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PROOF-OF-CONCEPT OF AN ERROR MODEL FOR PERFORMANCE ASSESSMENT OF AUTOMATIC DEPENDENT SURVEILLANCE SYSTEMS (ADS)

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Resumen

En el presente Trabajo de Fin de Grado se ha realizado la validación de un nuevo modelo de error propuesto por Eurocontrol para la corrección de las medidas de ADS-B usadas como uno de los métodos de posicionamiento de aeronaves para la gestión del tráfico aéreo. Para la validación, se utilizará un banco de pruebas desarrollado en matlab que permita evaluar modelos de error en sistemas de vigilancia aeronática. Una vez implementado dicho banco de pruebas, se utilizará para comparar y discutir los resultados obtenidos con el modelo de error propuesto con los obtenidos aplicando el modelo de error utilizado actualmente. Así se comprobará el nivel de mejora que se obtiene con el modelo de error propuesto en el Trabajo. Una vez validado, el nuevo modelo de error podría implementarse en herramientas de monitorización de sistemas de viginalcia para ATM, como el SASS-C, para su uso en ATC.

Resum

Al present Treball de Fi de Grau s'ha realitzat la validació d'un nou model d'error proposat per Eurocontrol per a la correcció de les mesures d'ADS-B utilitzades com un del mètodes de posicionament d'aeronaus per a la gestió del trànsit aeri. Per a la validació, s'utilitzarà un banc de proves desenvolupat a matlab que permeta evaluar models d'error en sistemes de vigilancia aeronàutica. Una vegada implementat aquest banc, s'utilitzarà per a comparar i discutir els resultats obtinguts amb el model d'error proposat en relació amb els obtinguts pel model d'error empleat actualment. Així,es comprovarà el nivell de millora que s'obté amb el nou model d'error proposat. Una vegada validat, el nou model d'error es podria implementar en ferramentes de monitorització de sistemes de vigilancia per a ATM, com el SASS-C, per al seu ús en ATC.

Abstract

In this Final Degree Project, the validation of a new error model proposed by Eurocontrol for the correction of ADS-B measurements used as one of the aircraft positioning methods for air traffic management has been carried out. For the validation, a test bench developed in matlab will be used to evaluate error models in aeronautical surveillance systems. Once this test bench has been implemented, it will be used to compare and discuss the results obtained with the proposed error model with those obtained by applying the error model currently in use. In this way, the level of improvement obtained with the error model proposed in the Project will be verified. Once validated, the new error model could be implemented in ATM surveillance system monitoring tools, such as SASS-C, for use in ATC.

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List of acronyms

ACAS Airborne collision avoidance system.

ADS-B Automatic dependent surveillance broadcast.

ADS-C Automatic dependent surveillance contract.

ARTAS ATM surveillance tracker and server.

ASA Airborne surveillance application.

ASTERIX All-purpose structured eurocontrol surveillance information exchange.

ATC Air traffic control.

ATIS Automatic terminal information service.

ATM Air traffic management.

ATS Air traffic service.

CARPET Computer-aided radar performance evaluation tool.

CMP Comparator.

CNS Communication, navigation and surveillance.

CPDLC Controller–pilot data link communications.

CRC Cyclic redundancy check.

DAW Data analysis workstation.

EASA European aviation safety agency.

EPU Estimated position uncertainty.

ERT External reference track.

EUROCAE European organisation for civil aviation equipment.

FUA Flexible use of airspace.

GNSS Global navigation satellite system.

ICAO International civil aviation organization.

IFF Identification friend or foe.

MLAT Multilateration radar.

MoF Mode of flight.

MSO Message start opportunity.

NACp Navigation accuracy category for position.

OFIS Operational flight information service.

OTR Opportunity traffic reconstruction.

PBCS Performance-based communication and surveillance.

PBN Performance-based navigation.

PBS Performance-based surveillance.

PSR Primary surveillance system.

RADAC Radar data acquisition converters.

RASS-S Radar analysis support system for sites.

RCP Required communication performance.

RMD Radar monitoring display.

RNAV Area navigation.

RNP Required navigation performance.

RRT Reconstructed reference trajectories.

RSP Required surveillance performance.

RTCA Radio technical commission for aeronautics.

SASS-C Surveillance analysis support system for ATC centres.

SSR Secondary surveillance radar.

TDMA Time division multiple access.

TDOA Time difference of arrival.

TIS Traffic information system.

UTC Coordinated universal time.

VHF Very high frequency.

Chapter 1

Introduction

The future of air transport and its evolution is mainly supported by the management of air control. From the first flights that took place in the first half of the 20th century to the network that is used nowadays, the air traffic control plays an important role in developing new technologies to avoid accidents and to overcome the different challenges, as for example: optimizing the amount of flights that the ATC(Air traffic control) is able to monitor or the airport's infrastructure that sometimes limits the operations.

Some of the most significant technologies created in this field, are the different types of survillance sensors developed to respond to the necessity to increase precision and integrity of the information. That information which is supported by software tools to automate the control of this parameters and to enlarge the performance of those surveillance sensors to the maximum.

Without the new sensors like secondary radars, multilateration systems or other surveillance techniques based on the transmission of data, among others aeronautical surveillance systems, which are the mainstay of air traffic management, it would be impossible to respond to the new challenges in a secure way. In order to achieve this goal, the precision, integrity and other parameters of the measurements needs to be guaranteed by the use of software tools that automatize the performance monitoring .

1.1 Previous concepts

Before getting down to business, it is important to explain some key concepts. Although they will be treated and explained in depth in upcoming chapters and sections, at this point it is important to have some basic knowledge about them.

The ATM (Air traffic management) is a concept that encompasses all systems and services that an aircraft use in the whole process of a flight, from its departure to the landing at the destination airport going through the traffic in the airspace. The mentioned management of the airspace is conducted by ATC at ground who handle the aircrafts at ground as at air to avoid accidents and manage traffic flow.

Air traffic management could be divided depending on their main tasks:

- **ATC:** Manage aircraft movement.

- **Airspace management:** Organize air traffic to allow different activities and traffic volumes claiming the security in those operations.

- **Flow and capacity management:** Optimize the capacity of the airspace.

This management is possible through the use of CNS (Communication, navigation and surveillance) systems which form the architecture used by the air traffic controllers and is responsible for guaranteeing the availability of the following tasks:

- **Communication:** Provides the way to exchange of information between aircrafts or with ground stations by radio as by the use of transponders for data and other information.

- **Navigation:** Supplies the systems to be able to position the aircraft to help pilots to afford to follow the route of the flight plan and to transmit their position to ATC.

- **Surveillance:** Provides the systems needed to determine the position of aircrafts to control the airspace and guarantee security.

This project is focus on surveillance systems, which are used to control, from a ground station, position, altitude and ID of the aircrafts at a determined airspace to ensure they follow the rules of this airspace regarding security distance, maximum flight level and obligatory systems on-board, mainly.

Two kinds of the aforementioned systems can be distinguished between:

- **Cooperative systems** They use on-board equipment for the detection and communication.

- **Non-cooperative systems** They can detect the aircrafts independently of their on-board equipments.

Both kind of surveillance systems are the basis of commercial aviation security. Those systems follow the standards defined and established by EUROCAE (European organisation for civil aviation equipment) as ED-142 or ED-129B which defined the minimum performance specifications for multilateration systems and ADS-B (Automatic dependent surveillance broadcast) systems respectively. This organisation works side by side with EASA (European aviation safety agency), whose function is to certify the minimum quality and technical standards for aviation systems.

Another important point to point out is the difference between air traffic management and air traffic control. The air traffic control is one of the basis of the air traffic management, which evolve together with commercial aviation. Moreover, the air traffic management is a newer concept more related to the interoperability of systems to help reduce the impact of changing between countries airspace.

As a matter of fact, it is significant in a continent like Europe, where the integration of common systems owing to the amount of little countries with their own airspace is very important. With the integration of common systems into those countries, an agreement can be reached without the necessity to take part in bureaucracy issues. To achieve it, the Eurocontrol (European Organisation for the safety of Air Navigation), which groups together 41 member states, plays an important role.

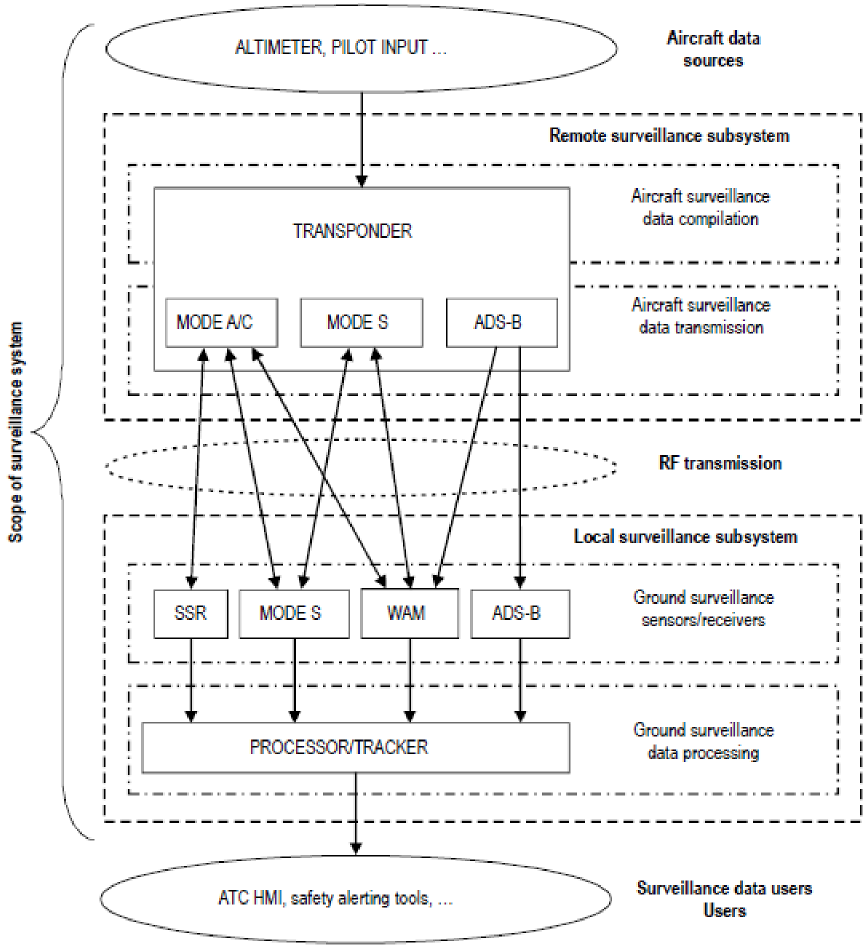

Figure 1.1: Multisensor air-ground surveillance systems

Eurocontrol works side by side with EASA, too. In this case, with EASA as the responsible entity of unifying common airworthiness standards from member states in the European Union.

One of those worldwide-used standards is the homogenization of information exchange to group together ATM and surveillance systems in the same network. This one is ASTERIX (All-purpose structured eurocontrol surveillance information exchange) which includes different categories with different types of information for each one. This standard is fundamental due to the amount of information systems work with nowadays.

1.2 Motivation

Aeronautical surveillance systems are one of the keys to modernization of air traffic management. The main objective of their use is to optimize airspace and traffic flows in order to maximize the number of aircraft in flight to meet future demands. In addition, it is important to use new types of surveillance sensors that are responsible for supervision in areas where the classic radars do not offer coverage, and which also allow the flexibility of flight trajectories due to their greater precision.

For this purpose, it is important to monitor the different surveillance sensors in order to assess if they accomplish with the required surveillance specifications.

This optimization is achieved by correcting known errors that are present in the transmission of measurements, such as delays, or introduced by the components used for communication, such as measurement deviations due to the receiving antennas or noise caused during transmission. For this purpose, the error models of the sensors are updated so that the errors are corrected as accurately as possible.

The state of the art standardization is oriented to performance instead of describing technical requirement and Performance-Based Surveillance requires some kind of monitoring once the system has been deployed. For this propose several tools are available, the most wildly use is SASS-C from Eurocontrol. This tool obtains different performance metrics and in order to obtain them it needs to build reference trajectories, process data and correct it by using error models.

1.3 Scope of the project

Aeronautical surveillance encompasses the rules and procedures to be followed to process the data that allow us to know on the ground information about the position, speed, altitude or identification of an aircraft, among others. It works with information that is useful on the ground to direct air traffic in an optimized and safe way.

The problem with these systems is that before reaching the controllers for use, the information goes through a long process from capture to processing (detailed in Figure 1.1).

Firstly, the data sources from which the data are extracted at the origin is found. They are devices that are on board and are responsible for taking the measurements, they can be receivers that obtain their position through GNSS(Global navigation satellite system) satellites or a barometric altimeter that measures the altitude. This information is transmitted by the aircraft's transponder, normally they can send data from Mode S and A/C to ADS-B and ADS-C (Automatic dependent surveillance contract).

This information is transmitted by using electromagnetic waves into a radio frequency channel to link with ground receptors equipped by local surveillance subsystems. Is important to mention that this kind of information is used by only some sensor, others, like the primary surveillance radar or the multilateration radar systems do not need to receive part of this information because they are able to calculate it.

Independently of the kind of sensor, this information is send to the ground surveillance data processing which present the measurements to the air traffic controller. In order to know if this information is accurate enough Eurocontrol created SASS-C (Surveillance analysis support system for ATC centres) tool, that allows the evaluation of the trajectory by the different sensors after the flight is completed. This way, enable to evaluate the performance of the different sensors and the accuracy of their measurements in order to improve the air traffic management.

SASS-C tool is obviously in continuous development by updates, for this reason, in this final degree project a new error model for ADS-B systems will be validated with the objective of improve the one used actually. The validation will be made in other programming environment because of the large number of lines of code (more than 300,000) contained in the SASS-C tool, which would be too heavy, especially if the new model does not improve on the current one.

In this new error model, instead of using indicators such as the NACp (Navigation accuracy category for position.) that overestimate the error, it seeks, by using a new error model that corrects Uncompensated Latency, a more accurate estimate of the error. This is because latency together with measurement error is responsible for the positional error on the along the trajectory axis.

This Uncompensated Latency comes from the time between the measurement is made using a GNSS constellation and the time the data is transmitted to a ground station. Specifically, it arises from two moments, the time between when the GNSS receiver makes the measurement until the transponder begins to process that information, and the time between when the transponder updates the ADS-B Out register and the information is transmitted.

1.4 Objectives

The main objective of this project is to evaluate the performance of the new error model proposed by Eurocontrol for ADS-B measurements using a modular test bench. Once the improvement is verified, it might be implemented for its use in ATC centers. In order to attain this main objective, several sub-objectives must be achieved during the project:

- Obtain the needed information about the trajectory to correct, the time of the measurements, speed of the aircraft among others from ASTERIX messages sent by aircraft's transponder.
- Once all the information is gathered, it have to be pre-processed to isolate the straight sections from a determinate flight with all the measurements that contain the required Items.
- At the moment when all sections are available, the only thing left to do is to implement the new error model algorithm and apply it to this sections.
- When the error model has been applied, graphs are taken to represent the results and compare it with the original trajectories.
- Analyze (mathematically and graphically) the new trajectories and compare them to claim the improvement on data correction with the new error model.

1.5 Project structure

To finish this first chapter, the structure that is going to be followed would be presented.

1. **Introduction.** This chapter gives some basic concepts accompanied by a general vision of the project with the motivations and main objectives.
2. **Aeronautic surveillance.** This chapter provides the basic theoretical fundaments of the different surveillance systems developed and how these systems evolved in order to understand the functioning of those that are being evaluated in the project.
3. **Project description.** This chapter explains what an error model is, what they are used for and the detailed process of analysis and application of the error model algorithm to radar and ADS-B measurements.

4. **Simulation, results and discussion.** This chapter contains the simulation and outcomes of the new error model and a comparison with the old model results.
5. **Conclusion and future lines of research.** This chapter provides the conclusions based on the results obtained from the simulation and proposes different lines of research for the future.
6. **Appendix A.** This chapter explain the method use to calculate the velocity of the different trajectories.
7. **Bibliography.** Present the list of documents and papers used to document the theoretical part of the project.

Chapter 2

Aeronautic Surveillance

The objective of this chapter is to explain both the organization of air traffic management systems and the theoretical concepts of the operation of the different types of sensors.

2.1 Historical introduction

In 1914, pilot Tony Jannus flew his hydroplane from St. Petersburg to Tampa (Florida, USA). He took some passengers and cargo with him, making it the first commercial flight. During the 20s, the first airlines in United States and Europe, started to appear and the number continued to increase in the following years.

The increasing amount of air traffic led to the establishment of some rules to their control and management. Owing to that, in the early 20th century, the air traffic management appeared.

The first aerodromes began to be built and the need to communicate with pilots to inform them about the atmospheric conditions and other crucial aspects showed up. At the beginning they used common things like flags to indicate the wind speed and direction, but the increasing traffic transformed these obsolete practices into procedures in which ground operators had to give instructions to the different aircrafts to avoid collisions, not just to inform pilots about the weather conditions.

In order to give those instructions, in 1922, Croydon aerodrome, in south London, launched the first air traffic control service. This aerodrome introduced some advantages as air-ground communications, radionavigation systems to control flight positions and a controlled airspace zone.

In like manner, after a mild collision some procedures were introduced, such us the takeoff request, the answer and authorisation from the controller and the standard procedure to enter in the aerodrome. In order to control these tasks, air traffic controllers positioned the aircraft in a map by processing the signals received through their radio systems and calculated the evolution to prevent incidents between aircrafts. This was the first and rudimentary surveillance system.

In contrast with the good control in the surrounding area of aerodromes, some important accidents in the 20s and 30s noted the necessity to use surveillance systems throughout the whole journey, not only in the aerodromes area. This led to the use of some rules to regulate commercial aviation. Two of them were the obligation to carry radio communication systems, and the weather information interchange between aerodromes. In the USA, in October 1929, the position nofication service was established for aircraft which used federal routes. During the following years, airlines implemented the first control centre to supervise the routes of their flights. A few years later, there were eight centres to control USA's airspace by the use of maps where air traffic controllers registered the position reported by pilots to detect, taking into account speed and time, future collision hazards in order to change their route to avoid them.

Some years later, in the 50s, there was a revolution due to, mainly, two important advantages: the primary radar, which become the most important surveillance system to monitor commercial aviation aircraft, and the development of long range communication systems supporting direct communication between pilots and air traffic controllers.

The first military radar appeared in German investigations in the early 20th century, but the first intensive use of radar systems was during the well-known 'Battle of Britain'. Radars played a key role in the Second World War and they were applied to civil aviation a few years after the end of the war. Its main advantage is that it operates independently from the target aircraft, i.e. it does not require any action from the aircraft to provide a radar return. This let air traffic controllers, by converting into ground position the bearing and distances obtained from the radar, to see the traffic in the radar range on a screen which showed periodic updates. This was the first automatic surveillance system used to manage commercial traffic and it made possible a growth of the traffic density.

Figure 2.1: Air traffic controllers using the first radars for traffic management

Despite being a huge revolution in the surveillance systems field, the primary radar presented a few shortcomings which had to be adressed in order to accomodate a steadily encreasing demand. The more critical issues with primary radars were the impossibility to distinguish targets that were close to each other, the inability to know or calculate the altitude of the target and the lack of identification of the aircraft without the communication with the pilot.

As a result, these disadvantages led to adapt for use in civil aviation another military system developed during WWII, the Identification of friend or foe (IFF). The IFF was developed as a means to distinguish friendly from enemy aircrafts. This new radar, known as Secondary Surveillance Radar(SSR), relies on a transponder which receives interrogations from ground stations and broadcast either Mode A replies (which contains a code assigned to the aircraft by the ATC) or Mode C replies (containing the encoded altitude obtained from the aircraft altimeter). In the 60s the use of SSR become mandatory to fly over some areas due to the increased safety provided by these systems. It was the first cooperative surveillance system.

