported by Google Earth and the animations are useful at contextualizing the events, although the data is not as accessible as in time-series graphs. These methods focus on showing the surroundings of the aircraft, the interaction of the crew with the instruments, and the flow of actions performed in a particular period of time. The greatest advantage of representing the flights on Google Earth is that it is possible to analyze the trajectory of the aircraft and compare it with a reference path or set of positions. One can also add the navigation charts corresponding to the portion of the trajectory that is under assessment. This is an important asset for the analysis of glide path deviations, such as the localizer deviation shown in Section 4.2.2. The analysis of taxiway and runway incursions also benefits from this method.

Unlike the static representation of the trajectory of the aircraft on Google Earth, animations show the flight in a dynamic medium, combining two characteristics of the aforementioned analysis methods: the ability to contextualize the events, like in Google Earth, and the possibility of assessing the evolution of parameters during the flight, like in graphical analysis. The analyst can visualize the flight from different perspectives, manipulate the time and speed of the animation, observe the evolution of the information shown on the instruments and analyze the events from a pilot's point of view. One can also draw conclusions about the flow of actions performed by the crew and the aircraft. These features are what makes animations such versatile, complete, powerful and innovative analysis tools.

4.3   Drawbacks and inconsistencies with real data

Despite the observed advantages, the animations produced with the method developed in this thesis naturally have some limitations and inconsistencies with what would be expected during a real flight. Some of these may be solved with further development and analysis, but others are rooted in the characteristics of the simulation software. Some limitations of these animations are identified in the list below.

- Some instruments do not behave as expected in the animations. For instance, the artificial horizon, as noted in Section 4.2.2, does not move with the aircraft. The aircraft may be banking or pitching up but the artificial horizon does not reflect this movement. This is the case for other instruments and parameters too, and it is due to the fact that they are simply not considered in the FDR file format.

- Due to the limitation pointed in the previous paragraph, the animation always initiates with a master warning - *FUEL PRESSURE LOW*. This happens because there is no information about the fuel pressure and the software assumes that it is 0. However, the warning can be turned off by clicking

on the corresponding cancel button above the PFD.

- Aircraft are equipped with redundant systems, sensors and instruments. The captain and the first officer have access to data from different sources and sensors to ensure redundancy and some systems even have a third source, which is compared to the main systems in case of a failure. In the animations, however, there is no distinction regarding these various sources and, therefore, there is no redundancy.

- Control surfaces are often divided into smaller portions, each one associated with a parameter in the QAR data frame that measures its deflection. For instance, the elevator consists of four surfaces - outer left, inner left, inner right and outer right - and the rudder comprises two parts - upper and lower -, but in both cases their deflection is represented by a single value. Although these smaller surfaces usually move harmoniously, this representation is not the most accurate, as it considers each surface as a whole.

- In addition, surfaces may not always deflect symmetrically, which is the case of the ailerons, that can deflect between $-15°$ and $25°$. In this work, this was simplified to consider only symmetrical small-angle deflections, which may not be fully accurate in the case of higher angles.

- Regarding the propulsion system, it is not possible to consider aircraft with more than four engines or engines with more than two spools, although either of these configurations is fairly rare.

- Thrust reversers are an important system, as they allow for shorter landing distances by decelerating the aircraft after touchdown. However, these animations do not account for their usage, since the FDR file format does not include the corresponding field.

- Similarly, the FDR file format does not consider spoilers, movable surfaces found on the wings of an aircraft that are used to reduced its speed. Although the format accounts for speed brakes, they differ from spoilers as the former only influence drag, whereas the latter directly impact the lift-to-drag ratio. Also, spoilers have other functions, such as aiding in roll control, which are not accounted for.

- Furthermore, there is no way of determining which member of the crew performed each action, as their interactions with the instruments are not included in the FDR file.

- In the pressure (`PRES`), temperature (`TEMP`) and wind (`WIND`) lines of the FDR code, the software expects a fixed value throughout the flight. However, these parameters vary with the position of the aircraft and assuming that they are constant is a considerable inaccuracy.

Moreover, there is very little documentation produced by the software developers regarding the FDR replay function. This makes it particularly difficult to ensure that the correct data is used to fill each space in the FDR files. Finally, the parameter sampling frequency also impacts the quality of the animations, since it influences the discontinuities between consecutive data points. The use of smoothing filters

results in smoother animations, but the values passed to the software may be slightly different from the recorded due to this data processing.