Both systems were the pillars of aeronautical surveillance for several decades.However, they cannot cope with the current demand for airspace (especially in the most congested areas) and will not be able to support the demand foreseen for the following decades (even taking into account the effect of COVID 19 on air traffic) nor they will allow advanced operations meant to reduce the aviation environmental footprint. That is the reason why ICAO (International civil aviation organization) since the end of the 70s is developing different air surveillance systems to improve the performance and the security in air surveillance as the Mode S, an evolution of Secondary Radar, the multilateration systems or the Automatic Dependant Surveillance systems (ADS-C and ADS-B).

2.2 Air Traffic Management

The Air Traffic Management consists of he dynamic, integrated management of air traffic and airspace safely, economically and efficiently through the provision of facilities and seamless services. ATM encompasses Air Traffic Services, Air Space Management, Air Traffic Flow and Capacity Management and is supported by Air Traffic Management Systems, as summarized in Figure 2.2. To achieve this goal, and due to the increase of traffic, the development and implementation of improved air traffic management tools have to be approached.

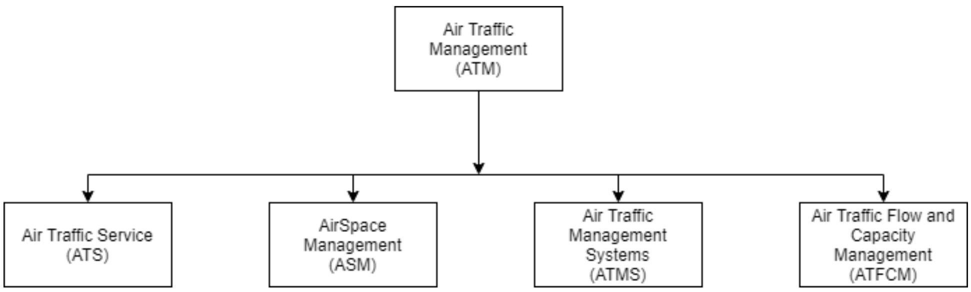

Figure 2.2: ATM structure recommended by ICAO

ENAIRE is in charge of ATM in Spain, and divides air traffic management into four tasks, following the ICAO guidelines. [12]

- **AirSpace Management (ASM)**, is responsible for design efficiency, service continuity and airspace optimisation plans through the implementation of projects such as Free Route, which aims to improve traffic flows and to create more direct flight segments in the European airspace. This results in the reduction of CO_2 emissions and time efficiency. It has been estimated that 3.5 million nautical miles have been saved in three years, that is to say, 38,900 tonnes of fuel would have emitted 123,000 tonnes of CO_2.

In adittion, they manage civil-military coordination by applying the FUA (Flexible Use of Airspace) concept, therefore, apart from commercial air transport operations, they perform:

  - *Military exercises*
  - *Aerial works*
  - *Sports activities*
  - *Security activities*

- **Air Traffic Flow and Capacity Management (ATFCM).** Its mission is to maximise the use of airspace in order to increase the traffic flow. This results in greater safety and efficiency for airlines.

  To achieve this, ENAIRE monitors the demands of different sectors and develops and applies measures to adjust their traffic demand. Their ATFCM services are:

  - **Provision of ATFCM services** to control centres, via the inflow control positions.
  - **National coordination of route availability and aeronautic environment** to facilitate the use of our air traffic management structures.
  - **Provision of ATFCM services** to other Spanish navigation service providers.
  - **Coordination with the Network Manager** on measures to reduce the impact of anomalous situations.

- **Air Traffic Service (ATS).** is made up of 3 tasks that form the basis of air traffic control:

  - **Air Traffic Control (ATC)** is carried out by air traffic controllers, whose role is to apply certain separation minima between aircraft and to authorise pilot's requests depending on the traffic conditions and the environment. Depending on the area in which the aircraft is located, the instructions are provided by:
    * **Area control center (ACC)**, ENAIRE has 5 of these centres from which it provides services. They are located in Madrid, Barcelona, Sevilla, Palma de Mallorca and Gran Canaria.
    * **Approach control service (APP)**, the controllers manage the ins and outs of flights in the control area. They are in charge of ordering and managing traffic during the following phases: the standby, approach, take-off and landing.
    * **Tower control service (TWR)**, the controllers manage the aircraft in and around the aerodrome.
  - **Flight Information System (FIS)**, provide real time information which is needed for the safe conduct of the different phases of flight: aerodrome, approach and en-route. This information is transmitted on VHF (Very high frequency) by means of the OFIS (Operational flight information service) or by the ATIS (Automatic terminal information service).
  - **Alarm service**. As a navigation services provider, ENAIRE acts when an aircraft has an incident. The alarm service notifies relevant agencies of the aircraft in need of assistance, and establishes assistance protocols and communications to provide useful information such as aircraft position and the kind of incident it suffered.

- **Air Traffic Management Systems (ATMS)** are the basis of air navigation. They can be divided into three systems according to their main performance:
  - **Voice Communications Systems (SCV)**, this systems provide a voice link between pilots and controllers. They are present in all three types of control centres (ACC, APP and TWR). They must provide service to:
    - Voice Air-Ground communications: Radio communications between aircraft pilots and air traffic controllers.
    - Voice Ground-Ground communications: Communications between controllers for coordinate operations, and between controllers and ground support personnel for its management.
  - **Automatic Air Traffic Control System (SACTA)**, is the responsible for manage all the ATC data. It enables automatic communication between local and foreign control centres. To this end, it uses international data exchange standards, automatically detects possible conflicts and provides flexibility for the reconfiguration of operational airspace.

    It processes all the information from the different sensors, associates them with its flight plan, monitors compliance and, in the event of deviations, alerts the controllers. In this way, management is done with solid and comprehensive data.
  - **Integrated COM/AIS/AIP Reporting Office Automated System (ICARO)**, is a system that automates the tasks and procedures related to the management of aeronautical information. This information is provided to SACTA together with weather information and the flight plan.

2.3 Air Traffic Surveillance systems

Data needed for surveillance tasks are obtained by different kinds of sensors installed on the aircraft and on the ground, which, by means of an information exchange using radiofrequency transmissions, make up the information network.

All the different surveillance systems are developed and designed to improve the capacity and the security of air traffic. To achieve this goal, those systems have to be able to provide constantly-updated and accurate information, in particular about the aircraft position (coordinates, altitude, speed) for the purpose of managing the traffic by the air traffic controllers. These systems have different performance requirements depending on the particular kind of service for which they are used:

- **Area control service.** Surveillance systems used for area control may cover large volumes of airspace, including remote zones like oceanic areas where the infrastructure is, normally, non-existent. However, at this zones, aircrafts are usually in cruise mode. Therefore, speed is almost constant, and there are no changes in altitude and heading except for the ones caused by conflicting traffic or weather conditions. Owing to that, except for areas with some congestion, the position updates do not need to be as frequent as in other areas.

  Also, in this area, it is important for surveillance systems to be able to warn the controller about changes into the flight route causing an aircraft to overfly a restricted area or if a medium-term conflict is detected.

- **Approach control service.** This service is provided to help controllers manage the traffic arriving or departing from one or more aerodromes. Its objective is to manage the flow of traffic to separate the arriving traffic from the departing one. It is important, especially in those airports with a lot of traffic, to achieve safe and efficient separation minima between flights.

  The systems for this service must be more precise due to the continuous changing in altitude and heading from the aircraft and with a higher update rate because aircraft altitude and heading are continuously changing, but coverage volumes are smaller than the required by the Area control service.

- **Aerodrome control service.** This service is the responsible for preventing collisions between aircraft in the surrounding area of the aerodrome and in the runways, and between aircraft and ground vehicle in the manoeuvring area. It is an important service, especially in busy periods and in low visibility conditions, when visual sighting, the main method to control aerodrome traffic, is not enough.

  The infrastructure of these systems must support a high degree of accuracy to determine the position of aircraft and vehicles, especially in runways and taxiways, and distinguish between quite close targets. As a consequence, a very high update rate is required, as well as runway incursion monitoring and other alerting tools.

Nowadays, to provide those services, different systems with specific technical characteristics can be used depending on the use they are going to be designated for. They can be classified into three different kinds of surveillance according to the fundamental aspects of its function:

- **Independent non-cooperative surveillance.** The aircraft position is derived from measurements without the cooperation of the remote aircraft. As an example, the Primary Surveillance Radar, which provides the horizontal position but not other aircraft data, can be mentioned .

- **Independent cooperative surveillance.** The aircraft position and other aircraft-derived information, like altitude or aircraft identity, is derived from measurements provided by a local surveillance subsystem that uses information received through aircraft transmissions emitted by their transponders. This is the method applied by Secondary Surveillance Radar or Multilaterion systems.

- **Dependent cooperative surveillance.** The aircraft position is obtained on-board using navigation systems and is shared with local surveillance subsystems along with additional data. This is the operating mode used in automatic dependent surveillance systems (ADS-C and ADS-B).

All those types of systems are part of the surveillance infrastructure that support the different services. For this purpose they use the different sensors to receive the information about the targets into the airspace they are monitoring, the on-board transponders that transmit data from the different equipments if the surveillance is cooperative and an information network that connects all the sensors to a processing centralized system called *Surveillance Data Processing Systems* (SDPS).

SDPS are responsible for combining the received surveillance data from the different sensors, integrating the surveillance data with other information and supplying this data to the controller after removing the possible different specificities of the different types of sensors. The one used by Eurocontrol is ARTAS (ATM surveillance tracker and server), which is able to process surveillance data reports from PSR, SSR, Mode-S, MLAT, ADS-B and ADS-C.

In the following sections, an overview of the aeronautic surveillance sensors that are currently used in aeronautical surveillance applications is presented .

2.3.1 PSR

At the end of the 19th century the investigations about the electromagnetic waves and how they reflect on metal objects started. This investigations continued during the beginning of the 20th century, when some engineers defined the theoretical basis of radar functioning. However, until the beginning of the Second World War radar systems did not have a relevant use. For commercial aviation, they began to be used in some aerodromes a few years after the Second World War.

The Primary Surveillance Radar (PSR) is an independent non-cooperative surveillance systems which works by detecting reflections as a result of a transmitted radio wave pulse. The PSR station normally consist of a transmitter, a receiver and a rotating antenna. Pulses are emitted by the transmitter on the station and then the reflections of the pulse caused by the target are detected by the receiver. The diagram of PSR functioning is shown on Figure 2.3. By the location of this elements two different types of radar can be distinguished:

- **Monostatic radar:** The transmitter and the receiver are at the same place.
- **Multistatic radar:** The transmitter and the receiver or receivers are separated.

The sensor is able to calculate the distance to the target with the ground station as the origin measuring the time elapsed from the transmission to the reception of the reflected pulse. It can also notice the position of the rotating antenna the moment the reflected pulse is received, and determinate the bearing of the target. These data are independently obtained of the aircraft on-board equipment.

This type of radar was used mainly in en-route surveillance but, due to the fact that it needs a great amount of energy to emit the pulses and that involves a high cost, and the fact that it is impossible to provide the identification of detected targets, which is needed with the increasing traffic densities, it was replaced by other sensors. With the requirement to carry on-board transponders when flying in a high dense traffic zone, SSR provided more surveillance information and in a cheaper way.

Despite providing less data than other sensors, PSR is still used for defence and for weather-monitoring purposes exploiting the reflection of transmitted radiation principle for which clouds reflect the electromagnetic waves. It is also used in airport surface surveillance applications and in major terminal areas.

The main advantages and limitations of this sensor are listed below:

Advantages

- The ability to detect non-aircraft objects that interfere in the airport tasks and the protected areas of the airport. It has become a useful tool in the wake of recent events, in which

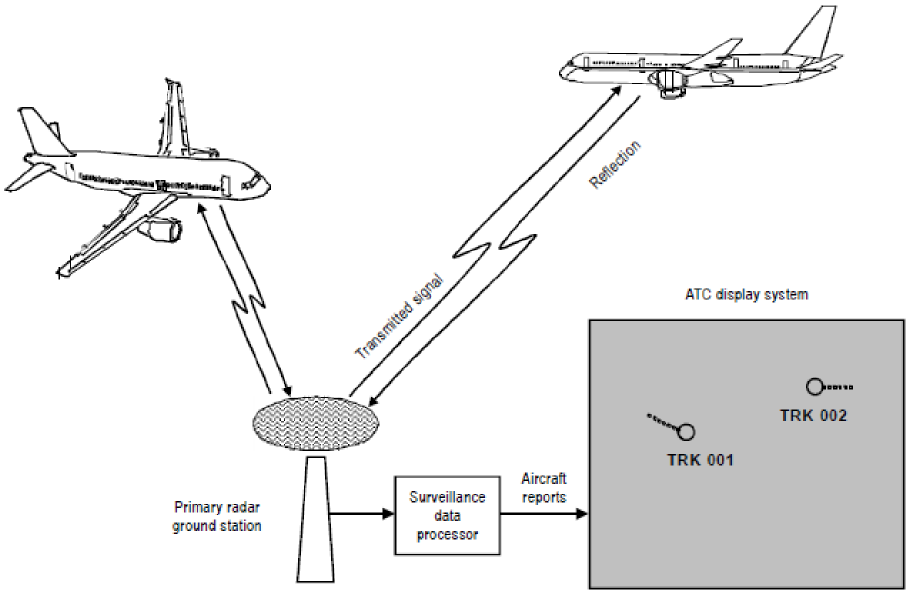

Figure 2.3: PSR functioning scheme

civilian drones have disrupted air traffic and caused airports to close. These detections are made because on-board equipment to obtain the data it is not needed, just an object made of a material that is able to reflect radio waves.

- It can be configured to detect meteorological conditions by processing pulses' reflection from precipitations.

- To provide surveillance data of non-cooperative aircraft, especially in the vicinity of large airports, as well as the ability to maintain a minimum level of surveillance in case of failure of a transponder.

Limitations

- The system presents problems which lead to it not being able to monitore closely spaced targets nor targets very far due to the range limitation derived from the maximum power of the pulse emitted.

- Related to the previous limitiation, it requires high power pulses to overcome the two-way path loss.

- It is also unable to provide some basic data from the target, such as altitude or identity.

- It suffers from a high rate of false detections.

- It has a cone of silence over it, which limits the detection of targets overflying the antenna.

2.3.2 SSR

The Secondary Surviellance Radar (SSR) was developed due to the impossibility to identify the aircraft by using the PSR. It is an independent cooperative sensor which consist of two main elements: transponder on-board the aircraft and a ground-based interrogator/receiver which is the responsible for processing the transponder messages. The SSR ground station also has a rotating antenna shared by the interrogator and the receiver.

As in the PSR case, the range is calculated by measuring the time it takes to the ground station to receive the replay to the interrogation signal. It is important to mention that the transponder has a fixed delay with which it decodes the interrogation signal and build the reply. This delay is taken into account by the sensor when it processes the round trip delay to compute the target range. Furthermore, the bearing of the aircraft is calculated through noting the position of the rotating antenna when the reply signal is received.

To verify the radar performance, there are some transponders installed at known places, called PARROTS. They alert controllers if the radar fails to receive the reply or the position reported by the transponder is outside a margin area centred on its true position. These characteristics let the Secondary Surveillance Radar be used for en-route and approach surveillance.

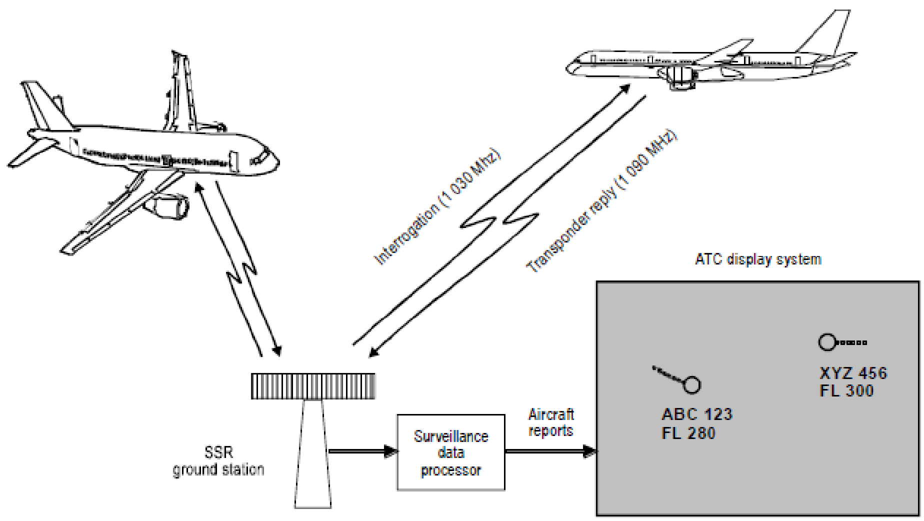

Figure 2.4: SSR functioning scheme

To carry out those surveillance transactions, the SSR uses the 1030 MHz frequency for interrogations and the 1090 MHz frequency for replies. Figure 2.4 summarizes the SSR functioning.

As it has been mentioned above in the historical introduction, the SSR has evolved from the militar IFF which identifies aircraft as hostile or friendly. Subsequently, the Mode A/C was developed for civil aviation. Mode A/C transponders provide an identity code (Mode A) and a pressure altitude code (Mode C) in the replies to the radar interrogations. The Mode A identity code is assigned by the ATC and the flight crew have to configure it in the transponder. It is provided as a four-digit octal number. Together with it, the data transmitted in Mode C code is calculated by an on-board pressure altitude encoder, which sends it to the transponder.

Once the functioning has been explained, some advantages and limitations of this sensor will be mentioned below:

Advantages

- It is more complete than PSR, and it is able to calculate the range and bearing and also to determine the pressure altitude and aircraft's identity.
- It is possible to alert of emergencies such as unlawful interferences or loss of radio communication using reserved Mode A codes for these purposes.
- Longer coverage range than PSR, since it doesn't suffer from a two-way path loss. The interrogation and reply signals only affected by one-way path loss because the transmitter and the transponder emit different signals.
- It is able to detect closely spaced targets in spite of overlapping replies.

Limitations

- Aircraft have to carry on-board a functioning transponder. Nowadays, to overfly the majority of airspaces, it is mandatory to carry some basic equipment, as transponders, for example.
- Lack of an inherent method of detecting data errors in both interrogation and reply signals.
- The airborne information is still limited to the traffic densities we work with.
- Accuracy is limited by the transponder delay tolerance and that makes it unusable for aerodrome surveillance tasks.

2.3.2.1 Mode S

After introducing the SSR Mode A/C, they tried to improve it, and as a result they developed the SSR Mode S, which introduced some improvements to solve the limitations discussed above.

The main improvement that the Mode S brought with it was the selective addressing of an aircraft by using a 24-bit aircraft address that identifies just an aircraft. By applying this method, each aircraft is able to establish a two-way data link between the aircraft and the radar's ground station for the exchange of information. Also, this Mode was designed to support and be compatible with all the roles provided by Mode A/C.

In addition, the Mode S data link allows the transmission of more flight information from the aircraft, such as: airspeed, heading, track angle, vertical rate, ground speed, track angle rate, roll angle, aircraft ID or altitude selected by the flight crew among others. These aircraft derived data are used to improve the tracking of the aircraft without needing of radio calls to ask for this information.

Also, this data link created between the radar and the aircraft could be used to uplink or sent information from the radar to the aircraft. It is used, for example, in TIS (Traffic information system), where the aircraft, on request, obtains information about aircraft around it detected by the radar.

Despite the correction of some of the Mode A/C limitations and many other advantages, Mode S still presents some limitations, mentioned in the points below:

Advantages

- Complete compatibility with Mode A/C capabilities.
- Mode S sends reports of pressure altitude whit increments of 100 or 25 ft.
- By the use of selective interrogation and the creation of a two-way data link, the interference between closely spaced aircraft are eliminated and it results in a high probability of message decoding in zones with high density traffic.
- The previously mentioned data link is also useful to obtain aircraft derived data.
- Mode S implement a CRC (Cyclic redundancy check), an error-detecting code to ensure data integrity and to protect it against transmission errors.

Limitations

- The aircraft have to carry on-board a functioning Mode S transponder. If not, they will not be compatible with the Mode S services.
- The proper configuration of aircraft installation as the 24-bit aircraft address used for identification is required.
- An assignment of interrogation codes (IC) and adequate management of ground installations in areas where the Mode S interrogator coverage is overlapped is needed.

2.3.3 MLAT

A multilateration system (MLAT) is an independent cooperative sensor which consists of the detection of aircraft's transmitted signals, in a number of receiving stations, to calculate their positions. The system contains a series of ground stations waiting to receive signals emitted by the aircraft's transponder. This requires a number of ground receiving stations capable of detecting such signals and a central processing station. This type of system is used for aerodrome control and area control services (WAM) to identify and locate the position of aircraft.

The multilateration systems used for civil purposes are only based in the use of SSR transponder signals. They use the 1090 MHz transponder signals and can operate with Mode A/C and S responses, or spontaneous transmissions (squitters).

Two types of sensors could be differenciated, passive systems if they are not able to interrogate directly the aircraft's transponder and active systems if they are able to ask directly for a response. The active systems are used when there are no other interrogation sources in the coverage area of the system to elicit SSR reply signals. This fact makes those systems independent of other sensors but could cause interference in 1030 and 1090 MHz channels.

Multilateration systems require a minimum of four receiving stations to calculate the aircraft's position. This number could be reduced to three stations if the aircraft's pressure altitude is known.

In practice, MLAT systems have more receiving stations to ensure coverage and performance parameters.

The MLAT systems do not have a linear accuracy in terms of coverage volume. The system geometry is important at this point, because when the aircraft is outside the area defined by the ground station positions, the accuracy decreases rapidly.

The technique used to calculate the position of aircraft is based in a technique known as TDOA (Time difference of arrival). There are some different ground stations which are strategically situated and waiting for reply signals from aircraft's transponder in response to secondary radar or active multilateration system interrogations. This signal would be received at different times for each station, which is used to calculate the aircraft position precisely. One of the ground stations is considered as the reference one. The time of arrival to the reference station is subtracted from the time of arrival to the rest of the ground stations, leading to a set of TDOA.

Each TDOA defines a hyperboloid on which the aircraft is located. When at least four of the stations detect the target, they create three surfaces, making it possible to estimate its position by calculating the intersection of these surfaces. The diagram of the MLAT system can be seen on Figure 2.5.

If the altitude is known, other surveillance systems or by Mode S information exchange could be used. Three detections make it possible to calculate the positions, since just two hyperbolas are needed to obtain the horizontal position. When more than 4 ground stations are used, the extra information makes it possible to verify the accuracy of the calculated position. In addition, by using active transmitting stations, the calculation obtained from the measurement of the distance using the reply is used to complement the multilateration TDOA information.

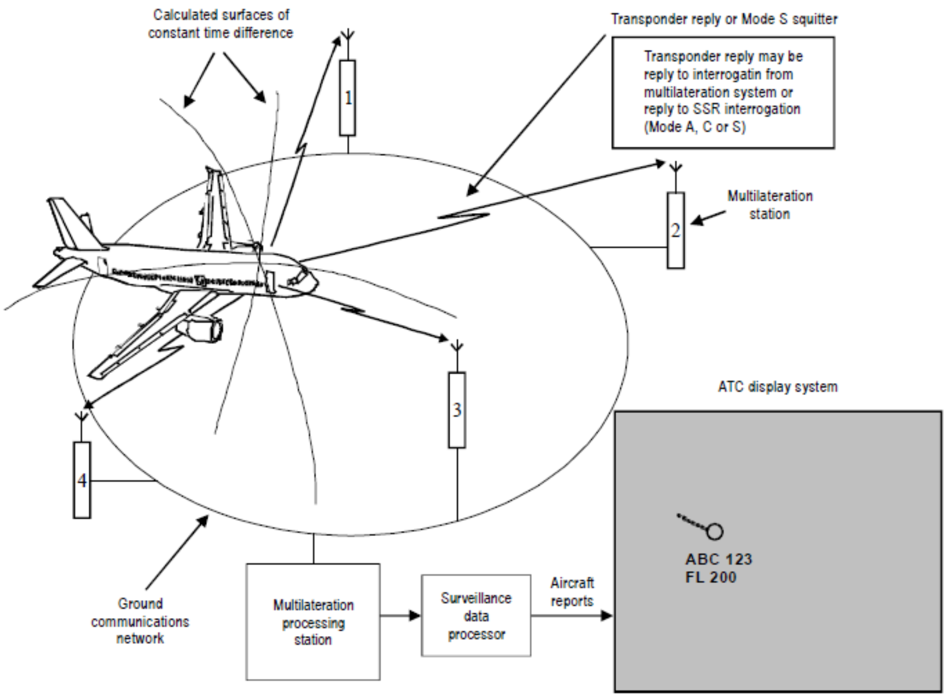

Figure 2.5: MLAT functioning scheme

Another important aspect in order to achieve accuracy when using TDOA is time synchronisation. A time stamp is applied during the signal digitisation process, while doing it, a certain delay to the arrival time is applied. Therefore, in order to precisely calculate the TDOA, it is necessary to know and take into account this delay. To address this problem, two synchronisation methods are proposed:

- **Common clock systems.** In those systems the signals are sent by an analogic connection to a central processing station where they are time-stamped using a common clock. The time elapsed between the message being received at the receiving station and after its transmission, received at the central station, must be calculated and taken into account. In order to know this time, messages are sent between stations to calculate the duration of that transmission. The architecture of this kind of systems is explained in Figure 2.6.
- **Distributed clock systems.** In those systems, all the receivers are synchronized by a common reference. The most used are GNSS or transmitters at a known location. As the location of the transmitter is known, the time of the signal reception can be calculated and monitored to ensure the receiver's clock remains synchronized. The explanation of the architecture used in this kind of systems is summarized in Figure 2.7.

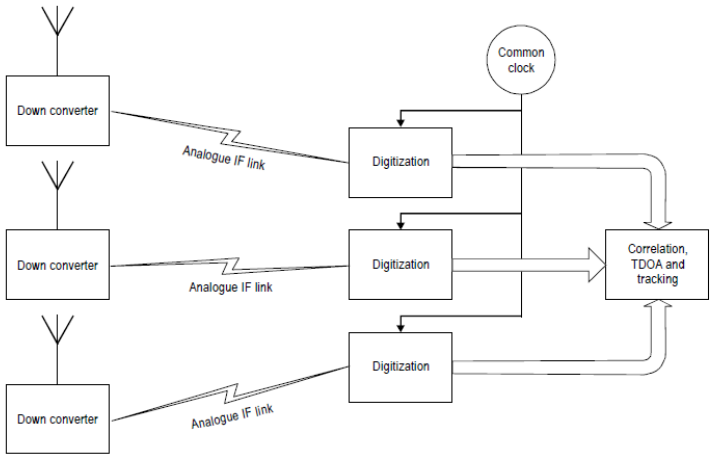

Figure 2.6: Common clock architecture

Multilateration systems present problems for surface applications because their use depends on the ability of aircraft transponders to operate on the ground. In many aircraft, due to the fact that functioning is controlled by the weight-on-wheels switch, the transponders can not operate in Mode A/C or, in case of Mode S, can only transmit squitters and answer selective interrogations. In contrast, for approach services are very useful for controllers as they allow them to control areas that may be hidden from other systems and improve aircraft positioning thanks to their accuracy and high update rate.

MLAT systems advantages and limitations are:

Advantages

- As it works with any signal, any transponder already installed on the aircraft can be used to broadcast the signals, without the need to add new equipment.

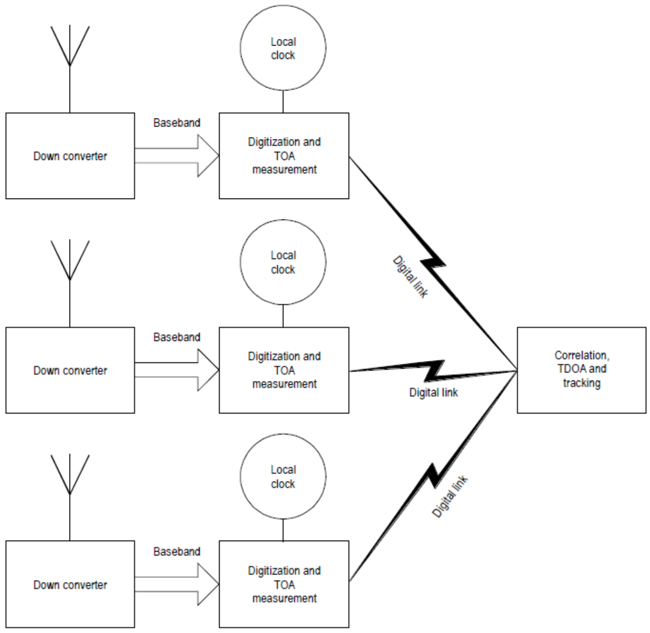

Figure 2.7: Distributed clock architecture

- It offers coverage even in difficult terrain. Its coverage area can be extended by adding more stations, up to the processing limit of the system.
- It also offer high accuracy and high update rates. Accuracy could be controlled by the location of receiving stations.

Limitations

- Connections are needed between remote receiver/transmitter and the central processing stations.
- Aircraft must be equipped with a functioning transponder.
- At least four receiving stations have to be available to correctly detect the transmitted signals.

2.3.4 ADS-C

The Automatic Dependent Surveillance by Contract, is a surveillance system where the aircraft is the responsible for providing information as its present position, obtained from the on-board navigation equipments, with time stamp and FOM, the predicted route including the following two waypoints, velocity and metereological data through a point-to-point data link.

This technique need navigation equipment and transponders on-board to get and to transmit the information. This information is received in a ground station, where it is processed. Thanks to that, the surveillance by ADS-C is available to operate in any environment. In addition, this information exchange does not require pilot intervention.

This new system consist of a ground ATM system which establishes a contract with the aircraft where are specified the terms under which information will be sent out. ADS on-board equipment confirm the contract. This equipment is able to combine contracts with different stations, which can be modified or cancelled during the flight. Those contracts specify the conditions under which the aircraft submits reports: periodically, on demand, in emergencies or based on events.

In periodically communications, an update rate and the information in each report is defined. For on demand contracts the air control management asks, occasionally, for a report. In case of a contract based on events, the report is send if an event occur. For the case of emergencies, the system send to all ground stations with which it has a contract, a report.

By the use of a point-to-point data link the reception of messages is guaranteed for as long as the contract is in force. In case of a total loss of communications, controllers are alerted. Also, using this type of link makes the information inaccessible to other aircraft or systems, reducing the risk of external intrusion.

The ADS-C systems are extremely useful for oceanic and remote areas where there is no radar. The report rate in oceanic operations is normally 15-25 minutes but it could be increased by controllers to support specific operations. For this situations is commonly used in conjunction with CPDLC (Controller–pilot data link communications) which allows, as an alternative to voice communications, electronic data communications between ATC and flight crew.

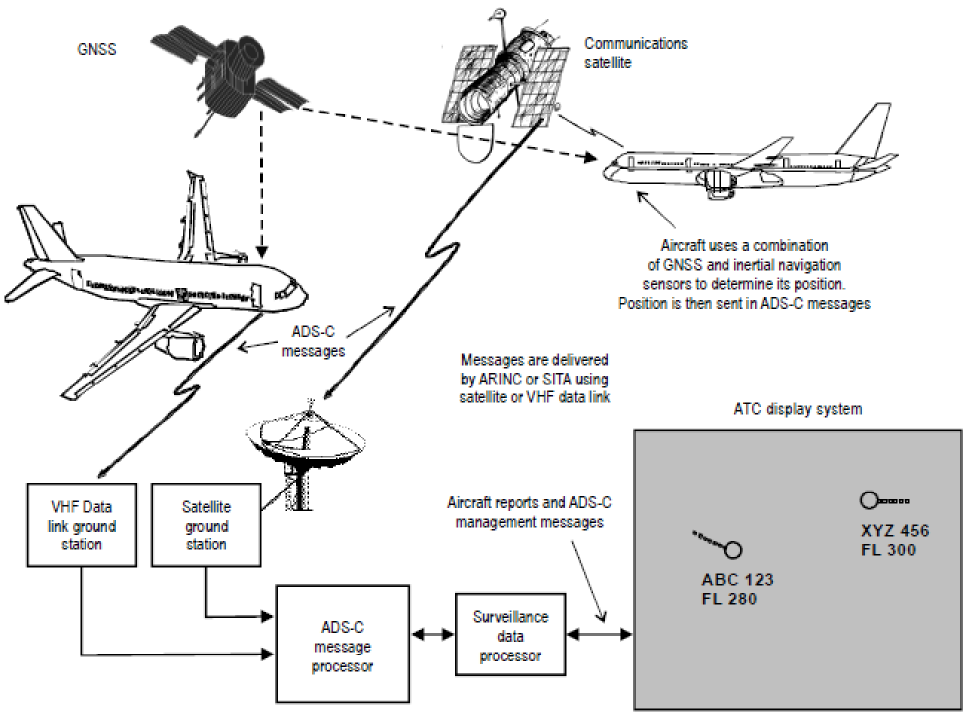

Figure 2.8: ADS-C functioning scheme

The advantages and limitations of this sensor are listed below:

Advantages

- Provides surveillance in areas where no radar or MLAT can be installed
- Provides report of future waypoints, which is useful to detect potential conflicts.
- The point-to-point data link protects the data while is being transmitted.

Limitations

- The proper functioning of the system depends on the aircraft having the correct equipment to transmit the data.
- When the data of the report transmission is carried by a data link service provider, as happens when VHF is not available and they need to use communications satellites, the cost of the transmission increases and results in a low update rate.
- As the information is inaccessible to other aircraft, it does not support ASA (Airborne surveillance application).
- It requieres additional avionics to be installed.

2.3.5 ADS-B

The Automatic Dependent Surveillance by Broadcast, is a dependent cooperative surveillance system. It is based on the periodic broadcasting of ADS reports via radio, without requiring interrogation or establishing data links with ground stations or other aircraft.

ADS-B systems can be used for any surveillance area from en-route to approach and surface. Furthermore, they offer significant advantages over radar systems such as target detection in challenging environments or a higher update rate.

These function is called ADS-B OUT, and is performed by means of on-board transponders that have access to the measurements made by other aircraft systems, such as the GNSS receiver, from which it obtains by trilateration a precise position, that is then broadcast along with other information such as speed, aircraft ID and data integrity indicators, using Mode S messages.

This messages can be received and processed by ground stations and other aircraft with ADS-B IN function or any suitable receiver. In addition, it could also receive, from the ground, additional data from other aircraft not transmitting ADS-B OUT or that transmit using a different ADS-B technology.

The ADS-B position messages from on-board inertial system were normally transmitted with a declaration of unknown accuracy or integrity. To solve that new aircraft installations transmit ADS-B messages with position, velocity and data integrity indicators using an integrated GNSS and inertial system that complements each other in a way that corrects the failures of the other system. Altitude is normally obtained from the pressure altitude encoder.

In the following sections it will be explained the 3 data links that are standardised for the transmission of ADS-B messages.

Mode S 1090 MHz ES

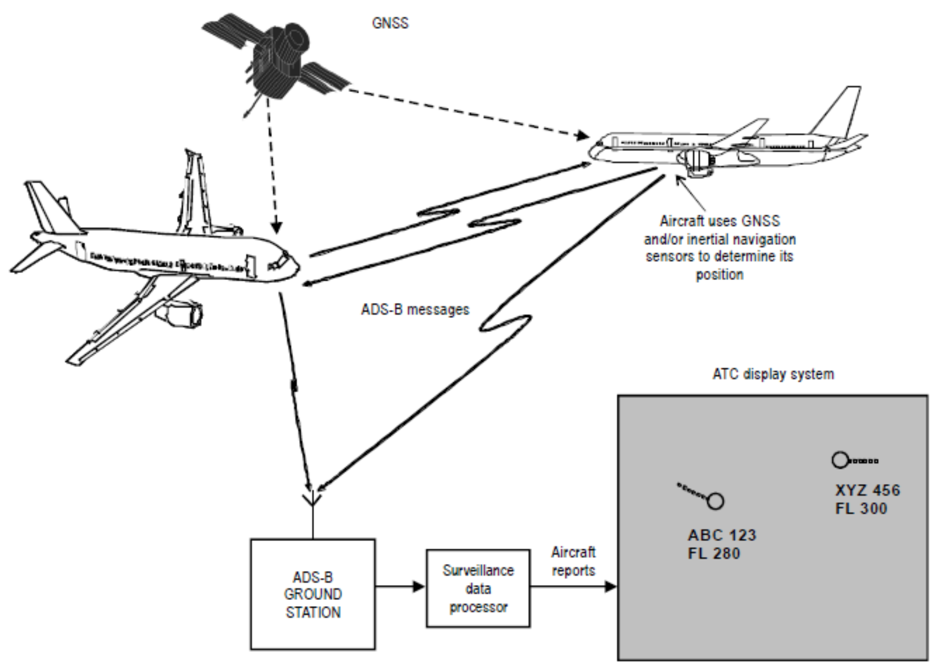

Figure 2.9: ADS-B functioning scheme

The 1090 MHZ ES(Extended Squitter) was developed for the Mode S system. The standard is 56 bits long, but the extended squitter version contains an adittional 56-bit data block with ADS-B information. The duration of each message is 120 microseconds. The frequency used for the transmission is 1090 MHz with a data transmission rate of 1 Mbps.

The ADS-B information is broadcast in different messages. Each of these messages contains a set of information. Position and velocity are transmitted twice per second and aircraft ID is transmitted every 5 seconds. The transmission of ES ADS-B is carried out by Mode S transponders, although non-Mode S transponders may also be used.

UAT

The UAT data link was developed as an aviation data link that allow uplink of information in addition to ADS-B data transmission. The frequency used is 978 MHZ and has a data transmission rate of 1 Mbps.

An UAT transceiver has been assigned a MSO (Message start opportunity), which is a time slot or channel, that could be used to transmit information. Channels may be allocated in one of two segments: the ADS-B segment and the ground one. The ADS-B segment channels have a duration of 250 microseconds and are assigned to aircraft for transmission of ADS-B data. On the other hand, the ground segment channels have a duration of 5.5 milliseconds and are reserved for broadcasting of weather and flight information obtained by the ground system known as FIS.

VDL Mode 4

VHF Digital Link Mode 4 was developed as a generic data link able to support CNS functioning. Initially its use was restricted to ADS-B and ADS-C surveillance applications, but this restrictions were removed and now is available as CNS data link.

The system supports broadcast, which is needed for ADS-B, and point-to-point communications used in air-ground and air-air applications. The frequency used is the VHF band (108-137 MHz) where it operates on 25 kHz channels. The access to the channels are self-organized with a TDMA (Time division multiple access) scheme, which is responsible for selecting empty slots for transmission, and synchronized to UTC (Coordinated universal time).

The advantages and limitations of the ADS-B are summarized below:

Advantages

- The ground station which receive the information from this sensor is simpler than the ones used in other sensors. This made the antennas installation cheaper. The reason why this happens is that they do not need to perform calculations or make interrogations to receive data, they simply listen and receive data that must then be decoded. The installation can be accommodated at VHF radios with existing infrastructure or at others navigation aid sites.
- In each report the sensor include, apart from data such as position, an indication of the integrity of this data, which can be used to determine the feasibility of using and supporting air-to-air surveillance systems such as ACAS (Airborne collision avoidance system).
- Can be used for airborne and ground-based surveillance applications

Limitations

- Depends on the equipment of all aircraft, but not all of them carry ADS-B compatible navigation system. This could be an important issue for some airspace because is needed an installed and certified navigation source capable of supplying the position and velocity information along with the required indication of accuracy/integrity. In the case of Europe, USA, part of Asia and other countries, a transponder which can transmit ADS-B messages is mandatory for aircraft with a maximum take-off weight above 5700kg.
- Depends on the correct functioning of GNSS to obtain position and velocity. This could result in outages when the performance or the geometry of the constellation is inadequate to support a given application. This problem will gradually be solved as new GNSS systems such as Galileo, instead of just GPS, are implemented and used for these applications.