Chapter 5

Conclusions

The previous chapters presented the development of this thesis work, from the foundations that sustain it, to the process of creating the animations and, finally, their analysis. This chapter synthesizes the work presented in this thesis and puts forward some ideas for future work, not only related to the improvement of the results but also to the implementation and analysis of the impact of the flight animations.

5.1   Achievements

The overall goal of this thesis was to develop a method for flight data reproduction in a simulation software. The resulting product will be used at Portugália within the scope of the Safety Department's activities, namely in the analysis of events, as a part of the FDM program and, consequently, the Safety Management System.

At the moment, FDM is performed at Portugália using two tools: AGS for graphical data analysis and event detection, and Google Earth for geospatial analysis. The animations will bring a new dimension to these analysis, as they provide new perspectives of the same data, namely the pilots' point of view.

The retrieval of the data for FDM is done with Quick Access Recorders, small data recorders, with large storage capacity and easy to access. Then, the QAR parameters are accessed through AGS by the FDM analyst. There are over 2000 available parameters, from a wide range of systems in the aircraft. These parameters are measured by the aircraft sensors, transmitted through data buses with well-defined frames and recorded by the QAR. The animations developed in this thesis also use data from the QAR, which is exported from AGS. With the purpose of determining the necessary QAR parameters, the data frames on both the QAR and the X-Plane sides were analyzed.

The X-Plane FDR data frame was first reviewed and compared to the available parameters on the

QAR. After choosing the QAR parameters for each FDR entry, taking into account the necessary conversions and computations, the algorithm that builds the FDR file was developed. It was necessary to take into consideration the parameter sampling frequency, its first recorded value, its units and other related parameters in order to compute the value of the parameter at each time instant to be written on the FDR file. A GUI was also designed to support the application and perform the conversion in a user-friendly format.

Afterwards, the animations were validated using data from flights operated by Portugália. A go around maneuver and a localizer deviation event were reproduced. It was determined that the animations confirm the analysis performed with AGS and Google Earth, but provide a more in-depth and immersive perspective of the events. They also help contextualize and explain events in a quick, efficient and dynamic way, as text and graphs are often too reductive.

In conclusion, the four objectives of the thesis established on Section 1.2 were fulfilled: the QAR and X-Plane's data frames were examined, the conversion process was successfully developed and the animations were validated using flight data from the airline. The main goal - developing the method for flight data reproduction - was, therefore, also met, and the animations will be used at Portugália to support FDM and other related activities at the company, such as support for the crew training department.

5.2 Future Work

This work marks a considerable evolution in terms of flight data analysis, as the animations complement the statistical and graphical analysis performed in FDM activities and provide new perspectives on events and occurrences, supporting their investigation. Nevertheless, this is only the first step for the use of animations at Portugália and there is room for improvement and further development. This list presents some ideas and challenges for future work, based on what was achieved in this thesis.

- Improving the quality of the simulations, considering the assets and limitations of the software. For instance, the altitude data was particularly difficult to manage, because of the software requirements, but the implemented solution may be improved through the integration of a database that feeds the program with airport elevation data and corrects the altitude with it.

- Analyzing the possibility of manipulating the X-Plane FDR data frame, in order to choose the flight parameters that best suit the company's needs.

- Assessing the impact of the animations in the Safety Department's activities, namely the investigation of events and occurrences, and their impact in the Training Department's activities, namely within the scope of evidence-based training.

- Including weather information in the animations, through the built-in X-Plane features, as well as navigation charts.

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Appendix A

Parameters in the X-Plane FDR files

The parameters included in the FDR files used to input flight data into X-Plane 11 that were discussed throughout this thesis are summarized and listed in table A.1.

Table A.1: Parameters to be included in the DATA fields of X-Plane 11 FDR files.

Parameter description	Units
Time from the beginning of the recording	seconds (s)
Outside temperature near the airplane at current altitude	degrees Celsius (°C)
Longitude	degrees (°)
Latitude	degrees (°)
True height above mean sea level	feet (ft)
Radio Altimeter value	feet (ft)
Aileron deflection ratio, from -1.0 (left) to +1.0 (right)	-
Elevator deflection ratio, from -1.0 (nose down) to +1.0 (nose up)	-
Rudder deflection ratio, from -1.0 (left) to +1.0 (right)	-
Pitch angle, with positive corresponding to nose up	degrees (°)
Roll angle, with positive corresponding to a right turn	degrees (°)
True heading	degrees (°)
Indicated Airspeed	knots (kt)
Indicated Vertical Speed	feet per minute (ft/min)
Slip angle, with positive corresponding to nose to the right	degrees (°)
Turn-slip indicator deflection, with positive indicating right	degrees (°)
Mach number	-
Angle of attack	degrees (°)
Stall warning turned on (1) or off (0)	-
Flap angle request ratio, from 0.0 (retracted) to 1.0 (extended)	-