2.4 ASTERIX

ASTERIX is a standard for the exchange of information in the field of air traffic services using as little data as possible. Is the responsible for the definition and assembly of the data. Its purpose is to enable an efficient and harmonised transfer of important data between two entities using a mutually agreed representation of the information to be exchanged. This standard was developed by Eurocontrol and now it is used worldwide.

To this end, it is important to have data processing and distribution systems in place that allow reliable information to be exchanged efficiently.

Category Number	Description
000-127	Standard civil and military applications
128-240	Special and military applications
241-255	Non-standard civil and military applications

Table 2.1: ASTERIX applications by caterogies

As this standard is used by some different sensors, where there are common information from all of them as position, ASTERIX specifies minimum requirements to be met to facilitate the exchange of information between different sensor applications. It bases the communication between two systems on a common core of monitoring data, which makes it easier for them to work in different ways, but to unify the way they transmit and present the information so that when working in the same system with the information from all the different sensors, it is simpler.

This protocol performs among other tasks the packaging of sensor data that will contain data specific to that sensor and common data offered by all sensors although with different accuracy and update rates. For this purpose, ASTERIX frames can be adapted to the characteristics of the type of sensor used.

Sensor data are organized in different data categories, to make easier identify the data type and process them faster. It consists of 256 categories, divided into blocks according to the type of application for which they have been designed, as detailed in Table 2.1. Each category includes a catalogue of specific data items, depending on the data that can be obtained from the sensor. These items are the minimum unit of information defined and standardised.

The rest of the section explains the way the different information fields are organized, whose structure can be seen in Figure 2.10.

- **Data category (CAT).** Is a field with a length of one octet which indicate the category of information in the message.
- **Length indicator (LEN).** Is a field with a length of 2 octets that indicates the length in octets of the complete ASTERIX message including CAT and LEN fields.
- **Data Record.** Is a field with variable length composed of:
  - **Specification Field (FSPEC).** Is a field with variable length similar to a table content where the presence or absence of a Data Field is indicated in binary format, with 1 standing for available data and 0 for unavailable ones.
  - **Variable number of Data Fields.** Each of this fields contains just a data item and could have fixed length or variable. There are some items for each category that must be included whereas others are optional.

2.4.1 CAT 021

There are some categories dedicated for the transmission of information from detection made by the different types of surveillance systems. Those categories contain different items to standardise the different information that surveillance systems can provide as altitude, position, time of measurement or quality indicators among others.

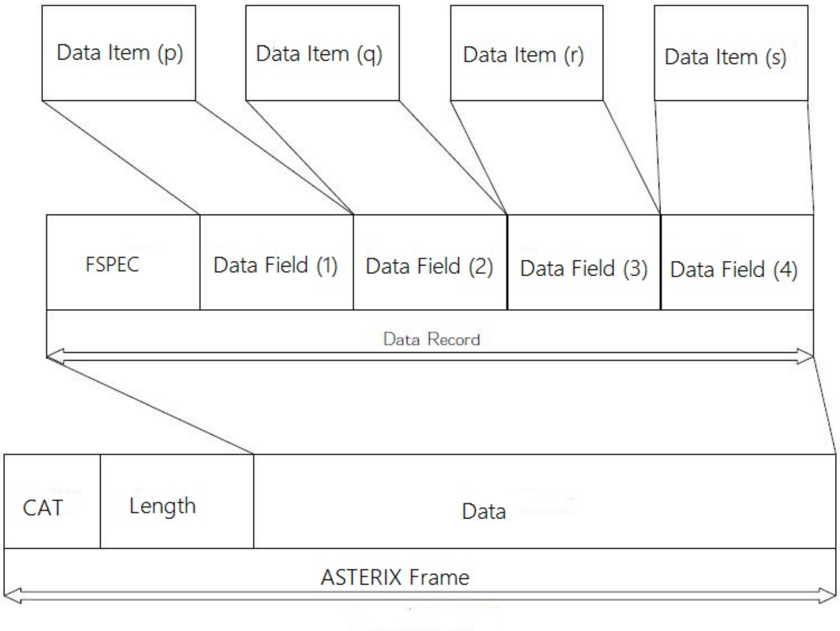

Figure 2.10: ASTERIX Frame architecture

The primary ASTERIX category related with ADS-B systems is CAT021 whose main items are described in Table 2.2.

Data Item	Description	Units
CAT021/I073	Time of Message Reception for Position	sec.
CAT021/I130	Position in WGS-84 co-ordinates	Degrees
CAT021/I145	Flight Level	FL=100 ft.
CAT021/I160	Ground Speed referenced to WGS-84	NM/h
CAT021/I160	Track angle referenced to North	Degrees
CAT021/I170	Aircraft ID code	-

Table 2.2: Useful Data Items from CAT021

2.5 Performance-Based Communication and Surveillance

The data collected and transmitted between the different sensors described in the previous section are not always valid and reliable, so tools to analyse the data started to be created. Initially, these were focused on evaluating the behaviour of the sensors explained above. This is the case of CARPET (Computer-aided radar performance evaluation tool) which evaluated and predicted the behaviour of radars.

Others also appeared whose objective was to evaluate the operational behaviour of senors, such as RASS-S (Radar analysis support system for sites) and RMD (Radar monitoring display), which emerged as extensions of the RADAC (Radar data acquisition converters) system. In the case of RASS-S, it is in charge of evaluating the different elements of a radar and RMD has the task of processing the surveillance data from the sensors.

The problem with these systems is that there were no minimum requirements for the integrity and quality of the sensor data, so is important to define some metrics for evaluating the behaviour both in simulations and with real flight data packages. But due to the limitations of the analysis and the simplifications that were necessary to carry out the evaluation of the data, the results with simulations were not at all accurate compared to the real data due to the lack of precision. As a result, only real traffic data were used, which were subsequently analysed and corrected. This is what led to the concept of PBCS (Performance based communication and surveillance).

PBCS is responsible for providing the systems in charge of evaluating the communication and surveillance technologies used in ATM with objective operational criteria. Once accepted, they are implemented and the feasibility of their implementation for a given ATM operation is tested against the standards pre-set by the PBCS.

Performance-based communication and monitoring are related to performance-based navigation and complement each other. On the one hand, PBN (Performance-based navigation) acts on area navigation (RNAV) and required navigation performance (RNP) specifications. On the other hand, PBCS applies on the required surveillance performance (RSP) and required communication performance (RCP) specifications.

Even though they have similar functions, although on different elements, there are differences such as the time at which each of them has to be applied.

As mentioned above, PBCS applies on RSP (Required surveillance performance) and RCP (Required communication performance) specifications, assigning criteria for communication services, aircraft capability, operator capability and other ATS (Air traffic services). It also includes both local and regional post-implementation monitoring programmes whose information is shared globally. This translates into greater analytical capacity, as it has information from the entire route, which is stored in batches of data for more convenient work.

In contrast, PBN, which applies to the RNP (Required navigation performance) and RNAV (Area navigation) specifications, assigns criteria only to the capability of the aircraft and its operator, including the integrity control of the measurements of the different sensors in real time in order to ensure the safety of surveillance, and the alert functionality of the aircraft capability. All quality functionalities are analysed by the DAW (Data analysis workstation) online.

PBCS is responsible for part of the provision of air traffic services and their use by operators, including on-board equipment. To this end, they use a variety of methods including certification of aircraft equipment that will provide communications and surveillance capabilities to support ATS, management of software for monitoring the current quality and integrity of communications, and monitoring compliance with RCP and RSP specifications in surveillance. In this way, if any type of error or mismatch is detected, it can be corrected so that it continues to operate within the specified requirements.

To monitor and evaluate the current performance of surveillance systems against specifications, the SASS-C software was developed by Eurocontrol, which is also responsible for supporting and updating it.

2.5.1 PBS tool: SASS-C

SASS-C is one of the most important software tools in the field of aeronautical surveillance systems. It is made up of two suites: the verification suite, which deals with the evaluation of actual surveillance systems, and the prediction suite, which deals with the theoretical calculation of the performance of these systems.

The software is based on the creation of reference trajectories, isolating sets of these measurements that will be used as a reference to evaluate the performance of the sensors, and multi-sensor associations in real time. This tool is also used for the correction of certain parts of the measurements such as sensor bias error, false alarms, measurement noise and other processes that were previously performed manually.

The software is in charge of monitoring, evaluating the quality of the received measurements, estimating a future measurement and comparing it with the obtained.

For the verification suite (SASS-C VERIF), which processes the information from the different sensors to evaluate their performance, the programme has several modules:

- **IRIS (IOSS Recording and Import into SCDB):** This module is in charge of collecting data from the sensors, in ASTERIX format, and recording and decoding them. The data are stored in an orderly manner so that they can be easily accessed by other SASS-C modules.
- **OTR (Opportunity Traffic Reconstructor):** This module allows the construction of reference trajectories from all sensor data. Then it uses these trajectories to correct for sensor errors (random and bias) by estimation and interpolation, so that the trajectory is reconstructed to create a more accurate trajectory.
- **CMP (Comparator Evaluation Suite):** This is the module responsible for the evaluation of the quality of the measurements taken by the sensors by analysing the information processed by the previous stages and comparing it with imported references and with those generated by OTR (Opportunity traffic reconstructor) using real traffic.
- **REPORT:** This module deals with the generation of reports on the analysis of results.
- **DISPLAY:** It is a visualisation module that allows us to visualise surveillance data, reconstructed trajectories, and performance metrics in different types of formats.

At the same time, the prediction suite (SASS-C PREDICT) allows the performance of sensors to be calculated theoretically using digital elevation models, probability of receipt of message, models for environment interference, and position measurement accuracy.

2.5.1.1 OTR functioning

OTR is the core of SASS-C. OTR collects data from many sensors, corrects them, associates them and outputs RRT (Reconstructed reference trajectories), associations between target reports and RRTs, relationships between trackers and RRT, as well as sensor noise estimates and covariances for further use by the CMP (Comparator).

For the correct functioning of this module, it has to run the following processes:

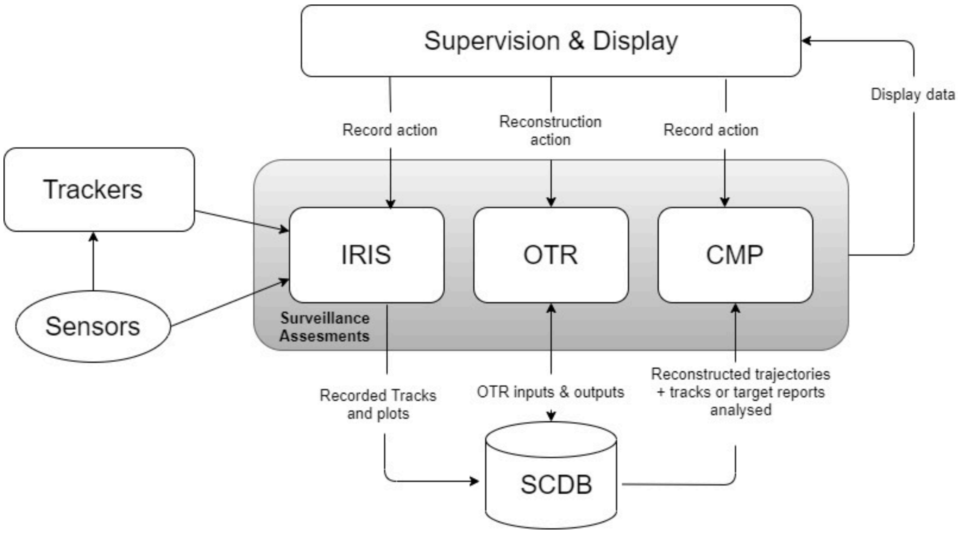

Figure 2.11: SASS-C surveillance assessment architecture
[8]

1. **Gross asociation:** once the measurements are expresed in the same coordinate system, the next step is to group the sensor data into single-sensor tracks related to a target, and then group the single-sensor tracks together to create multi-sensor tracks, which must have a minimum length. This association is not very conservative; thus, so not all the target reports will be associated to a track.

2. **Constant velocity segmentation:** trajectories are segmented into sections with constant velocity, to isolate straight sections where it is assumed that the same MoF (Mode of flight) is used, to find out if this assumption is correct, single and multi-sensor trajectory measurements are used. Velocity data and other data obtained from the aircraft such as barometric and geometric altitudes are used. At the end of the process, straight sections with constant velocity are obtained.

3. **Noise estimation and covariance correction:** First of all, it is a matter of correcting the random noise estimated from external sources, for which all the segments and tracks available are used. The noise is computed independently for each straight path by means of a least squares filter. Subsequently, corrections for this noise are applied to the target reports and the measure covariance matrix is updated.

4. **Bias estimation and correction:** the bias error is a type of error that always appears and has a constant value. It can be caused either by the sensor (then once it is estimated, it is corrected for all its measurements) or by the target (it is the same when that target is related to sensors of the same type).

   For the correction, an error model is used for the sensor that has taken the measurement, in order to know the error and its source. Once it is known, the bias errors of the measurements are corrected, first the global one of the sensor and then the specific one of the target under analysis. After this, the correction is applied to the entire trajectory of the target.

5. **Fine association:** once measurements have been corrected, the OTR moves on to associate monotracks and single reports with multitracks already associated in the gross association.

To do this, first monotracks are created with every single reports. Then, the tool tries to associate the monotracks with each other creating multitracks, and finally, if they meet a minimum length, it tries to associate them with other contiguous multitracks.

6. **Reconstruction:** in this process, vertical, horizontal and RRT segments are obtained from multi-sensor trajectories. For this purpose, horizontal MoF detection is performed and filtering is carried out to determine the beginning and end of the manoeuvres. For the vertical segments, a one-dimensional adaptive iterative Kalman filter is used. Finally, by combining all the information obtained, the RRTs are created.

7. **Postprocessing:** first of all, the trajectory is classified. Also, it uses a gap analysis to identify and reconnect trajectories separated by long detection gaps. Finally, it indicates the kind of aircraft of each trajectory.

8. **RRT update:** this process includes correlation with system tracks and with ERTs (External reference trajectories) in order to update the information of the RRTs with the ERTs.

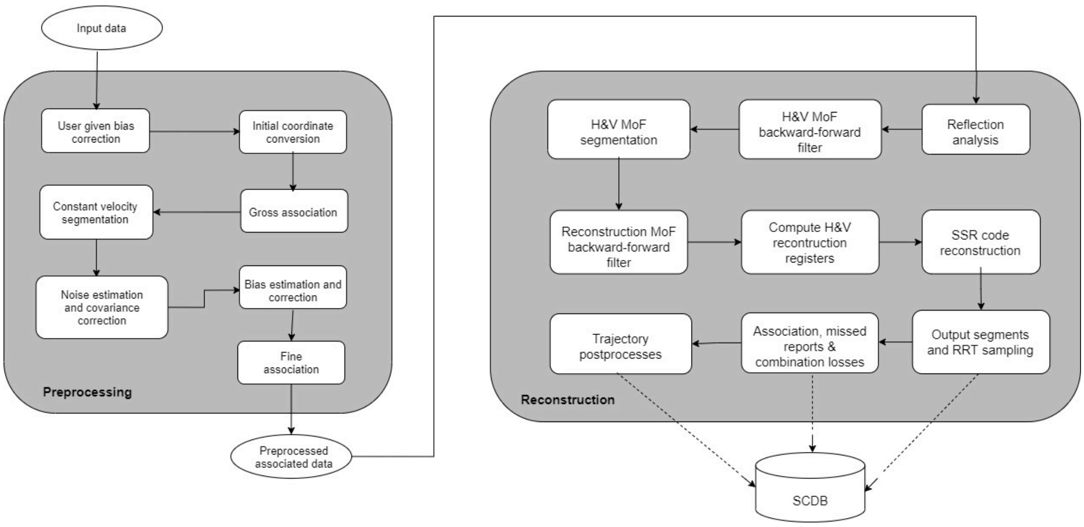

Figure 2.12: OTR module processes
[8]

2.6 Technical performance requeriments for surveillance systems

The fundamental function of the aeronautical surveillance infrastructure is to supply a precise estimation of the horizontal position and altitude of an aircraft at a particular time, as well as its identity. The horizontal position and altitude must be updated at an appropriate rate which depends on the operational environment and the service it is required for. It may also need other information, such as aircraft velocity and short-term intention.

In order to achieve the performance required for surveillance systems, the most basic elements are the type of surveillance data and their quality. Also is important to emphasise that those surveillance requirements are not enough to authorize an operational separation, since there are other factors that must be considered for achieving secure operations.

The main parameters which contribute to quality of services are:

- **Data item.** The information as such as horizontal position, identity or intent that is required to provide the surveillance systems with.
- **Accuracy.** The degree of conformity applicable to a data item which is measured or calculated by the system compared with its real value at the time the data item is used.
- **Data integrity.** The probability that an information error larger than the threshold is not detected by the system. In the cases where the system is only a communication medium and should not modify the value, is the degree of undetected changes between the input and the output value.
- **System integrity.** The probability, for a certain time, of an undetected error in a functional element results in providing erroneous surveillance information to the end-user.
- **Availability.** The probability that the end-users can access to the required surveillance information when needed.
- **Continuity.** The probability that the surveillance system performs its function without unplanned crashes during the intended operation.
- **Reliability.** The frequency with which error do not occur within the system while it performs its function achieving performance requirements, in a specified period under given operating conditions.
- **Update rate.** The mean time difference between two reports containing the same type of information from the same aircraft.
- **Coverage.** The volume of airspace where the surveillance system will provide their service and within which their performance accomplish the requirements.

The determination of the minimum performance of the different surveillance systems, based on the different parameters proposed in this list, is carried out in different standards and specifications, proposed by organisations such as Eurocontrol, EUROCAE or RTCA (Radio technical commission for aeronautics), which propose a series of metrics that are used to evaluate the performance of the systems.

This definition of standards and specifications of minimum data quality or integrity should not be subject to the type of system used but should depend on the requirements of the application for which the data are to be used. In this way, the design of systems will be more efficient, and will be based on the operating environment. This is known as PBS (Performance-based surveillance), explained in the previous section.

These systems have to be regularly checked for compliance with these specifications, either by control measures, by in-system analysis or by external monitoring of the system.

Chapter 3

Project description

3.1 Methodology overview

First of all, before going on to explain how the different parts of the SASS-C system work to try to correct errors in the system, it is important to explain the process that SASS-C follows to correct them.

The process in question is the one shown in Figure 3.1.

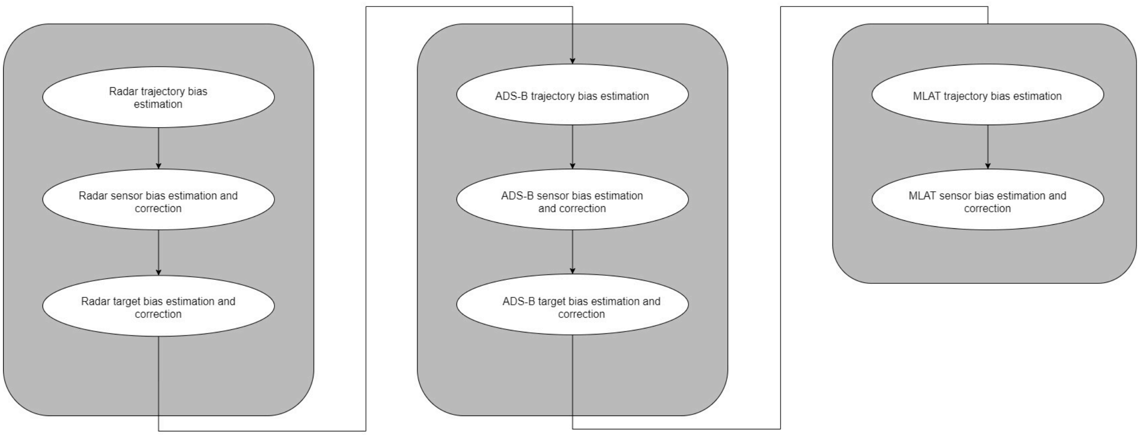

Figure 3.1: Bias error treatment process

Following this order, first the radar measurements are processed in order to estimate their error and correct them. The reason for starting by radars instead of newer, more performing systems like ADS-B, is that there are often more than one radar providing information on all the aircraft in the operational volume, which is a requirement for bias estimation. Once radar data are corrected, measurements provided by ADS-B sensors will be processed and corrected .