Flap deflection ratio, from 0.0 (retracted) to 1.0 (extended)	-
Slat deflection ratio, from 0.0 (retracted) to 1.0 (extended)	-
Speedbrake deflection ratio, from 0.0 (retracted) to (1.0 extended), and 1.5 (ground-deployed)	-
Landing Gear handle, up (0) or down (1)	-
Nose gear deployment ratio, from 0.0 (retracted) to 1.0 (down)	-
Left gear deployment ratio, from 0.0 (retracted) to 1.0 (down)	-
Right gear deployment ratio,from 0.0 (retracted) to 1.0 (down)	-
Elevator trim ratio, from −1.0 (nose down) to 1.0 (nose up)	-
Nav−1 frequency in a 5-digit integer form with no decimal	-
Nav−2 frequency in a 5-digit integer form with no decimal	-
Nav−1 type (NONE=0, NDB=2, VOR=3, LOC=5, ILS=10)	-
Nav−2 type (NONE=0, NDB=2, VOR=3, LOC=5, ILS=10)	-
Omnibearing selector 1	degrees (°)
Omnibearing selector 2	degrees (°)
Distance to the DME station 1	nautical miles (NM)
Distance to the DME station 2	nautical miles (NM)
Nav-1: horizontal deflection (localizer), from −2.5 to 2.5 dots, with positive indicating flying right	dots
Nav-2: horizontal deflection (localizer), from −2.5 to 2.5 dots, with positive indicating flying right	dots
Nav−1: Nav (0), To (1) or From (2)	-
Nav−2: Nav (0), To (1) or From (2)	-
Nav-1: vertical deflection (glideslope), from −2.5 to 2.5 dots, with positive indicating flying up	dots
Nav-2: vertical deflection (glideslope), from −2.5 to 2.5 dots, with positive indicating flying up	dots
Aircaft passed over outer marker beacon, true (1) or false (0)	-
Aircaft passed over middle marker beacon, true (1) or false (0)	-
Aircaft passed over inner marker beacon, true (1) or false (0)	-
Flight director turned on (1) or off (0)	-
Pitch angle of the flight director, positive indicating up	degrees (°)
Roll angle of the flight director, positive indicating right	degrees (°)
The speed held by the autopilot is in knots (0) or Mach number (1)	-
Autothrottle turned on (1) or off (0)	-
Autopilot heading mode: wing-level (0), heading (1), localizer or other CDI (2)	-

Autopilot altitude mode: pitch sync (3), indicated vertical speed (4), airspeed (5), airspeed with altitude armed (6), altitude hold (7), terrain-follow (8), glideslope hold (9)	-
Localizer CDI armed for capture on (1) or off (0)	-
Glideslope CDI armed for capture on (1) or off (0)	-
Back-course approach on (1) or off (0)	-
Speed held by the autopilot	knots (kt) or Mach
Magnetic heading selected by the autopilot	degrees (°)
Vertical speed held by the autopilot, feet per minute	feet per minute (ft/min)
Indicated altitude above mean sea level held by the autopilot	feet (ft)
Barometric pressure dialed into the altimeter	inches Mercury (inHg)
Decision height above ground level dialed into the radio altimeter	feet (ft)
Master Caution alerting on (1) or off (0)	-
Master Warning alerting on (1) or off (0)	-
Ground Proximity Warning on (1) or off (0)	-
Map mode in simulation: 0 through 4 gives different map results	-
Map range in simulation: 0 through 6 gives different map ranges	-
Throttle ratio from 0.0 to 1.0.	-
Propeller rotations command. One line per engine.	rotations per minute (rpm)
Actual propeller rotations. One line per engine.	rotations per minute (rpm)
Propeller pitch in degrees. One line per engine.	degrees (°)
Rotational speed of the low speed spool (N1). One line per engine.	%
Rotational speed of the high speed spool (N2). One line per engine.	%
Engine Manifold Pressure. One line per engine.	inches Mercury (inHg)
Engine Pressure Ratio. One line per engine.	-
Engine torque. One line per engine.	foot pounds (ft lb)
Fuel flow. One line per engine.	pounds per hour (lb/h)
Interstage Turbine Temperature. One line per engine.	degrees Celsius (℃)
Exhaust Gas Temperature. One line per engine.	degrees Celsius (℃)
Cylinder Head Temperature. One line per engine.	degrees Celsius (℃)

Appendix B

Correspondence between X-Plane and AGS Parameters

The AGS parameters that were used to calculate each FDR value are listed in table B.1.

Table B.1: Correspondence between FDR and AGS parameters.

FDR Parameter	AGS Parameters
Time	None
Ambient air temperature	SAT_PIL, SAT_COP, SAT_FDC_CL
Longitude	LONPC, LONP1, LONG_FMS
Latitude	LATPC, LATP1, LAT_FMS
Height (MSL)	ALT_GEOM, ALT_QNH
Radio Altimeter	RALT, RALT_2
Aileron ratio	AILL, AILR
Elevator ratio	ELEV_LI, ELEV_LO, ELEV_RI, ELEV_RO
Rudder ratio	RUDD_LO, RUDD_UP
Pitch	PITCH_IRS_8HZ, PITCH
Roll	ROLL
True heading	HEAD_T, HEAD_TRUE
Indicated Airspeed	IAS, IAS_COP
Vertical speed	IVV_4s, VSI_REC, VS_GGF1
Slip	SIDESLIP_BEF, SIDE_SLIP
Turn-slip indicator	Not available
Mach	MACH, CK_MACH
Angle of attack	AOA_BD1, AOA_BD3

Stall Warning	AOA_WA1, AOA_WA3
Flap handle position ratio	FLAP_LVR, FLAP_LEVER
Flap ratio (actual)	FLAP
Slat Ratio	SLAT
Speed break ratio	SPD_BRK, SPD_BRK3, SPD_BRK4, SPD_BRK
Gear handle position	LDG_SELDW, LDG_SELUP
Nose gear deployment ratio	LDGNOS_POS
Left gear deployment ratio	LDGL_POS
Right gear deployment ratio	LDGR_POS
Elevator trim ratio	PITCH_TRM
NAV−1 frequency	NAV_FRQ1
NAV−2 frequency	NAV_FRQ2
NAV−1 type	NAV_SRC_P
NAV−2 type	NAV_SRC_C
Omnibearing selector 1	HEAD_SEL
Omnibearing selector 2	HEAD_SEL
DME 1 distance	DME_DIS1
DME 2 distance	DME_DIS2
NAV−1 horizontal deflection	LOC_DEVC
NAV−2 horizontal deflection	LOC_DEVC2
NAV−1 Nav/To/From	Not available
NAV−2 Nav/To/From	Not available
NAV−1 vertical deflection	GLIDE_DEV_1_DOTS
NAV−2 vertical deflection	GLIDE_DEV_2_DOTS
Outer marker	OUT_MK
Middle marker	MID_MK
Inner marker	INR_MK
Flight director	FDEN_PB_PL, FDEN_PB_CP
FD pitch	FDPITCHCMD
FD Roll	FDROLLCMD
Knots or Mach	ASPD_TYPE
Auto-throttle	AT_EGD, AT_ENG_MWS
Heading mode	LAT_MOD_ACT31
Altitude mode	VERT_MOD_ACT31
Localizer armed	LAT_MD_ARM_PIL, LAT_MD_ARM_COP
Glideslope armed	VER_MD_ARM_PIL, VER_MD_ARM_COP
Back course	Not used at Portugália

AP speed	IAS_SEL, MACH_SEL
AP heading	HEAD_SEL
AP vertical speed	IVV_SEL_P, IVV_SEL_C
AP altitude	ALT_SEL
Barometric pressure	ALT_CPT_INHG, ALT_FO_INHG
Decision height	DH_SEL_P, DH_SEL_C
Master Caution	MASTER_CAUT, MCAUTION
Master Warning	MWAR
GPWS Warning	GPWS_WARN
Map mode	Not chosen from AGS
Map range	Not chosen from AGS
Throttle ratio	TLA1, TLA2
Propeller RPM command	Not applicable
Propeller RPM (actual)	Not applicable
Propeller pitch	Not applicable
N1	N11, N12
N2	N21, N22
Engine Manifold Pressure	Not applicable
Engine Pressure Ratio	Not available
Engine torque	Not applicable
Fuel flow	FF1, FF2
Interstage Turbine Temperature	ITT1, ITT2
Exhaust Gas Temperature	CK_EGT1, CK_EGT2
Cylinder Head Temperature	Not applicable