In order to do these corrections error models will be used for both radar and ADS-B sensors. For this purpose, each has a customised model for that type of sensor. The aim of these models is to be able to estimate the error in the measurements characterised by:

- The bias error, which is a systematic error that the radar has and which, being constant, once calculated can be used for that sensor in a fixed way.

- The noise error, which is an error introduced in the measurements due to factors external to the sensor, such as the distance from the target to the sensor or the specifications of the transponder of the transponder emitting the data.

As described in the section 2.5.1.1 where the operation of the OTR is explained, this process takes place once the *gross association* has been performed and there are still measurements that have not been associated to their trajectory, so it is necessary to estimate the two types of error and correct them in order to determine, once the measurements have been improved, which trajectory they belong to, which is done in the *fine association*.

PBCS systems use an algorithm based on Kalman filters, characterised by the error model of the sensor being analysed, to obtain an estimate of the measurements, which is compared with the measurement taken and updated.

In order to test the new error model, and to perform algorithmic debugging and software optimisation tasks more easily, a reverse engineering analysis of the algorithms that perform the association steps in SASS-C has been carried out. Therefore, both the Kalman filter and the error models have been reprogrammed and redesigned for the Matlab software, which uses higher level programming.

It is also worth mentioning that this algorithm can only be used for testing, as it could not be integrated into the code as it is a higher level language, it would have to be converted to C++ and integrated into SASS-C.

3.2 Sources of error in ADS-B

The total latency of the position information is the time delay between the time the measurement is taken and the time the position is transmitted. It can be compensated for by advancing the position in the direction of flight. Some of the latency is not compensated for, resulting in uncompensated latency.

When the ADS-B transmission subsystem synchronises with the source of the position measurement, the uncompensated latency is virtually eliminated. If it cannot be synchronised, uncompensated latency is introduced due to unknown delays in the data stream.

For the following explanations the following notation is defined in Figure 3.2:

- T_X: Time the data crosses interface X.
- TOA_X: True time of applicability of the data that crosses interface X. Is the ideal time of applicability of the data at interface X.
- TTOA: Transmit Time of Applicability. The value of TTOA is the time that is expected to be decoded by the ADS-B Receiving subsystem as being the time to which the position contained in the ADS-B Airborne or Surface Position Message is accurate.
- $\triangle T_{X \rightarrow Y}$: Is the total amount of time compensated by equipment between x and y.

As an example, for GNSS industry, although TOA$_{B1}$ is the ideal time of application, the standard is for T$_{B1}$-TOA$_{B1}$ to be < 200ms.

As mentioned above, the value of the T bit affects the TTOA, so that if it is set to 0, TTOA=T$_{D}$, if it is set to 1 TTOA is the appropriate 200 ms.

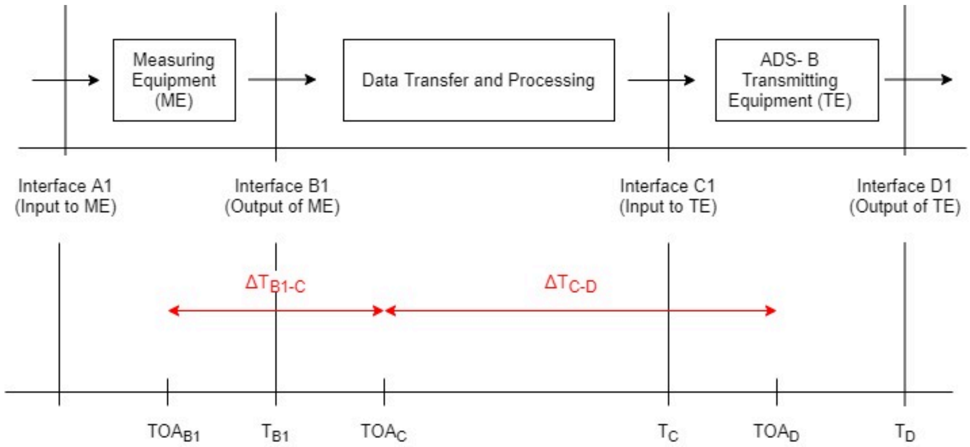

Figure 3.2: General Time Diagram

3.2.1 Total latency

The total latency is the amount of time taken to broadcast a position relative to the time of applicability of the position measurement.

$$TL = T_D - TOA_{B1} = (T_D - T_C) + (T_C - T_{B1}) + (T_{B1} - TOA_{B1}) \tag{3.1}$$

Total latency is recommended to be less than 1.5 seconds. It can be broken down into 3 parts:

- T$_{B1}$-TOA$_{B1}$: Industry standards ensure that it is less than 200 ms.
- T$_{C}$-T$_{B1}$: It is recommended to reduce this delay to <200 ms. This is the time taken from the measurement source to the data interface. If this is done by wiring, the delay is reduced.
- T$_{D}$-T$_{C}$:The time elapsed between updating the position and preparing the information for transmission. It is limited to 100ms.

The 1.5 seconds set as maximum latency is the case where one measurement is not updated in time before the next measurement arrives, and one of the position measurements has to be used twice. Then the time between the first measurement used twice and the third measurement cannot be longer than this value.

3.2.2 Uncompensated latency

Uncompensated Latency (UL) is the amount of total latency that can not be compensated for by the receiver. Is the difference between the time of applicability for the receiver and the true time of applicability of the transmitted data:

$$UL = TTOA - TOA_D = TTOA - (TOA_{B1} + \triangle T_{B1 \to D}) \tag{3.2}$$

For truth data, as the case of TOA$_D$, UL is just the error in TTOA.

- In case of non-GNSS coupled transmissions, TTOA=T$_D$. So,

$$UL = T_D - (TOA_{B1} + \triangle T_{B1 \to D}) = TL - \triangle T_{B1 \to D} \tag{3.3}$$

- For GNSS coupled transmissions, uncompensated latency is considered negligible.

In addition to non-GNSS coupled transmission, they are required to comply:

$$|(T_D - T_C) - \triangle T_{C \to D}| < 100ms \tag{3.4}$$

Complying with this ensures that most of the delay on ADS-B transmitting subsystems is compensated but there are two components of uncompensated latency.

- The delay between the TOA of the measurement by the equipment and the time that the data is delivered across interface B1 (T$_{B1}$-TOA$_{B1}$). For GNSS equipment is limited to 200ms and is recommended to ensure the same if the measurement equipment is going to be used for ADS-B.
- The delay between the time that the data is delivered across interface B1 and the time is provided to ADS-B Transmission Subsystem (interface C). [(T$_C$-T$_{B1}$)-$\triangle T_{B1 \to C}$]. There is no standard limiting T$_C$-T$_{B1}$. and $\triangle T_{B1 \to C}$ is zero in every fielded installation (TOA$_{B1}$=TOA$_C$).

  Is expected that the measurements source is wired to ADS-B transmitted subsystem. Delays used by data routing or queuing are undesirable.

The MOPS requierements lead to an uncompensated latency budget of -200 < UL < 400 ms for T=0.

In some ADS-B transmitting systems, the delay T$_C$-TOA$_{B1}$ is partly or full estimated and compensated. For example, for certain GPS/GNSS systems, T$_C$-TOA$_{B1}$=150ms on average with a margin of 50 ms, which is compensated by updating the position at interface C. For all these techniques the budget is kept from -200 to 400 ms.

In case the bit T=1, but the receiver is not synchronised with UTC, the UL is limited to $\pm$200ms.

3.3 Radar sensor error model

The error in radar position measurements has two main sources, bias error and noise error, which are corrected separately.

3.3.1 Bias error model

A systematic error is always introduced in the position measurements taken by sensors, which is modelled in order to know the deviations of the measurements with respect to the real position, and to be able to correct them. To achieve this, it is necessary to know the sources of bias error of the different sensors.

In the case of radars, 6 sources of bias error have to be addressed, which are: range bias, range gain bias, azimuth bias, bias in the two eccentricity terms and time offset bias. To take into account the effect of the different bias terms on the position error, the following projection matrix is used:

$$\mathrm{H}_b = \begin{bmatrix} \frac{R_{incl}}{R_{proj}} * \sin(\theta) & \frac{\frac{R_{incl}^2}{R_{proj}} * \sin(\theta)}{s_{fac}} & \frac{R_{proj} * \cos(\theta)}{s_{fac}} & \frac{R_{proj} * \cos(\theta) * \sin(\theta)}{s_{fac}} & \frac{R_{proj} * \cos(\theta)^2}{s_{fac}} & \frac{\overline{vel_x}}{v_{fac}} \\ \frac{R_{incl}}{R_{proj}} * \cos(\theta) & \frac{\frac{R_{incl}^2}{R_{proj}} * \cos(\theta)}{s_{fac}} & \frac{-R_{proj} * \sin(\theta)}{s_{fac}} & \frac{-R_{proj} * \sin(\theta)^2}{s_{fac}} & \frac{-R_{proj} * \cos(\theta) * \sin(\theta)}{s_{fac}} & \frac{\overline{vel_y}}{v_{fac}} \end{bmatrix} \quad (3.5)$$

Each column corresponds to one of the bias error sources, while the first row relates the bias terms to the error in the x-coordinate and the second one provides the error in the y-coordinate. All terms depend on the trajectory to be analysed and are then variable.

The parameters used in Equation 3.5 are:

- R_{incl} corresponds to the slant range before being projected, in inclined coordinates
- R_{proj} corresponds to the range already projected, in stereographic coordinates.
- $\overline{vel_x}$ corresponds to the average speed of the trajectory measured by the radar in the x-axis direction
- $\overline{vel_y}$ corresponds to the average speed of the trajectory measured by the radar in the y-axis direction
- s_{fac} corresponds to the generic scaling value, which has a value of 1000
- v_{fac} corresponds to the scaling value of the speed, which has a value of 1000

3.3.2 Noise error model

Noise error is unavoidable in aircraft position measurements by sensors, therefore a correction method to compensate for its effect consisting of a variable model that depends on the measurements taken by the respective radar must be applied.

This model uses a least squares technique that, using all the data, looks for a continuous function that approximates the data, and then compares it with the data to obtain the difference, which will be the noise. This is why it is only performed once for each radar sensor. The process is shown below:

for u=2 to (length(Radar)-1) do

$$PreviousRange = \sqrt{Rho(u-1)^2 - altura\_vuelo^2} \tag{3.6}$$

$$CurrentRange = \sqrt{Rho(u)^2 - altura\_vuelo^2} \tag{3.7}$$

$$SubsequentRange = \sqrt{Rho(u+1)^2 - altura\_vuelo^2} \tag{3.8}$$

where Equations 3.6-3.8 stand for the ranges, already projected on the local plane, of the current, previous and subsequent measurements.

$$Previous\_\theta = Theta(u-1) * \frac{\pi}{180} \tag{3.9}$$

$$Current\_\theta = Theta(u-1) * \frac{\pi}{180} \tag{3.10}$$

$$Subsequent\_\theta = Theta(u-1) * \frac{\pi}{180} \tag{3.11}$$

Where Equations 3.9-3.11 stand for the values of the angle of the measurement, already projected in the local plane and transformed to radians, of the current, previous and subsequent measurements. Using the previous equations, an average of the current range position and azimuth is calculated:

$$R_{LS} = \frac{PreviousRange + SubsequentRange}{2} \tag{3.12}$$

$$\theta_{LS} = \frac{Previous\_\theta + Subsequent\_\theta}{2} \tag{3.13}$$

Then, the square error between the measurment and the average is computed:

$$R_{diff} = (R_{LS} - CurrentRange)^2 \tag{3.14}$$

$$\theta_{diff} = (\theta_{LS} - Current\_\theta)^2 \tag{3.15}$$

Lastly, the errors are stored in vectors.

$$R_{error} = [R_{error}, R_{diff}] \tag{3.16}$$

$$\theta_{error} = [\theta_{error}, \theta_{diff}] \tag{3.17}$$

end for

Once the error of all the measurements has been obtained, the algorithm calculates the mean of the vector in which they have been stored.

$$RangeError^2 = \overline{R_{error}} \tag{3.18}$$

$$\theta Error^2 = \overline{\theta_{error}} \tag{3.19}$$

The flight height error does not depend on the sensor, so a fixed value is used:

$$HeightError^2 = (25 * 0.3048)^2 \tag{3.20}$$

Similarly, the initial values of the variances of the range (introduced by the transponder) and azimuth are set to a constant value:

$$Range\_var = 1875 \tag{3.21}$$

$$Azim\_var = 0.000000001 * \frac{\pi}{180} \tag{3.22}$$

Once all the values are calculated, matrix P$_{slant}$, which will be used for the whole trajectory, can be built:

$$P_{slant} = \begin{bmatrix} RangeError^2 + Range\_var & 0 & 0 \\ 0 & \theta Error^2 + Azim\_var & 0 \\ 0 & 0 & HeightError^2 \end{bmatrix} \tag{3.23}$$

This matrix is obtained in inclined coordinates, so it has to be projected in order to convert it into stereographic coordinates. To do this, the transformation matrix *transf* is used:

$$\mathit{transf} = \begin{bmatrix} \frac{R_{incl} * \sin(\theta)}{R_{proj}} & R_{proj} * \cos(\theta) & -\frac{altura\_vuelo * \sin(\theta)}{R_{proj}} \\ \frac{R_{incl} * \cos(\theta)}{R_{proj}} & -R_{proj} * \sin(\theta) & -\frac{altura\_vuelo * \cos(\theta)}{R_{proj}} \end{bmatrix} \tag{3.24}$$

Applying matrix *transf* on P$_{slant}$, matrix P_{transf}, that will be used in the estimation and correction of the error, is obtained:

$$P_{transf} = \mathit{transf} * P_{slant} * \mathit{transf}^T \tag{3.25}$$

3.3.3 Error estimation and correction

The next step, after noise estimation and correction, constists of applying a Kalman filter to a state vector ζ containing the position, velocity and bias terms of each radar in the operational service volume. The algorithm that decodes the Kalman filter for the case of its application on radar sensors.

In order to be able to analyse trajectories, prior to the execution of the algorithm, a selection of straight sections of the trajectories has been made, i.e., the sections of the trajectories in which the aircraft are en route at a constant flight altitude have been delimited.

The algorithm focuses on the vector of estimates and the covariance matrix, which vary in size depending on the number of sensors covering the trajectory of the target in question and its type, in this case radar. This vector of estimates (Equation 3.66) is composed of N+1 subvectors of length M containing the estimates, where N is the number of sensors that cover this trajectory, and M is the number of error terms of the type of sensor that performs the measurement. These M terms are initialised to 0 when the first measurement from a sensor is analysed. In the case of radar, irrespective of the type (PSR, SSR or Mode S), M shall have a value of 6 as this is the number of bias error terms.

As mentioned above, the size is N+1 is because the first subvector of ζ is not used for any sensor, but stores the position and velocity estimates. This subvector is not initialised to 0 like those containing error terms, but is initialised with the initial position and velocity provided by the first measurement of the first sensor.

$$\zeta = \begin{bmatrix} \zeta(1) \\ \vdots \\ \zeta(i) \\ \vdots \\ \zeta(N+1) \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{v_x} \\ \tilde{v_y} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} b_{i,1} \\ \vdots \\ b_{i,M} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} b_{N,1} \\ \vdots \\ b_{N,M} \end{bmatrix} \end{bmatrix} \tag{3.26}$$

On the other hand, the covariance matrix also mentioned, which can be seen in Equation 3.27, represents the variability that a measurement has with itself, with respect to other sensors or with respect to the measurement itself, due to factors such as noise, among others. This covariance matrix is composed of a map of sub-matrices. In each submatrix it is indicated by the subindices which position corresponds to it within the global covariance matrix P, and secondly, the covariance of which sensors this submatrix compares. The comparison of sensors is carried out in such a way that, for example, $C_{i,j}$ represents the covariance between sensor i and sensor j. In the case of comparing sensors the sub-indices start from 2, since 1 is reserved for position and velocity measurements as mentioned above.

$$\left|\left[P_{1,1} \rightarrow C_{1,1}\right]_{4x4}\right| \quad \left|\left[P_{1,2} \rightarrow C_{1,2}\right]_{4xM}\right| \quad \left|\left[P_{1,3} \rightarrow C_{1,3}\right]_{4xM}\right|$$

$$\left|\left[P_{2,1} \rightarrow C_{2,2}\right]_{MxM}\right| \quad \left|\left[P_{2,2} \rightarrow C_{2,3}\right]_{MxM}\right| \tag{3.27}$$

$$\left|\left[P_{3,1} \rightarrow C_{3,3}\right]_{MxM}\right|$$

The sub-matrices $P_{N,N}$ of the global matrix P are initialised as indicated in Equations 3.28 and 3.29, while the rest of the sub-matrices are created with the indicated dimensions and initialised to 0.

$$P[1][1] = \begin{bmatrix} \sigma^2_{pos} & 0 & 0 & 0 \\ 0 & \sigma^2_{pos} & 0 & 0 \\ 0 & 0 & \sigma^2_{pos} & 0 \\ 0 & 0 & 0 & \sigma^2_{pos} \end{bmatrix} \tag{3.28}$$

$$P[i][1] = \begin{bmatrix} \sigma^2_{Range\_bias} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{Range\_gain} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{\theta\_bias} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{\theta\_bias} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{\theta\_bias} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_{time\_offset} \end{bmatrix} \tag{3.29}$$

Once the estimation vectors and the covariance matrix of all the sensors that provide information in the analysis have been initialised, the algorithm begins to iterate as many times as there are total measurements provided by all the sensors, performing the programmed bias estimation calculations and updating the result to obtain a reconstruction of the aircraft trajectory. To achieve this, the following steps are carried out:

First, the F-matrix is calculated by applying Equation 3.30, where T stands for the time difference measured in seconds between the ToD of the current measurement and the next one.

$$F = \begin{bmatrix} 1 & 0 & T & 0 \\ 0 & 1 & 0 & T \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.30}$$

Matrix F is used to update only the position and velocity estimators:

$$\zeta[1] = F \cdot \zeta[1] \tag{3.31}$$

Next, the plant noise, Q, is calculated using Equation 3.32 where T is the difference in ToD between measurements and σ_{acel} is the standard deviation of the acceleration of the target.

$$Q = \begin{bmatrix} \frac{T^4}{4}\sigma_{acel}^2 & 0 & \frac{T^3}{3}\sigma_{acel}^2 & 0 \\ 0 & \frac{T^4}{4}\sigma_{acel}^2 & 0 & \frac{T^3}{3}\sigma_{acel}^2 \\ \frac{T^3}{3}\sigma_{acel}^2 & 0 & T^2\sigma_{acel}^2 & 0 \\ 0 & \frac{T^3}{3}\sigma_{acel}^2 & 0 & T^2\sigma_{acel}^2 \end{bmatrix} \tag{3.32}$$

Then, position and velocity covariance matrices, (corresponding to the sub-matrices of the first row of the Equation 3.27) are updated using Equation 3.33.

$$P[1,1] = F \cdot P[1,1] \cdot F^T + Q \tag{3.33}$$

for j=2 to size (P,2) do

$$P[1,j] = F \cdot P[1,j] \tag{3.34}$$

end

After this the matrix H_{pos} is defined as shown in Equation 3.35.

$$H_{pos} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{3.35}$$

Once it is defined, the residual of the Kalman filter is calculated as detailed in Equation 3.36. Regarding the term x_m, it refers to the value of the current measurement being analysed projected onto a local plane with a centre at a common point for all sensors. On the other hand, the matrix H_b refers to the bias projection matrix, which is given by the error model of each sensor. The model is explained in more detail in section 3.3.1

$$r = x_m - H_{pos} \cdot \zeta[1] - H_b \cdot \zeta[n] \tag{3.36}$$

For the sake of simplicity, matrix P_{transf}, which contains the covariance of the measurement, projected in the stereographic plane is renamed as matrix R. The derivation of matrix P_{transf} is explained in section 3.3.2.

$$R = P_{transf} \tag{3.37}$$

After this, the residual covariance matrix is calculated:

$$S = H_{pos} \cdot P[1,1] \cdot H_{pos}^T + H_{pos} \cdot P[1,n] \cdot H_b^T + H_b \cdot P[1,n]^T \cdot H_{pos}^T + H_b \cdot P[n,1] \cdot H_b^T + R \tag{3.38}$$

Next, two lists of matrices, B and their transposes, BT, are calculated. Each of them is composed of N+1 matrices, where N is the number of sensors as before. The index N in the equations indicates the sensor from which the measurement under analysis is derived while the index i indicates the position of the vector in the list of sub-matrices.

for *i*=1 to *N+1* **do**

if $i < n$

$$B[i] = H_{pos}P[1,i] + H_bP[i,n-i+1]^T \tag{3.39}$$

$$BT[i] = B[i]^T \tag{3.40}$$

if $i \geq n$

$$B[i] = H_{pos}P[1,i] + H_bP[n,i-n+1] \tag{3.41}$$

$$BT[i] = B[i]^T \tag{3.42}$$

end for

Matrices BT are used to calculate a list of sub-matrices containing the Kalman filter gains.

for *i*=1 to *N+1* **do**

$$K[i] = BT[i]S^{-1} \tag{3.43}$$

end for

Matrices B are used to update the sub-vectors of the estimator of the sensors for which a measurement has already been processed.

for *i*=1 to *N+1* **do**

$$\zeta[i] = \zeta[i] + K[i] \cdot r \tag{3.44}$$

end for

Finally, the covariance matrices are updated.

for *i*=1 to *N+1* **do**

for *i*=1 to *N+1* **do**

$$P[i,j] = P[i,j] - K[i]B[i+j-1] \tag{3.45}$$

end for

end for

After each iteration, the positions $\zeta[1]_{1,1}$ and $\zeta[1]_{2,1}$ must be stored in order to have the position data with respect to the x- and y-axis respectively for each point of the reconstructed trajectory.

For each position measurement, once estimated and corrected, a bias for that measurement is obtained. As iterations of the Kalman filter are performed, this bias eventually converges to a value, which remains in the vector of estimates after the last iteration of the filter with the last measurement.

But this bias is specific to the trajectory that has been analysed, which is why it gives us the 'Trayectory bias estimation', but what is needed is the 'Sensor bias estimation and correction', so it will be calculated.

For the radar sensor bias estimation, the first step is to select several trajectories that meet the conditions to be able to apply the filter to them. Once they have been identified, they are analysed and the result of the vector of estimations of the last iteration is stored, as well as submatrices P22 and P33, which represent the variability of a measurement offered by a sensor with respect to the same sensor.

Once the vector of estimations, as well as the submatrices P22 and P33 of all the trajectories are obtained, (in this work a total of 25 trajectories were used), the sensor bias error terms are calculated by computing a weighted arithmetic mean of the trajectory bias error terms, using as weighting factor the estimation error obtained from the estimation covariance matrices. This weighted average is optimal in the sense that it has the minimum squared error.

Equation 3.46 details how the weighted arithmetic mean is computed, where 'k' is the error term numbered from 1 to 6, 'j' is the sensor in the order in which it has been initialised and 'i' is the number of the analysed trajectory, in our case a number between 1 and 25.

$$b_k^j = \sum_{i=1}^{25} \left(\frac{b_{k,i}^j}{P^j(k,k)} \right) \cdot \sum P^j(k,k) \tag{3.46}$$

3.4 ADS-B sensor errors

3.4.1 Current error model

The main purpose of ADS-B is, as in all surveillance systems, to obtain information from the aircraft being monitored in order to optimize airspace management. The measurements taken by the GNSS satellites are known to be accurate, but the onboard navigation equipment requires that data from the navigation sensor measurements must be converted to the standard ADS-B data format.

A parameter is created that specifies the accuracy of the position reported by the ADS-B transmission subsystem. The parameter used is called NACp.

The EPU (Estimated position uncertainty), usually called as Horizontal Figure of Merit if it is reported by a GNSS is defined as the radius of a circle centered at the true horizontal position within which the measured horizontal position lies with 95% probability. The NACp parameter

NACp	95% Horizontal Accuracy Bound (EPU)	Standard deviation σ	Comment
0	EPU $\geq 10NM(18.52km)$	6547.8088 m (Default)	Unknown accuracy
1	EPU < 10 NM (18.52 km)	6547.8088 m (Default)	RNP-10 accuracy
2	EPU < 4 NM (7.408 km)	6547.8088 m	RNP-4 accuracy
3	EPU < 2 NM (3.704 km)	3273.9044 m	RNP-2 accuracy
4	EPU < 1 NM (1.852 km)	654.7809 m	RNP-1 accuracy
5	EPU < 0.5 NM (926 m)	327.3904 m	RNP-0.5 accuracy
6	EPU < 0.3 NM (555.6 m)	163.6952 m	RNP-0.3 accuracy
7	EPU < 0.1 NM (185.2 m)	65.4781 m	RNP-0.1 accuracy
8	EPU < 0.05 NM (92.6 m)	32.739 m	e.g., GPS (with SA)
9	EPU < 30 m	3.5355 m	e.g., GPS (SA off)
10	EPU < 10 m	1.0607 m	e.g., WASS
11	EPU < 3 m	1.0607 m	e.g., LASS

Table 3.1: Navigation Accuracy Category for Position (NACp)

uses 4 bits to represent the EPU in its ADS-B broadcast state vector report. Table 3.1 shows the relationship of the EPU size for the different values that the NACp parameter can take.

The NACp parameter is reported in order to let surveillance applications determine if the reported position has an acceptable level of accuracy for the intended use.

But, as mentioned, the NACp is simply a quality parameter to indicate the degree of accuracy of the measurement. But it does not take into account the errors due to uncompensated latency that dominate the error equation.

3.4.2 New error model

The new model aims to estimate the part of the latency that is not compensated and to correct it in order to increase the positioning accuracy so that Kalman Filters used in trajectory reconstruction can yield more accurate results.

On the other hand, unlike the previous one, it does not use any of the parameters received in the ASTERIX frames, such as the NACp, to obtain the sigma to be used in the calculation of the navigation related error covariance matrix. This sigma value is proposed to be a fixed value of 12.3 metres, which is equivalent to the 30m radial accuracy value that must be ensured in ADS-B. This value comes from an analysis of GNSS actual accuracy carried out by internal report developed by Eurocontrol.

Until now, the uncompensated latency (UL) was not corrected, although the maximum tolerable latency is specified, depending on the version of the 'ADS-B Out' installation that collected the measurement. On the other hand, we calculate the uncompensated latency of each target by calculating the bias of its position in the received measurements and the speed at which the aircraft is travelling.

In this case, as the bias obtained is referred to the X and Y axes as well as the velocity obtained with the Kalman filter (Appendix A), it must be projected on the new Along-track (LT) and Across-track (XT) axes to obtain the position error and the velocity in them. In this way, latency in the direction carried by the aircraft (LT) corresponds to the time it takes to travel that position error on the LT axis at the speed at which it flies. The XT latency will not exist because all the position error must be in the direction of flight of the aircraft.

3.4.2.1 Bias error model

All sensors used to measure aircraft positions have an error model to estimate the non-random deviations of the measured positions from the current position due to their systematic error.

It is important to know and apply it when analysing the measurements so that the bias error contained in the measurements, which is provided by a given sensor, can be corrected.

In the case of ADS-B, to calculate the latency it is necessary to know the bias of the position measurements in each of its axes, i.e. the bias in the x-axis and in the y-axis. Each column corresponds to one of the bias terms and each row to a coordinate, in the case of the first row to the x-coordinate and in the second row to the y-coordinate.

Therefore, the projection matrix, which models the bias error, is the one found in Equation 3.47. Each column corresponds to one of the bias terms and each row to a coordinate, in the case of the first row to the x-coordinate and in the second row to the y-coordinate. Thus, the result is an identity matrix.

$$Hb = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{3.47}$$

3.4.2.2 Noise error model

The new model uses a variable noise error model, which is formed by the sum of 3 error matrices, each of them modeling a given error component:

- Quantification error covariance matrix:

  This matrix is the one that models the quantification error of ADS receiving stations in radians for latitude measurements ($\triangle_\phi$) and longitude measurements ($\triangle_\lambda$). The use of two different errors is due to the assumption that the errors of quantification in latitude and longitude are statistically independent.

$$P_q = \frac{1}{12} \begin{bmatrix} \triangle_\phi^2 & 0 \\ 0 & \triangle_\lambda^2 \end{bmatrix} \tag{3.48}$$

$$\triangle_\lambda^2 = \triangle_\phi^2 = 94^{-9} \quad \text{radians} \tag{3.49}$$

- Navigation related error covariance matrix:

  This is the error matrix where the most notable change occurs, since the sigmas in the diagonal are no longer a value provided in a parameter of the target report as in the previous model, whose value was associated with the NACp parameter, but a fixed value of 12.3 metres, for a 30m radial accuracy value that should be practically met at ”all times”.

$$P_{Nav} = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix} \tag{3.50}$$

$$\sigma = 12.3 \quad \text{meters} \tag{3.51}$$

- Along track covariance matrix:

  Finally, we model the along track covariance error by first initialising the matrix with the square of the minimum velocity. Then, we add to the initialised matrix the 2x2 matrix resulting from multiplying the velocity matrix by its transpose. Finally, to transform the matrix P$_{LT}$ from velocity to distance, we multiply it by σ_{LT}^2.

$$P_{LT} = \begin{bmatrix} v_{min}^2 & 0 \\ 0 & v_{min}^2 \end{bmatrix} \tag{3.52}$$

$$P_{LT} = P_{LT} + \begin{bmatrix} V_x \\ V_y \end{bmatrix} * \begin{bmatrix} V_x & V_y \end{bmatrix} \tag{3.53}$$

$$P_{LT} = \sigma_{LT}^2 * P_{LT} \tag{3.54}$$

This σ_{LT}^2, is obtained by rotating the measurement error covariance matrix to align it with the along-track(LT)/across-track(XT) plane of the aircraft trajectory. This is done as follows:

First of all, the error in the measurements between the theoretical position and the current reported position is calculated. To perform this calculation, the position at tn is estimated by performing a linear interpolation between the previous (t(n-1)) and the next (t(n+1)) measured values. Then, the difference between the estimation and the actual measurement at tn is computed, as shown in Figure 3.3.

The calculation of the theoretical position is calculated from the formula 3.55 and the difference with 3.56.

$$\hat{x}(t_n) = \frac{x(t_{n+1}) - x(t_{n-1})}{t_{n+1} - t_{n-1}} \cdot (t_n - t_{n-1}) + x(t_{n-1}), 2 \leq n \leq N-1 \tag{3.55}$$

$$\triangle\, x(t_n) = x(t_n) - \hat{x}(t_n) \tag{3.56}$$

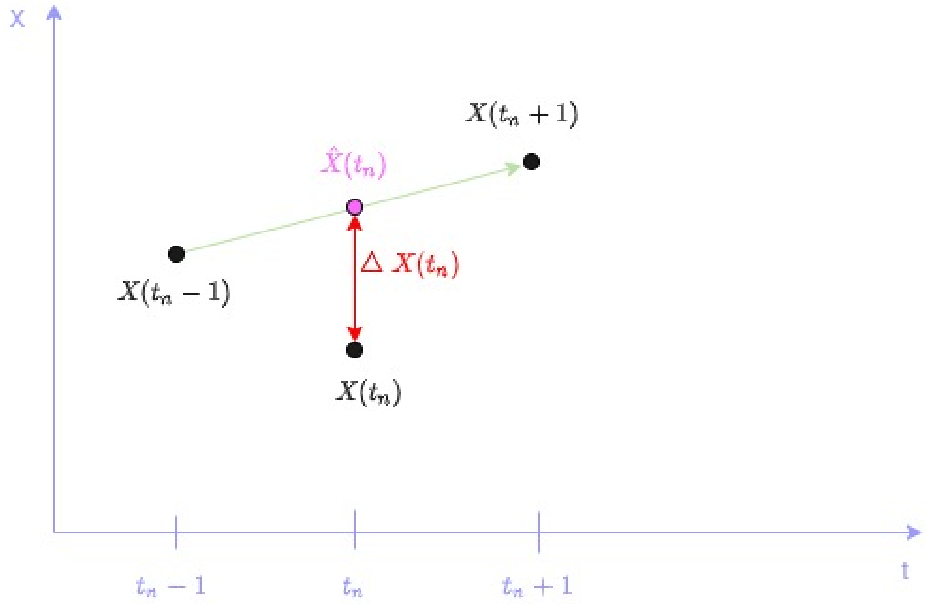

Figure 3.3: Calculation of the difference between theoretical and reported position

A similar procedure is applied to obtain $\hat{y}$ and $\triangle$y(t$_n$).

$$\triangle\ y(t_n) = y(t_n) - \hat{y}(t_n) \tag{3.57}$$

At this point, the error vector in xy coordinates will be:

$$\triangle\ r_n = \begin{bmatrix} \triangle x(t_n) \\ \triangle y(t_n) \end{bmatrix} \tag{3.58}$$

Now, to rotate this matrix, it is multiplied by matrix Rn, where α_n is the track angle calculated for the n-th target report. In this way the error vector is aligned with the x' and y' axes corresponding to XT and LT, respectively as it is graphically summarised in Figure 3.4.

$$\triangle\ r'_n = R_n \cdot \triangle r_n \tag{3.59}$$

$$R_n = \begin{bmatrix} sin(\alpha_n) & cos(\alpha_n) \\ -cos(\alpha_n) & sin(\alpha_n) \end{bmatrix} \tag{3.60}$$

With all this data the sigma in the new reference frame can be computed using Equations 3.61, 3.62 and 3.63, where N is the number of reports for that flight.

$$\sigma^2_{LT} = \frac{1}{N-2} \sum_{n=2}^{N-1} \triangle x'(t_n)^2 \tag{3.61}$$

$$\sigma_{XT}^2 = \frac{1}{N-2}\sum_{n=2}^{N-1} \triangle y'(t_n)^2 \tag{3.62}$$

$$\sigma_{LX} = \sigma_{XL} = \frac{1}{N-2}\sum_{n=2}^{N-1} \triangle x'(t_n) \triangle y'(t_n) \tag{3.63}$$

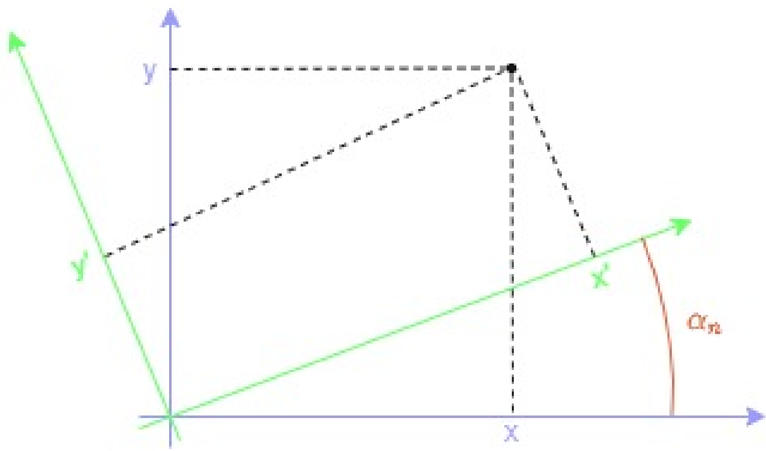

Figure 3.4: Rotation of the axes

Finally, when all sigmas are calculated, the rotated error covariance matrix, R_{LT-XT}, can be built as:

$$R_{LT-XT} = \begin{bmatrix} \sigma_{LT}^2 & \sigma_{LX} \\ \sigma_{XL} & \sigma_{XT}^2 \end{bmatrix} \tag{3.64}$$

To conclude, as mentioned at the beginning, the sum of the matrices of the 3 errors described above is the one used to model the noise error in the Kalman filter.

$$R = P_q + P_{Nav} + P_{LT} \tag{3.65}$$

3.4.2.3 Noise and bias error estimation and correction

This section describes the algorithm that implements the Kalman filter for ADS-B sensors. As in the previous case, the error models and the number of associated bias terms are characterised by the sensor being analysed, so the changes that occur with respect to the algorithm described in section 3.3.3 will be explained below.

As it was made for radar analysis, prior to the execution of the algorithm, a selection of straight sections of the trajectories has been made, i.e., the sections of the trajectories in which the aircraft are en route at a constant flight altitude have been delimited.

ADS-B measurements are not analysed alone, but they are processed along with the radar measurements corrected with the sensor bias that has been calculated using the weighted arithmetic mean described in Equation 3.46.

Once these measurements have been corrected, they are put together with the ADS-B measurements ordered by the ToD. With this step done, the filter is initialised as explained below.

$$\zeta = \begin{bmatrix} \zeta(1) \\ \vdots \\ \zeta(i) \\ \vdots \\ \zeta(N+1) \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{v_x} \\ \tilde{v_y} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} b_{i,1} \\ \vdots \\ b_{i,M} \end{bmatrix} \\ \vdots \\ \begin{bmatrix} b_{N,1} \\ \vdots \\ b_{N,L} \end{bmatrix} \end{bmatrix} \tag{3.66}$$

The only difference with the radar case is that the ADS-B sensor subvector (located in the last subvector L) has just 2 elements, instead of 6, as the error model for radar had. On the other hand, vector ζ contains N+1 subvector, being N the number of sensors and the first subvector initialised with the position and velocity measurements of the first measurement.

In the same way, matrix P containing the map of sub-matrices indicating the covariances is formed. The sub-matrices with the covariances of ADS-B will be added to those already built for radars, so they will be placed on the last diagonal. As with the vector of estimates, the value of L will be 2 for the case of an ADS-B sensor and the value of M will be 6 for the case of a radar sensor, although the size of the matrix P will vary for our case with 2 radar sensors and one ADS-B sensor, so that it will be as shown in Equation 3.67.

$$\begin{matrix} \left|\left[P_{1,1} \rightarrow C_{1,1}\right]_{4x4}\right| & \left|\left[P_{1,2} \rightarrow C_{1,2}\right]_{4xM}\right| & \left|\left[P_{1,3} \rightarrow C_{1,3}\right]_{4xM}\right| & \left|\left[P_{1,4} \rightarrow C_{1,4}\right]_{4xL}\right| \\ \left|\left[P_{2,1} \rightarrow C_{2,2}\right]_{MxM}\right| & \left|\left[P_{2,2} \rightarrow C_{2,3}\right]_{MxM}\right| & \left|\left[P_{2,3} \rightarrow C_{2,4}\right]_{MxL}\right| & \\ \left|\left[P_{3,1} \rightarrow C_{3,3}\right]_{MxM}\right| & \left|\left[P_{3,2} \rightarrow C_{3,4}\right]_{MxL}\right| & & \\ \left|\left[P_{4,1} \rightarrow C_{4,4}\right]_{LxL}\right| & & & \end{matrix} \tag{3.67}$$

The new matrix $P_{4,1}$, is initialised as shown in Equation 3.68.

$$P[4][1] = \begin{bmatrix} \sigma_{initpos} & 0 \\ 0 & \sigma_{initpos} \end{bmatrix} \tag{3.68}$$

As in the previous case, once the estimation vectors and the covariance matrices of all the sensors have been initialised, the algorithm starts iterating as many times as it has measurements from all the sensors estimating and correcting the bias in them and updating the results to reconstruct the aircraft trajectory. To achieve this, it follows the same steps as mentioned in section 3.3.3 with a small change. The change is due to the fact that radar measurements are corrected for bias, whereas ADS-B measurements are not.

Therefore, in the case of measurements coming from a radar sensor the residual of the Kalman filter is computed using Equation 3.69 instead of Equation 3.36, the residual covariance matrix is computed using Equation 3.70 instead of 3.38 and the list of matrices B and BT are computed using Equations 3.71 and 3.72 respectively (irrespective of the values of the indices n and i) instead of Equations 3.39, 3.40, 3.41 and 3.42.

For the case of biased measurements, those of ADS-B, the algorithm described in section 3.3.3 is used without any change.

$$r = x_m - H_{pos}\zeta[1] \tag{3.69}$$

$$S = H_{pos}P[1,1]H_{pos}^T + R \tag{3.70}$$

$$B[i] = H_{pos}P[1,i] \tag{3.71}$$

$$BT[i] = P[1,i]^T H_{pos}^T \tag{3.72}$$

As it is obvious, in the case of measurements coming from ADS-B, the Kalman will be run with the ADS-B error model, using the R that models the noise error described in section 3.4.2.2 in Equation 3.38 and the H_b described in section 3.4.2.1 in Equations 3.36, 3.38, 3.39, 3.40, 3.41 and 3.42.

It can be seen that these equations, where the H_b of the ADS-B model is applied, are the ones that change for the case of 'corrected measurements', in which the bias modelling term disappears as it is corrected. However, the R that models the noise is maintained for the corrected measurements, which will use the one that models the radar noise error described in section 3.3.2.

Once the analysis of all the measurements has been carried out, using for each measurement the corresponding formulas according to the sensor type, the final vector of estimates contains the bias of the position in the X and Y axes.

As the latency of interest is in the direction of the aircraft, the bias in X and Y and the calculated velocities in X and Y are rotated, according to the diagram in Figure 3.4 in order to obtain the bias and the along-track and across-track velocity. Thus, applying Equation 3.73, the uncompensated latency in the direction of the aircraft is obtained.

$$UL_{LT} = \frac{Bias_{LT}}{Velocity_{LT}} \tag{3.73}$$

It must be pointed out that, as the correction of the radar measurements is better in some sections than in others, it would be interesting to divide the trajectory used into sections and calculate the latency of the trajectory using the weighted arithmetic mean, which will give more weight to the calculations made with more precise corrections. Therefore, the trajectories used for testing were split in sections and the bias was computed individually for each of them by applying the Kalman filter. Once the bias of all sections are computed and projected on the LT direction, Equation 3.46 is applied to obtain the new bias, which is more accurate than the previous one.

Chapter 4

Simulation, results and discussion

The new proposed error model has been tested using a test bench which shows graphical results. First of all, this section describes the test bench developed for validation purposes, emphasising its modularity and showing which parts can be modified to perform tests with the aim of optimising the software.

The results shown in this chapter, are based on target reports provided by two SSR surveillance sensors approximately 215 km apart, as well as by an ADS-B sensor from which each radar is approximately 190 km and 100 km apart. It is worth mentioning that the selection of the trajectories used for the analyses presented in the next paragraphs was done graphically, ensuring that all the sections contained data from the three sensors.

With regard to the results, it should also be noted that the location of the trajectories is not shown on the map. Regarding the latitudes and longitudes that can be seen on the axes of the graphs, they are measured by placing the position of 0ºN and 0ºE in the first measurement. This is done with the aim of not sharing data on the air routes and trajectories used in order to respect the privacy and integrity of the data used in the analysis.

4.1 Test bench modules

The test bench developed for the work is modular, so that when all its modules are executed, a software is formed that simulates the operation of the estimator and the bias and noise corrector modules used in the SASS-C tool. The modules that make up this test bench are shown in Figure 4.1.

The development has been done in a modular way, so that there are modules, such as target selection and straight sections, or limiting the trajectory to where measurements from both radars coincide, which can be used with little modification for the analysis of trajectories from other sensors.

The modules, being independent, allow for much simpler debugging of faults, as modules outputs can be checked in order to find the module where the fault occurs, without having to search through the entire code. This also facilitates the design, since a module is not introduced into the test bench until it is validated with its outputs. The outputs of the last module are also used to check if the results obtained with the new error model improve the ones provided by the original

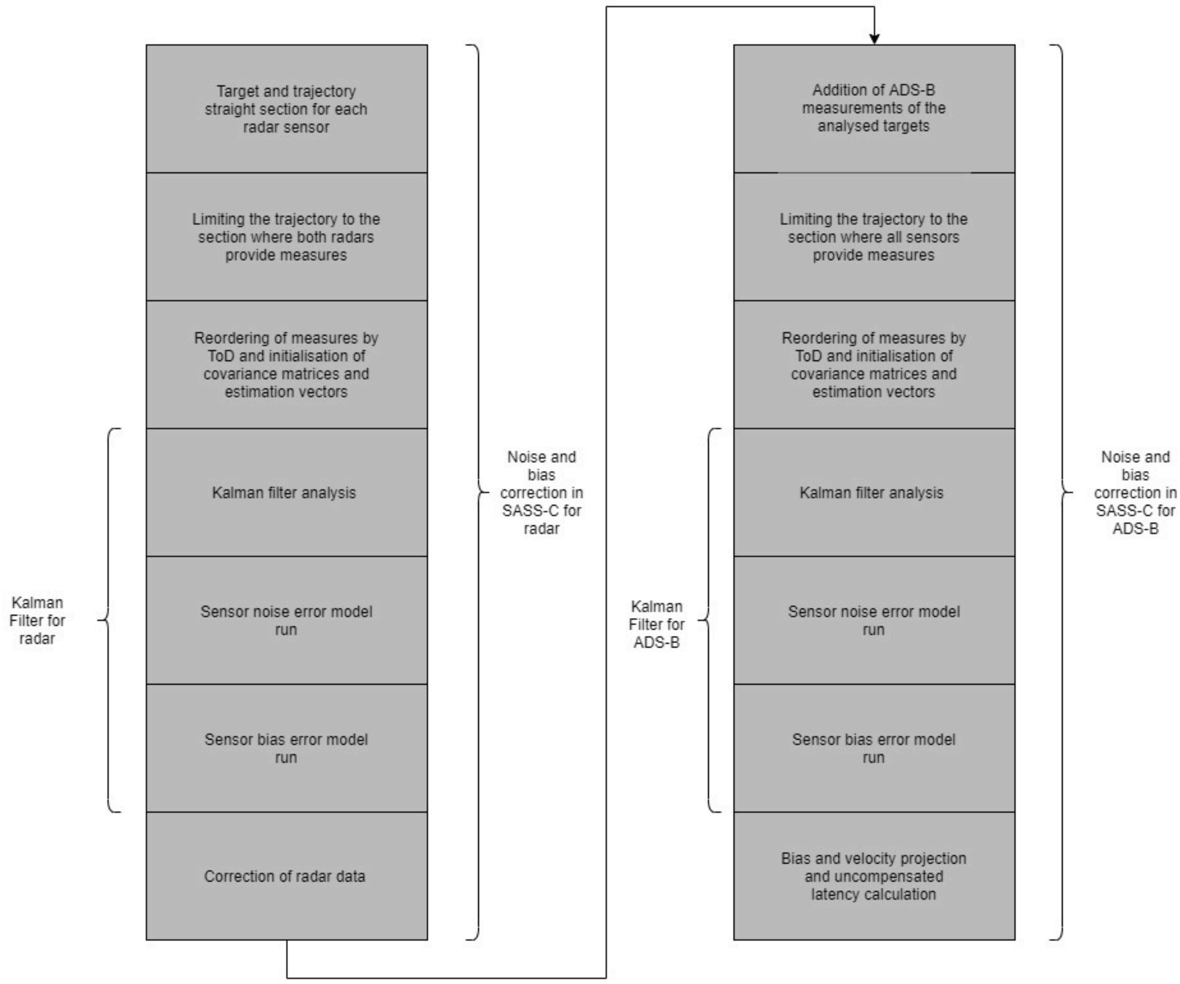

Figure 4.1: Test bench modules

error model.

4.2 Graphical analysis of the results

As the uncompensated latency is not a parameter that is currently taken into account or calculated with the current error model, there are no reference values to compare with in order to check the quality and completeness of the numerical results obtained in the latency calculation. This is why the only way to check the improvement or not of the results obtained with the new model is by means of graphics. For this purpose, the test bench described in the previous section will be run for noise and bias correction of several pre-selected trajectories.

The results shown below will consist of a screenshot of the trajectory analysed, and others enlarged to show the results in detail and to comment on them. It is worth mentioning that the reference to the trajectories will be Trajectory 1, Trajectory 2, ... In order to, as explained before, respect the confidentiality of the data.

For each target 3 trajectories will be shown, the one measured by ADS-B from the ASTERIX messages sent by the transponder, the reference trajectory resulting from correcting the data with the current model (described in section 3.4.1), and the reference trajectory resulting from correcting the data with the new model (described in 3.4.2.1 and 3.4.2.2).

When mentioning reference trajectories, is refered to the step after the noise and bias correction, in which the *fine association* of the monotracks that were not associated with any trajectory in the *gross association* is performed with the multitracks that were already associated. Once they have been associated, the merging of the aforementioned contiguous multitracks is sought, including other data obtained such as barometric height. Once joined, they are filtered again with a four-state Kalman filter to obtain a trajectory, which is the reference trajectory.

The main problem observed is that in the turns, the trajectories that are created, having latency, have a *lag* so they continue straight and start the turn further forward than where the aircraft has actually turned. This problem is due to the last Kalman filter analysis, which introduce this *lag*. The aim is to reduce this *lag* with the correction derived from applying the new error model.

4.2.1 Trajectory 1 analysis

The first trajectory that is going to be analysed is a trajectory covering about 270 kilometres between the most distant points. It contains two sharp bends in the middle of the trajectory. This trajectory can be seen in Figure 4.2.

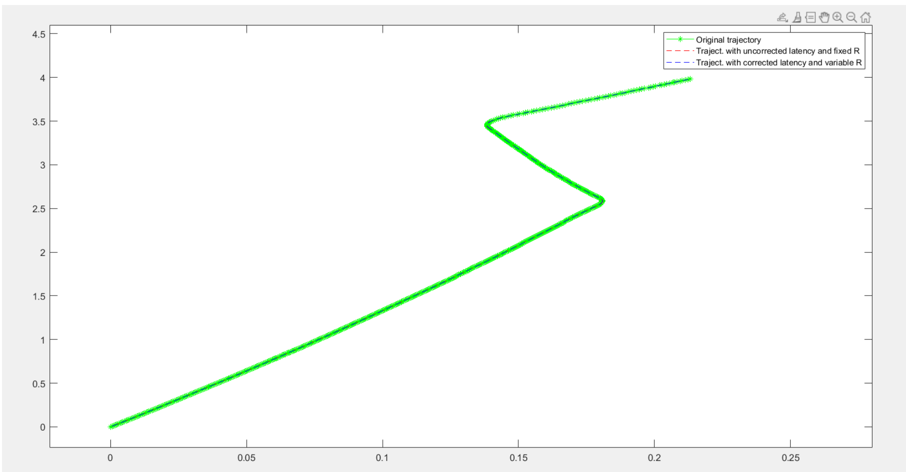

Figure 4.2: Complete trajectory 1

It is worth mentioning that during the section in which the trajectory is straight, the measurements of the reference trajectory are the same as the original received measurements, which shows that the reference trajectories are very precise and fulfil their function properly.

In this trajectory it can be seen graphically very accurately, how the Kalman puts that mentioned *lag* when the measurements reach a curve. The first curve (Figure 4.3), on the left, shows how at the moment the curve starts, both reference trajectories tend to continue in the direction they were going, but the one built from the new model(color blue) detects the turn much earlier and performs it also keeping very close to the original measurements, while the one built after using the current model(color red), accuses more the *lag* in the curve.

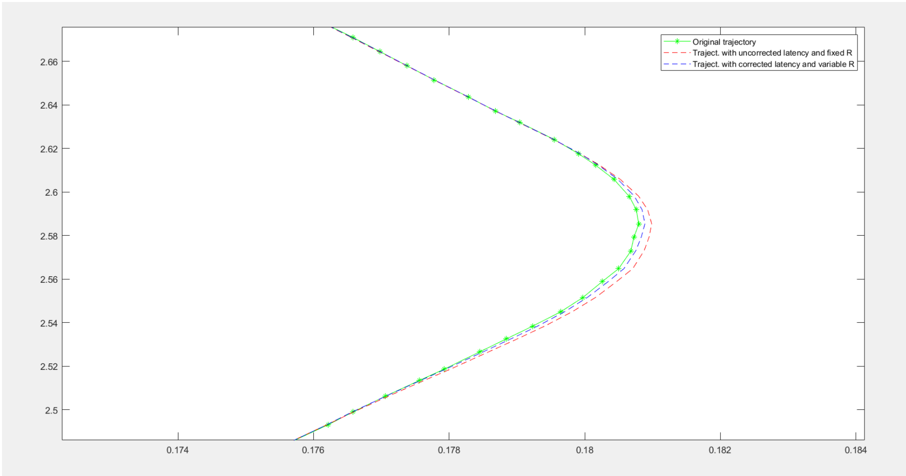

Figure 4.3: Test bench modules

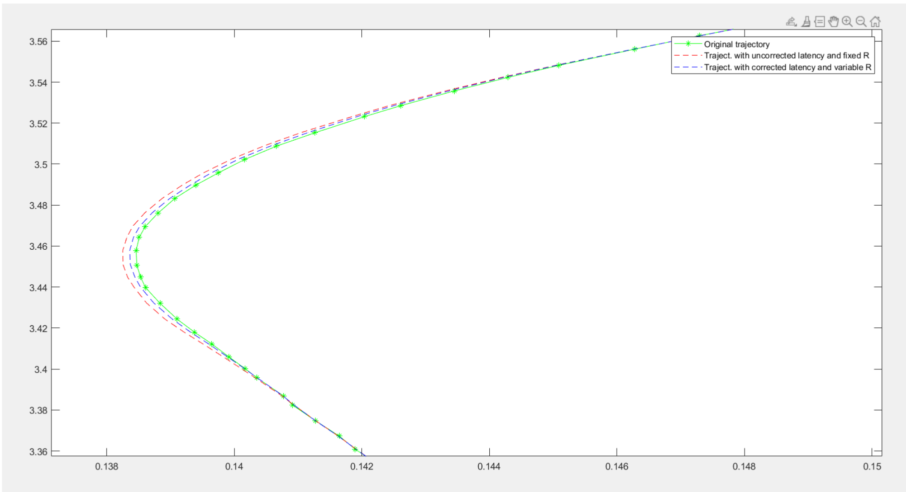

Figure 4.4: Test bench modules

It can be seen that this is no coincidence when looking at Figure 4.4, which shows the second curve, this time right-handed, with identical results showing a lag correction in the trajectory built after applying the new model with respect to the other one.

4.2.2 Trajectory 2 analysis

The second trajectory which is going to be analysed is a trajectory covering about 280 kilometres between the most distant points. It contains a curve at one end. This trajectory can be seen in Figure 4.5.

As can be seen in Figure 4.6, as with the previous trajectory, both the reference trajectory created with the old error model and the one created with the new error model, in the straight section, are practically identical to the original measurements received from the ADS-B sensor.

When they cross the curve, it can be seen in Figure 4.7 in more detail how the *lag* affects the

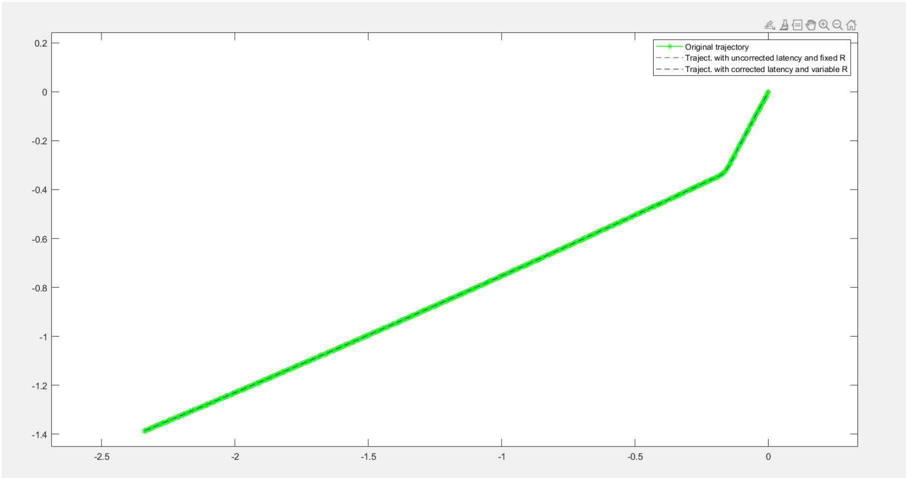

Figure 4.5: Complete trajectory 2

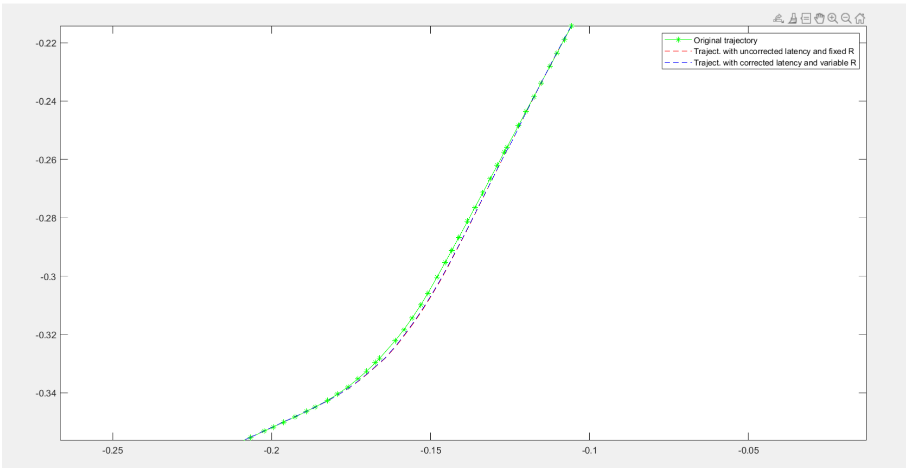

Figure 4.6: Trajectory 2 curve far view

trajectory built after using the old error model (red colour), causing a separation from the original trajectory, which also suffers, although to a lesser extent, the trajectory that has been corrected with the new model.

Once the curve is finished, the measurements are closer to the original ones until they are on top of them again in the straight section.

4.2.3 Trajectory 3 analysis

The last trajectory considered is a trajectory that covers about 265 kilometres between the most distant points. It contains a curve in the middle of the trajectory. This trajectory can be seen in Figure 4.8.

As was the case in the analysis of trajectory 2, the curve in this trajectory is a very slight change in the aircraft's heading, so the difference in *lag* between the reconstructed trajectories is also less noticeable in this case. Even in this case, it can be clearly seen how the measurements in the straight

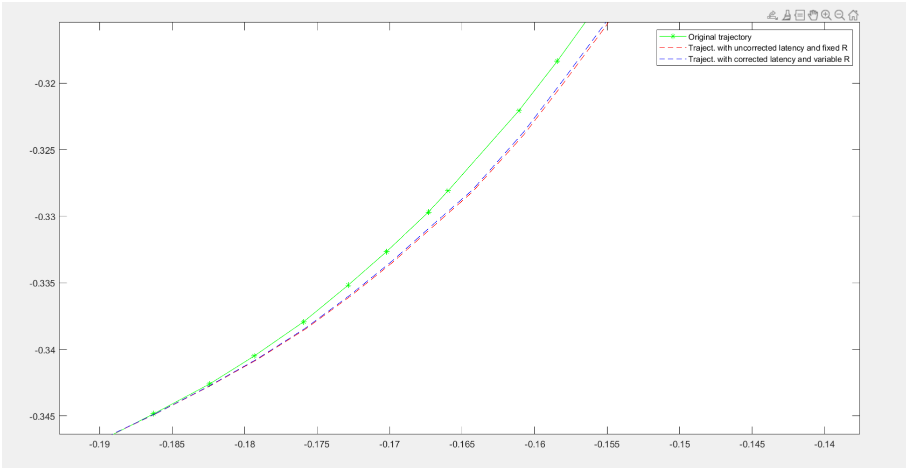

Figure 4.7: Trajectory 2 curve close-up view

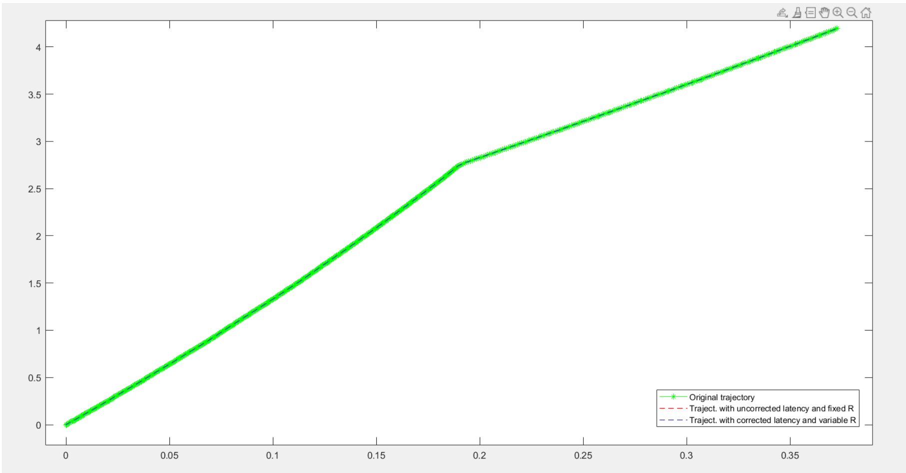

Figure 4.8: Complete trajectory 3

section equal the original ADS-B measurements, with the reconstructions running on top of it.

Similarly, once the curve is entered, it can be clearly seen in Figure 4.10 how the Kalman filter effect makes the trajectory tend to continue straight, although the one with the latency corrected is able to notice earlier that it is a turn and starts to make the curve sooner until it ends and the 3 measurements overlap again for the straight section.

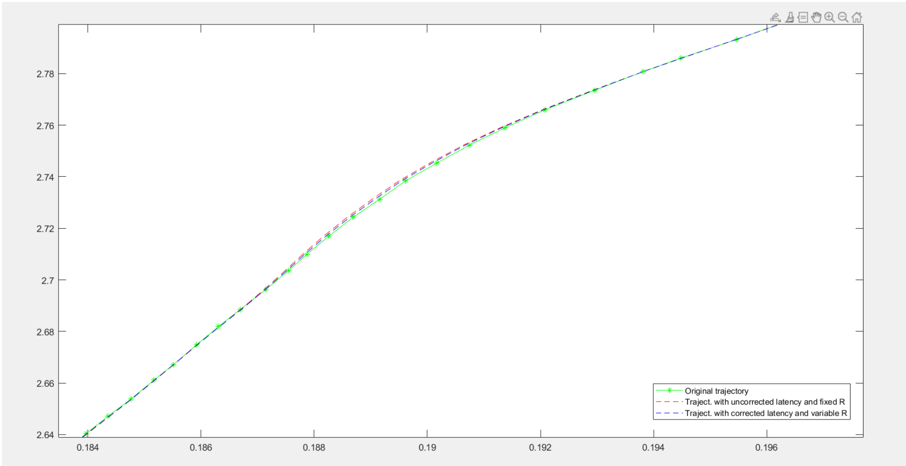

Figure 4.9: Trajectory 3 curve far view

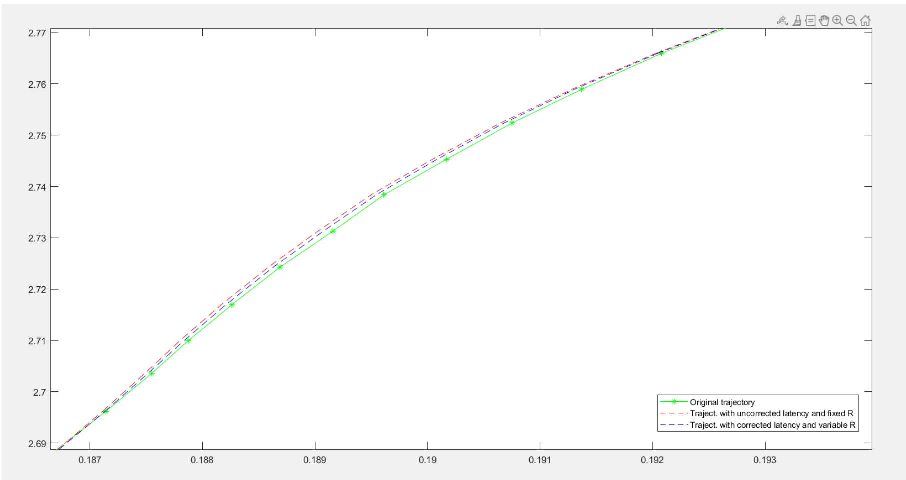

Figure 4.10: Trajectory 3 curve far view

Chapter 5

Conclusion and future lines of research

5.1 Conclusions

With the constant growth of air traffic, which was only weighed down last year by COVID-19, the importance of improving surveillance systems is growing along with it. Therefore, one of the critical points, the accuracy of positioning data, has to be optimised. To ensure the good quality of these data, their accuracy is assessed by means of PBCS systems such as Eurocontrol's SASS-C.

As SASS-C is a system currently in use, it is difficult to carry out tests, for this reason an external test bench have been carried out where the new error model have been tested in order to check its improvement with respect to the previous model before implementing it.

The model has been tested to graphically verify the results and it has been observed that while it is true that in the case of straight sections, both are very accurate, in the case of curved sections the latency correction makes a notable difference in the reference trajectory constructed. Although it is important to mention that the smoother the curve, although still improving, the difference between the use of both models is reduced.

Thus, and after visualising and analysing the results shown in the figures in the section below, it can be concluded that the new model used in the bench test improves significantly on the one currently used and offers better reference trajectories after reconstruction. After confirmation, the model is available for implementation in SASS-C for the improvement of the OTR module.

5.2 Futures lines of research

This project has created a basis for the improvement of latency in data transmission that can lead to different lines of research to continue improving systems and developing new technologies that help to improve air safety. Some lines of research that could be viable are:

- A future research line is to apply this new error model to surface surveillance in airports, where the effect of the uncompensated latency is much critical due to the trajectories of aircraft and service vehicles therein.
- Another future line of research is to develop a similar analysis for the surveillance systems

that are going to be used for drones. Although they will not use ADS-B due to regulatory constrains, the system which will be used is quite similar to it and will present the same issue due to uncompensated latencies.

Part I

Appendixes

Appendix A

Obtaining velocity and track angle data

The data sets from which we extracted the data to work came from Eurocontrol, who shared them with us to carry out the project, but we soon saw that using this data we were missing information we needed to analyze the measurements and accurately calculate the Uncompensated Latency, from now on UL. That is why we requested a new data set containing this information, but since the I160 is an Item that is not mandatory to be sent by the aircraft in the ASTERIX message, the new data set did not contain it either.

In this situation we thought that the best solution was to use the first data set, which contained trajectories that we were more interested in for our analysis, since they were straight trajectories at a constant altitude and in the process of en route flight, that is to say that a priori there should be no changes in speed, direction, etc.

Regarding the velocity problem, we decided that to solve it we should, from the data provided by ASTERIX, make an estimation of the velocity by using filters.

Firstly, we try with a alpha-beta discounted least square filter. To apply it, we follow the following steps:

1. To begin with, we look for different trajectories that meet the requirements we mentioned before, constant altitude and no change of course (straight trajectory), since this indicates that the aircraft is en route. Once we know the aircraft has a track record that meets the requirements, we extract the coordinates position and the ToD vector for each position report.

2. We continue with the conversion of geodetic coordinates to cartesian coordinates referring to the ADS-B In antenna that take the measurements.

3. We choose different parameter K values. Parameter K indicates the accuracy level we are looking for in our data. Once we have this parameter, we solve the equation in A.1 and choose the result with only real part and that it complies $0 < \theta < 1$.

$$-(1+K)\theta^4 - 2\cdot(1+K)\theta^3 + 2\theta^2 + (6+2K)\theta + K - 5 = 0 \tag{A.1}$$

   When we obtain this value of θ, clearing from the equations A.2 and A.3, we obtain the values of alpha and beta for that K parameter.

$$\alpha = 1 - \theta^2 \tag{A.2}$$

$$\beta = (1-\theta)^2 \tag{A.3}$$

4. Finally, we apply the filter, we give the coordinate data of one of the two axes, the Time of Day (ToD) vector, and the alpha, beta and K values. Once the filter achieve the accuracy level indicated by parameter *K*, the measures will converge and continue working with the calculated alpha and beta values for the rest of reports. When all the measures are filtered we obtain 2 vector with the velocity and position estimations for the given axis.

As we saw, the accuracy of the velocity data was not as precise as we need to try the new error model, we try with other type of filter, in that case a four states Kalman filter. We apply it, by following the following steps:

1. We use the data we obtain after applying the first two steps of the filter application above. Cartesian coordinates from en-route trajectories and ToD vector.
2. After that, we calculate the measurement error covariance matrix. To derive this matrix, we must first calculate the error in the measurements between the theoretical position and the current reported position. To perform this calculation, we take the measurement for which we want to calculate the error and the measurements before and after it. Then we join the before and after and get the theoretical position. Then we calculate the difference between the theoretical and the reported position as shown in figure A.1.

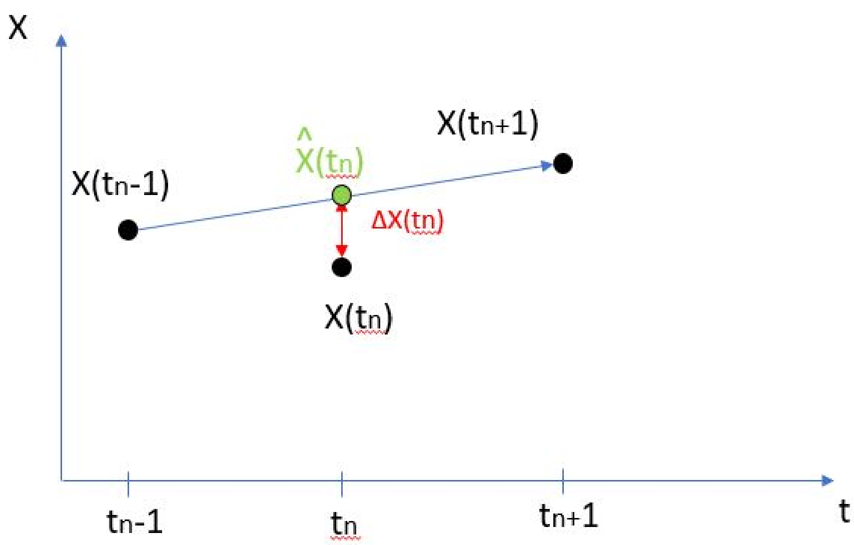

Figure A.1: Calculation of the difference between theoretical and reported position

The calculation of the theoretical position is calculated from the formula A.4 and the difference with A.5.

$$\hat{x}(t_n) = \frac{x(t_{n+1}) - x(t_{n-1})}{t_{n+1} - t_{n-1}} \cdot (t_n - t_{n-1}) + x(t_{n-1}), 2 \leq n \leq N-1 \tag{A.4}$$

$$\triangle x(t_n) = x(t_n) - \hat{x}(t_n) \tag{A.5}$$

After this we perform the same calculations but in this case for the y-axis so that we obtain $\hat{y}$ and $\triangle$y(t$_n$). With all this data now we can calculate the sigma for the different axis using the formulas A.6, A.7 and A.8 with N as the number of reports for that flight.

$$\sigma_x^2 = \frac{1}{N-2} \sum_{n=2}^{N-1} \triangle x(t_n)^2 \tag{A.6}$$

$$\sigma_y^2 = \frac{1}{N-2} \sum_{n=2}^{N-1} \triangle y(t_n)^2 \tag{A.7}$$

$$\sigma_{xy} = \frac{1}{N-2} \sum_{n=2}^{N-1} \triangle x(t_n) \triangle y(t_n) \tag{A.8}$$

Finally, when all sigmas are calculated, then we have the measurement error covariance matrix, C.

$$R = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} \tag{A.9}$$

3. In this step we are going to apply the Kalman filter, to apply it we give the coordinate data of both axes, the ToD vector, the measurement error covariance matrix and the aceleration standard deviation of the model. The Kalman filter works in such a way that it performs iterations with this data using only the current input measurements, the previously calculated state and its uncertainty matrix. In this way, it estimates the data but with each iteration it gives more weight to its estimates to the detriment of the input data. Once applied, it returns the estimated velocity and position in geodetic coordinates for both axes.

4. Once we have the information, we proceed to the Track Angle (θ) calculation by means of A.10.

$$\theta = \text{arctan}(\frac{V_x}{V_y}) \tag{A.10}$$

5. Once we have the track angle calculated for each report, as it is a straight section, the track angle must be constant, although as it is born from the estimation, it has a small variability. For this reason, we will take only the track angles that have a difference with the previous one less than 10^{-4}, which is when it has already converged, and we will use the average of the track angles that meet this condition as the fixed track angle.

6. Finally, we are going to calculate the total velocity, since the velocity we have obtained is separated into the velocity per axis. To achieve this we will use the formula A.11

$$V = \sqrt{V_x^2 + V_y^2} \tag{A.11}$$

As expected, the use of the four states Kalman filter has a higher accuracy in the estimation of velocity data and the Track Angle derived from it. Below we can see a comparison where the estimation of both filters is compared for two flights.

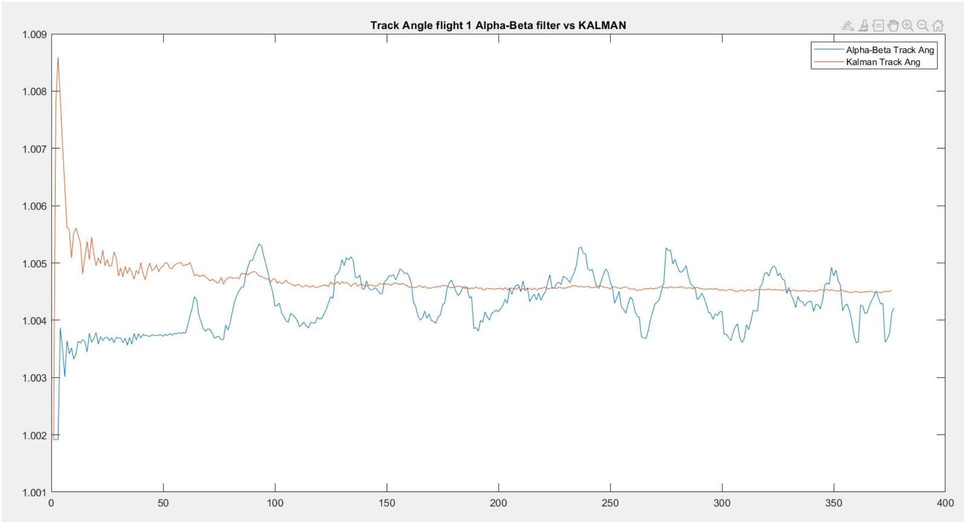

Figure A.2: Comparison of filters for track angle estimation for flight 1

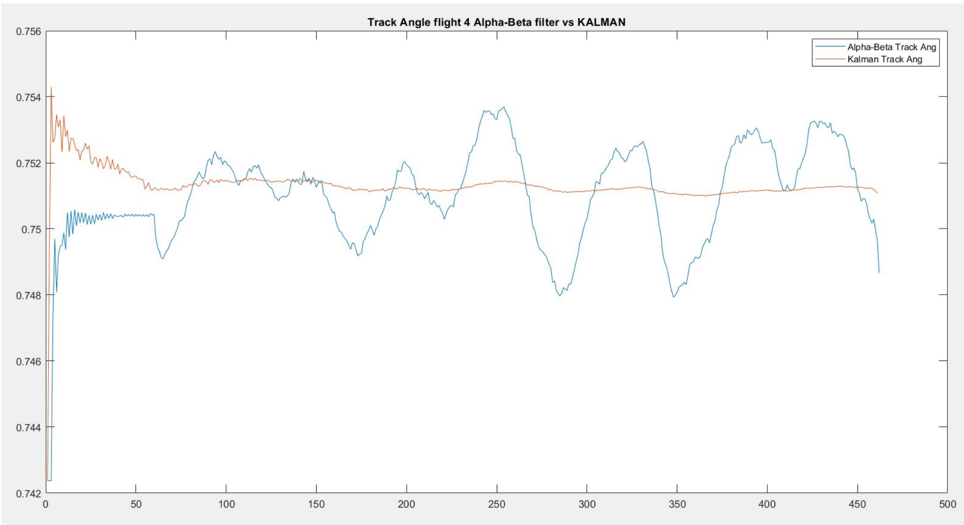

Figure A.3: Comparison of filters for track angle estimation for flight 4

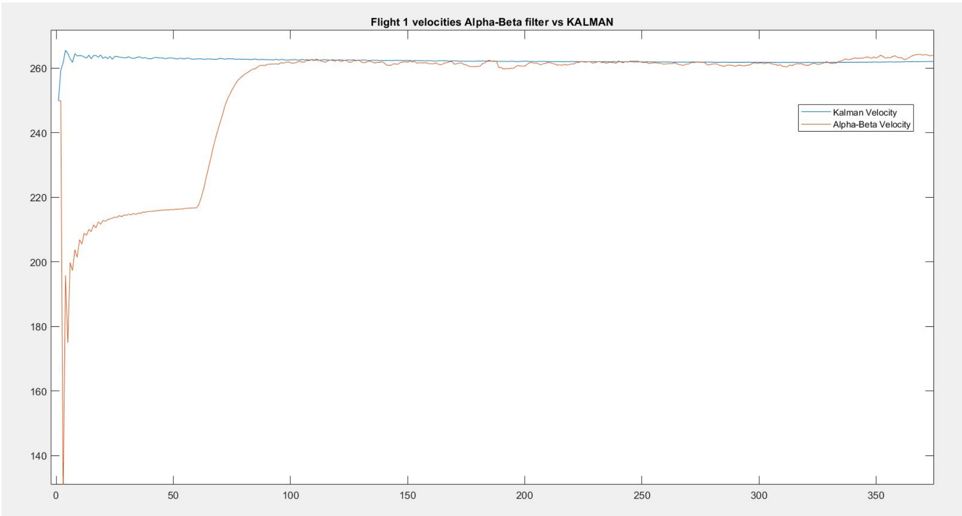

Figure A.4: Comparison of filters for velocity estimation in flight 1

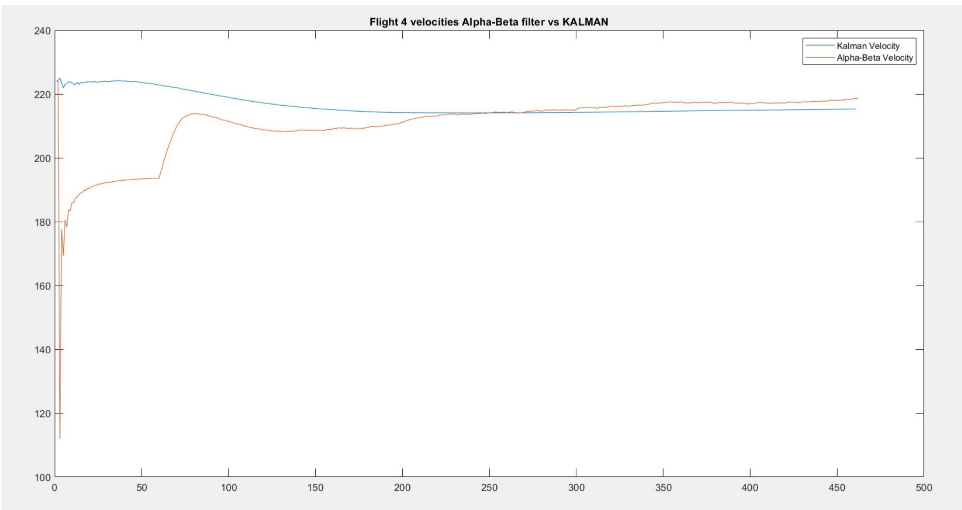

Figure A.5: Comparison of filters for velocity estimation in flight 4

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